21^{st} INTERNATIONAL CONGRESS OF THEORETICAL AND APPLIED MECHANICS

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ICTAM04
Abstracts and CD-ROM Proceedings

Edited by:

W. Gutkowski & T.A. Kowalewski

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PREFACE

The International Congress of Theoretical and Applied Mechanics held in Warsaw, Poland is the twenty first congress of a series started eighty years ago in Delft, Netherlands. The idea of congresses devoted to mechanics, can be traced back to a conference on problems of fluid mechanics held in Innsbruck, 1922. It was organized by four individuals, whose names, are and will, remain very well known to next generations of scientists, C. W. Oseen, T. Levi-Civite, T. von Kármán, and L. Prandtl. This conference was so fruitful, that the organizers decided to arrange similar meetings in the future, every four years, and to extend the scope of the future meetings to include solid mechanics.

From the meetings of the Congress Committee sprang the idea of a more permanent organization to look out for the world interests in the mechanical sciences. Thus, IUTAM, the International Union of Theoretical and Applied Mechanics, was formed on September 26, 1946. In 1947 IUTAM became a member of ICSU, the International Council of Scientific Unions, itself founded in 1931. The highest authority of IUTAM is the General Assembly, with delegates from the Adhering Organizations, each of which is affiliated with a national learned society in a given country.

Contemporary mechanics poses both, the fundamental problems from the area of pure science, and its strong links with modern technology. It spreads over such areas of our knowledge as oceanography, physical chemistry, biology, medicine, geophysics and astrophysics. Hence, any conclusions deduced in the framework of mechanics, are likely to have a value for other fields. We do hope that this meeting will contribute in widely spreading the knowledge in our field of interest and the advancement of mutual human understanding. James Clerk Maxwell put it in a short conclusion:

> *The true seat of science is not in the volume of transactions, but in the living mind, and the advancement of science consists in the direction of the men's minds into a scientific channel.*

One of these channels, the 21st International Congress of Theoretical and Applied Mechanics was invited to be held in Warsaw by the:

- Polish National Committee of IUTAM,
- Institute of Fundamental Technological Research of the Polish Academy of Sciences,
- Warsaw University of Technology.

We hope that the Congress will stimulate the endeavours to find the solutions to open problems of mechanics, and will pose new questions, to be answered in future. We would like to thank all the contributors of this Congress. Your contribution of up to minute research makes the Congress a success. Welcome in Warsaw!

Witold Gutkowski
Tomasz Kowalewski

Warsaw, 20.07.2004

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Scientific Program

The scientific program consists of plenary opening and closing lectures, sectional lectures, mini-symposia, and contributed papers presented in lecture and seminar presentation sessions. These are intended to cover all aspects of mechanics. This volume contains 1417 papers, having been drawn on from the oral and the seminar presentations of the congress. Each paper consists of a printed Short Abstract and an Extended Summary recorded on an enclosed CD-ROM. Obviously, the book that has to be available at the congress is based on papers that had to be submitted over half a year ahead. Therefore, the congress itself, in many cases, may deliver more recent data and evaluative work than had been possible to allude to in the publication.
All contributed papers were peer reviewed. Recommendations had been received from Pre-selection Committees of the National Committees of the nine countries: Canada, France, Germany, Japan, PR China, Poland, Russia, UK and USA. Moreover, recommendations had been received from the Chairs of the Mini-Symposia and of the Pre-nominated Sessions with classifications of the papers submitted within the topics of their Symposia/Sessions. Finally, the International Papers Committee paid careful attention to the above recommendations. Accordingly, of the 2086 eligible submissions 1574 contributions were invited by the IPC for their presentation. The total number of submitted and accepted papers represents a quite substantial enhancement relative to the previous congresses, providing evidence of vitality of the contemporary mechanics.

Codes used for Lectures and Sessions

Throughout the book and CD-ROM all papers are coded using letters and numbers denoting appropriate session code, presentation type, presenting author's ID, presentation day, time and lecture room. Following codes are used to mark sessions:

Opening and Closing Lectures	– OL, CL
Sectional Lectures	– SL
Mini-Symposia	– MS
Pre-nominated Sessions	
– Fluid Mechanics	– FM
– Solid Mechanics	– SM
– Topics involving both	– FSM

Presentation types are: Plenary (I), Lecture (L) and Seminar (S).

CONTENTS

Mini Symposia

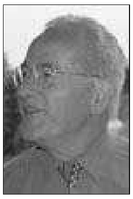
Pre-Nominated Sessions

Fluid Mechanics

Solid Mechanics

Topics involving both fluid mechanics and solid mechanics

Opening Lecture



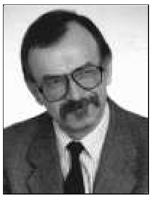
Interplay Between Air and Water

Leen van Wijngaarden
University of Twente J.M. Burgers Centre for Fluid Mechanics, Netherlands

OLI_10498
Mon • 11:00 • 000

In the Introduction I will recall, among others, the period of the Cold war in which thanks to Polish colleagues scientific contacts between East and West were maintained. After that several aspects of the flow of mixtures of air and water will be discussed and illuminated with examples. Finally I will give some comments on the differences and similarities between fundamental and applied science and scientists.

Closing Lecture



Stochastic Dynamics of Engineering Systems

Kazimierz Sobczyk
IPPT PAN, Warsaw, Poland

CLI_10697
Fri • 14:30 • 000

The main objective of this plenary lecture is to expose the most notable models and results of stochastic dynamics a huge branch of contemporary science investigating real physical/engineering systems in the presence of random excitations. The lecture will consist of two parts. First, the general nonlinear stochastic governing equations of a wide class of real engineering systems will be presented along with their possible interpretations and the associated applicatory problems and results; in particular, a methodology used for the reliability assessment of randomly excited mechanical/structural systems will be discussed. Afterwards, various qualitative phenomena generated (in nonlinear systems) by random noise will be expounded (e.g. explosions of the response, noise-induced phase transitions, stochastic resonances, bifurcations, etc.). In the end of the lecture some computational problems and new challenges will be indicated

Sectional Lectures

Some Issues in Active Vibration Control of Smart Structures

Andre Preumont
Active Structures Laboratory, Brussels, Belgium

SL13I_10930
Tue • 09:30 • 208

The paper is divided into three parts. The first one is devoted to the active damping of structures with collocated actuator/sensor pairs, with a particular attention to performance prediction, stability and robustness. A few examples are described, related to space, precision engineering and civil engineering projects. The second part is concerned with vibration isolation; various implementations of the celebrated sky-hook single-axis isolator are discussed and compared; a particular attention is given to the case where the isolator is attached to a very flexible structure. Next, a six-axis isolator based on the architecture of a cubic Stewart platform is discussed in the context of space applications; the close relation between performance and technology is emphasized. The third part is devoted to the spatial filtering with discrete sensor arrays and distributed piezoelectric films. The paper discusses how discrete arrays can be programmed to provide modal filtering or frequency shaping of frequency response functions; the limitations due to spatial aliasing are also described. Finally, a porous electrode design is described, which allows to tailor the equivalent piezoelectric properties of piezo films to achieve a wide class of distributed filters.

Ocean Circulation and Its Influence on Climate

Peter B. Rhines
University of Washington, Seattle, USA

SL14I_12781
Tue • 09:30 • 134

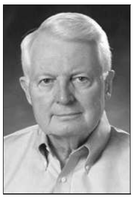
Heat- and water transports by the atmosphere- and ocean circulations are principal elements of global climate. Natural variability and human-induced emissions combine to create active patterns of climate change which are not reflected in overall averages like global mean-surface temperature. Some of these patterns are well-known, like el Nino/Southern Oscillation cycles and the North Atlantic Oscillation; others are less familiar and may be abrupt: the 30-year decline in salinity of the northern Atlantic, invasion of the Arctic by warm Atlantic waters, and the rise and subsequent decade-long decline in the subpolar North Atlantic circulation, and the pattern of global heat content and upper ocean salinity increase in the subtropics. Dynamical elements of Rossby-wave theory, jet dynamics, stratified spin-up, and rotating convection seem to be important. We also describe a new invention, the Seaglider, with which we are patrolling the cold northern oceans to examine the structure of abruptly changing climate.

Micromechanics and Microviscoelasticity of Cells

Erich Sackmann
University of Munich, Garching, Germany

SL15I_11327
Tue • 09:30 • 309

Magnetic tweezer microrheometry combined with colloidal strain-field mapping enable local measurements of absolute Young moduli of cell envelopes. Microrheometry enables real time studies of rapid reorganizations of the membrane coupled actin cortex of vascular endothelial cells by activation with inflammational agents (e.g. histamine involved in allergic reactions). Actin corteces are enforced by formation of stress fibers or micromuscles induced by a sol-gel transition triggered by activation of myosin and Ca-induced actin polymerization within $\sim$1 sec. The reorganisation induces centripetal contractions of cells leading to the formation of gaps within the endothelium. Evaluations of the quasi-random transport of magnetic tweezers and creep responses show: the cytoplasm consists of soft streets separated by forbidden zones. The intracellular space behaves as viscoplastic body. Creep responses are described as random transitions within multiwell potentials. This enables weak forces (10 pN) to transport intracellular compartments through hard regions by statistical bond breakage.

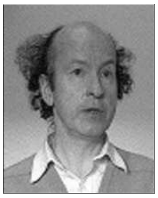


Electrokinetics and Electrohydrodynamics in Microfluidics

D.A. Saville
Princeton University, USA

SL16I_10529
Tue • 09:30 • 306

Electric fields offer an exquisite means of control over small-scale fluid and particle motion. In some instances – electrokinetics – the applied field acts on the intrinsic (equilibrium) electric charge arising from covalently bound ionogenic groups bound to an interface. In other cases – electrohydrodynamics – the charge arises from the action of a field on an otherwise electrically neutral system. Despite this similarity, descriptions of electrokinetic and electrohydrodynamic motion developed more or less independently. The theoretical underpinnings of electrokinetics were laid down by Helmholtz and Smoluchowski in the late 19th and early 20th centuries; the theory of electrohydrodynamics was set forth by G. I. Taylor and J. R. Melcher in the 1960's. Nevertheless, both descriptions stem from the same fundamental model: the Navier–Stokes equations augmented with an electrical body force, Gauss's law, and conservation equations for the several ionic species. The development of a unified picture will be described along with its implementation. Special attention will be will be given to microfluidic applications involving the movement of particles and fluids by electrophoresis and electroosmosis and the assembly of colloidal crystals.



Near-critical Point Hydrodynamics and Microgravity

Daniel A. Beysens
CEA, Service des Basses Températures, Grenoble, France

SL3I_10880
Tue • 09:30 • 315

Near their critical point, fluids exhibit anomalous behavior of thermodynamic parameters (divergence of specific heat, compressibility and expansion coefficients) and transport coefficients (heat conductivity, thermal diffusivity). It results in a very particular hydrodynamics where in earth gravity field the fluid is extremely sensitive to even minute temperature gradients. I will emphasize here two examples where weightlessness experiments play a key role in revealing phenomena hidden on earth by convection and sedimentation. One is a very fast thermalization effect ("piston effect") where a thermal boundary layer expands and adiabatically heats the whole fluid. Critical slowing down and microgravity are also used to investigate the dynamics of phase separation with no gravity-induced sedimentation. The key role of the coalescence of domains makes valid only two growth laws. Their occurrence depend only on the gas and liquid volume fraction. This universality permits to successfully apply these evolution laws to a well-known biological problem: the sorting of embryonic cells.

Nanoscale Mechanics of Biological Materials

Huajian Gao
Max Planck Institute for Metals Research, Stuttgart, Germany

SL5I_10772
Tue • 09:30 • 219

In this lecture I will discuss mechanical properties associated with the nanostructures of biological materials. A simple and universal model is firstly introduced to describe the generic nanostructure of a wide variety of biological materials including bone, shell, dentin, wood, and tendon. We show that the superior mechanical properties of biological materials stem from the unique characters of their generic nanostructure in which perfection and harmony are achieved between stiff mineral nanoparticles and soft protein matrix: The mineral provides stiffness and strength for the composite structure while protein serves a multitude of support and relaxation functions. We conclude that the soft protein layer can homogenize stress distribution around the mineral and serve as a buffer to isolate damage.The nanometer size of mineral particles may have evolved to achieve maximum strength and maximum tolerance of flaws. The large aspect ratio of mineral crystals is selected to compensate the softness and weakness of protein and plays a crucial role in various mechanical properties of biological materials, such as the stiffness, stability, viscoelastic properties and interface strength. As a closely related topic, I will describe mechanics of hierarchical adhesion structures of Gecko where the nanometer size may have again been selected to achieve maximum strength while tolerating flaws in contact with a substrate. The flaw tolerance is key to robust design of structures and robustness is the key to survival.

Mechanics of Rubberlike Solids

Raymond W. Ogden
University of Glasgow, Glasgow, UK

SL12I_10143
Thu • 08:30 • 309

The lecture begins with an overview of the large deformation stress-strain response of rubberlike solids based on experimental observations, in particular of vulcanised natural rubber. First, experimental results that characterize the elastic behaviour of rubber are described. This is followed by illustrations of how the behaviour departs from the purely elastic; we examine stress softening associated with the Mullins effect, and the different degrees of stress softening for different rubbers are highlighted. Other inelastic effects such as hysteretic stress-strain cycling following pre-conditioning of the material (to remove the Mullins effect) are also described. Different approaches to modelling these behaviours on the basis of the isothermal phenomenological theory of elasticity and inelasticity are then described in detail and the quality of the comparison between theory and experiment is discussed. Finally, we discuss recent theoretical work concerning the coupling of mechanical and magnetic effects in so-called magneto-sensitive elastomers, which are being used as active components in various applications where the mechanical stiffness of the material can be changed rapidly by the application of a suitable magnetic field.

Probability Distribution Functions for a Rapidly Rotating Turbulent Flow: Experiment and Theory

Harry L. Swinney, Charles N. Baroud, S. Jung
University of Texas at Austin, Austin, USA

SL18I_10495
Thu • 08:30 • 208

We have made velocity measurements on a quasi-two-dimensional turbulent flow in a rapidly rotating annulus (Reynolds number 20000, Rossby number (0.1). The probability distribution function (PDF) for velocity increments measured over a wide range of distances between measurement points is non-Gaussian, but the PDF is self-similar (independent of the distance between measurement points). The non-Gaussian PDF for the velocity increments is described well by a form deduced from nonextensive statistics. Using conservation of potential enstrophy and energy, we obtain a PDF for the vorticity by maximizing a nonextensive entropy function. The resultant PDF is in better accord with the measurements than the PDF derived assuming extensive entropy.

Suspensions: From Micromechanics to Macroscopic Behavior

John F. Brady
California Institute of Technology

SL4I_12160
Thu • 08:30 • 306

It's morning. You pour cereal in your bowl, shake the orange juice, fill your glass, and pour milk over your cereal. Why did you shake the orange juice and not the milk? Why do you pour cereal? These are just some everyday examples of complex fluids – materials that often behave like water or air, but just as often display quite different behavior. Many complex fluids are in the form of particles dispersed in a host liquid or gas, and it is the particle-level interactions that give rise to interesting macroscopic phenomena, such as shear thinning and thickening, viscoelasticity and structure formation. This talk will discuss the micromechanics of particulate dispersions and how the interplay of colloidal, Brownian and hydrodynamic forces sets the material's microstructure and determines its macroscopic properties. So why did you shake the orange juice and not the milk?

Variational and Multiscale Methods in Turbulence with Particular Emphasis on Large Eddy Simulation

Thomas J.R. Hughes
The University of Texas, Austin, USA

SL6I_13003
Thu • 08:30 • 315

We present a review of progress in applying the Variational Multiscale Formulation to turbulent flows. We begin with a description of the type of engineering applications we are interested in and follow with a critical evaluation of the conventional approach to Large Eddy Simulation based upon the filtered equations. We then discuss modeling and consider the classic Smagorinsky model (inspired by Von Neumann). According to the analysis of Lilly, by discretizing into the inertial subrange, assuming a Kolmogorov spectrum, and equating model and turbulent dissipation, the parameters of the Smagorinsky model are determined. However, we argue that the effect is to dissipate too much energy from the large scales. The anatomy of the model is further elucidated by considering the Spectral Eddy Viscosity concept of Heisenberg. With this background, we argue that numerical analysis considerations suggest a multiscale framework for modeling. We then describe the Variational Multiscale Formulation, which obviates many of the shortcomings of the filtered equations and possesses enhanced potential for modeling. We demonstrate numerically that the simplest instantiations of the idea lead to significantly improved performance on homogeneous flows, and equilibrium and non-equilibrium turbulent channel flows. We mention in closing the results of some other investigators who have also obtained very good results with various implementations of the approach and we describe current research activities.

Nonlinear Dynamics in Ocean Engineering

Edwin Kreuzer
Technical University Hamburg-Harburg, Mechanics and Ocean Engineering, Hamburg, Germany

SL8I_10544
Thu • 08:30 • 134

There is an increasing demand world wide on ocean engineering systems. The ability to predict and characterize the dynamic behavior of such systems before large financial commitments are made to their manufacture is an essential ingredient of contemporary engineering. Linear models often will not provide sufficient accuracy and reliability to analyze and predict the dynamics of the real system in a satisfying manner. Nonlinear effects have to be taken into account when setting up tools which support the design process. For example ship motions in rough sea, moored platforms and crane vessels under wave excitation show essentially nonlinear behavior. Unfortunately, these systems operate under certain conditions at the stability limit and this sometimes leads to serious accidents with loss of human lives and causing huge environmental pollutions. A future goal should be the optimization of ship design and ship as well as crane vessel operations such as the nonlinear dynamics is taken into account. In this sectional lecture the dynamics of floating ocean engineering structures is discussed in detail.

A Bridge Between the Micro- and Mesomechanics of Laminates: Fantasy or Reality

Pierre J. Ladeveze
ENS Cachan, Cachan, France

SL9I_10508
Thu • 08:30 • 219

The last quarter-century has witnessed considerable research efforts in the mechanics of composites in order to understand their behavior and to model or calculate them – the ultimate goal being the design of the materials/structures/manufacturing processes. Even in the case of stratified composites (which are the most studied and, therefore, the best understood), the prediction of damage evolution up to and including final fracture remains a major challenge in the modern mechanics of composite materials and structures. One could jokingly say that there is, on the one hand, the micromechanics of laminates where one counts cracks and, on the other, the meso- or macromechanics of laminates where one measures stiffnesses – with only few links between the two. How to bridge the micro-and mesomechanics aspects and how this affects the understanding and prediction of localization and final fracture are the two main questions discussed here.

Multibody Dynamics: Bridging for Multidisciplinary Applications

Jorge Ambrósio
Instituto Superior Técnico, Lisboa, Portugal

SL1I_11040
Fri • 08:30 • 208

The design requirements of advanced mechanical and structural systems and the real-time simulation of complex systems exploit the ease of use of the powerful computational resources available today to create virtual prototyping environments. These advanced simulation facilities play a fundamental role in the study of systems that undergo large rigid body motion while their components experience material or geometric nonlinear deformations, such as vehicles, deployable structures, space satellites, machines operating at high speeds or robot manipulators. If in one hand the nonlinear finite element method is the most powerful and versatile procedure to describe the flexibility of the system components on the other hand the multibody dynamic formulations are the basis for the most efficient computational techniques that deal with large overall motion. Therefore, it is no surprise that many of the most recent formulations on flexible multibody dynamics and on finite element methods with large rotations share some common features. In multibody dynamics methods body fixed coordinate frames are generally adopted to position each one of the system components and to allow for the specification of the kinematic constraints that represent the restrictions on the relative motion between the bodies. Several formalisms are published suggesting the use of different sets of coordinates, such as Cartesian [1], natural [2] and relative coordinates [3]. Depending on the type of applications pursued by the user, on the experience of the developer or on any specific objectives each one of the referred types of coordinates has advantages and disadvantages relative to the others. Due to their ease of computational implementation, their physical meaning and the wide spread knowledge of their features all the formalisms presented in this work are based on the use of Cartesian coordinates. However, it must be noted that the same formulations can also be developed with any other type of coordinates selected to describe the multibody systems. The equations of motion of the multibody systems are obtained using the Euler–Lagrange equations and the principle of virtual works [1]. To kinematic constraints that restrict the relative motion between the different components of the system are added to the equilibrium equations by using Lagrange multipliers. The set of equations obtained in this manner, together with the acceleration constraint equations, are solved to obtain the system accelerations. The system state variables are then integrated in time, using typically a variable order and variable time step integration algorithm [4] for a pre-defined period of time. The methodological structure of the equations of motion of the multibody system obtained allows the incorporation of the equilibrium equations of a large number of disciplines and their solution in a combined form. The description of the structural deformations exhibited by the system components by using linear [5] or non-linear finite elements [6] in the framework of multibody dynamics is an example of the integration of the equations of equilibrium of different specialities. Of particular importance in the applications pursued with the methodologies proposed is the treatment of contact and impact which are introduced in the multibody systems equations either by using unilateral constraints [7] or by applying a continuous contact force model [8]. The readily availability of the state variables in the multibody formulation allows for the use of different control paradigms in the framework of vehicle dynamics, biomechanics or robotics and its integration with the multibody equations [9]. The coupling between the fluid and structural dynamics equations allows for the development of applications where the fluid-structure interaction is of importance, especially for cases where the large absolute motion of the system or the large relative rotations between the system components are of importance [10, 11]. The research carried at IDMEC and the different collaborative works developed with other research groups provide the examples offered in this presentation. Application cases involving the modelling of realistic mechanisms, passive safety of road and rail vehicles, impact and human locomotion biomechanics, automotive and railway dynamics and the control of multibody systems are used to demonstrate the developments listed in this presentation. In the process of presenting the different applications several possibilities for future developments are discussed.

Turbulence and Large-Eddy Simulations

Marcel Lesieur
Grenoble National Polytechnic Institute, Grenoble, France

SL10I_10731
Fri • 08:30 • 315

After having discussed the limits of turbulence direct-numerical simulations, one presents large-eddy simulations methods, where small scales are filtered out and modelled by appropriate eddy coefficients in the evolution of large scales. Scalar mixing is studied as well. We concentrate on Grenoble models developed originally in Fourier space. One presents coherent-vortex dynamics obtained thanks to these models for incompressible isotropic turbulence at infinite Reynolds number, and statics of a channel flow. It is shown that the LES compressible formalism may be simplified by using a macro-pressure and a macro-temperature. One displays an animation of quasi-longitudinal vortices in a channel at low Mach. Then the compressible jet controlled upstream is studied at Mach 0.7 and 1.4 (Reynolds 36000). With a white-noise forcing, the supersonic jet is more focused than the subsonic one. With other types of forcings, one can generate a blooming jet.

Probability Phenomena in Perturbed Dynamical Systems

Anatoly Neishtadt
Space Research Institute RAS, Moscow, Russia

SL11I_10551
Fri • 08:30 • 219

If in a deterministic dynamical system a small variation of initial data produces a big variation of dynamics, the behavior of this system can be treated as a random one. This nonrigorous assertion known as a principle "small causes and big effects" is in the basis of the theory of deterministic chaos. Remarkably, such quasi-random behavior exists also in the systems which differ by an arbitrarily small perturbations from the systems with very simple (periodic, quasi-periodic) dynamics. Different types of perturbed dynamics have certain probabilities. Analysis of long-term dynamics leads to random walk problems. In the talk we shall discuss probability phenomena associated with passages through separatrices and passages through resonances in perturbed dynamical systems. The theory which describes these phenomena has applications in different problems including problems of capture of satellites into resonances, of acceleration of charged particles, of chaotic advection of impurities.

Problems in Astrophysical Fluid Dynamics

Edward Spiegel
Columbia University, New York, USA

SL17I_10158
Fri • 08:30 • 134

The variety of fluid processes observed throughout the universe staggers the imagination, yet the subject has not attracted nearly as much serious interest from professional fluid dynamicists, as have geophysical fluid problems. Yet, in the sixties and seventies of the previous century, several symposia were held that brought astrophysicists and fluid dynamicists together under various titles such as Cosmical Gas Dynamics; we might even follow Lighthill's lead in another subject and speak of Astrofluiddynamics. Those old symposia were well attended and quite stimulating. To give an idea of the kinds of problems that arise in astrophysics I outline here a (subjective!) selection of fluid dynamical problems faced by astrophysicists. I begin with thermal instability, a characteristic process discussed in astrophysics and this flows naturally into the larger domain of radiative fluid dynamics wherein radiation affects the dynamics both thermally and dynamically and also plays a significant role in the observations. Astrophysicists must also face the problems associated with long mean free paths in plasmas and in their gravitational analogues – gases whose constituent particles are stars or even galaxies. As time permits, I shall also speak of fluid dynamics in accretion disks and rotational processes in the sun. This selection only scratches the surface of the subject and it is meant to be introductory. My subject is really astrophysically motivated fluid dynamics and the approach to be used in this discourse is largely analytic. However, I would stress that, on the hard core astrophysical side, progress is being made largely in the development of simulations. This is true throughout the subject, and is especially evident in a wide range of compressible flows such are encountered in stellar convection, the dynamics of interstellar gas clouds and in the formation of large-scale structure in the early universe.

Rapid Formation of Strong Gradients and Diffusion in the Transport of Scalar and Vector Fields

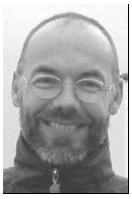
Konrad Bajer

Institute of Geophysics, Warsaw University, Poland

SL2I_10042

Fri • 08:30 • 309

An important issue in the theory of transport by moving fluids is the role of dissipation when the medium is nearly ideal. The central problem of this nature is understanding viscous dissipation at very large Reynolds numbers. We will discuss a few problems in the same category but linear and therefore more promising although, as it turns out, surprisingly rich and far from being resolved. Their common denominator is the interplay between diffusion and advection. In a typical flow the latter tends to decrease the characteristic length scales of the spatial variations of the transported quantity, thus increasing the rate of diffusion. Depending on a particular configuration either this rapid diffusion prevails and efficiently annihilates all gradients, or a kind of balance is reached and a quasi-steady dissipative structure emerges. We discuss both types of behaviour paying special attention to spiral structures formed by a diffusing passive scalar and to current sheets in magnetohydrodynamics.



Non-Newtonian Fluid Mechanics Using Molecular Theory

Roland Keunings

CESAME, Université catholique de Louvain, Louvain, Belgium

SL7I_10512

Fri • 08:30 • 306

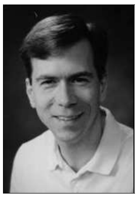
Many natural and synthetic fluids are viscoelastic materials, in the sense that the stress endured by a macroscopic fluid element depends upon the history of the deformation experienced by that element. Notable examples include polymer solutions and melts, liquid crystalline polymers, and fibre suspensions. The remarkable rheological properties of viscoelastic liquids cannot be described by the Navier–Stokes equations, but rather are governed by the flow-induced evolution of molecular configurations. In the present lecture, I survey the field of multiscale simulation of viscoelastic flow using molecular models, and present recent results based on tube theory of linear entangled polymers. The talk will be of a general nature so that it is (hopefully) both understandable and useful for colleagues and students working on other topics in theoretical and applied mechanics.

MINI SYMPOSIA

MS1

Smart materials and structures

Chairpersons: N. Sottos (USA), J. Holnicki-Szulc (Poland)



Autonomic Healing of Polymers and Composites

MS1I_11684

Mon • 13:30 • 208

Scott R. White[(1)], Nancy R. Sottos[(2)], Jeffrey S. Moore[(3)], Eric N. Brown[(2)], Alan Jones[(2)], Joseph Rule[(3)]

(1) *Aerospace Engineering, University of Illinois, USA*
(2) *Theoretical and Applied Mechanics, University of Illinois, USA*
(3) *Chemistry, University of Illinois, USA*

Inspired by biological systems in which damage triggers an autonomic healing response, structural polymers and polymer matrix composites have been recently developed that possess the ability to self-heal. Self-healing is accomplished by incorporating a microencapsulated healing agent and a catalytic chemical trigger within a polymer matrix. When the material is damaged, the microcapsules rupture and release the healing agent into the damaged region through capillary action. As the healing agent contacts the catalyst, polymerization is initiated and the damage is repaired. One promising healing chemistry based on the ring-opening-metathesis-polymerization (ROMP) of dicyclopentadiene and Grubbs' catalyst has yielded static fracture recovery in excess of 90% and greatly extended fatigue life. New healing chemistries and alternate healing approaches are explored with utility in a variety of structural polymer and polymer composite applications.

A Way to Search for Smart Materials with Unprecedented Physical Properties

MS1I_10722

Mon • 14:30 • 208

Richard D. James

University of Minnesota, USA

These thoughts begin with the observation by physicists, probing new phenomena through the use of first principles' studies, that the simultaneous occurrence of ferromagnetism and ferroelectricity is unlikely. While these studies do not consider the possibility of a phase transformation, there is a lot of indirect evidence that, if the lattice parameters are allowed to change a little, then one might have co-existence of "incompatible properties" like ferromagnetism and ferroelectricity. Thus, one could try the following: seek a reversible first order phase transformation, necessarily also involving a distortion, from, say, ferroelectric to ferromagnetic phases. If it were highly reversible, there would be the interesting additional possibility of controlling the volume fraction of phases with fields or stress. The key point is reversibility.Even big first order phase changes can be highly reversible (liquid water to ice, some shape memory materials), and we argue that it is the nature of the shape change that is critical. We suggest, based on a close examination of measured hysteresis loops in various martensitic systems, that reversibility is governed by the presence of certain special relations among lattice parameters. We give a example of the systematic use of these relations to discover new low hysteresis shape memory materials. Besides ferroelectricity – ferromagnetism, there are many potential property pairs that exhibit lattice parameter sensitivity and are candidates for the proposed strategy: soluability for H_2, optical nonlinearity, high band gap – low band gap semiconductors, insulator – conductor (electrical or thermal), opaque – transparent (at various wavelengths), high – low index of refraction, luminescent – nonluminescent, and new kinds of thermoelectric and thermomagnetic materials.

Elastic Wave Propagation Development for Structural Health Monitoring

Wiesław M. Ostachowicz

Institute of Fluid Flow Machinery PAS, Gdańsk, Poland

MS1I_10680
Tue • 08:30 • 208

This paper is a personal perspective of structural health monitoring technology and its applications as see from a current literature and projects. Recently, laminated composites with built-in piezoelectrics have attracted significant attention among researchers because of their potential application to controlling vibrations, suppressing noise, as well as monitoring the health of the structures. The investigated damage detection system is based on the known fact that material discontinuities affect the propagation of elastic waves in solids. The change in material characteristics, such as a local change in stiffness or inertia caused by a crack or material damage, will affect the propagation of elastic waves and will modify the received signals. Wave frequencies that are most sensitive to damage depend on the type of structure, the type of material, and the type of damage. Elastic waves are generated and sensed by an array of transducers either embedded in, or bonded to, the surface of the structure. Wave frequencies associated with the highest detection sensitivity depend, among others, on the type of the structure, the type of material, and the type of the damage. The proposed approach deals with the spectral finite element analysis method as a means of solving the wave propagation problems in structures. The change of the wave propagation process due to a damage appearance is examined by comparing the differences between the responses from damaged and undamaged structures. The influence of the damage growth for the wave propagation is also analysed. The differences in the propagating waves allow indicating the damage location and size in a very precise way. The proposed model can easily be used for detection of damage in complicated situations, i.e. multiple delaminations located in different places. The paper is not intended to be a comprehensive survey but merely to present a flavour of recent activity in this important subject.

A Novel Approach to the Application of Ferroelectric Thin Films to Micro-actuation

Kaushik Bhattacharya

California Institute of Technology, Pasadena, USA

MS1L_11731
Mon • 16:00 • 208

A micro-actuator capable of significant force and displacement remains an outstanding challenge in the development of micromachines. Active materials are attractive for their large work per unit volume, and specifically ferroelectrics since they are electrically activated. However, conventional piezoelectric materials display limited strains (0.1%), and conventional configurations like bi-morph cantilevers are too constrained to deliver the necessary performance. This talk will describe an alternative strategy that combines a new mode of electrostriction in ferroelectrics that explicitly use domain switching to deliver extremely large strains (1–6%) at moderate forces and electrical fields along with a new approach to microactuators that use partially released thin films. Together this strategy enables micro-actuators with large force and displacement. This talk will describe the theoretical analysis of the domain patterns in bulk and thin film ferroelectric perovskites that led to this strategy, detailed computational studies for specific designs and the subsequent experimental validation.

Stress Effects on Ferroelectric Thin Film Patterning, Properties and Performance

N.R. Sottos, T. Berfield, R. Ong, D.A. Payne

University of Illinois at Urbana-Champaign, USA

MS1L_11685
Mon • 16:20 • 208

Recent developments in soft lithographic patterning and micro-contact printing techniques enable the integration of ferroelectric thin films on a chip, rather than added as a discrete component in the system. As integrated device applications push the characteristic length scale of these materials smaller and smaller, surface and interface effects dominate response, producing significant scientific challenges in the characterization of mechanical properties, performance and reliability. In this paper, we investigate the complex roles of microstructure, interface effects and residual stresses on ferroelectric thin film performance. PZT films ranging in thickness from 200 nm to 1.0 micron are deposited by the sol-gel method onto a platinized Si substrate. The average residual stress, which is highly dependent on film thickness, is calculated from laser

reflectance measurements of wafer curvature during processing. Field-induced strains are measured interferometrically for films with well-characterized residual stress-states. Results indicate significant increases in film performance with a decrease in residual stress. Residual stress development also plays a significant role in the patterning and lift-off process. Preliminary investigations of interfacial adhesion and crack initiation of the sol-gel film on a functionalized Si substrate provide some insight into the stress driven mechanisms for mediated patterning.

Upper and Lower Bounds of Electric Induction Intensity Factors for Multiple Piezoelectric Cracks by the BEM

MS1L_12786
Mon • 16:40 • 208

Mitsunori Denda, Mayur Mansukh
Rutgers University, New Jersey, USA

The coupling of mechanical and electrical behaviors of the piezoelectric materials has find its many applications. However, they are plagued with the brittleness of the widely used piezoceramic materials. The lack of understanding and modeling tools of the piezoelectric fracture is limiting the further progress in the piezoelectric material based technology. This paper addresses issues on the crack surface electric boundary conditions. and suggests the upper and lower bound approach in the determination of the electric induction intensity factors using the boundary element method. These bounds are obtained by the using the impermeable and permeable crack solutions. The numerical Green's function for the crack is developed by the analytical integration of the continuous distribution of the generalized dislocation dipoles. The Green's function has the generalized stress singularity and no post process for the intensity factor determination is needed.

Ultrasonic Characterization of Phase Transformation in NiTi Wire During Thermomechanical Loading

MS1L_12637
Mon • 17:00 • 208

Michal Landa(1), Petr Sedlák(1), František Marsík(1), Petr Šittner(2), Vaclav Novák(2)
(1) *Institute of Thermomechanics, Academy of Sciences, Dolejskov, Prague, Czech Republic*
(2) *Institute of Physics, Academy of Sciemces, Na Slovance 2, Prague, Czech Republic*

Evaluation of thermo-mechanical properties of NiTi wires intended for vascular stent applications is carried out by combination of tensile tests at constant temperature with in-situ ultrasonic measurements (wave speed, attenuation) and electrical resistivity measurements. It is found that the mechanical and electric resistance results are mainly sensitive to R-B19 stress induced martensitic transformation, but the ultrasonic wave speed and attenuation vary most significantly when the R-phase reorientation or distortion take place.

SMA Hybrid Composites: Self-healing, Self-Stiffening and Shape Control Simulations

MS1L_12027
Mon • 17:20 • 208

Catherine L. Brinson, Deborah Burton, Xiujie Gao
Northwestern University, Evanston, USA

The usage of shape memory materials has extended rapidly to many fields, including medical devices, actuators, composites, structures and MEMS devices. For these various applications, shape memory alloys (SMAs) are available in various forms: bulk, wire, ribbon, thin film, and porous. In this paper, we consider the design and simulation of SMA Hybrid Composites with self-healing, self-stiffening and shape control functions. These composites are created by using SMA ribbons or wires inside a matrix material: SMA wires in a low melting point metallic matrix for self-healing materials or SMA wires/ribbons in a polymeric based composite panel/beam for adaptive stiffening or shape control via selective resistance heating. To study these materials, we develop an ABAQUS user element with an SMA constitutive law to simulate structural response of the SMA hybrid composites. Several examples are presented in which the critical design features and possibilities are highlighted.

Self-Healing Polymer Composites for Extended Fatigue Life

MS1L_13011
Mon • 17:40 • 208

Eric N. Brown(1), **Alan S. Jones**(2), Scott R. White(2), Nancy R. Sottos(2)
(1) *LANL, Los Alamos, USA*
(2) *UIUC, Urbana, USA*

A novel approach is explored for improving the fatigue life of thermosetting polymers through the addition of self-healing functionality. Thermosetting polymers are used in a wide variety of applications, but are susceptible to the initiation and

propagation of small cracks deep within the structure where detection is difficult and repair is virtually impossible. The material under investigation is an epoxy matrix composite that utilizes embedded microcapsules to store a healing agent and an embedded catalyst. A propagating crack exposes particles of catalyst and ruptures the microcapsules, which release healing agent into the crack plane. Polymerization of the healing agent is triggered by contact with the catalyst. Fatigue crack retardation and arrest from self-healing functionality result from crack-tip shielding mechanisms, such as hydrodynamic pressure and artificial-crack closure. In situ healing is observed to significantly extend fatigue life or permanently arrested fatigue crack growth over a wide range of loading conditions.

Transient Eigenstrains Without Incremental Displacements in a Hyperelastic Body

MS1L_10784
Thu • 09:30 • 208

Hans Irschik, Uwe Pichler
Institute for Technical Mechanics, University of Linz, Linz, Austria

We consider a hyperelastic body in a static intermediate configuration, loaded by an additional distribution of transient eigenstrains, the latter being e.g. due to the electric field in a piezoelastic body, or due to the temperature in a thermoelastic body. We seek for distributions of eigenstrain, such that that the incremental displacements vanish throughout the body. In the present paper, within the framework of the theory of small dynamic deformations superimposed upon a static strain, we derive solutions for eigenstrains that are applied at a sub-region of the body only.

Direct Identification of the State Equation in Complex Nonlinear Systems

MS1L_13007
Thu • 09:50 • 208

Sami F. Masri[(1)], John P. Caffrey[(1)], Thomas K. Caughey[(2)], **Andrew W. Smyth**[(3)], Anastasios G. Chassiakos[(4)]
(1) *USC, California, USA*
(2) *Caltech, California, USA*
(3) *Columbia University, New York, USA*
(4) *CSU Long Beach, California, USA*

A crucial element in the modeling and control of adaptive ("smart) systems, is the ability to develop high-fidelity, reduced order and reduced complexity nonlinear (i.e., not-necessarily linear) mathematical models for the physical systems of interest. Building on the basic idea behind the *Restoring Force Method* for the nonparametric identification of nonlinear systems, a general procedure is presented for the direct identification of the state equation of complex nonlinear systems. No information about the system mass is required, and only the applied excitation(s) and resulting acceleration are needed to implement the procedure. Arbitrary nonlinear phenomena spanning the range from polynomial nonlinearities to the noisy Duffing–van der Pol oscillator (involving product-type nonlinearities and multiple excitations) or hysteretic behavior such as the Bouc-Wen model can be handled without difficulty. In the case of polynomial-type nonlinearities, the approach yields virtually exact results. For other types of nonlinearities, the approach yields the optimum (in least-squares sense) representation in nonparametric form of the dominant interaction forces induced by the motion of the system. Several examples involving synthetic data corresponding to a variety of highly nonlinear phenomena are presented to demonstrate the utlity as well as the range of validity of the proposed approach.

The Concept of Multifoldig and Its Experimental Validation

MS1L_13015
Thu • 10:10 • 208

Jan Holnicki-Szulc, **Piotr Pawłowski**
IPPT PAN, Warsaw, Poland

The problem of energy absorption under impact loading is very important in a wide range of engineering applications. Although typically designed, passive energy absorbing systems provide a sufficient level of energy dissipation, they are unable to optimally decrease the level of acceleration. In contrast to the passive solutions, the proposed approach offers ability of structural adaptation to the conditions of the impact. Due to the presence of controllable micro-fuses, elements of the Multifolding Microstructure can optimally adjust their internal forces and therefore provide better performance in comparison to the passive absorbers. The undertaken experiment aims at the validation of the concept of multifolding and the verification of numerical models and control strategies applied in previous research.

Composite Plates with Active Fibres

MS1S_10136

Tue • 14:30 • 208

Mieczysł aw S. Kuczma
University of Zielona Góra, Zielona Góra, Poland

The bending problem of composite plates reinforced with active fibers is considered. The fibers are made of a shape memory material which may undergo a martensitic phase transformation. The matrix is treated as an elastic medium. Due to the phase transformation in fibers the deformation process is dissipative and accompanied by hysteresis loops. We study the stress-induced phase transformation under isothermal conditions and control this dissipation mechanism by imposing the requirements of the second principle of thermomechanics and making use of a set of internal variables describing distributions of austenite and different variants of martensite. We formulate this hysteretic problem in the form of a variational inequality of evolutional type. The finite dimensional counterpart of it is derived by the finite element method, and is solved incrementally as a sequence of complementarity problems. Results of numerical simulation will be presented.

Shape Fixity and Shape Recovery of Shape Memory Polymer and their Applications

MS1S_10821

Tue • 14:35 • 208

Hisaaki Tobushi(1), Ryosuke Matsui(1), Tsuyoshi Takada(1), Shunichi Hayashi(2)
(1) *Aichi Institute of Technology, Toyota, Japan*
(2) *Mitsubishi Heavy Ind., Yokohama, Japan*

The thermomechanical properties of polyurethane-shape memory polymer (SMP) foams are investigated experimentally and applications of SMP are introduced. The results obtained can be summarized as follows. (1) By cooling the foam after compressive deformation at high temperature, stress decreases and the deformed shape is fixed. By heating the shape-fixed foam under no-load, the original shape is recovered. The ratio of shape fixity is 100% and that of shape recovery 98%. (2) Recovery stres increases by heating under constraint of the fixed shape. Recovery stress is about 80% of the applied stress. (3) The shape deformed at high temperature is maintained for six months under no-load at Tg-60K without depending on maximum strain, and the original shape is recovered by heating thereafter. (4) If the deformed shape is kept at high temperature, secondary-shape forming appears. (5) Main properties of SMP and their applications are summarized.

Vibration Control of Stiffened Plates with Integrated Piezoelectrics

MS1S_10985

Tue • 14:40 • 208

Jin-Young Jung, **Ji-Hwan Kim**
Seoul National University, Seoul, S. Korea

The model is a laminated composite plate with stiffeners and PZT piezoceramic layers embedded on top and bottom surfaces to act as sensor and actuator, respectively. A uniformly distributed blast pressure is assumed over the entire plate surface for the sake of simplicity. The first-order shear deformation theory is adopted and the Hamilton's principle is used to derive the finite element equation of motion. The stiffness of a stiffener is reflected at all nine nodes of the plate element in which it is placed. The modal superposition technique and the Newmark-beta method are used in numerical analysis to calculate the dynamic response. Using linear quadratic regulator control, vibration characteristics and transient response are studied. When piezoelectric patches are distributed on the entire surface of plate, the effect of stiffener's location is investigated. Furthermore, the effect of piezoelectric patch's position on the transient response of the stiffened plate subjected to blast load is also studied.

Smart Diagnosis the Structural Damages Of Buildings: Fuzzy-genetic Approach

MS1S_11541

Tue • 14:45 • 208

Serhiy Shtovba, Olga Pankevich
VNTU, Vinnitsa, Ukraine

We have proposed a hybrid fuzzy-genetic approach for smart diagnosis (determination of cause) the structural damages of buildings. The approach consists of the following procedure: (1) description of the diagnostic model structure by hierarchical tree of fuzzy logical inference; (2) presentation of state parameters in linguistic variable form; (3) formalisation of linguistic terms by fuzzy sets; (4) formalisation of expert judgements about relationship state parameters – diagnosis by fuzzy knowledge bases; (5) tuning the fuzzy knowledge bases by genetic algorithms. An application of the approach is illustrated the fuzzy expert system, finding the cause of stone construction crack of buildings. An usage of hierarchically connected fuzzy rule bases provides the transparent and compact diagnostic model. Tuning the fuzzy model by a genetic algorithm provides low misclassification level. The proposed fuzzy-genetic approach seems to be feasible to creation decision making support systems for damage detecting and diagnosis for various mechanical constructions.

A Geometrically Non-Linear Finite Shell Element with Piezoelectric Layers

MS1S_11752
Tue • 14:50 • 208

Sven Lentzen, Ruediger Schmidt
IAM RWTH Aachen, Aachen, Germany

A geometrically non-linear total-Lagrangian finite element method is presented to investigate composite shells with integrated piezoelectric layers. The displacement field assumption is based on the first order Reissner-Mindlin theory and the strain-displacement relations for the mid-surface are valid for small strains but moderate rotations. Special attention is given to properly defining the electrical field quantities in material coordinates. By means of several benchmark problems certain phenomena are observed. Comparing the finite element solutions with analytical results based on beam theory it is concluded that the clamping effect is not negligible. For sensing purposes of the piezoelectric layers it is shown that the effect of the induced membrane strains is even larger.

Piezodiagnostics a New SHM Method and its Potential Engineering Applications

MS1S_11810
Tue • 14:55 • 208

Jan Holnicki-Szulc, **Przemysław Kołakowski**, Anita Orłowska, Andrzej Świercz,
Dariusz Wiącek, Tomasz G. Zieliński
IPPT, Warsaw, Poland

This paper presents a novel approach to damage identification based on the phenomenon of elastic waves propagation. The theoretical background is the dynamic Virtual Distortion Method, which is capable of modelling both a reference excitation signal propagated in the intact structure over a time domain and a perturbed signal due to some damage in the structure. The damage is modelled as stiffness loss. A dynamic inverse analysis is carried out in the time domain in order to identify multi-damage cases in terms of their locations and intensities. The main focus is taken on addressing numerical aspects of the presented approach as well as its potential engineering applications. The related methodology is presented including a brief description of experimental verification. Numerical example with successful identification is demonstrated. Advantages of the approach as well as its challenging points are discussed.

Thermal-Induced Fracture of Electroded Piezoelectric Composites

MS1S_11857
Tue • 15:00 • 208

Cun-Fa Gao, Masayuki Ishihara, Naotake Noda
Department of Mechanical Engineering, Shizuoka University, Japan

This paper deals with a generalized two-dimensional problem of an interface crack in a piezoelectric bi-material system, which consists of a soft internal electrode layer and two dissimilar piezoelectric semi-bodies located at the upper and lower two sides of the electrode layer. The crack is located between the electrode layer and the upper semi-body, and the two semi-bodies are assumed to be only subject to uniform heat flux at infinity. Based on the Stroh formalism for mixed boundary conditions of thermo-piezoelectric materials, the problem is at first reduced to an interfacial crack problem equivalent to that in purely elastic media, and then the explicit expressions are presented for the complex potentials. Finally, the structure of singular fields ahead of the interface is discussed. It is shown that the singular fields near the electrode-matrix interfacial crack are the same as those in a purely elastic bi-material system with interface cracks, that is, the crack-tip singularities of electrode-matrix interface cracks can uniquely be characterized by an inverse square root singularity and a pair of oscillatory singularities.

Thermal Buckling of Active Composite Plates with Shape Memory Alloy Fibers

MS1S_12011
Tue • 15:05 • 208

Rivka Gilat[(1)], Jacob Aboudi[(2)]
(1) *The college of JAS, Ariel, Israel*
(2) *TAU University, Ramat Aviv, Israel*

Micromechanically established constitutive equations for unidirectional composites with shape memory alloy fibers embedded in polymeric or metallic matrices are derived. These equations are subsequently employed to analyze the thermal buckling of rectangular composite plates. The shape memory alloy fibers are activated by a mechanical loading and unloading of the composite to an overall traction-free state, prior to the application of the thermal load. The present micro-macro-

structural approach enables an accurate modelling that accounts for the interaction of shape memory alloy fibers with its surrounding rather than the commonly adopted simplified analyses.

Study of Non-Linear Magnetomechanical Constitutive Relations of Ferromagnetic Materials

MS1S_12016

Tue • 15:10 • 208

Daining Fang, Xue Feng, Yongping Wan, Keh-Chih Hwang
Department of Engineering Mechanics, Tsinghua University, Beijing, China

In this investigation, both experimental and theoretical study on developing nonlinear magnetomechanical constitutive relations of ferromagnetic materials is performed. A novel magnetomechanical testing setup and the measurement techniques, which were developed for the measurement of the nonlinear magnetomechanical response of both magnetostrictive and soft ferromagnetic materials subjected to coupled magnetomechanical loading, are introduced. The detailed experimental results are presented and discussed. a general constitutive relation for ferromagnetic and magnetostrictive materials, based on the internal variable theory, is developed. A non-quadratic magneto-mechanical yield surface is introduced for both isotropic and anisotropic materials. The macroscopic features of ferromagnetic materials, such as hysteresis loop, magnetostrictive, magnetostrictive hysterisis, can be predicted. The calculated results are consistent with the experimental data well.

Optimum Control of Thermoelastic Deformation in a Smart Composite Disk

MS1S_12018

Tue • 15:15 • 208

Fumihiro Ashida[1], Theodore R. Tauchert[2]
(1) *Shimane University, Shimane, Japan*
(2) *University of Kentucky, Kentucky, USA*

This paper deals with a smart composite circular disk that controls a thermoelastic deformation resulting from an unknown thermal load. The disk consists of a transversely isotropic structural layer onto which two piezoceramic layers are bonded. An unknown heating temperature distribution acting on the structural layer surface is inferred from the induced electric potential distribution assumed to be measured in the middle piezoceramic layer. Then a step-wise electric potential distribution is applied to electrodes concentrically arranged on the top piezoceramic layer, in order to control the thermoelastic displacement distribution on the structural layer surface. This problem is analyzed using a potential function approach. The voltage applied to each electrode is determined by optimization so that the difference between the induced and desired displacement distributions is minimized subject to stress constraints. Numerical results are presented in graphical and tabular form.

Active Control of FGM Plates Using Distributed Piezoelectric Sensors and Actuators

MS1S_12147

Tue • 15:20 • 208

V. Balamurugan[1], **S. Narayanan**[2]
(1) *CEAD, Combat Vehicles R & D Establishment, India*
(2) *Department of Applied Mechanics, Indian Institute of Technology Madras, India*

“Functionally graded materials” (FGMs) are relatively new class of composite materials which are characterized by the smooth and continuous variation of the mechanical properties from one surface to the other. Due to its superior thermo-mechanical properties, FGMs have found extensive applications in aerospace, automobile, biomedical and nuclear industries. In the present work, distributed sensing and active control FGM plates using piezoelectric sensors and actuators are studied. A nine nodded shear deformable piezolaminated plate finite element based on first order shear deformation theory has been developed incorporating the FGM material model and the electromechanical coupling constitutive relations of the piezoelectric sensors/actuators. The FGM plate considered for case study is made of the combined aluminium oxide and a titanium alloy, Ti-6Al-4V and its properties are graded through the thickness direction according to a volume fraction power law distribution. The vibration control performance is explored using constant gain negative velocity feedback and LQR optimal control law which is based on state feedback. The influence of the constituent volume fraction of Ti-6Al-4V is also studied for the static deflection, natural frequency and controlled dynamic response of the FGM plates.

Transient Analysis of Piezoelectric Plates with Thermal Effects

MS1S_12385
Tue • 15:25 • 208

Stefano de Miranda, **Francesco Ubertini**
DISTART, University of Bologna, Italy

In this paper a finite element method for transient analysis of piezoelectric plates with thermal effects is presented. The kinematics of the model is based on a higher order plate theory. In particular, the plate is assumed to be able of thickness distensions and the electric potential and the temperature can vary through the thickness. The variational statement which supports the finite element formulation is of mixed type, involving mechanical, electrical and thermal both primary and secondary variables. The time integration is performed based on a discontinuous Galerkin approach.

On a Model of Layered Piezoelectric Beams Including Transverse Interactions Between Different Layers

MS1S_12552
Tue • 15:30 • 208

Corrado Maurini[(1)], **J. Pouget**[(1)], F. dell'Isola[(2)]
(1) *LEMA, Université de Versailles/Saint-Quentin-en Yvelines, Versailles, France*
(2) *DISG, Universita di Roma La Sapienza, Roma, Italy*

In this paper, models of layered piezoelectric beams are discussed. The influence of hypotheses on three-dimensional sectional deformations and stress distributions on the estimate of the beam electromechanical properties is analysed. By exploiting a mixed variational formulation and Lagrange multipliers method, an Euler-Bernoulli-like beam model which accounts for transverse interactions between different is presented. The fully coupled electromechanical nature of the system is described by including both mechanical and electrical kinematical descriptors and both direct and inverse piezoelectric effects. For a sandwich piezoelectric beam and for a two-layers beam, expressions of the beam constitutive coefficients are provided and the main features of the proposed model are highlighted. Comparisons with experimental data and results from standard modelling approaches are presented. As main peculiarity, the proposed beam model coherently estimates the equivalent piezoelectric capacitance and transverse normal stress distribution also for beam composed by elastic and piezoelectric layers of comparable thickness.

MS2

Tissue, cellular and molecular biomechanics

Chairpersons: P. Janmey (USA), D. Barthes-Biesel (France), A. Hoger (USA)

Molecular Mechanics of Cytoskeletal Components

MS2I_10709
Mon • 13:30 • 309

Christoph F. Schmidt(1), M. Atakhorrami(1), K. Addas(2), G.H. Koenderinck(1), F.C. MacKintosh(1), J.X. Tang(3)

(1) *Vrije Universiteit Amsterdam, Dept. Phys., Amsterdam, Netherlands*
(2) *Indiana University, Dept. Phys., Bloomington, IN, USA*
(3) *Brown University, Dept. Phys., Providence, RI, USA*

The dynamics of cells are governed by polymeric structural materials, forming the cell membrane or attached to it, or making up the cell-internal cytoskeleton. Molecules involved are polymeric sugars, lipid membranes and protein polymers. The cytoskeleton is largely made up of linear protein polymers of three types, microtubules, actin filaments and intermediate filaments. These filaments have in common that they are rather rigid on the scale of a typical cell and can be modeled as semiflexible polymers. The dynamics of individual filaments and of networks of such filaments is not well described by conventional (flexible) polymer theory. I will here sketch the peculiar properties of semiflexible polymers and their solutions and networks and will present experimental results from microscopic measurements of viscoelastic parameters of such systems. Much of the data will be from microrheology experiments, a method for dynamically probing viscoelastic properties on a micron scale.
ABIOMED guest

Tissue Mechanics

MS2I_10933
Mon • 14:30 • 309

Susan S. Margulies
University of Pennsylvania, Philadelphia, USA

The tissue mechanical properties are central to understanding macroscopic and microscopic effects of disease, aging, and altered loading conditions. More recently, the macroscopic mechanical milieu has been shown to affect cellular responses. Furthermore, tissue properties are used in computational models to estimate local and global stresses and strains and predict tissue injury, perfusion, functional responses. As such, determination of accurate tissue mechanical properties is fundamental to the fields of orthopaedics, cardiovascular and pulmonary mechanics, injury mechanics, rehabilitation engineering, and tissue and cellular engineering. Using a broad range of tissues, techniques for in vivo and in vitro measurement of tissue mechanics will be presented, as well as issues related to study design, specimen handling, and validation. Experimental and analytical approaches for nonlinear, anisotropic, and viscoelastic materials will be covered. Influences of developmental age, species, and disease will be introduced with the goal of presenting a format for determining relevant tissue mechanics.

Elastic Interactions of Biological Cells

MS2I_12811
Tue • 08:30 • 309

Samuel Safran(1), Alice Nicolas(2), Ulrich Schwarz(3)

(1) *Weizmann Institute, Rehovot Israel*
(2) *CRPP, Bordeaux, France*
(3) *MPI Golm, Postdam, Germany*

Modifications of the elasticity of the cytoskeleton of biolgical cells are responsible for dramatic changes in cell shape. Adhering cells exert forces on their environment; experiments on micropatterned elastomer substrates showed that these

forces are correlated with the size and orientation of adhesion regions. The adhesions act as mechanosensors that convert the mechanical forces within the cytoskeleton into biochemical signals that cause these adhesions to grow in response to external stress. Averaging the forces due to the adhesions shows that each cell can be modeled as a pair of oppositely directed elastic forces. We predict theoretically that the cells deform the medium and this gives rise to an effective interaction among the cells that can be either attractive or repulsive, depending on their orientations and the boundary conditions. Our theory for the physical origin of the mechanosensor action of focal adhesions, models the adhesion molecules as a grafted layer whose effective elastic modulus determines its response to cytoskeletal forces. The model may explain the observed force dependent anisotropy of the focal adhesions. [Experimental collaborators: B. Geiger, A. Bershadsky, N. Balaban]
ABIOMED guest

Micromechanics of Cytoskeletal Actin Networks

MS2L_10627
Mon • 16:00 • 309

Erik Van der Giessen, Patrick Onck
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The cytoskeleton in living cells comprises an interpenetrating network of actin microfilaments, intermediate filaments and microtubules, each made of different proteins. We propose a multiscale modeling methodology for cytoskeletal mechanics starting from the scale of individual cytoskeletal filaments, via networks of filaments to the entire cell. The focus of the current paper is on the scale transition of the actin filament scale to the network scale. First we critically examine the commonly adopted worm-like chain model for the coupling between the chain deformations and thermal undulations. Next, based on this single filament model, we construct random three-dimensional actin networks using the finite element method, featuring a tunable density of cross-links. This allows us to explore the dependence of the overall response on network architecture, the strength of cross-links/entanglements and the actin poperties. Special emphasis will be put on the structural alterations that occur in the networks during straining.

Theory of Polymorphism in Bacterial Flagella

MS2L_11866
Mon • 16:20 • 309

Srikanth V. Srigiriraju, **Thomas R. Powers**
Brown University, Providence, USA

Escherichia coli and Salmonella swim using several flagella, each of which consists of a rotary motor, a universal joint known as the hook, and a helical filament which acts a propeller. The filament is normally left-handed in the absence of external stress, but undergoes mechanical phase transitions to other helical states (polymorphs) in response to external torque. The filament is made of identical flagellin protein subunits which are organized into eleven protofilaments which wind around the filament. We develop an effective theory in which the flagellin subunits and their connections along the protofilaments are modeled with a double-well potential. A helical spring represents the other connections of the subunits, and introduces a twist-stretch coupling and an element of frustration in our model. We solve for the ground states and the phase diagram for filament shapes.

Stress and Strain in a Yeast Cell under High Hydrostatic Pressure

MS2L_12031
Mon • 16:40 • 309

Christoph Hartmann, Antonio Delgado
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The mechanical effects of the compression of a yeast cell (*Saccharomyces cerevisiae*) under high hydrostatic pressure up to 500 MPa as used in food science are modelled and simulated with the finite-element-method. The cell model consists of a cell wall, cytoplasm a lipid filled vacuole and the nucleus. Material parameters have been taken from literature or have been derived from thermodynamic relationships. Mechanical damage due to transient pressure application can be excluded by dimensional analysis, unless pressure oscillation frequencies of 700 MHz are applied. The deformation of the cell deviates strongly from isotropic volume reduction. Organelle membranes exhibit an effective strain up to 80% at a load of 400 MPa, being critical upon disruption. In the cell wall, the stress state is heterogeneous. Von-Mises stress reaches the critical value upon failure of the cell wall of 70±4 MPa at a pressure load between 415 MPa and 460 MPa.

Hydrodynamic Interaction Between Two Bioartifical Capsules in Shear Flow

MS2L_11961
Mon • 17:00 • 309

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The hydrodynamic interaction between two liquid filled identical spherical capsules is studied in simple shear flow. The centres of mass of the capsules are initially located in the shear plane, where they remain during motion. The membrane is hyperlelastic, infinitely thin and devoid of bending resistance. The boundary element method is used with bi-cubic B-splines as basis functions to map each capsule surfaces on a structured mesh. This guarantees continuity of second order geometrical properties with respect to the position of the Lagrangian particles used for tracking the location of the interface at each time step. When interacting, the capsules undergo large deformation. In the wake, an oscillation in the elastic tensions may lead to local buckling of the membrane and eventual damage. A trajectory shift that increases the cross streamline separation is predicted. It depends in a complicated fashion on initial particle separation, membrane properties and flow strength.

From Individual Cells To Complex Tissues – an Immersed Boundary Approach

MS2L_10689
Mon • 17:20 • 309

Katarzyna A. Rejniak
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We present a computational technique which can be applied in modeling development of complex tissues composed of various types of cells. This method allows us to treat cells as individual entities, with their own elastic plasma membrane, fluid cytoplasm, point nucleus and partial cytoskeleton, but also enables formation of cell clusters or cell sheets that act together as one complex tissue. The cell model includes membrane receptors used to sense signals from the surrounding microenvironment and based on these signals the cells can undergo different processes, such as growth, proliferation, apoptosis or chemotaxic migration. This model is based on the immersed boundary method and couples the dynamics of separate elastic cells with continuous description of a viscous incompressible cytoplasm. Applications include several computer simulations, such as formation of an early carcinoma or outgrowth of a capillary sprout in the early angiogenesis.

Approximations of Stiffness Tensor of Bone – Determining and Accuracy

MS2L_11808
Mon • 17:40 • 309

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The paper deals with properties of the apparent stiffness tensor of bone. We used the computer reconstruction method combined with spectral and harmonic decomposition. Hexahedral samples of trabecular bone was reconstructed from computer microtomograph images, next Finite Element models of samples was build and numerical tests combined with averaging procedure was performed in order to identify the fully anisotropic apparent stiffness tensor. Subsequently, the spectral and harmonic decompositions of the tensor were performed. Six Kelvin moduli and invariants of projectors were evaluated. The closest isotropic tensor and possible orthotropic approximation were specified basing on the harmonic decomposition. Analysis of these quantities allowed to discuss symmetries of apparent stiffness tensor and to measure the deviation of the proposed approximations from the actual stiffness tensor.

Wrinkling and Buckling of Isotropic Biological Tissues

MS2L_10267
Tue • 11:00 • 309

Luigi Gambarotta, **Roberta Massabo**, Vittoria Villa
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The problem of the wrinkling and buckling of membranes characterized by an isotropic Tong-Fung type constitutive behavior has been formulated and solved within the framework of finite strain hyperelasticity. The formulation has been guided by the theories proposed by Wu and Canfield (Quart. Appl. Math, 1981) and Pipkin (IMA J. Appl. Math., 1986). A criterion for the wrinkling based on the natural width, which defines the natural contraction of a membrane loaded in uniaxial tension, has been introduced. The out of plane geometric nonlinearities have been treated as constitutive nonlinearities through a modification of the elastic potential (relaxed energy density). Close form solutions have been found for the natural width and the relaxed energy density. The model has been implemented in a finite element code and applied to simulate procedures of reconstructive surgery where the extrusion of the edges of the wound may occur after the suture due to the buckling and wrinkling of the skin.

Mechanics of Venus' flytrap Closure

MS2L_11581
Tue • 11:20 • 309

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We investigate the snapping closure of the carnivorous plant Venus flytrap (Dionaea muscipula), which exhibits one of the fastest motion in the vegetable kingdom (typically 100 ms). The three-dimensional dynamics of the leaves during the snap is recorded using a high-speed camera and the strain field before and after closure is precisely measured using microscopy techniques. From the experimental measurements, we propose that the very fast closure of the trap results from a mechanical instability similar to the elastic bucking of a shell, the instability being damped by the diffusion of water inside the leaves. In order to test this mechanism, a simple mechanical model for the snapping of a poroelastic shell is written, which allows to explain the main experimental observations.
ABIOMED guest

Residual Stress Fields in Soft Tissues

MS2L_10670
Tue • 11:40 • 309

Anders Klarbring, **Tobias Olsson**, Jonas Staalhand
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The main task in this work is to identify the residual stresses and strains for an elastic body, and from that identification estimate the stresses and strains in a loaded configuration. The theory is built on the existence of local stress free reference configurations which do not necessarily give a compatible domain. The residual strains are defined by the tangent map between this stress free configuration and a stressed unloaded compatible configuration. The residual stress plays an important roll in soft tissue mechanics, because it reduces the stress gradients in the tissue. The residual strains can be identified as the solution of a minimization problem. As a closing example, we used this theory on a human aorta. The identification was solved as a least square problem were the minimization was done over the difference between the calculated and measured luminal pressure. The results indicate that the theory agrees with other studies made on human arteries.

Mechanics of Deep Penetration of Soft Solids

MS2L_10988
Tue • 12:00 • 309

Norman Fleck, Oliver Shergold
Cambridge University, Cambridge, UK

Micromechanical models are developed for the deep penetration of soft solids by a flat-bottomed and a sharp-tipped cylindrical punch such as a hypodermic needle. The soft solid represents mammalian skin and silicone rubbers, and is modelled by a one term Ogden strain energy function. The flat-bottomed punch penetration model assumes that penetration is by the formation of a mode II ring crack that propagates ahead of the penetrator tip. The sharp-tipped punch penetration model assumes that penetration is by the formation of a planar mode I crack which is wedged open by the advancing punch. The steady-state penetration load is obtained by equating the work done in advancing the punch to the sum of the fracture work and the strain energy stored in the solid. The penetration pressure for a flat-bottomed punch is three times that for a sharp-tipped punch, in agreement with experimental observations.

Measuring the Mechanical Properties of Soft Biological Tissues

MS2L_12064
Tue • 12:20 • 309

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Mechanical models for soft biological tissues are required for medical applications (e.g. diagnostics, surgery planning, surgery simulators). Special experimental techniques are needed for the mechanical characterization of soft tissues. Two novel techniques are presented: a quasi-static and a dynamic experiment. Quasi-static tests are performed by means of an aspiration experiment. Dynamic tests are performed by making the soft tissue a part of a vibrating system. Both methods are suitable for in-vivo applications. Applications of the experimental techniques on animal and human organs as well as the procedure for determining the constitutive model parameters are presented. Different types of models are evaluated for the description of the soft tissue response measured in the experiments. In particular, the quasi-linear viscoelastic model (Fung) and the elastic-viscoplastic model (Rubin–Bodner) are used. The constitutive behavior of biological tissues is characterized over a wide frequency range from the combination of quasi-static and dynamic test results.

Modeling of Periodic Load Effects in Bone Tissue Adaptation

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MS2L_12315
Tue • 12:40 • 309

Bone functional remodeling is influenced by time characteristics of mechanical loading. Periodic loads usually have more effect on the adaptation and associated evolution of tissue structure than a static one. In the present work, an approach, based on the hypothesis of optimal response of bone, is proposed. It enables derivation for a viscoelastic material a family of adaptation formulas. In this derivation, an assumption is made that the bone is loaded harmonically, and that the frequency of oscillations is so small that the inertia effects are negligible. It follows that the stimulus is frequency dependent and that functional relation between stimulus and load frequency depends on the constitutive material model applied in the formulation. In some cases, the stimulus grows to some maximal value and next drops to zero with steering to infinity frequency of load oscillations what was already observed in experiments. The results of sample computer calculations are included. The proposed approach might offer an attractive tool in investigations of frequency effect on bone remodeling but more research and experimental confirmation are necessary.

Travelling Waves in a Model of Skin Pattern Formation

Kazimierz Piechór, Bogdan Ka´zmierczak
IPPT PAN, Warsaw, Poland

MS2S_10838
Tue • 14:30 • 309

According to the Cruywagen-Murray (1992) model, the skin consists of two layers, epidermis and dermis, separated by a basal lamina. The epidermis is modelled as a two-dimensional visco-elasic continuous medium. The Reynolds number of the motion of the epidermis is assumed to be low. The body force balances the elastic force, the viscous force, and the cell traction generated within the epidermis by a morphogen produced in the dermis. In this model the motion of the dermal layer is described by a reaction-diffusion equation containing chemotaxis like term. The aim of this paper is a rigorous mathematical analysis of travelling wave solutions of the described equations, under a simplifying assumption that the force exerted by the basal lamina is much larger than the other forces acting on the epithelium. Using the Implicit Function Theorem the existence of travelling waves with positive dermis cell density is proved, and a discussion of the minimal wave-speed problem is carried out.

Mechanics of Elastic and Viscous Magnetic Filaments

Andrejs Cebers, I. Javaitis
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MS2S_11102
Tue • 14:35 • 309

Dynamics of elastic magnetic rod in magnetic fields is considered. Rod in static magnetic field has U like metastable states. In rotating field rod has bent shape rotating synchronously with the field and undergoes the periodic motion with subsequent straightenings and bendings at high frequencies. The model of elastic magnetic rod may be applied to describe the chains of magnetic particles in magnetorheological suspensions which are held together by magnetic attraction forces. The critical frequency of chain breaking agrees well with the existing experimental data. In simplified case the nonlinear PDE of the rod dynamics in the rotating field is analogous to the equation for the tangent angle of elongated viscous magnetic drop. In this case the propagation of the tangent angle shockwave is found which allows to interpret the experimental observations. Buckling of the magnetic particle chains in magnetotactic bacteria and other biological applications are considered.
ABIOMED guest

Intracellular Control Mechanisms of Cardiac Contraction & Energetics

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MS2S_11148
Tue • 14:40 • 309

The major hypothesis underlining the present study is that the regulation of cardiac muscle contraction, and cardiac work, is based on the intracellular control of calcium kinetics and crossbridge cycling. The cardiac muscle fiber contraction and the LV function are determined by two intracellular control mechanisms: a cooperativity mechanism and a negative mechanical feedback. The hypothesis is substantiated by the successful description of the cardiac fiber mechanical performance and the analytical explanation of the regulation of biochemical to mechanical energy conversion by the sarcomere, i.e., the force-length relationship,the force-velocity relationship, the control of relaxation and the linear relationship between energy consumption and the generated mechanical energy.
ABIOMED guest

Models of Hair Cell Bundle Functioning

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MS2S_12059
Tue • 14:45 • 309

Animals utilize sensory (vestibular, lateral-line, auditory) systems with hair cells to detect a variety of mechanical stimuli from their environment. The forces exerted on the hair cell (cilia) bundle (HCB) due to its interaction with the moving environment result in deformation of the special fine strands (tip-links) located between cilia. It leads to cell polarization that modulates neural activity of the afferent. Two extreme cases of the HCB interaction with the moving gel (vestibular system) were modeled: 1) the HCBs exactly follow the gel displacement; 2) stiff stereocilia and weak surrounding gel allow the motion of the bundle relative to the gel. The results suggest that the HCB structure with stereocilia of varying heights is designed to transform the temporal pattern of external acceleration (or its time derivative) in temporal pattern of cell depolarization by measuring spatial distribution of displacements (or velocities) of the gel caused by this acceleration.

Anisotropic Hyperelastic and Pseudo-hyperelstic Materials and Applications to Soft Tissue Modelling

Stanisław Jemioło[1], Józef Joachim Telega[2]
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(2) *IFTR PAS, Warsaw, Poland*

MS2S_12100
Tue • 14:50 • 309

Fung's model of pseudo-elastic behaviour of soft is not appropriate both from the viewpoint of continuum mechanics and interpretation of experimental data as well as implementation of this model in FEM. Therefore a consistent mathematical model applicable to pseudo-hyperelastic behaviour of orthotropic soft tissues has been proposed. The model describes loading and unloading processes as well as the dissipation in cyclic process. An appropriate approximation of constitutive relationships in respect to Lagrange strain measure reduces them to the orthotropic model of the Saint-Venant-Kirchhoff. Having in mind available experimental data, our considerations have deliberately been restricted to the plane stress state.

Molecular Dynamics Study of Permeation Process of Small Molecules Through A Lipid Bilayer

Taisuke Sugii, Shu Takagi, Yoichiro Matsumoto
The Univ. of Tokyo, Tokyo, Japan

MS2S_12192
Tue • 14:55 • 309

Recently a cell membrane and a liposome are actively studied in various fields. In this research, the transport characteristics on the lipid bilayer were analyzed using the molecular dynamics method. The free energy profiles of small molecules (O_2, CO, NO, H_2O, and several artificial diatomic molecules) across the three kinds of pure lipid membranes (DLPC, DMPC, and DPPC) were calculated. We investigated the effect of the polarity of the solute molecules and the length of the hydrocarbon chains of the lipid molecules. Furthermore, we calculated the vdW potential field and the electrostatic potential field. The potential field is very important for the investigation of permeation process because it can represent the local and instantaneous state of the system. In the calculation of the electrostatic potential field, the contribution from the lipid molecules and the water molecules were calculated separately, and it is shown that each profile had own its characteristic.

A Particle Method Computer Simulation of Blood Flow

Ken-ichi Tsubota, Shigeo Wada, Takami Yamaguchi
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MS2S_12453
Tue • 15:00 • 309

A particle method computer simulation of the blood flow is proposed to directly evaluate mechanical interactions between red blood cells (RBCs) and plasma. A moving particle semi-implicit method was used for flow analysis of blood plasma, and an elastic membrane model for deformation and movement of RBC. A two-dimensional particle model of blood flow between parallel plates was constructed in order to examine the feasibility of the proposed method. Temporal changes in mechanical behavior of RBC were obtained such as movement into downstream direction due to pressure drop of plasma flow and deformation in a parachute shape during the movement. The results corresponded to experimental observations, indicating the validity of the simulation method. The proposed method will give us an insight into the mechanism of the blood flow at from microscopic level of the blood cells and plasma and up to resultant rheological properties.

MS3

Mechanics of thin films and nanostructures

Chairpersons: K. Kim (USA), Z. Suo (USA), H. Jensen (Denmark)

Mechanics of Nanostructures

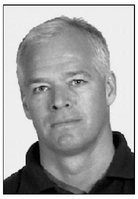
Rodney S. Ruoff

Northwestern University, USA

MS3I_11594

Mon • 13:30 • 219

The topics will be (I) Experimental studies by my group of carbon nanotubes and nanocoils, boron nanowires, and carbon nanotubes projecting from the fracture surfaces of CNT composites (a) subjected to tensile loading (b) driven into mechanical resonance by mechanical or electrical excitation. (II) The ideal strength of materials and fracture in nanostructures (a) ab initio calculations of ideal strength (b) experimental work on nanostructure fracture (c) modeling of the fracture strength of nanostructures with 0, 1, 2 adjacent, 3 adjacent, . . . , n adjacent defects (d) following this summary of prior work, a new theory (developed with Nicola Pugno, Politecnico di Torino) for fracture of nanoscale structures will be presented. (III). We close with discussion of a new method that my group is developing, for achieving nm-resolution for measurements of the displacement field. I acknowledge grant support from NASA LaRC, NSF, and ONR.



Mechanics of Thin Film Structures

Henrik Myhre Jensen

Aalborg University, Denmark

MS3I_11070

Mon • 14:30 • 219

With emphasis on interface delamination in thin film structures, a variety of phenomena are discussed. The effects of curvature of the substrate on buckling-driven delamination of thin films in compression are analysed. Details in the morphology of buckling-driven delamination and in particular the causes of the so-called telephone cord blister are discussed. Conditions for delamination at edges and corners are formulated and it is shown that steady-state delamination at a corner is possible at significantly lower stress levels than delaminations at straight-sided edges.

A Hybrid Molecular/continuum Analysis of IFM Experiments on a Self-assembled Monolayer

Kenneth. M. Liechti[(1)], M. Wang[(1)], J.M. White[(1)], P.J. Rossky[(1)], R.M. Winter[(2)]

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(2) *Chemical Engineering, South Dakota School of Mines and Technology, Rapid City, USA*

MS3I_12132

Tue • 08:30 • 219

Polymeric self-assembled monolayers (SAMs) are used to minimize stiction in MEMs devices and control adhesion in composites. Nanomechanical models of friction, adhesion and fracture require the properties of these SAMs. This paper examines the use of molecular dynamics and continuum analyses and a novel scanning probe microscope for this purpose. An interfacial force microscope (IFM) is used to probe self-assembled monolayers of octadeciletrichlorosilane (OTS) on silicon. Its unique self-balancing force sensor allows the full attractive and repulsive portions of the force–displacement response of the tip/surface interactions to be obtained. The measured force profiles are used judge the validity of linear

and nonlinear elastic models of the OTS behaviour in continuum analyses that include surface interactions. The nonlinear behavior is motivated by molecular dynamics analyses of simple stress states. The linear elastic analyses yield high Young's moduli, corresponding to the high degree of order. The nonlinear analysis is more promising.

Thermomechanical Continuum Representation of Atomistic Deformation at Arbitrary Time and Size Scales

MS3L_10105
Mon • 16:00 • 219

Min Zhou
Georgia Institute of Technology, Atlanta, USA

A thermomechanical equivalent continuum (TMEC) theory for the deformation of atomistic particle systems at arbitrary size and time scales has recently been developed. The description of coupled thermomechanical continuum behavior is derived directly from the ground up, using molecular dynamics concepts. This theory is a further advancement from a pure mechanical equivalent continuum (EC) theory developed recently. These new theories provide fully dynamic continuum interpretations of atomistic deformation with different resolutions for atomic particle motion.

Ratcheting-induced Wrinkling of an Elastic Film on a Metal Layer Under Cyclic Temperatures

MS3L_10699
Mon • 16:20 • 219

Rui Huang, S.H. Im
The University of Texas, Austin, USA

A compressively strained elastic film on a compliant substrate can form wrinkles. Previous studies have focused on elastic, viscous, and viscoelastic substrates. The present study develops a theoretical model for wrinkling of an elastic film on an elastic-plastic metal layer caused by cyclic temperatures. The thermal expansion mismatch between the metal layer and the underlying substrate causes the metal to deform plastically. Each cycle the metal gains a small amount of plastic deformation, driven by the normal and shear tractions at the interface between the metal and the film. As the ratcheting deformation accumulates in the metal, the film forms wrinkles, analogous to wrinkling on a viscous layer. Analytical solutions are obtained for linear perturbation analysis and equilibrium states. Numerical simulations show the evolution of wrinkles. The implications of the results for structural evolution and failure mechanisms in integrated electronic devices and thermal barrier coating systems will be discussed.

Atomistic study of Size Effect in Torsion Tests of Nanowire

MS3L_11122
Mon • 16:40 • 219

Akihiro Nakatani, Hiroshi Kitagawa
Osaka University, Department of Adaptive Machine Systems, Osaka, Japan

Existing theories have had to be modified as a result of trends in miniaturization. For smaller nanostructures and nanostructured materials, the continuum theory must be reconsidered. In this paper, the torsion deformation of the atomistic model of single crystal and polycrystalline nanowire is studied using molecular dynamics. Torsion deformation is incorporated using a twisted periodic boundary condition (TPBC). We focus on grain refinement and size effect as they are affected by the combination of two length scales, i.e., radius of specimen and grain size. The result is compared with that from continuum strain-gradient plasticity. The efficiency of TPBC is confirmed in the analysis. Polycrystallization is observed in single crystal cases. The torque-twist curves show a tendency for smaller to be softer. A discrepancy exists with continuum predictions from dislocation theory. An important result is that deformation at the grain boundary is significant in nano-scale deformation rather than dislocation movement.

Solid Mechanics Methods in Nano-technologies

MS3L_11260
Mon • 17:00 • 219

Elena A. Ivanova(1), Anton M. Krivtsov(1), Nikita F. Morozov(2), Boris Semenov(2)
(1) *St. Petersburg State Polytechnical University, Russia*
(2) *St. Petersburg State University, Russia*

Advances in high technologies using nanometer-size structures requires calculation of mechanical properties for the objects of the nanosize scale level. Majority of the theoretical mechanical models for nanoobjects is based on the macroscopic equations of theory of elasticity. However, a lot of researchers have noted inconsistency between the values of the elastic moduli obtained from micro- and macroexperiments. The presented paper is devoted to theoretical investigation of the influence of the scale effects on Young modulus, Poisson's ratio and the bending stiffness of a nanocrystal, which is extended in one direction and has a limited number of atomic layers in another direction. The model of the elamination processes of a preliminary stressed bi-layered plate from rigid foundation is proposed. On the basis of the considered solution of specified dependence of its diameter on the parameters of plate layers is found.

Microstructural and Atomistic Simulation for Deformation of Nano-grained Metals

MS3L_11279
Mon • 17:20 • 219

Yang Wei
Department of Engineering Mechanics, Tsinghua University, Beijing, China

Nano-grain metals deform mainly by neighboring grains sliding pass each other. We adopted a structural evolution algorithm to simulate the process. Actual deformation minimizes the plastic dissipation and stored strain energy for representative steps of grain neighbor switching. Numerical simulations are given for a representing cell composed of 200 non-uniform grains. A theoretical framework concerning the insertion and rotation of 9-grain clusters is proposed that quantifies the experimental data. We also conduct investigation for the rapid stretching of nano-grained metals via molecular dynamics simulation. For nano-grained copper stretched up to 200% at ultra-fast strain rate, the MD simulation indicates a transition from ordered to disordered state.

Size-dependent Elastic State of Embedded Nano-inclusions & Quantum Dots

MS3L_11474
Mon • 17:40 • 219

Pradeep Sharma, Lewis Wheeler
Department of Mechanical Engineering, University of Houston, Houston, USA

The classical formulation of Eshelby for embedded inclusions is revisited and modified to, at least partially, account for size-effects likely to be prominent at the nanoscale. In this two-pronged work, we firstly incorporate the previously excluded surface/interface stresses, tension and energies. The latter effects come into prominence at inclusion sizes in the nanometer range. Unlike the classical results, our modified formulations render the elastic state of an embedded inclusion size-dependent making possible the extension of Eshelby's original formalism to nano-inclusions. Presuming that, at least for some material systems, the inherent long-wavelength assumption of elasticity is violated for nano-size inclusion sizes, we also derive a modified Eshelby tensor in the framework of second gradient elasticity with couple stresses. Several applications of the present work are illustrated; in particular, the size-dependent strain state of quantum dots and the consequent effect on its optoelectronic properties along with limited empirical evidence are discussed.

Characterization of MEMS Materials

MS3L_12384
Tue • 11:00 • 219

Jurg Dual, Gerd Simons, Jacqueline Vollmann
ETH Zurich, Zurich, Switzerland

Mechanical characterization of MEMS materials is increasingly important in view of improving reliability and assessing the life time of new devices. In this paper a number of testing methods are described. These methods include tensile, torsion and fatigue testing of specially designed microstructures, as well as wave propagation methods based on an optical pump probe setup to test thin films. Difficulties arise from manufacturing and handling of small structures and the determination of its geometrical dimensions, which directly affect the accuracy of material parameters extracted from the experiments. In addition the measurement of the mechanical parameters like small forces and torques or strains on small specimens or with ps time resolution pose challenges. This talk will focus on size effects in copper foils of thickness between 10 and 100 microns and probing of inhomogeneities caused e.g. by diffusion at interfaces in thin films.

An Analytical Model of Oxide Rumpling as the Mechanism Leading to Failure in Thermal Barrier Coatings

MS3L_12386
Tue • 11:20 • 219

Daniel S. Balint[(1)], John W. Hutchinson[(2)]
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(2) *Harvard University, Cambridge, USA*

Thermal barrier coatings are deposited on superalloy turbine blades to protect them from engine temperatures in excess of 1000C. Failure of these multi-layer coatings is known to involve undulations that develop in the oxide layer, between the ceramic top-coat and the metallic bond-coat. At temperatures above 600C, the bond-coat creeps readily under stress. Thermal mismatch with the superalloy substrate and, for PtNiAl bond-coats, a reversible phase transformation accompanied by a change in volume, give rise to a large equi-biaxial stress in the bond-coat that dramatically reduces its ability to resist transverse deformation at elevated temperatures. The nonlinear interaction between the stress in the bond-coat and the tractions applied at the surface of the bond-coat by the compressed, undulating oxide film allows an increment of undulation growth to occur each thermal cycle. An analysis of oxide rumpling and the resultant cracking in the top-coat that leads to failure will be presented.

Interfacial Adhesion of PZT Ferroelectric Thin Films Determined by Nano-Indentation Method

MS3L_12486
Tue • 11:40 • 219

X.J. Zheng, Y.C. Zhou
Xiangtan University, China

In this paper, we propose an elastic groundsill beam model with piezoelectric effect considered to assess the interfacial adhesion of ferroelectrics thin films, complemented and validated by nano-indentation fracture test of Pb $(Zr_{0.52}Ti_{0.48})O_3$ (PZT) thin films deposited by metal organic decomposition (MOD). In the experiment, it was observed that the hardness and the elastic modulus of thin films depend on the indentation depth, but the dependence could not be explained by strain gradient theory. From the load-indentation depth curves and atomic force microscopy (AFM) images, it was also found that the fracture failure of PZT thin films induced by nano-indentations could be divided into three typical stages: no damage, bulging and spallation. The delamination of brittleness thin film system could be modeled as an interfacial crack propagation problem and characterized by the energy release rate, which could be determined from the elastic groundsill beam model in good agreement with experimental results. For PZT thin films deposited on single Si substrate with thickness of 350 nm and 500 nm, the energy release rates per unit of new crack area are in the range of 3.399–52.432 J/m^2 and the phase angles are constant of 13.357 degree. The corresponding mode I and mode II stress intensity factors are in the range of 0.413–1.622 MPa·m$^{(1/2)}$ and 0.554–2.176 MPa·m$^{(1/2)}$.

Wrinkling Instability in Nano-layers: Anisotropy and Sliding Effects

MS3L_12502
Tue • 12:00 • 219

Neila Mokni, **Francois Sidoroff**, Alexandru Danescu
LTDS – École Centrale de Lyon, Ecully, France

Following an idea of Suo et al. we extend the linear stability analysis of a two-layer structure, intended to model the relaxation of a thin elastic film on a viscous layer, to account for both anisotropy of the elastic film and friction at the interface between the film and the substrate. The main appli-cation concerns the feasibility of strain relaxed InAsP and InGaAs compliant substrates. We compare our theoretical estimates for both the orientation and the wavelength of the periodic undulation of the film with experimental results obtained for In0:65Ga0:35As on a Si host via Apiezon wax.

Mechanical Behaviour of Nano Grained Metals

MS3L_12705
Tue • 12:20 • 219

Aman Haque, **Taher Saif**
U. of Illinois, Urbana-Champaign, USA

Mechanical behavior of free standing nano grained thin Al and gold films are studied experimentally under uniaxial tension using a newly developed novel microinstrument. Here, the sample and the instrument are patterned (lithographic technique) and fabricated together, thus eliminating the problem of alignment and attachment. We find, as grain size decreases, yield stress increases, elastic modulus decreases, and the metals begin to show non-linear elasticity upon unloading. There appears to be a critical grain size at which the material shows maximum strength. Below this size, the failure appears to be macroscopically brittle. We believe that as grain size decreases, dislocation slip induced plasticity ceases to exist due to lack of dislocations, and grain boundary mechanisms begin to dominate. However, if the grain size is such that it is small enough that few dislocation exists but not small enough for grain boundary assisted mechanisms to dominate, the material shows highest strength.

Nano-scale Planar Field Projection of Atomistic Decohesion of Crystalline Solids

MS3L_12778
Tue • 12:40 • 219

Seung Tae Choi, Kyung-Suk Kim
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An atomistic cohesive zone of a crack tip is characterized by a nano-scale planar field projection of the elastic field of a crack tip, analyzing the near-tip deformation field with a molecular statics simulation of gold. The atomistic simulation

with an embedded atom method (EAM) potential is made for a crystal decohesion along $[11\bar{2}]$ direction in a (111) plane. A general form of planar elastic field projection is derived to identify cohesive-zone constitutive relations from the elastic field of a cohesive crack tip sitting on an interface between two anisotropic solids. The cohesive traction, the interface separation and the surface-stress gradient caused by gradual variation of surface formation within the cohesive zone can be obtained by the nano-scale planar field projection. Details of energy partition in various modes of nano-scale separation processes are analyzed with atomistic simulations and the field projection method.

A Microstructural Approach to the Ballistic-diffusive Heat Transfer

MS3S_10386
Tue • 14:30 • 219A

Jan Saczuk
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Heat transport in nanostructures is highly nonequilibrium and dominated by the interfacial processes. The ballistic-diffusive heat model is presented as tool to deal with transient heat conduction problems in low-dimensional structures such as thin films and supperlattices. Heat carriers viewed as a collection of randomly moving and interacting particles and quasiparticles are described by space-time distributions within a combined thermodynamic and microstructural diffusive-kinetic approach. Knowledge of these distributions permit the evaluation of the heat flux and the internal energy. The local temperature considered as a measure of the local internal energy is composed from the ballistic and diffusive parts. The hyperbolic ballistic-diffusive heat conduction equation is then derived and a comparison with other models and its numerical verification are presented.

Energy-based Approach to Limit States in Nanostructures. Calculation of the Critical Values of Energy from Firt Principles

MS3S_11444
Tue • 14:35 • 219A

Kinga Nalepka[(1)], Paweł Nalepka[(2)], Ryszard B. Pęcherski[(1)]
(1) *Cracow University of Technology, Cracow, Poland*
(2) *Agriculture University of Cracow/IPPT PAN, Poland*

The application of the energy-based approach to limit states proposed by Rychlewski for elastic materials can appear helpful in the field of nanomechanics filling the gap between atomistic calculations and continuum mechanics modelling of the behaviour of different kinds of crystalline nanostructures. We propose to calculate the critical energy of pertinent proper elastic states from quantum mechanical theory of nanostructures. The quantum mechanical model for an ideal single crystal of Cu is studied and the comparison with the results obtained for Al crystal is made. Using the Wigner–Seitz cellular approach and the Slater method the structure of the s, d, f and p energy bands was calculated. This enables obtaining of the internal energy of the crystal volume confined in the deforming Wigner-Seitz cell. Finally the critical energy for the particular proper state was determined.

Fracture Criterious for Bridged Crack: from Macro to Nanoscale

MS3S_11599
Tue • 14:40 • 219A

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A multi-scale bridged crack model for the evaluation of fracture and strength parameters of interfaces with cracks is proposed. We suppose that distributed nonlinear bonds link the crack surfaces in some zones starting from the crack tips. The sizes of these zones are not assumed to be small as compared to the crack length on every bridging level. The system of singular integral-differential equations is derived for normal and shear bond stresses evaluation. Two fracture criterions of quasistatic crack growth are considered. The first condition in the both criterions is the same: it is the condition of the bond limit stretching or strain at the trailing edge of the bridge zone. Two types of the second condition of fracture is considered: a) the force condition which is the condition for the critical stress intensity factor and b) the proposed energetic condition based on the equality of the values of the strain energy release rate and the energy dissipation by the bonds at the crack limit state. The regimes of the bridged zone and the crack tip equilibrium and growth are analyzed for the both types of these criterions. The application of this model and the comparison the criterions for different problems from macro to nanoscale of the interface cracks are presented. It is noted that the most differences between the results from the force and energetic fracture conditions are observed for the cracks of micro and nano sizes.

Investigation of Wave Propagation in Multiwall

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MS3S_12181
Tue • 14:45 • 219A

Abstract: The wave propagation in individual multiwall carbon nanotubes subjected to transverse disturbing, modeled a multiple-elastic-shell model is studied in this paper. The present model predicts when the disturbing frequency is below all critical frequency, the vibration models are almost coaxial. However, when the frequency is higher than at least one of the critical frequencies, non-coaxial vibration model emerges and the waves propagate at various speeds. Hence, tetrahertz disturbing waves in multiwall carbon nanotubes exhibit complex hpenomena and are essentially non-coaxial. In particular, tetraherz waves in multiwall carbon nanotubes propagate depending not only on the frequency, but also on the non-coaxial vibration model. Keywords: carbon naotube, wave propagation, vibration frequencies

Homogenisation Models of Carbon Nanocomposites Mechanical Properties

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MS3S_12251
Tue • 14:50 • 219A

It is well known that single walled (SWCN) or multi walled carbon nanotubes (MWCN) offer a significant amount of stiffness (1–4 TPa) or strength comparing with those obtained for classical graphite or carbon fibres. However, those nanomaterials cannot form structures used for engineering purposes. On the other hand, nanocomposites made of SWCN or MWCN can loose a lot of their magnificent mechanical properties when will be joined with the matrix. Of course, the same situation is observed for classical carbon/graphite microcomposites. The general aim of the present paper is following: (1) to present the theoretical homogenisation models for the evaluation of the Young modulus values for nanocomposites reinforced with SWCN and MWCN, (2) to propose method of numerical modelling nanocomposites reinforced by SWCN and a polymer matrix, (3) to compare the obtained results with classical microcomposites in order to demonstrate advantages and disadvantages of both composite materials. Numerical results illustrate features and advantages of different models.

Micro- and Nano-mechanics of Carbon Nanotubes Composites

Xi-Qiao Feng[(1)], Dong-Li Shi[(1)], Y. Huang[(2)], Keh-Chih Hwang[(1)]
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(2) *University of Illinois, USA*

MS3S_12314
Tue • 14:55 • 219A

The constitutive relation and failure of carbon nanotube-reinforced composites are studied using methods of micromechanics and nanomechanics. First, we examined the factors that influence the overall mechanical property of carbon nanotube composites, including the weak bonding between carbon nanotubes and matrix, the curviness and agglomeration of carbon nanotubes. Even though the adhesion strength between the nanotubes and the matrix may significantly affect the strength and failure behavior of composites, its influence on the effective elastic modulus of composites can be negligible. A novel micromechanics model is then developed to consider the waviness or curviness effect and the agglomeration effect of nanotubes on the constitutive relations. It is established that these two mechanisms may significantly reduce the stiffening effect of carbon nanotubes. Second, we established a hybrid continuum/micromechanics/atomistic method theory to investigate the defect nucleation in a carbon nanotube embedded in a polymer matrix. We have given the critical tensile strains of defect nucleation and final fracture, which show a strong dependence on the chiral angle It is found that due to the interaction effect, the fracture strength of a carbon nanotube in a composite is lower than that of a free-standing nanotube.

Instabilities of Composite Materials Reinforced by Nano-Fibres: a Re-examination of Elastic Buckling

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Dept. of Solid Mechanics, Materials and Systems, Tel-Aviv University, Ramat Aviv, Israel

MS3S_12432
Tue • 15:00 • 219A

Elastic instability of composites reinforced by nano-fibres is investigated. Such composites are necessarily dilute and when reinforced by fibres of exceedingly high stiffness (such as carbon nanotubes) may, in fact, buckle elastically. As opposed to the classical solution given by Rosen, where instability is found to occur either in a shear mode with an infinite wave length or in a transverse mode, it is shown analytically that buckling can occur only in the shear mode with finite wave length and that the transverse mode is spurious. The shear buckling is shown to exist under two régimes with buckling of dilute composites occurring with finite wavelengths. Based on the analysis, a model is constructed which defines the fiber concentration at which the transition between the two régimes occurs. For the case of dilute composites which is the case of interest of nano-fibre reinforced composites, the solution differs markedly with the Rosen solution. The buckling strains for dilute composites are shown to have realistic values compatible with elastic behavior. The investigation demonstrates that elastic buckling may thus be a dominant failure mechanism of composites consisting of very stiff fibers fabricated in the framework of nanotechnology.

A Cellular Automaton for Modelling Evolution of Heteroepitaxial Systems

MS3S_12627
Tue • 15:05 • 219A

Simon P.A. Gill
Department of Engineering, University of Leicester, Leicester, UK

An algorithm is presented for the implementation of surface and bulk diffusion within a cellular automaton. Relaxation of the elastic strain in heteroepitaxial systems via morphological change and interdiffusion is investigated.

Effective Thermoelastic Properties of Nanocomposites with Prescribed Random Orientation of Nanofibers

MS3S_12718
Tue • 15:10 • 219A

Ajit Roy[(1)], V.A. Buryachenko[(2)]
(1) *Air Force Research Laboratory, AFRL/MLBCM, WPAFB, USA*
(2) *University of Dayton Research Institute, Dayton, USA*

Nanocomposites are modeled as a linearly elastic composite medium, which consists of a homogeneous matrix containing a statistically homogeneous random field of spheroid nanofibers with prescribed random orientation. Estimation of effective thermoelastic properties of NC was performed by the effective field method (see Buryachenko, Appl. Mech. Review 2001, 54(1), 1-47). The independent justified choice of shapes of inclusions and correlation holes provides the matrix of effective moduli which is symmetric (in opposite to Mori-Tanaka approach). One estimates also the effective tensor of thermal expansion and stress concentrator factors. The interface fiber-matrix is modeled as a thick coating with cylindrically anisotropic varying thermoelastic properties.

MS4

Microfluids

Chairpersons: P. Tabeling (France), R. Adrian (USA), J. Santiago (USA)

Miniaturization of Explosive Technology and Microdetonics

D. Scott Stewart
Department of Theoretical and Applied Mechanics, University of Illinois, USA

MS4I_12976
Mon • 13:30 • 306

Condensed phase explosives used in conventional explosive systems have a charge size on the order of a meter or a sizable fraction of a meter. We discuss a range of issues, theoretical, computational and experimental required to scale the size of explosive systems downwards by a factor of one hundred to one thousand, and applications and prospects for a ubiquitous new technology.

Electrokinetic Flow Instabilities in Microfluidic Systems

Juan G. Santiago
Department of Mechanical Engineering, Stanford University, USA

MS4I_12961
Mon • 14:30 • 306

Microfabrication technology has enabled the application of electrokinetics as a method of performing chemical analyses and achieving liquid pumping in electronically-controlled microchip systems with no moving parts. This talk reviews progress at Stanford including novel methods for sample stacking and fundamental studies of electrokinetic fbw instabilities. Field amplifi ed sample stacking (FASS) leverages conductivity gradients as a robust method of increasing sample concentration prior to capillary electrophoresis separation. We have developed novel chip systems that can achieve signal increases of more than 1000 fold using FASS. Electrokinetic instabilities (EKI) present a major challenge to optimizing FASS devices, as well as an opportunity to achieve rapid on-chip mixing. We have developed generalized models for heterogenous electrokinetic systems for both FASS and EKI, and validated these models with experiments. This work shows that electric body forces associated with the accumulation of charge in the bulk liquid are the cause of EKI. Suppression and/or control of electrokinetic fbw instabilities is directly applicable to sample stacking as conductivity-gradient-induced instabilities dramatically increase dispersion rates and thereby limit stacking effi ciency.

Slip, Patterns, and Other Small Things in Microfluidic Systems

Patrick Tabeling
École Normale Supérieure, Paris, France

MS4I_12960
Tue • 08:30 • 306

Microfluidics is about fbw of liquids and gases, through microdevices fabricated by MEMS (i.e. Micro ElectroMechanical Systems) technology, using hard (silicon or glass) or soft (polymers) materials. The domain is fostered by exciting applications, representing important industrial challenges. It also embraces a number of fundamental issues, interesting in their own right. The introductory talk will concentrate on some of them, through a presentation of a number of experiments we have been carrying out at ESPCI, over the last three years. I will discuss the controversial topics of slip between liquid and solid, and the less controversial phenomenon of slip of gas in microchannels. Mixing is difficult in microsystems, and this has been a source of motivation for studying chaotic micro-mixers. I will present an experimental study of chaotic micromixing, which led to observe a novel resonance phenomenon. I will finally present studies on two-phase flows in microsystems, which led to produce rich, and potentially interesting, patterns. In many cases, microfluidics offers a context for the observation of unexpected behaviors of fluid systems, often inspiring novel engineering concepts.

A Second-order Slip Model for Early-transition-regime Flows

MS4L_11437

Mon • 16:00 • 306

Nicolas G. Hadjiconstantinou
Mech. Eng. Dept., MIT, USA

We present a second-order slip model which extends the Navier–Stokes description of small-scale gaseous flows to second order in the Knudsen number. The model is based on the hard-sphere approximation and accounts for the effect of the Knudsen layers close to the walls which become important as the Knudsen number increases. We validate this model by comparing its predictions to direct Monte Carlo (DSMC) solutions of the Boltzmann equation for three different flows, namely, steady pressure-driven flow, unsteady impulsive-start flow and oscillatory shear flow. In all three cases, excellent agreement is found between the DSMC solutions and the model results up to Knudsen numbers of 0.4 for both the velocity and the stress fields. The agreement continues to be satisfactory beyond this Knudsen number. Given the prohibitive cost associated with solving the Boltzmann equation, especially in higher dimensions, this model should prove to be of great use for modeling isothermal small-scale flows.

Direct Measurement and Simulation of Apparent Slip Velocities in Sub-micron-scale Flows

MS4L_11604

Mon • 16:20 • 306

Peter Huang, **Kenneth S. Breuer**
Division of Engineering, Brown University, Providence, Rhode Island, USA

The possible existence of slip of liquids in close proximity to a smooth surface is studied experimentally and numerically via the dynamics of small particles suspened in a shear flow. Sub-micron fluorescent particles suspended in water and imaged using Total Internal Reflection Fluorescence Microscopy (TIRFM) and a PTV algorithm. The measurements are in excellent agreement with Monte Carlo simulations of particle dynamics, and show that the observed apparent slip velocity is a direct consequence of the small, but finite, measurement volume, and that slip, if present, is minimal at the low shear rates tested (< 2500 /sec). Issues associated with the experimental and simulation techniques and the interpretation of results are also discussed

Theoretical and Experimental Study of Microchannel Blockage Phenomena

MS4L_11607

Mon • 16:40 • 306

Eiichiro Yamaguchi, Ronald J. Adrian
University of Illinois at Urbana-Champaign, TAM, Urbana, USA

Microchannel blockage phenomena by hard, spherical particles have been investigated. Statistical data of the blockage in straight cylindrical glass channel were taken over a range of particle-to-channel diameter ratio of $0.14 < R < 0.65$ at $7.8 < Re < 16.3$. The visualization of particle motion was also performed. The experimentally obtained values of critical particle concentration for the blockage (ϕ_c) are surprisingly low, however dependency to R at constant average share rate ($\bar{G}$) has been successfully predicted by the modified orthokinetic flocculation theory for the channel. It failed to predict the strong negative relation between ϕ_c and $\bar{G}$. Since the theory is adequate to estimate collision frequency of the particle at initial stage of the flocculation, the result indicates significant effect of $\bar{G}$ on following arch formation process. It also suggests that the forming of larger aggregate could be skipped by counting possibility of individual particle or the small aggregation come together to form the arch simultaneously.

Induced-Charge Electro-Osmosis: Theory and Microfluidic Applications

MS4L_11777

Mon • 17:00 • 306

Todd M. Squires(1), Martin Z. Bazant(2)
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(2) *Dept. of Mathematics and Institute for Soldier Nanotechnologies, MIT, Cambridge, USA*

Induced-charge electro-osmosis (ICEO) involves the nonlinear electro-osmotic slip caused by an applied field E_0 acting on induced ionic charge in the vicinity of a polarizable surface. A simple physical picture is presented, and quadrupolar

ICEO flows around conducting cylinders in steady and unsteady electric fields are described, giving perhaps the clearest example of a non-equilibrium electrokinetic phenomena. The ICEO slip velocity scale is $u_s \propto \varepsilon_w E_0^2 L/\mu$, where L is a length scale, and is set up on a time scale $\tau_c = \lambda_D L/D$, where λ_D is the screening length and D is the ionic diffusion constant. Breaking the symmetry of the conductor or field yields even richer behavior: a steady, directed flow can be driven parallel or perpendicular to an AC applied field, and an object can be made that rotates under any AC field. These phenomena naturally suggest microfluidic pumps and mixers that operate without moving parts in low-voltage AC fields.

An Accurate Velocity Profile Measurement System for Microfluidics: A Direct Measurement of the Slip Length

MS4L_12673
Mon • 17:20 • 306

Pierre Joseph, Patrick Tabeling
MMN, ESPCI, Paris, France

We describe an accurate method to measure velocity profiles in thin microchannels, using particle image velocimetry combined with a nano-positioning system. The experimental setup is used to measure the slip length for water flowing along an hydrophilic surface, pyrex glass, and an hydrophobic one, a monolayer of octadecyltrichlorosilane on silicon. This method has a few percent precision on the velocity, 100 nm-accuracy on the determination of the wall position, and a similar precision for the position of the fluid layer where the measurement is performed. These characteristics allow to determine, with unprecedented accuracy (±100 nm), slip lengths for water flows over glass; this represents a substantial improvement (a factor of 6 or so) compared to previous work using a direct method. When applied to glass surfaces, one gets slip lengths equal to 0±100 nm. For functionalized silicon surfaces, the accuracy is lower. One obtains 200±300 nm in this particular case.

Tunable Microfluidic Bubble Generator

MS4L_12966
Mon • 17:40 • 306

Piotr Garstecki[(1)], Howard A. Stone[(2)], George M. Whitesides[(1)]
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(2) *Division of Engineering and Applied Sciences, Harvard University, Cambridge, USA*

We use a flow-focusing geometry incorporated in a microfluidic device to force breakup of nitrogen bubbles in an aqueous medium. We report experimental results on: i) stable formation of monodisperse bubbles, ii) independent control over the size of the bubbles and volume fraction of the dispersed phase, and iii) dynamic assembly of the bubbles into ordered arrays. We propose a quantitative description of the dynamics of breakup and propose a mechanism behind the narrow size distribution of the bubbles and droplets formed in flow-focusing devices. In a broad range of the liquid and gas pressures applied to the system we observe dynamic assembly of bubbles into highly ordered, flowing lattices. The properties of these lattices can be tuned by adjusting the flow rates of the two fluids.

Water Flows in Copper and Quartz Nanochannels

MS4S_10971
Tue • 14:30 • 315A

Anna Kucaba-Pietal[(1)], Z. Walenta[(2)], Z. Peradzynski[(3,2)]
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(2) *IPPT PAN, Warsaw, Poland*
(3) *Warsaw University, IPPT PAN, Warsaw, Poland*

In the present paper the generalised Navier–Stokes theory – the theory of micropolar fluids – has been applied to water flows in narrow channels. The predictions for velocity and microrotation are compared with molecular dynamics simulations of water flows. Two channel widths, equal to 5 and 10 diameters of a water molecule are considered. Two kinds of the channel walls, made of quartz and copper, are taken into account. The obtained results show that the micropolar theory gives a reasonable description of the flow for the wider channel only. In all considered cases a velocity slip and non-zero microrotation at the walls could be observed. The slip effects are more pronounced for smaller channel widths and for walls made of copper. The interaction of water molecules, which have dipole moment, with the electric charges at the quartz crystals seem to have at least some influence on the slip and microrotation at the walls.

Transition Thresholds in Microchannels under the EDL Effect

Sedat Tardu, **Huan Shiu**
LEGI, Grenoble, France

MS4S_11400
Tue • 14:35 • 315A

We have recently shown that the electric double layer destabilizes considerably the micro-channel flows. Thus, the critical Reynolds number may decrease by a factor of 10 under the EDL effect and some circumstances. Due to the subcritical nature of the instability, both the non linear saturation of the primary stability and formation of a secondary flow, together with the secondary instability processes have to be analyzed in EDL flow similarly to the Poiseuille macro-flow. The analyze of the EDL effect on the nonlinear stability mechanism is performed through the spatio-temporal development of a spot in a channel flow by Direct Numerical Simulations in this investigation. A perturbation related to a pair of counter rotating vortices is followed in time and space with and without EDL. Results show the profound destabilizing EDL effect providing that the liquid contains a very small amount of ions with large enough Zeta potential and low conductivity/viscosity.

Using Microfluidics to Investigate Reaction-diffusion Phenomena in Simple Flows

Laure Menetrier(1), Fridolin Okkels(1), Charles N. Baroud(2), Jean-Baptiste Salmon(1), Patrick Tabeling(1)
(1) *ESPCI, Paris, France*
(2) *École Polytechnique, Palaiseau, France*

MS4S_12047
Tue • 14:40 • 315A

We report new experimental and theoretical results on the problem of reaction-diffusion in a microfluidic chip. The chemical reactor under study is a T-shaped microchannel (about 200 μm wide and 10–20 μm deep) in which the two analytes are bring into contact at a constant flow rate. In the interdiffusion zone, the local concentration of the reaction product is measured using optical epi-fluorescence. To extract useful informations about the reaction kinetics, one needs to model the reaction-diffusion zone and compare the simulations with the experiments. We show that such a microfluidic device is a well-suited method to access fast chemical kinetic rates.

Magnetic Particles Aggregation in the Presence of a Hydrodynamic Shear

Guillaume Degre, Edouard Brunet, Fridolin Okkels, Patrick Tabeling
ESPCI, Paris, France

MS4S_12130
Tue • 14:45 • 315A

We present an experimental study of the aggregation of paramagnetic particles, carried out in the presence of a controlled laminar shear, in micro-channels. Superparamagnetic particles, advected by the flow, and immersed in a magnetic field, are found to spontaneously form chains. In a range of time extending up to hundreds of seconds, the growth mechanism is an accumulation of isolated particles or small clusters onto existing chains, moving at different speeds. In this range of time, the chain length increases linearly with time, with a growth rate increasing as a power law with the shear. Smoluchowsky model, assuming single particle-chain interactions only, reproduces well the observations, both at quantitative and qualitative levels. In particular the evolution of the growth rate of the chain lengths with the shear, predicted as a power law with an exponent equal to 0.25, is found consistent with the experiment.

Transport Coefficients of a Fluid at Nanoscale

Xiao-Bing Mi, Allen T. Chwang
Department of Engineering Mechanics, Tsinghua University, Beijing, China

MS4S_12361
Tue • 14:50 • 315A

The generalized theoretical expressions for the transport coefficients of a nanofluid are presented in this paper. The Chapman-Enskog functional perturbation method is employed to solve the derived Enskog-like integro-differential kinetic equation which describes the dynamical behavior of a fluid at nanoscale. The analytical solutions for the nanofluid viscosity, thermal conductivity and other nominal transport coefficients are acquired according to the reduced transport equation and classical definitions in fluid mechanics. The molecular dynamics (MD) simulation is further used to verify the theoretical results via the model of a Lennard-Jones fluid in a nano Couette flow. The nanofluid transport coefficients are calculated by considering both the weak and strong fluid-wall interactions. By comparing theoretical results to MD simulations, it is found that both are in qualitative agreement in the present study.

Chaotic Mixing and Resonances in a Microfluidic System

MS4S_12536

Tue • 14:55 • 315A

Arash Dodge[1], **Caroline Jullien**[2], Fridolin Okkels[1], Patrick Tabeling[1]
(1) *MMN-ESPCI, Paris, France*
(2) *SATIE, ENS-Cachan, Bruz, France*

The paper is dedicated to the study of a particular system – the cross-channel micromixer; this system consists of a main channel where two fluids, flowing side by side, are perturbed by a transverse, oscillating periodic flow, in a cross-channel intersection. The perturbation leads to the formation of tendrils and whorls, inducing chaotic-like regimes. This particular system is the host of a novel phenomenon – a spatio-temporal resonance effect, in which the interface between the two fluids returns to its original shape after it has been perturbed, if certain conditions on the frequency of the perturbation are satisfied. The paper shows an experimental study of the resonances and chaotic regimes, using a microfluidic device, in which PDMS integrated valves, remotely controlled, allow to produce the transverse oscillating flow, under well defined conditions

MS5

Microgravity flow phenomena

Chairpersons: J. Legros (Belgium), G. Neitzel (USA), I. Alexander (USA)

Foams, Films and Surfaces in Microgravity

Denis Weaire, S. Cox

Department of Physics, Trinity College, Dublin, Ireland

MS5I_10598
Mon • 13:30 • 315

Beginning with a broad view of the role of surface tension and gravity in free liquid surfaces, thin films and foams, we identify the motivation for the microgravity research conducted in these systems over the last quarter century. In the case of foams, experiments have been quite limited in scope, and the intention to study *wet* foams has yet to be fully realized, except perhaps in the case of two-dimensional samples. New experiments are planned for MAXUS rockets and possibly the International Space Station (ISS).

Collisional Granular Flows with and without Gas Interactions in Microgravity

Haitao Xu, **Michel Y. Louge**

Mechanical & Aerospace Engineering Cornell University, Ithaca, USA

MS5I_10714
Mon • 14:30 • 315

We illustrate the convenience of a long-lasting microgravity environment for studying fbws of granular materials with and without gas interaction. We consider collisional granular fbws of nearly elastic spheres featuring a single constituent or binary mixtures in various bounded geometries. We review the equations of the kinetic theory for the conservation of mass, momentum, fluctuation energy and species concentration. We illustrate their solutions for shear fbws in rectilinear or axisymmetric rectangular channels with or without a body force. We show that proper boundary conditions yield numerical solutions in good agreement with molecular dynamical simulations and with data from physical experiments carried out in microgravity.

Microgravity and Microscale Fluid Mechanics

George M. Homsy

Mechanical Engineering, UCSB, USA

MS5I_11133
Tue • 08:30 • 315

This Introductory Lecture will cover aspects of Microgravity Fluid Mechanics by first describing the characteristics of the microgravity environment and establishing the manner in which the body force of gravity appears in the basic scalings and diimensionless parameters. The following themes are then developed: (i) the Space environment is characterized by transient accelerations, which implies that both the magnitude and direction of g are time-dependent, and; (ii) the magnitude of g is important only in combination with other intrinsic scales, with the consequence that microgravity and microscale fluid mechanics have much in common. The lecture will then focus on two classes of problems. The first is a class of so-called g-jitter phenomena driven by the time dependence of g, and the second is a class of interfacial fluid mechanics problems in which the essential driving force is applied tangential stresses due to Marangoni effects. If time allows, the

inclusion of non-hydrodynamic forces will be mentioned, particularly in reference to the invited talk SL16, Electrokinetics and electrohydrodynamics in microfluids, by D.A. Saville.

Mathematical Models of Microconvection for Isothermally Incompressible and Weakly Compresible Liquids

MS5L_11757
Mon • 16:00 • 315

Vladislav V. Pukhnachov(1), Olga N. Goncharova(2)
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(2) *Altai State University, Barnaul, Russia*

The term microconvection was originally introduced to characterize non-solenoidal flows driven by density (depending on temperature only) changes. These phenomena were analyzed for thermal buoyancy-driven convection (Pukhnachov, 1991) and for diffusive-induced flows (Perera and Sekerka, 1997). The effect on non-solenoidality is equally important for the description of non-stationary convection in microgravity conditions and in microscales. Recently this approach was extended up to convective motions of a weakly compressible liquid (Pukhnachov, 2002). On the basis of the microconvection model, there are studied a number of problems describing the convection in a vertical layer with the thermal fluxes oscillating in a phase and in an anti-phase, flows in a circular ring and in a prolate rectangular, mixed thermocapillary/gravitational convection in a semicircle with a free flat boundary.

Onset of Oscillations in High-Prandtl Thermocapillary Liquid Bridges: Linear-stability Analysis vs. Experiment

MS5L_11843
Mon • 16:20 • 315

M.K. Ermakov
Institute for Problems in Mechanics RAS, Moscow, Russia

The float-zone crystal growth process is studied in the framework of the half-zone model. Linear-stability analysis is used to compare the onset of oscillations in liquid bridge thermocapillary convection upon liquid bridge volume with experimental data for high-Prandtl fluid. Well-known structure of neutral stability curve for high-Prandtl fluid, consisting of two branches separated by an overstability gap, has been clearly reproduced. Travelling hydrothermal waves with unit azimuthal wave number correspond to critical perturbations for both branches. An influence of the temperature-dependent viscosity, the heat loss through free surface and the gravity level is determined.

Spherical Two-phase Interface in a Near-critical Fluid. Gradient Approach

MS5L_12402
Mon • 16:40 • 315

Anatoly M. Vorobev(1), D.V. Lyubimov(2), **T.P. Lyubimova**(1)
(1) *Institute of Continuous Media Mechanics UrB RAN, Perm, Russia*
(2) *Perm State University, Russia*

On macro-scales the liquid-gas interface is classically modeled by a surface of discontinuity. However, on micro-scales, there is a transitional region, where the properties are changed continu-ously. This makes reasonable a description of two-phase system, including the interface, within a hydrodynamic approach. In this approach, the new term proportional to density gradient is added to the internal energy. Near the critical point, where there is no strong difference between liquid and its vapor, the gradient approach is quite reasonable. Based on this approach we considered the formation of new phase nucleus in a closed cav-ity; and analyzed its stability. The results are in agreement with classical Laplace approach, while considering the states far from the critical point. In near-critical region, the results are proved to be intriguing. It is shown that within the framework of one-dimensional problem the system remains single-phase and homogeneous even for negative values of mechanical compressibility.

Transition to Chaotic Marangoni Convection in Liquid Bridge

MS5L_12427
Mon • 17:00 • 315

V. Shevtsova, D. Melnikov, J.C. Legros
MRC, University of Brussels, Brussels, Belgium

Marangoni convection is investigated in cylindrical column using a liquid with $Pr = 4$. The present results are targeting on the study of the non-linear characteristics of the flow under zero-gravity conditions. The transitions to periodic, quasi-periodic and chaotic flows are investigated numerically. The 3-D oscillatory flow is a result of a supercritical Hopf bifurcation and the periodic orbit represents the unique stable solution near the onset of the instability. The non-linear system admits regime of bi-stability. A traveling wave with azimuthal wave number $m = 2$ bifurcates from the basic branch of axisymmetric

steady state; this branch remains stable in the considered range of parameters. A second stable branch with azimuthal wave number m = 3 appears for higher Marangoni numbers and reveals other periodic, quasi-periodic and chaotic properties. The transitions between the two stable orbits with m = 2 and m = 3 have never been observed.

Capillary Pressure of a Liquid Between Uniform Spheres Arranged in a Square-packed Layer

MS5L_12447
Mon • 17:20 • 315

J. Iwan D. Alexander[1], Lev A. Slobozhanin[1], Stephen H. Collicott[2]
(1) *CWRU, Cleveland, Ohio, USA*
(2) *Purdue University, Indiana, USA*

The capillary pressure in the pores defined by equidimensional close-packed spheres is analyzed numerically. In the absence of gravity the menisci shapes are constructed using Surface Evolver code. This permits calculation the free surface mean curvature and hence the capillary pressure. The dependences of capillary pressure on the liquid volume constructed here for a set of contact angles allow one to determine the evolution of basic capillary characteristics under quasi-static infiltration and drainage. The maximum pressure difference between liquid and gas required for a meniscus passing through a pore is calculated and compared with that for hexagonal packing and with an approximate solution given by Mason and Morrow. The lower and upper critical liquid volumes that determine the stability limits for the equilibrium capillary liquid in contact with square packed array of spheres are tabulated for a set of contact angles.

Recent Advances in Permanent Noncoalescence and Nonwetting

MS5L_12651
Mon • 17:40 • 315

G. Paul Neitzel[1], Pasquale Dell'Aversana[2], Peter Nagy[1], Maria-Isabel Carnasciali[1]
(1) *Georgia Institute of Technology, Atlanta, USA*
(2) *Microgravity Advanced Research and Support Center, Naples, Italy*

Permanent noncoalescence between two drops of the same liquid or nonwetting between a liquid and a surface normally wetted by it have been the subject of study for the past several years. Such behavior may be driven through the use of thermocapillarity or relative tangential-surface motion. Potential applications range from frictionless mounts and vibration dampers for microgravity experimental packages to frictionless bearings in low-load terrestrial applications. Recent research has focused on the characterization of failure modes and mechanisms in these systems, knowledge of which is crucial for a successful application, and on the measurement of frictional forces associated with sliding, isothermal nonwetting droplets. The presentation will provide an overview of the subject and a discussion of recently obtained results.

Heat Transfer Due to High Frequency Vibration: a New Approach for Achieving Thermally Optimum Geometry Under Microgravity Conditions

MS5S_10980
Tue • 15:05 • 315A

M.C. Charrier Mojtabi[1], Y.P. Razi[2], K. Maliwan[2], A. Mojtabi[2]
(1) *Energy Laboratory, UPS Toulouse, France*
(2) *IMFT/CNRS/UPS Toulouse, France*

This study aims to draw attention to the possibility of heat transfer enhancement under microgravity conditions. The geometry considered is a rectangular enclosure, filled with a pure fluid, heated differentially and undergoing mechanical vibration. The vibration is periodic with zero mean, and is in the limiting range of high frequency and small amplitude. The direction of vibration is perpendicular to the temperature gradient. The time-averaged formulation is adopted and the governing equations are solved by finite volume method. Numerical simulations are performed to predict the heat transfer and fluid flow characteristics of the resulting thermo-vibrational convection. Different fluid flow structures are presented and discussed. Correlations for Nusselt number and optimum configuration as a function of Rav (vibrational Rayleigh number), Pr (Prandtl number) and A (aspect ratio) are proposed. The results demonstrate the existence of an optimum geometry for which the heat transfer rate is maximal. The findings have significant applications in space industry.

Thermocapillary Convection in Liquid Bridges and Annuli

MS5S_11483

Tue • 15:10 • 315A

Bok-Cheol Sim[1], **Abdelfattah Zebib**[2]
(1) *LG Siltron, Gyeongbuk, Korea*
(2) *Rutgers University, Piscataway, USA*

Thermocapillary convection in two types of cylindrical geometry is investigated in two- and three-dimensional numerical simulations: a liquid bridge heated from the upper wall and an open annulus heated from the outside wall. For the parameter ranges considered, it is found that dynamic free-surface deformations are negligible and do not induce transitions to oscillatory convection in axisymmetric models. Moreover, only steady convection is possible at any Reynolds number (Re) in strictly axisymmetric computations. In our three-dimensional models, the nondeformable free surfaces are either flat or curved as determined by the fluid volume (V) and the Young-Laplace equation. Convection is steady and axisymmetric at sufficiently low values of Re with either nondeformable or deformable surfaces. Transition to oscillatory three-dimensional motions occurs as Re increases beyond a critical value dependent on the aspect ratio, the Prandtl number and V. Good agreement with available experiments is achieved in all cases.

The Stability of Connected Pendant Drops

MS5S_12765

Tue • 15:15 • 315A

Lev A. Slobozhanin, J. Iwan D. Alexander
Case Western Reserve University, Cleveland, Ohio, USA

The stability of an equilibrium system of two drops suspended from circular holes is examined. The drop surfaces are disconnected surfaces of a connected liquid body. For holes of equal radii and identical pendant drops axisymmetric perturbations are always the most dangerous. The stability region for two identical drops differs considerably from that for a single drop. Loss of stability leads to a transition from a critical system of identical drops to a stable system of axisymmetric non-identical. This system of non-identical drops reaches its own stability limit (to isochoric or non-isochoric perturbations). For non-identical drops, loss of stability results in dripping or streaming from the holes. Critical volumes for non-identical drops have been calculated as functions of the Bond number, B. For unequal hole radii, stability regions have been constructed for a set of hole radius ratios, K. The dependence of critical volumes on K and B is analyzed.

Hydrodynamic Effect of Slow Phase Transitions in Microgravity

MS5S_12828

Tue • 15:20 • 315A

Eleonora K. Bevza, O.O. Kochubey, D.V. Yevdokymov
Dniepropetrovsk National University, Dniepropetrovsk, Ukraine

Slow phase transitions are widespread in microgravity condition, because thermal conduction and diffusion processes, governing phase transition there, often cannot provide enough high intensity of the process. Small Stefan number corresponds to slow phase transition and it is quite natural to apply small parameter method to the problem, using a Stefan number as a small parameter, what was made in previous works of the authors. However due to density difference between origin and created phases there must be fluid flow (quite week because of slow process), what is the main object of the present work. Correspondent convective flux is smaller than heat conduction one, but its influence must be estimated too. Using the same small parameter method it can be shown that the convective term has first order with respect to Stefan number, therefore it is absent in zero approximation, what gives an opportunity to build an analytical solution in one-dimensional (in space) case and to obtain a numerical solution in two- and three-dimensional cases. Boundary element method is used for numerical solution of boundary-value problem, if it is necessary, and Euler scheme is used for time integration, if analytical integration is impossible.

MS6

Atmosphere and ocean dynamics

Chairpersons: J. Sommeria (France), M. McIntyre (UK)

Transport And Mixing in the Atmosphere

Peter Haynes
DAMTP, University of Cambridge, UK

MS6I_10987
Mon • 13:30 • 134

Transport and mixing of atmospheric chemical species is a vital part of the chemical-climate system. Transport and mixing processes in the atmosphere operate on scales from millimeters to thousands of kilometers. In certain parts of the atmosphere the large-scale 'layerwise two-dimensional' flow appears to play the dominant role in transport and in the stirring process that leads ultimately to true (molecular) mixing at very small scales. There is therefore much in common with fluid dynamical topics such as 'chaotic advection' or 'Batchelor-regime turbulence'. My lecture will describe how, with appropriate modification, some of the theoretical tools developed in these contexts can be used, in conjunction with observational data on large-scale velocity fields or on chemical species, to quantify different aspects of transport and mixing in the atmosphere.

Wave Vortex Interactions in the Atmosphere and Oceans; with Applications to Climate

Onno Bokhove
Department of Mathematics, University of Twente, The Netherlands

MS6I_10716
Mon • 14:30 • 134

In the atmosphere and oceans, there is often a large separation in time scales between the slow large-scale motion of the fluid and the rapid small-scale wave motion and turbulence. These small-scale processes cannot be captured by numerical models. Hence, the feedback of the unresolved wave and turbulent motion on the large-scale dynamics requires parameterization. For hydrostatic primitive equations, we introduce the dynamics of gravity-wave and vortical modes, potential vorticity, and the (Hamiltonian) balanced description of the slow, large-scale dynamics in terms of the vortical motion. Various mechanisms to generate and absorb gravity waves will be reviewed with an eye on extending current parameterization schemes. Our aim is to address the question: can we construct an accurate (atmospheric) climate model with a balanced model as dynamical core and with dissipative and non-dissipative parameterization schemes for the gravity-wave activity?

Assimilation of Observations into Numerical Models

Olivier Talagrand
Laboratoire de Meteorologie Dynamique, IPSL, Paris, France

MS6I_10803
Tue • 08:30 • 134

Assimilation of meteorological or oceanographic observations is the process by which observations are combined together with a numerical dynamical model of the flow in order to produce as accurate as possible a description of the state of the flow. Assimilation can be considered as a problem in bayesian estimation, made particularly difficult by the very large numerical dimensions involved, and by the complexity of the underlying dynamics. Two main classes of algorithms exist for assimilation. In sequential assimilation, the most recent estimate of the state of the flow is constantly updated with new observations. In variational assimilation, the assimilating model is globally adjusted to the observations distributed over a period of time through minimization of an appropriate scalar objective function. Assimilation, which has become a major component of numerical meteorology and oceanography, is progressively extending to other fields, such as atmospheric and oceanic chemistry, or surface hydrology. It also plays a critical role in such applications as the definition and optimization of observing systems, or the study of the predictability of the atmospheric or oceanic circulation.

Modelling Oceanographic Coastal Currents in Small-scale and Large-scale Laboratory Experiments

MS6L_10261
Mon • 16:00 • 134

Peter J. Thomas[1], Paul F. Linden[2], David Marah[1]
(1) *Fluid Dynamics Research Centre, University of Warwick, Coven, UK*
(2) *Dept. of Mech. and Aerospace Eng., Univ. of California, La Jolla, USA*

Laboratory experiments simulating gravity-driven oceanographic coastal surface currents are discussed. The current height, its width and its propagation velocity are investigated. The analysis of results from two complementing studies on substantially different spatial scales and in different parameter regimes is presented for the first time. One study was conducted in a small rotating tank with diameter 1 m while the second used the world's largest rotating turntable at the Coriolis Facility (Grenoble) with its 13-metre diameter tank. Dimensional analysis yields a set of non-dimensional parameters which are used to develop a geostrophic model. The data analysis reveals that the model enables collapsing all corresponding results from small-scale and large-scale experiments onto single curves for the first time. Very good agreement between experiments and model is found in the geostrophic regime. The data show how the model gradually becomes less appropriate as ageostrophic experimental conditions are approached.

Near-surface Turbulence in a Neutral Planetary Boundary Layer: Comparison of LES with the CASES'99 Experiment Observations

MS6L_10513
Mon • 16:20 • 134

Pierre Carlotti[1], Philippe Drobinski[2], Jean-Luc Redelsperger[3], Rob K. Newsom[4], Robert M. Banta[4]
(1) *CETU, Bron, France*
(2) *IPSL/SA, Paris, France*
(3) *CNRM/M-F, Toulouse, France*
(4) *ETL/NOAA, Boulder, USA*

This work compares the results of the field experiment CASES'99 with an idealized LES simulation performed with Méso-NH. This comparison is done for an atmosphere in neutral stability conditions. The conditions are set so that the LES reproduced as well as possible the friction velocity, the ground roughness, the inversion heigth, and the geostrophic wind of the real case, and energy profiles and flow patterns of the real case and the LES are compared, showing a good agreement. In particular, the LES shows the formation of near-surface streaks spaced of approximately 390 m, in agreement with high resolution Doppler lidar radial velocity recorded in CASES'99, which shows evidence of an approximate spacing of the streaks of 315 m.

Geophysical Turbulent Boundary Layers: the Nature, the Theory and the Role in the Atmosphere-ocean System

MS6L_12833
Mon • 16:40 • 134

Sergej S. Zilitinkevich
Department of Earth Sciences, Uppsala University, Sweden

Turbulent boundary layers control the exchange processes between the atmosphere and the ocean/ice/land. The key problem of boundary-layer physics is to determine the momentum, energy and matter fluxes in a wide range of boundary-layer regimes from stable and neutral to convective. This paper presents the state of the art and modern developments in boundary-layer physics with focus on the recently recognised non-local mechanisms overlooked in the traditional theories, namely, the effect of internal gravity waves on vertical transports in stably stratified flows and the role the buoyancy-driven large-scale semi-organised eddies in convective flows. New developments are compared with experimental and large-eddy simulation (LES) data. They are motivated by urgent necessity to improve boundary-layer parameterisations in very high resolution environmental models, particularly, in the coupled atmosphere-ocean models.

Meridional Flow of Source Driven Grounded Abyssal Flow in a Wind Driven Basin with Topography

MS6L_10634

Mon • 17:00 • 134

Gordon E. Swaters
Institute for Geophysical Research, University of Alberta, Edmonton, Canada

A hybrid 3-layer quasi-geostrophic/planetary geostrophic (QG/PG) model is introduced to examine the baroclinic evolution and meridional flow of abyssal currents in a wind-driven, stratified and differentially-rotating basin with variable bottom topography. The model resolves mesoscale processes and allows for the formation of a wind driven surface intensified ocean circulation, with a poleward western boundary current, and a source driven equatorward flowing deep western boundary undercurrent. Baroclinic and barotropic instability within the surface intensified western boundary current, and baroclinic instability between the abyssal current and the overlying wind driven circulation, is resolved. The model allows for finite amplitude variations in the height field of the abyssal current so that groundings in the thickness or isopycnal field associated with the undercurrent are resolved.A southern boundary upwelling scheme is introduced, within the context of a closed basin with no-slip boundary conditions, to balance the northern source of abyssal water thereby allowing the meridional transport of abyssal water to evolve toward a steady state.

Remote Recoil and Wave Capture: Wave–vortex Interactions in Atmosphere-Ocean Models

MS6L_10977

Mon • 17:20 • 134

Oliver Bühler[1], **Michael McIntyre**[2]
(1) *Courant Institute, New York, USA*
(2) *University of Cambridge, Cambridge, UK*

In a recent paper (J. Fluid Mech 492, 207) we described a fundamentally new wave–mean or wave–vortex interaction effect able to force persistent, cumulative change in mean flows in the absence of wave breaking or other kinds of wave dissipation. It is associated with the refraction of nondissipating waves by inhomogeneous mean (vortical) flows. The simplest relevant case is that of a narrow beam of sound waves, or shallow-water gravity waves, weakly refracted by a single vortex in two dimensions. An effective recoil force arises. This accords with expectation from a naive photon analogy or 'pseudomomentum rule' EXCEPT that it acts not where the waves refract, but at the vortex core, even if the core is spatially separated from the refracting beam of waves. Strong refraction brings further phenomena including catastrophic 'wave capture', a nontrivial variant of classical critical-layer absorption; see the more detailed presentation on this by Buehler in this Minisymposium. One implication is that there are missing forces not yet accounted for in atmospheric climate and weather-prediction models. Connections with the 'pseudomomentum rule' and the 'wave momentum myth' are discussed.

Anisotropic Large-Scale Turbulence on Giant Planets and in the Ocean

MS6L_11152

Mon • 17:40 • 134

B. Galperin[1], S. Sukoriansky[2], H. Nakano[3]
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(2) *Mechanical Engineering, BGU, Beer-Sheva, Israel*
(3) *Oceanographic Research Department, MRI, Ibaraki, Japan*

Barotropic two-dimensional turbulence with Rossby waves is distinguished by strong anisotropy and energetic zonal jets in alternating directions. Flows on the beta-plane and in thin shells on the surface of a rotating sphere develop strongly anisotropic spectrum with steep, n^{-5}, slope for the zonal flows and Kolmogorov–Kraichnan, $n^{-5/3}$, slope for the residuals. The n^{-5} zonal spectrum was found on all four giant planets of our solar system, both with regard to its slope and the amplitude. This spectrum can be used to analyze some basic characteristics of large-scale circulations on giant planets and for interplanetary comparisons. Recently, it was found that the mid-depth ocean currents in the north Pacific ocean also develop a system of alternating zonal jets and build up the same n^{-5} and $n^{-5/3}$ zonal and residual spectral distributions. The main characteristic of the planetary and oceanic flows under consideration is the smallness of their Burger number, $Bu = (L_d/R)^2$, where L_d is the first baroclinic Rossby radius of deformation and R is the planetary radius. Exploring the planetary-ocean analogy, we conclude that the fine-scale oceanic zonal jets are driven by strongly nonlinear, anisotropic dynamics of quasi-2D turbulence with Rossby waves and argue that the latitudinal scaling of these jets is determined by the large-scale friction processes.

Turbulent Horizontal Convection and the Global Thermohaline Circulation of the Oceans

MS6L_11499

Tue • 11:00 • 134

Ross Griffiths, Graham Hughes, Julia Mullarney
Australian National University, Canberra, Australia

Our laboratory and numerical experiments show that convection in a long box driven by differential heating at a single horizontal boundary can be turbulent. A convective mixed layer forms within a stable thermocline, deepens toward the end of the box, penetrates through the depth of the thermocline at the end, and feeds into a turbulent plume. The mean 'sinking' occurs at one end and, in the rotating case, involves unsteady chimney structures. Using an analytical model with zero net buoyancy flux and depth-dependent vertical velocity in the interior we correctly predict the mass transport and density structure for both the experiments and the meridional overturning circulation of the ocean. The ocean prediction is consistent with data when we assume a vertical diffusivity equal to that measured in the open oceans. Thus the much larger diffusivity inferred by others and energy input from winds and tides are not required, and the overturning circulation can be driven by the surface heat fluxes.

Instability of Gravity Driven Coastal Current in a Turntable Experiment

MS6L_11547

Tue • 11:20 • 134

E. Thivolle-Cazat, **J. Sommeria**
LEGI-CNRS, Grenoble, France

The instability of a current driven by gravity and maintained along a vertical lateral wall by the Coriolis force is investigated in laboratory experiments, performed in the large Coriolis turntable (Grenoble). The flowing water floats over a homogeneous denser layer. It represents for instance the Algerian current, made of the light Atlantic water entering the Mediterranean Sea. This current is unstable, generating meanders and vortices. This is classically attributed to baroclinic instability, but in our case it is forbidden by the absence of potential vorticity gradient in the lower layer. However we find that the instability of the viscous boundary layer initiates the process: the wall vorticity concentrates into vortices, which then interact with the main current potential vorticity as propagating dipoles, mimicking the usual process of baroclinic instability. For oceanic modelling, a proper representation of the meander initiation therefore requires a good resolution of the viscous boundary layer.

Intrusive Gravity Currents in a Stratified Ambient – novel Theoretical Results and Insights

MS6L_11585

Tue • 11:40 • 134

Marius Ungarish
DCS, Technion, Israel

The intrusion of a fixed volume of "mixed" fluid which is released from a lock (of rectangular or cylindrical shape) and then propagates horizontally at the neutral buoyancy level in a stratified ambient fluid is considered. The density change is linear, in a restricted layer or over the full-depth of the ambient. A closed one-layer shallow-water formulation is used to obtain solutions of the initial-value problem and similarity solutions for the large-time developed motion. The theory is corroborated by numerical Navier–Stokes solutions and comparisons with previous experiments. Novel insights are derived on essential features of the flow-field, in particular: the governing dimensionless parameters, the fact that the initial propagation is with constant speed (for rectangular lock only), the effect of the shape of the lock, the spread with time at some power, the sub-critical (compared to leading linear waves) speed, and the interaction with internal gravity waves.

Interactions of Planar Waves with a Baroclinic Vortex

MS6L_11829

Tue • 12:00 • 134

Frédéric Moulin, **Jan-Bert Flór**
LEGI-CNRS-UJF, Grenoble, France

We investigate the interaction of inertia-gravity waves on the dynamics of a baroclinic vortex in a rotating stratified fluid using WKB theory – adapted to cylindrical coordinates – in combination with experimental observations. The vortex is either lenticular or elongated in shape and interacts with a planar wave-field emitted by an oscillating cylinder. The trapping of the wave energy is characterized as a function of the vortex aspect-ratio, H/R, the wave-Froude-number, Fr–w, based on the wavelength and the maximum azimuthal velocity of the vortex and wave frequency. With increasing Frw the trap-region focuses, implying energy amplification, leading to wave-breaking or damping by viscous effects. In the latter case, the maximum amplification of wave energy is a function of Frw and Reynolds number based on the vortex shear. The results

show that waves break in the periphery of mainly tall vortices, resulting in a deposit of momentum, which modifies the vortex velocity profile.

Spontaneous Generation of Inertia-gravity Waves by Balanced Motion

MS6L_12104
Tue • 12:20 • 134

Jacques Vanneste
School of Mathematics, University of Edinburgh, Edinburgh, UK

The spontaneous generation of inertia-gravity waves by balanced motion leads to fundamental limitations in the accuracy of balanced models. In the standard quasi-geostrophic regime (with small Rossby number and order-one Burger number) the amplitude of the inertia-gravity waves can be expected to be exponentially small in the Rossby number. We demonstrate this explicitly by deriving asymptotic estimates for this amplitude in two models described by ordinary differential equations: the five-component model of Lorenz and Krishnamurthy; and a model describing the evolution of sheared disturbances in a three-dimensional Boussinesq fluid. In both cases the asymptotic estimates are confirmed by numerical experiments. The concepts and techniques used in our analysis (optimal truncation of asymptotic series, Borel–Laplace transform, complex-time dynamics) help clarify a number of issues in balanced dynamics and initialization. Their relevance to more realistic models of the atmosphere and oceans is discussed.

Wave Capture and Wave-vortex Duality

MS6L_12157
Tue • 12:40 • 134

Oliver Bühler[1], Michael E. McIntyre[2]
(1) *Courant Institute, New York University, New York City, USA*
(2) *University of Cambridge, UK*

New and unexpected results are presented regarding the nonlinear interactions between a small-scale wavepacket and a large-scale mean flow, with an eye towards internal wave dynamics in the atmosphere. These are to do with an unusual wave breaking scenario termed ‘wave capture’, which differs significantly from the standard wave breaking scenarios due to critical layers or mean density decay. We focus on the very peculiar wave-mean interaction scenario that accompanies wave capture. We present examples of these interactions in 2d shallow water and in the 3d Boussinesq system. Specifically, we point out an analogy between slow wavepackets and vortex dipoles that shows a peculiar and apparently so-far unrecognized ‘wave-vortex duality’, which throws a new light on the relation between wave dissipation and mean-flow forcing.

Generation of Internal Waves in the Deep Ocean by Barotropic Tides

MS6L_12210
Thu • 09:30 • 134

Jonas Nycander
Dept. of Meteorology, Stockholm University, Stockholm, Sweden

The internal waves generated by tides over rough bottom topography are considered to be the main energy source for the vertical mixing in the deep ocean, which is a critical link in the global overturning circulation. Here the energy flux into the internal wave field due to this mechanism is calculated from first principles, using linear wave theory. The analytic solution of the problem in the form of a Fourier integral over spectral space has long been known. Inverse Fourier transformation shows that the flux density in real space is given by a convolution integral. This integral is here calculated numerically over the global ocean. Three data sets are used as input in the calculations: the Smith and Sandwell bottom topography, the Egbert tidal velocity, and the density stratification from the SAC database.

Instability of Corotating Vertical Vortices in a Stratifield Fluid: Why Strongly Stratifield Turbulence is not Similar to 2D Turbulence

MS6L_12294
Thu • 09:50 • 134

Pantxika Otheguy, Paul Billant, Jean-Marc Chomaz
LadHyX, École Polytechnique, Palaiseau, France

We show numerically the existence of a new instability of two corotating vertical vortices in a vertically stratified fluid. This three dimensional instability induces the formation of thin horizontal layers with a thickness inversely proportional to the Brünt-Väisälä frequency. This instability is due to the coupling of vortex displacement modes and the strain field induced by the companion vortex. Experimental observations have confirmed the existence of this instability. It speeds up the merging in some layers and delays it in other layers. Since this instability occurs during the pairing of vortices, it may

play a major role in energy transfer in stratified turbulence and question the classical Lilly's theory of a two dimensional dynamics in the mesoscale atmospheric turbulence.

Multiple Jet Formation in a Convectively Driven Flow on a Beta-plane

MS6L_12494
Thu • 10:10 • 134

Peter L. Read[1], Yasuhiro H. Yamazaki[1], Stephen R. Lewis[1], Paul D. Williams[1], Joel Sommeria[2], Henri Didelle[2]

(1) *University of Oxford, Clarendon Laboratory, Parks Road, Oxford, UK*
(2) *LEGI Coriolis, Grenoble, France*

We present results from laboratory experiments carried out on the Coriolis rotating platform in Grenoble, France, to investigate the influence of a topographic beta-plane (obtained via a sloping bottom) on convectively-driven geostrophic turbulence. Dense, salty water is sprayed continuously onto the surface of the tank, which leads to the formation of a field of convective vortices. In the presence of a sloping bottom, the vortices interact nonlinearly, leading to the formation of a series of quasi-steady, parallel azimuthal jets on a scale comparable with the so-called Rhines scale $L_R = \pi\sqrt{2U/\beta}$. Such jets are not found with a flat bottom. Statistics of jets and vortices appear to be broadly consistent with the theory of Rhines et al. and some recent numerical models of geostrophic turbulence on a sphere. Implications will be discussed in the context of various geophysical problems, including the atmospheres of the outer planets and the Earth's oceans.

Agradient Velocity and Vortical Motion in Rotating Fluids

MS6S_11313
Tue • 14:30 • 134

Georgi Sutyrin
GSO/URI, Narragansett, USA

A new approach to modelling slow vortical motion and fast inertia-gravity waves is suggested within the rotating shallow-water primitive equations with arbitrary topography. The velocity is exactly expressed as a sum of the gradient wind, described by Bernoulli function, and the rest, agradient part, proportional to the velocity tendency. Then the equation for inverse potential vorticity, as well as momentum equations for agradient velocity include the same source of adiabatic flow evolution expressed as a single term of the Jacobian operator of Bernoulli function and potential vorticity. This approach allows for the construction of balance relations for vortical dynamics and potential vorticity inversion schemes even for moderate Rossby and Froude numbers. The components of agradient velocity are used as the fast variables slaved to potential vorticity. The ultimate limitations of constructing the balance are revealed in the form of the ellipticity condition for balanced tendency of Bernoulli function which incorporates both known criteria of the formal stability: the gradient wind modified by the characteristic vortical Rossby wave phase speed should be subcritical.

Strong Vortex Insteractions in Quasi-Geostrophic Flows

MS6S_11336
Tue • 14:35 • 134

Jean N. Reinaud, David G. Dritschel, Ross R. Bambrey
University of St Andrews, St Andrews, UK

We examine the strong interaction between two quasi-geostrophic vortices. The interaction depends on 6 parameters: the volume ratio, the potential vorticity ratio, the height-to-width aspect ratios, and the vertical and horizontal offsets. The parameter space is huge and highly efficient methods are needed to cope with the size of the problem. We primarily use a novel solution method, the Ellipsoidal Model (ELM), which models vortices as ellipsoids and filters higher-order deformations. It proves to be highly accurate and allows us to determine steadily rotating equilibria for both like-signed and opposite-signed vortices. We next determine the margin of linear stability of these states which we associate with the critical distance for strong vortex interactions. We complete the description of the interactions by illustrating the nonlinear evolution of selected unstable interactions here using the full dynamical equations (including non-ellipsoidal deformations).

Irreversible Transition to a State with Higher Entropy Production in Oceanic General Circulation

MS6S_11732
Tue • 14:40 • 134

Shinya Shimokawa[1], Hisashi Ozawa[2]

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(2) *Frontier Research System for Global Change, Yokohama, Japan*

The mechanism of transitions among multiple steady states of thermohaline circulation is investigated from a thermodynamic viewpoint. A new quantitative method is developed to express the rate of entropy production for a large-scale open

system and its surroundings by the transports of heat and matter. An oceanic general circulation model is used to obtain multiple steady states under the same set of a wind forcing and mixed boundary conditions, and the rate of entropy production is calculated during the transition among the multiple steady states by this new method. The results always show a tendency to move to a state with higher entropy production, except when the perturbation destroyed the system's initial state altogether. It is suggested that the rate of entropy production represents relative stability of multiple steady states in nonlinear fluid systems in general, including our climate system.

A New Spectral Closure Model of Turbulent Flows with Stable Stratification and Its Application to Atmospheric SBLS

MS6S_11942
Tue • 14:45 • 134

Semion Sukoriansky(1), Boris Galperin(2), Veniamin Perov(3)
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A new model for turbulent flows with stable stratification is presented. This model belongs in the class of the quasi-Gaussian closures; its parameters are calculated based upon a self-consistent recursive procedure of small-scale modes elimination starting at the Kolmogorov scale kd. The model includes both vertical and horizontal eddy viscosities and diffusivities thus explicitly recognizing the anisotropy induced by stable stratification. There are significant differences in the behavior of these turbulent exchange coefficients with increasing stratification. Generally, the vertical coefficients are suppressed while their horizontal counterparts are enhanced. The model accounts for the combined effect of turbulence and internal waves on the exchange coefficients. A dispersion relation for internal waves in the presence of turbulence is derived. A threshold criterion for the wave generation in the presence of turbulent scrambling is obtained. The new model can be used to derive subgrid-scale parameterizations for LES and eddy viscosities and diffusivities for RANS models. The latter approach is used to develop a new $K-\varepsilon$ model which is tested in simulations of the atmospheric stable boundary layer (SBL) over sea ice. The new model performs well in both moderately and strongly stratified SBLs.

Roll Vortices in the Atmospheric Boundary Layer

MS6S_12035
Tue • 14:50 • 134

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Despite being quite turbulent, the atmospheric boundary layer shows forms of organized vortices with horizontal axis orientated in the mean flow direction. The secondary circulations (lateral and vertical) can be identified by clouds organizing themselves as parallel lines in the updraft regions between pairs of counter-rotating roll vortices. Those kind of horizontal roll vortices are well known from laminar boundary layers over rotating disks or Ekman layers in rotating fluids. In the atmospheric boundary layer, the origin of roll vortices is also attributed to classical Ekman layer instability for unstratified flow and to buoyancy-induced instability in unstably stratified cases. Both mechanisms are known for laminar flows from linear theory and laboratory experiments. But as the atmospheric boundary layer is always turbulent, one might wonder, how large scale structures can still form. To investigate this problem, we have conducted numerical simulations with a parallelized large-eddy simulation (LES) model. Results of the simulations will be presented with emphasis on the structure of organized vortices and their impact on surface wind stress over the oceans.

The Energy Cycle of the Tropical Madden-Julian Oscillations seen through Wavelets

MS6S_12140
Tue • 14:55 • 134

Jun-Ichi Yano
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The Madden–Julian Oscillations (MJO) are probably the most notable planetary-scale convective equatorial waves in the tropical atmosphere, which propagates around the globe eastwards with 30–60 day period. The MJO constitute a good example among the complex phenomena associated with geophysical flows. Their understanding and simulations remain a challenging fluid mechanics problem with complex interactions between planetary–scale flows and small-scale moist deep convection. Even their basic mechanism is hard to identify by conventional Fourier–based analyses due to strong nonlinearities in cloud physics associated with moist deep convection. Here, the wavelet is proposed as a general methodology for analyzing complex geophysical flows, and this method is used in order to identify the maintenance mechanism of MJO

under an energy cycle. The analyses of the simulation results from global models show that this system is not necessarily maintained by moist deep convection in a simple manner as expected from the current dominant view.

A New Theory For Convection In Rapidly Rotating Spherical Systems

MS6S_12169
Tue • 15:00 • 134

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Thermal convection in rapidly rotating, self-gravitating Boussinesq fluid spherical systems is a classical problem and has important applications for many geophysical and astrophysical problems. The convection problem is characterized by the three physical parameters, the Rayleigh number R, the Prandtl number Pr and the Ekman number E. This paper reports a new convection theory in rapidly rotating spherical systems valid for a small E and all values of Pr. The new theory units the two previously disjointed subjects in rotating fluids: inertial waves and thermal convection. Both linear and nonlinear properties of the problem will be discussed.

Vortex-based Models of Quasigeostrophic Turbulence

MS6S_12194
Tue • 15:05 • 134

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A vortex-based model of the quasigeostrophic turbulence is developed, based on the fact that the vorticity field develops coherent vortex structures and that their interactions dominate the dynamics of the turbulence. Each coherent vortex is modeled by an ellipsoid of uniform potential vorticity embedded in a 'locally uniform shear field' induced by other vortices (Meacham's ellipsoid). The equations of motion are derived following the procedure of Hamiltonian moment reduction. The degree of freedom of N interacting vortices is 3 N, and even a two-body system shows chaotic behavior. The validity of the ellipsoidal moment model is assessed by performing direct numerical simulations based on the CASL-algorithm. It is shown that the model captures the merger of co-rotating vortices well but that it fails to predict the robustness of a counter-rotating vortex pair. A possible way to refine the model is suggested.

Laboratory and Numerical Modelling of Exchange Flows

MS6S_12408
Tue • 15:10 • 134

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In this paper the hydrodynamics of exchange flows is investigated with focusing on the role of non-hydrostatic effects, friction and entrainment in the long straits. The simulation of the exchange flows in a long and narrow straits with a sill and with contraction for the configuration of experiments of Maderich (1998, 2000) were performed with three-dimensional, non-hydrostatic, numerical model of free surface stratified flows (Kanarska Y., Maderich V, 2003). The model is a non-hydrostatic extension of the free-surface primitive equation POM model. Calculations and analysis based on a three-layer decomposition with an intermediate layer of variable density showed the importance of entrainment and friction for hydrodynamics of the long straits. As a result the composite Froude number is significantly lower in comparison to predictions of two-layer hydraulic theory according to the concept of the maximal exchange.

Wave—mean Flow Interaction in Coupled Atmosphere–ice–ocean Systems

MS6S_12463
Tue • 15:15 • 134

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A dynamically consistent framework for modelling atmosphere–ocean interaction must take account of surface waves, either implicitly or explicitly. We may account for the waves explicitly by employing a numerical spectral wave model, and applying a suitable theory of wave—mean flow interaction. Below the water surface the generalized Lagrangian mean (GLM) formulation is suitable, and a closed system of equations may be obtained to second order in wave slope by applying wave action conservation equations in the propagation of the spectral wave components. The coupled model system will also take account of the Earth's rotation, the momentum balance during wave generation and dissipation, the effect of depth-varying currents on wave propagation, the presence of surface films and sea ice, the effect of waves on the mean water level, and the generation of Langmuir circulations.

Intermittency in Stratified Turbulence Produced by Breaking Internal Gravity Waves

MS6S_12601

Tue • 15:20 • 134

Pascale Bouruet-Aubertot[(1)], Joel Sommeria[(2)], Christophe Koudella[(3)]

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(3) *DAMTP/University of Cambridge, Cambridge, England*

Internal gravity waves nonlinear interactions lead to intermittent breaking events with density overturning and vertical turbulent mixing. We analyze the statistics of density and velocity fluctuations in this process, using direct numerical simulations. We characterize the density and velocity gradients at different scales along the vertical direction. The velocity gradients behave in a very similar way to usual turbulence, while the density gradients are very intermittent. This can be attributed to the formation of sheets with strong stable density gradients. Unstable density gradients are rare and form intermittent patches of different scale for which we have analyzed the statistics. We discuss the link with mixing properties of the internal wave fi eld and compare with observations in the ocean and the atmosphere.

Measurements of the Influence of Ocean Surface Kinematics on Air-sea Heat Fluxes

MS6S_12722

Tue • 15:25 • 134

Farbice Veron[(1)], W. Kendall Melville[(2)]

(1) *University of Delaware, College of Marine Studies, Newark DE, USA*
(2) *University of California, San Diego, Scripps Institution of Oceanography, La Jolla CA, USA*

We present results of several fi eld experiments on the kinematics of small-scale surface turbulence, the influence on the surface skin layer, and the resulting transfers of heat across the diffusive layer at the surface of the ocean. A variety of optical and electro-mechanical instruments are used to measure the evolution of the surface and sub-surface velocity, and temperature fi elds. These include visible and infrared imaging of the surface, thermal/IR surface velocimetry, and fast-response thermometry. We show that at low wind speed, it is the small-scale turbulence at the surface of the ocean, rather than breaking waves that most influence and disrupt the surface skin layer. We fi nd that the enstrophy of the surface turbulence correlates with the surface heat flux, and that the surface wave fi eld modulates a component of the total air-sea heat flux.

Linear Waves and Baroclinic Instability in an Inhomogeneous-density Layered Primitive-equation Ocean Model

MS6S_12776

Tue • 15:30 • 134

Francisco J. Beron-Vera, M.J. Olascoaga, J. Zavala-Garay

RSMAS, University of Miami, Miami, USA

We consider linear waves and baroclinic instability in a multilayer primitive equation model for ocean dynamics and thermodynamics. The model is a generalization to an arbitrary number of layers of Ripa's single-layer model with variable velocity shear and stratifi cation. In addition to vary arbitrarily in horizontal position and time, the model's horizontal velocity and buoyancy fi elds are allowed to vary linearly with depth within each layer. The model enjoys several properties which make it very attractive. For instance: unlike slab layer models, in which all fi elds are set to be depth independent, the model represents explicitly within each layer the thermal-wind balance which dominates at low frequency; unlike homogeneous-density layered models, the model can incorporate thermodynamic processes, which are particularly important in the upper part of the ocean; and, in the absence of forcing and dissipation, the model has several integrals of motion including volume, mass, buoyancy variance, energy, and momentum. Our preliminary results on waves and instabilities suggest, in particular, that a confi guration involving a few layers can be used as a basis for a quite accurate and, at the same time, numerically effi cient ocean model.

Simulation of Sea Surface Temperature Trends Under Severe Wind Forcing With a Full Atmosphere-Ocean Coupled Model

MS6S_13017

Tue • 15:35 • 134

Arnaldo Longhetto[1], Roberto Purini[2], Claudio Cassardo[1], Nicola Loglisci[3], **Silvia Ferrarese**[1], Renzo Richiardone[1]

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A Regional two-way Atmosphere/Ocean Coupled Model (TWAOCM), developed by our joint research team, has bee applied to a stron wind episode (Bora) occurred in the Northern Adriatic Sea. TWAOCM showed a signifi cantly better ability to simulate the observed values of Sea SurfaceTemperature (SST) and their time trend during the whole development of the episode in comparison with a simpler model using only a One-Way atmospheric forcing of the Sea. This result is very interesting and important not only concerning possible application of TWAOCM as a precursor model for future operational prediction schemes of the state of the Sea, but also because it revealed the importance of the ocean forcing of the atmosphere, which was unexpected due to both the high frequency variability conditions that are typical of short and severe Bora wind events, and the shallow ocean layer in the northernmost regions of the Adriatic basin.

PRE-NOMINATED SESSIONS

FLUID MECHANICS

FM1

Biological fluid dynamics

Chairpersons: M. Gharib (USA), F. van de Vosse (Netherlands)

Mechanics of the Bounding Flight Revisited

FM1L_10132
Thu • 11:00 • 213

Takeshi Sugimoto
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Biofluiddynamicists insist that the bounding flight is advantageous for high speed flight, because the former studies, based on arguments in terms of instantaneous dynamics, led to the lower speed bound suited for the bounding flight. Bounding flyers, however, make most of this technique in almost all the speed ranges. The present study relies on control theory and rigorous argument in terms of time averages. Two major conclusions are obtained by this novel analysis: the bounding flight is considered as the optimal bang-bang control for the unstable back-side flight; it is also revealed by the newly derived analytic solution for the time-averaged quantities that the bounding flight saves more energy than the continuous powered-flight in wide speed ranges, in particular at low speeds, and hence that the formerly known speed bound is found to be insufficient to account for the phenomenon. The present analysis supports the fixed-gear hypothesis proposed by biologists.

How to Breathe in a Liquid-Filled Lung: Symmetry of Airway Reopening

FM1L_11013
Thu • 11:20 • 213

Charles N. Baroud[1], Matthias Heil[2]
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Many respiratory diseases cause the occlusion of pulmonary airways with viscous fluid. The subsequent airway reopening is assumed to occur by the propagation of an air finger into the liquid-filled airways. We investigate the behavior of the air finger as it reaches a single bifurcation and determine under what conditions the finger branches symmetrically. If the fluid pressure in both channels ahead of the branching finger are equal, the finger will preferentially reopen a single path through the branching network. If the ends of the channels are capped with compliant chambers, representing the lung elasticity, the pressure required to drive the air finger can be dominated either by viscous losses or by elastic forces. Below a critical velocity, elastic forces dominate and symmetric branching is predicted to occur. We augment our theoretical model with an experimental study in which the problem is investigated using microfluidic channels.

Bacterium Swimming Motion Close to a Wall

FM1L_11441
Thu • 11:40 • 213

Tomonobu Goto[(1)], Kousou Nakata[(1)], Yukio Magariyama[(2)], Masaharu Nishimura[(1)]
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(2) *National Food Research Institute, Tukuba, Japan*

The mechanism of some characteristics about swimming motion of the marine bacterium, Vibrio alginolyticus, close to a boundary was investigated. The motion of the microorganism that possesses single polar-flagellum propelling the cell body was dealt with as an outer flow problem from a bio-fluid dynamics viewpoint. Numerical analyses based on the boundary element method in addition to the resistive force theory were applied to elucidate the effects of the boundary on the swimming motion. The boundary reduces the swimming speed when a bacterium moves along it. Forward swimming is stable in pitching motion and backward swimming is unstable. The swimming speed varies depending on the attitude of the bacterium. When the flagellum is closer to the boundary, the trajectory of the bacterium draws a curve. These results qualitatively agree with the observed motions and have potential to explain the mechanism of the phenomena.

In Vivo PIV Measurement in the Embryonic Chicken Heart

FM1L_11900
Thu • 12:00 • 213

Peter Vennemann[(1)], Kenneth T. Kiger[(2)], Beerend P. Hierck[(3)], Nicolette T.C. Ursem[(4)], Timo L.M. Ten Hagen[(5)], Jerry Westerweel[(1)]
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(2) *Department of Mechanical Engineering, University of Maryland, USA*
(3) *Department of Anatomy and Embryology, Leiden University MC,the Netherlands*
(4) *Department of Obstetrics and Gynaecology, Erasmus MC, the Netherlands*
(5) *Department of Surgical Oncology, Erasmus MC, Netherlands*

Blood flow is an important factor influencing the embryonic heart development. The flow induces shear stress that act on the vascular endothelium and modulate gene expression. Previous work has qualitatively shown that modification of the flow through the heart can significantly alter the heart development. To enlighten the relationship between fluid shear stress and gene expression, the blood flow of a chicken embryo is manipulated. Combining the fluorescent visualization of gene expression with a quantitative measurement of the instantaneous flow field using PIV, a direct relation between shear stress and gene response can be found. In vivo PIV measurements are performed at different phase angles of the cardiac cycle. Fluorescent lipid micro-spheres serve as tracer particles. The velocity distribution within the ventricle and the atrium is resolved. Current work is focused on improving the spatial resolution and accuracy in the near-wall region along with accurate registration of the wall boundary.

Bioirrigation in Marine Sediments: Ecological Conclusions from Numerical Modelling

FM1L_12063
Thu • 12:20 • 213

Oleksiy S. Galaktionov, Filip J.R. Meysman, Jack J. Middelburg
Netherlands Institute of Ecology, Yerseke, the Netherlands

Porewater flow in the marine sediments due to pumping activity of the benthic animals (the lugworm Arenicola marina is used as a model organism) was simulated using finite element approach. The hydromechanical insulation of the burrow walls turns essential for ensuring the oxygen supply. This may explain a semi-permanent nature of the lugworm burrows: actively lining the walls with mucus requires extra energy, while passive insulation due to accumulation of iron oxides takes time. Disturbed sediment inside a quick sand channel seems to play a limited role in the total solute transport, which means that oxygen and other dissolved substances are effectively reaching deeper layer of sediments below the animal burrow due to advective flux (not merely by molecular diffusion).

Three-Dimensional Airway Reopening – Finite-Reynolds-Number Effects

FM1L_12295
Thu • 12:40 • 213

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Motivated by the physiological problem of airway reopening, we study the steady propagation of an air finger into a buckled elastic tube, containing an incompressible, Newtonian fluid. The fluid mechanics is governed by the Navier–Stokes equations, and the solid mechanics by Kirchhoff–Love thin-shell theory. The resulting three-dimensional, fluid-structure-interaction problem is solved numerically by a fully-coupled, finite-element method. The main aim of the study is to determine the propagation speed of the air finger as a function of the applied pressure. A characteristic two-branch behaviour in

the propagation velocity-pressure curve is similar to earlier two-dimensional models. Furthermore, we find that fluid inertia has a significant effect, even at the low values of the Reynolds number that occur in the airways of the lung.

Cell Permeabilisation and Transport Focused Around Oscillating Microbubbles

FM1L_12400
Fri • 11:00 • 213

Philippe Marmottant(1), Sascha Hilgenfeldt(1), Michel Versluis(1), Han Gardeniers(2), Albert van den Berg(2), Detlef Lohse(1)

(1) *University of Twente, Enschede, the Netherlands*
(2) *MESA+ Institute, Enschede, the Netherlands*

The ultrasound-driven oscillation of a microbubble drives a steady streaming focused around the bubble. The study of individual bubbles attached to a wall shows vivid recirculations. When cells are in the vicinity of these bubbles, also used in medecine as contrast agent for ultrasound echography, they experience considerable shear rates. We introduce in the flow giant unilamelar lipid vesicles, acting as artificial cells. Rupture of the lipidic membrane with the opening of pores is revealed by high-speed camera recordings. A reversible permeation of the membrane wall can also be obtained, demonstrating at the micron scale the efficiency of microbubbles to deliver drugs in cells. The streaming flow of bubble on a surface can be further controlled, with the adjunction of a solid obstacle nearby: the flow turns to be directed. We will present a microfluidic device using the principle of bubble/obstacle doublets to locally transport small objets such as cells.

Red Blood Cell Dynamics, Deformation and Rheology via Microfluidic Experiments

FM1L_12423
Fri • 11:20 • 213

Manouk Abkarian(1), Magalie Faivre(1), Annie Viallat(2), Howard A. Stone(1)

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Blood is principally made of a calibrated suspension of red blood cells (RBC). Depending on the flow, RBCs move alone or in aggregates (rouleaux), often in capillaries of smaller sizes than their own radius. Blood is an “intelligent” fluid, as its rheological properties adapt according to the different situations of the flow. This capacity, which is not fully understood, comes partly from the significant deformability of RBCs. The understanding of the flow behavior of a single confined RBC is a first step to understand the basic rheological properties of the blood in arteries. To achieve this goal, we used microfluidic technology as a tool to explore hydrodynamics of a single cell and the hydrodynamic interactions among cells. We are also using such measurements to infer the individual mechanical properties of their membrane.

Flow in an Integrated Model of Heart and Aorta

FM1L_12522
Fri • 11:40 • 213

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Computational fluid dynamics of blood flow in the left ventricle and the aorta was carried out in an integrated manner to investigate the effect of flow dynamics created within the ventricular cavity on the aortic flow. The results showed that recirculating flow beneath the aortic valve that was brought about by blood inflow during diastole effectively redirected blood to the outflow tract, thus accommodating ventricular blood ejection to the aorta during systole. It was also demonstrated that ejected blood flow through the open aortic valve had markedly skewed velocity profiles with increasing velocity to the mitral valve side in early systole and to the septum side in later systole with swirling secondary flows. They led to the generation of helical flow in the aorta during later systole. These findings addressed the importance of inclusion of intraventricular flow in the analysis of the aortic flow.

On the Issue of Optimal Trans-Mitral Flow

FM1L_12784
Fri • 12:00 • 213

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The mean value of 4 for the formation number appears to indicate the existence of a universal time scale that may describe the optimum range for trans-mitral flow during diastole. The statistical significance and importance of the narrow range of the formation number becomes obvious when one considers the broad spectrum of the ages and backgrounds of the test subjects. A low formation number might indicate poor volume efficiency due to low average velocity or a short diastolic period. A typical example can be found for the cases with dilated cardiomyopathy when decreased systolic function and increased cardiac chamber size is accompanied by reduced left ventricular wall motion, increased filling pressures and abnormal relaxation of heart muscle. A high value of Formation numbers can be indicative of a high heart rate which results in excessive mean velocities through the mitral valve. The results presented in Figure 1 indicate that the normal heart as a responsive system operates around a Formation number of approximately 4. Whether this base line has a significant fluid mechanical value is an important issue that needed to be addressed through an understanding of the vortex formation process. Gharib et al. (1998) showed that the formation number of 4 is directly related to the circulation saturation of forming vortex rings. Kruger and Gharib (2000) extended these studies to show that this range of formation number is associated with the optimal (maximum) impulse that can be produced by a forming vortex ring. These studies all indicate that perhaps the formation number of 4 is an effective parameter for defining an optimal range of trans-mitral flow dynamics. It is important to mention that other trans-mitral flow parameters such as peak E-wave to A-wave velocity ratio are not as robust as Formation number. In this report, we will discuss these parameters and other important aspects of Formation number in defining the optimal transmitral flow.

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Numerical Modeling of Cardiovascular Flows: Integrating High Resolution CFD and Experimental Techniques

FM1L_12863
Fri • 12:20 • 213

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In recent years the advent of powerful and affordable computational platforms along with the development and proliferation of advanced commercial and academic software have contributed to the emergence of CFD as a useful bioengineering research tool alongside with in vitro and in vivo studies. Cardiovascular flows take place in complex, multi-connected domains with compliant walls and flexible immersed boundaries and are dominated, among others, by pulsatile effects, 3D separation and vortex formation, regions of flow reversal, periodic transition to turbulence and laminarization, and non-Newtonian effects. These complexities pose unique modeling challenges and necessitate a close synergy and integration between CFD modelers and experimentalists to guide model development and validation. In this paper we report recent progress toward the development and validation of a high resolution numerical method capable of quantitatively accurate predictions of complex cardiovascular flows. The method employs domain decomposition with body-fitted, domain-structured, Chimera overset grids to discretize arbitrarily complex, multi-connected geometries. Results will be presented for two flow cases, each representative of different kinds of modeling challenges: 1) flow through a bileaflet mechanical heart valve with the leaflets fixed at the fully open position; and 2) flow through an anatomically realistic Total Cavopulmonary Connection (TCPC). For both cases the numerical simulations and laboratory experiments are carried out concurrently to validate the numerical model and elucidate the complex hemodynamics of these flows over a range of Reynolds numbers.

Direct Numerical Simulation of Red Blood Cell Flow and Aggregation

FM1L_12124
Fri • 12:40 • 213

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The rheology of blood and its transport have physiological significance in blood circulation. The aggregation of red blood cells (RBC) plays a significant role in the rheology and flow characteristics of blood. Furthermore, RBC aggregation has clinical significance as it is used diagnostically to evaluate blood plasma concentration of certain macromolecules such as immunoglobulin and fibrogen (Fung, 1997). The aggregation of RBC is being studied using direct numerical simulation based on the lattice-Boltzmann (LB) computational approach (Aidun et al., 1998, Ding and Aidun 2003). Results show that it is possible to develop "universal" scales that can be used to predict aggregation size distribution. Because of the high concentration of the RBC and the deformability of the membrane, a number of modifications are made to the LB method. Most significant is the capability to impose cell-cell and cell-wall interaction forces at the link-to-link level. The computational approach and the scale for aggregation distribution function will be presented.

Deformation of Vesicles Flowing Through a Capillary

Victoria Vitkova, Maud Mader, **Thomas Podgorski**
CNRS-UJF Grenoble, France

FM1S_10741
Thu • 14:30 • 315A

Giant vesicles are closed, deformable membranes which can be a useful model when trying to understand the fluid mechanics and rheology of cell suspensions, such as blood. The flow of giant vesicles through cylindrical capillaries is experimentally investigated. Vesicles (20–50 microns in diameter) are deflated with reduced volumes between 0.8 and 1. Both interior and exterior fluids are sugar solutions with viscosities close to 1 cP. Vesicles are aspirated into a capillary tube with a diameter close to the vesicle size and a constant flow rate is imposed. Significant deformation of the membrane occurs, with vesicle shapes such as ellipsoids, bullet shapes or parachute shapes. We quantitatively investigate the deformation as a function of velocity, reduced volume and confinement. The mobility of vesicles (ratio of their velocity to the average velocity of the carrier fluid) is also studied and consequences on flow resistance is discussed.

Computational Exploration of Liver Acinus Microstructure

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(2) *National Taiwan University Hospital, Taiwan*

FM1S_11188
Thu • 14:35 • 315A

Microcirculation and its regulatory mechanisms are gaining increasing importance for a variety of medical applications. The intimate relationship between many liver diseases and the circulation is emphasized for obvious cases such as cirrhosis and portal hypertension as well as liver cancer. In this study, we focus on the computational hepatic blood circulation analysis. One of the most important and challenging problems in the hepatic vasculature is the understanding of mixing of high pressure/velocity hepatic arterioles and low pressure /velocity portal venule which drains into the hepatic venules. The choice of radial flow was based on mimicking the flow distribution patterns in vivo. At the microscopic level, the acinar arrangement of the vascular system creates a unique series of microenvionments, which are acknowledged to be of paramount importance in controlling the functional characteristics of the parenchymal cells. In the current study we considered a simple liver acinus, which represents a small parenchymal mass consisting of terminal hepatic arteriole and portal venule along with a sinusoidal space surrounded by the fenestrated endothelial cells and hepatic venule. The model solves the Navier–Stokes equations for unsteady Newtonian fluid flow using a finite volume approach. The results discuss the transmittent activity of the hepatic arteriole, pressure distribution in the sinusoidal space, the effect of mass flow rate on the hepatic cells and their consequences.

Vortex Rings in Stenotic Arterial Models

Sean D. Peterson, **Michael W. Plesniak**
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FM1S_11825
Thu • 14:40 • 315A

Atherosclerosis, a disease of the vasculature characterized by plaque formation in arteries, is of the leading causes of death in the western world. The global aim of the current work is to directly link fluid mechanical stimuli to cellular response in physiologically relevant geometries. This paper focuses on the vortex ring formation observed downstream of an occlusion in a tube subjected to a sinusoidal forcing function. Particle Image Velocimetry was used to measure the velocity fields at the tube centerline between 1.2 and 2.9 tube diameters downstream of the occlusion. It was found that the shear layer in the recirculating region reduces the circulation of the vortex ring as it progresses downstream within the tube. Future work will involve a more detailed investigation of the vortex ring formation and breakdown, and implications of these phenomena on cellular mechanotransduction.

A CFD Study of the Effects of Physiological Vessel Wall Motion on Oxygen Transport in Coronary Arteries

FM1S_11851
Thu • 14:45 • 315A

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The principle objective of this paper is to present the development of a CFD methodology to simulate motion of a coronary artery and luminal transport of oxygen to the wall using a commercially available CFD solver. To study the effects of physiological motion on oxygen transport two simulations were carried out, with (dynamic) and without (static) motion. The pulsatile blood flow and wall motion are based on physiological velocity and vessel motion waveforms derived from previously published works. The results demonstrate that the oxygen transport in coronary arteries is altered by the wall motion. In the cases presented here the SDR was not only greater in the dynamic model but the differences between the inner and outer wall as seen in the static model disappeared in the dynamic model. However, it should be noted that this will of course depend upon the motion patterns used in this study.

A Model of Plankton Dynamics Coupled with a LES of the Surface Mixed Layer

FM1S_11908
Thu • 14:50 • 315A

David M. Lewis
Liverpool University, Liverpool, UK

The concentration of phytoplankton in the sea is affected by biological processes, such as growth/mortality rates, predatory zooplankton concentrations and nutrient levels. Phytoplankton concentrations are also affected by physical processes, in particular the mixing properties of the local fluid environment. On planktonic scales (10–1000 micro metres) one can assume the local turbulent flow is isotropic, with no distinction between horizontal and vertical mixing. However, agglomerations of phytoplankton into patches are observed on larger scales of up to tens of metres, whose formation will be influenced by the anisotropic advection/mixing properties, and large-eddy structures prevalent in, the surface mixed layer. This paper presents the results of the coupling of a LES model of the mixed layer, with an advection-diffusion system of equations for nitrate-phytoplankton-zooplankton concentration, incorporating parameterisations of the biological processes. The aim will be to understand how the characteristics of the mixed layer turbulence influence the observed distribution of phytoplankton.

Self-Propulsion of an Oscillatory Wing

FM1S_11943
Thu • 14:55 • 315A

Adrian S. Carabineanu
University of Bucharest

In this paper we show that the oscillatory motion of a wing in an incompressible inviscid fluid can determine the apparition of a propulsive force. In the framework of the linearized theory the dimensionless lifting surface equation for oscillatory wings is: $\frac{\varpi}{4\pi}\int\int_D^* \tilde{f}(\xi,\eta)\exp(-i\tilde{\omega}(x-\xi))\left(\int_{-\infty}^{x_0}\frac{\exp(i\tilde{\omega}u)}{(u^2+\varpi^2(y-\eta)^2)^{3/2}}du\right)d\xi d\eta = -\left(\frac{\partial h(x,y)}{\partial x}+i\tilde{\omega}h(x,y)\right)$, where $Re[\tilde{f}(x,y)\exp(i\omega t)]$ is the pressure coefficient, ω is the frequency of the oscillation, $\widetilde{\omega}$ is the reduced frequency, and $z=h(x,y)\exp(i\omega t)$ is the equation of the wing. Employing adequate quadrature formulas, we discretize the integral equation and we obtain the values of $\tilde{f}$ in the nodes of the grid. For certain oscillatory delta wings we calculate the drag coefficient and we notice that if ω surpasses a critical value, the drag coefficient becomes negative i.e. there appears a *propulsion force*.

Computational Model of Selected Transport Processes in an Infant Incubator

FM1S_12409
Thu • 15:00 • 315A

Maciej K. Ginalski, Andrzej J. Nowak
ITC SUT Gliwice, Poland

The major objective of this study was to investigate transport processes of heat and mass flow within an infant incubator, were the premature newborn baby is nursed, using the modern numerical techniques. Up to now, analysis, considering those subjects, has been made only through experimental methods with a large factor of results generalization. In those days it is possible to examine that kind of problems with high accuracy by using Computational Fluid Dynamics which were successfully used in many different domains. In order to create an appropriate numerical model a three-dimensional model of the incubator itself and a newborn child were created in CAD application and examined with a commercial CFD package called Fluent. This experiment includes calculations of the coupled heat transfer due to heat conduction,

convection, thermal radiation and evaporation and mass transfer inside of the incubator. Obtained results of calculations were numerically verified as well as compared with results published in the subject literature.

Transverse Flows in Rapidly Oscillating Cylindrical Tubes

FM1S_12479
Thu • 15:05 • 315A

Matthias Heil[1], Sarah Waters[2]
(1) *Univ. of Manchester, Manchester, UK*
(2) *Univ. of Nottingham, Nottingham, UK*

Many physiological flows (e.g. blood flow in the veins and arteries or the flow of air in the pulmonary airways) are strongly affected by the interaction between the fluid flow and the vessel wall elasticity. In many applications this interaction causes the development of large-amplitude self-excited oscillations (e.g. wheezing during forced expiration). Motivated by this problem, we analyse the flows that develop in the cross sections of fluid-conveying pipes whose walls perform high-frequency oscillations. Using numerical and asymptotic methods, we show that the velocity perturbations induced by the wall oscillation are dominated by their transverse components. The transverse velocity field consists of an inviscid core flow and thin Stokes layers near the wall. The total viscous dissipation is shown to depend sensitively on the mode shapes of the wall oscillation.

In Vivo Visualization of the Water Refilling Process in Xylem Vessels Using Synchrotron X-Ray Micro-Imaging

FM1S_12655
Thu • 15:10 • 315A

Yang-Min Kim, **Sang-Joon Lee**
Department of Mechanical Engineering, POSTECH, Pohang, S. Korea

Synchrotron X-ray micro-imaging was employed to non-invasively monitor the refilling process of water inside the xylem vessels in bamboo leaves. The consecutive phase-contrast X-ray images clearly showed both plant anatomy and the transport of water within the xylem vessels. Traces of water-rise, vapor bubbles and variations in contact angle between the water front and the xylem wall were all measured in real time. During the refilling process, air bubbles are removed when the rising water front halts at a vessel end for a while; subsequently, it starts rising again at a higher velocity than the normal refilling speed. Repeated cavitation was found to lessen the refilling ability in xylem vessels. In the absence of light, the water refilling process in xylem vessels was facilitated more effectively than in bright illuminated conditions. Finally, X-ray micro-imaging was deemed to be a powerful, high resolution, real time imaging tool to investigate the water refilling process in xylem vessels.

FM2

Boundary layers

Chairpersons: P. Duck (UK), A. Kluwick (Austria)

A Combined Numerical and Asymptotic Approach to Boundary Layer Receptivity Problems

FM2L_12241
Wed • 11:00 • 327

Matthew R. Turner, P.W. Hammerton
School of Mathematics, University of East Anglia, Norwich, UK

The interaction of free-stream disturbances with the leading edge of a body and its effect on the transition point is considered. This paper presents a method which combines an asymptotic approach in the receptivity region, and a numerical method to march through the Orr-Sommerfeld region. The asymptotic receptivity analysis produces a three deck eigensolution which in its far downstream limiting form, produces an initial condition for our numerical Parabolized Stability Equation (PSE). We discuss the advantages of this method against existing numerical and asymptotic analysis and present results which justifies this method for the case of a semi-infinite flat plate, where asymptotic results exist in the Orr-Sommerfeld region. The results show that the upstream boundary conditions being imposed are consistent, leading us to discuss how this method can be applied to more general bodies with curvature.

3D Distributed Boundary-Layer Receptivity to Non-Stationary Free-Stream Vortices in Presence of Surface Roughness

FM2L_10275
Wed • 11:20 • 327

V.I. Borodulin, A.A. Fedenkova, A.V. Ivanov, **Y.S. Kachanov**, V.Y. Komarova
Institute of Theoretical and Applied Mechanics, Russian Academy of Sciences, Novosibirsk, Russia

The paper is devoted to investigations of the three-dimensional (in general) problem of boundary-layer receptivity to non-stationary free-stream vortices (with spanwise and wall-normal orientations of the vorticity vector) due to their scattering on distributed surface non-uniformities. The main goals of the study are: (i) to develop a method of experimental determination of the distributed vortex-receptivity coefficients and (ii) to obtain their experimental values. The experiments are performed at controlled disturbance conditions. It is found that for the two studied free-stream vortex orientations the Tollmien-Schlichting waves are excited in the boundary layer in a distributed way despite in the case of the spanwise orientation the distributed receptivity is much weaker than for the wall-normal orientation. The receptivity coefficients are obtained both for the distributed vortex receptivity on smooth surface and for the roughness-vortex distributed receptivity. It turned out that the two types of the receptivity mechanisms, investigated in the wall-normal vorticity case, are the strongest for the free-stream vortices having the largest spanwise scales. An important role of streamwise-wavenumber resonances of evolved perturbations is shown and analyzed.

Why do Dolphins Have Cutaneous Ridges?

FM2L_11887
Wed • 11:40 • 327

Peter W. Carpenter, Reza Ali
University of Warwick, Coventry, UK

The existence of small-scale static waves on dolphin skin has been known for some time. These cutaneous ridges are aligned with crests approximately perpendicular to the local flow direction. No function, hydrodynamic or otherwise, has hitherto been suggested for the cutaneous ridges. Here we report a DNS study of 3D Tollmien-Schlichting waves propagating over wavy compliant surfaces. The boundary-layer disturbances are generated by a line body force, located at the boundary-layer edge, that varies harmonically with time and sinusoidally in the spanwise direction. For rigid surfaces, quasi-2D TS waves grow most rapidly and wall waviness increases their growth rate. But for compliant walls, 3D TS waves grow most rapidly and their growth rates are substantially reduced over wavy walls with wavelengths closely matching those of the cutaneous

ridges. This reveals a novel effect of "wall roughness" on transition, suggesting that cutaneous ridges help to achieve the dolphin's laminar-flow capability.

Aspects of the Laminar-Turbulent Transition in Axisymmetric Boundary Layers

FM2L_12631
Wed • 12:00 • 327

N. Vinod, Rama Govindarajan
JNCASR, Bangalore -560 064, INDIA

The boundary layers over axisymmetric bodies have been studied far less than those over two-dimensional surfaces. Our main obective is to understand how the laminar-turbulent transition process in a boundary layer over an axisymmetric body is different from that over a two-dimensional surface. We study the primary (linear) instability, the secondary instability, and the transition zone, and find that all these are qualitatively different from 2D boundary layers. It is shown that transverse curvarture has a significant stabilizing effect on the primary stability. Consistent with the recent findings of Tutty *et al* [1], we see that three-dimensional modes can go unstable first, whereas over a 2D surface 2D modes are most unstable (Squire's theorem[2]), Interestingly, an opposing effect of curvature is seen on secondary instability behaviour: competing primary modes produce a rich variety in secondary disturbance growth, indicating early entry into the nonlinear domain. Early stages of the transition zone, where turbulent spots grow as they convect, are similar to 2D flow, while due to the spots wrapping around the body, transition proceeds slower in the later stages.

Non-Unique Quasi-Equilibrium Turbulent Boundary Layers

FM2L_11083
Wed • 12:20 • 327

Bernhard Scheichl, Alfred Kluwick
Institute of Fluid Mechanics and Heat Transfer, Vienna University of Technology, Vienna, Austria

Classical large Reynolds number asymptotics of turbulent boundary layers is consistent with the assumption that the Rotta–Clauser parameter is a quantity of $O(1)$. However, as known from, among others, similarity solutions, this parameter may be large or even tend to infinity under certain limiting conditions. It is the aim of the present investigation to show that also these cases can be covered by rigorous asymptotic analysis, which is essentially independent of the choice of a specific Reynolds stress closure. This requires the introduction of an additional small perturbation parameter which reflects the slenderness of the boundary layer and accounts for the then wake-like structure of the velocity profile. Most interestingly, in the specific case of quasi-equilibrium flow the transition from classical small-defect to a pronounced wake flow is associated with double-valued solutions, a phenomenon seen to agree well with early experimental observations.

Flow Along a Long Thin Cylinder

FM2L_12320
Wed • 12:40 • 327

Owen. R. Tutty(1), A.T. Parsons(2), W.G. Price(1)
(1) *University of Southampton, Southampton, UK*
(2) *QinetiQ, Winfrith, Dorset, UK*

Calculations have been performed for the flow along long thin cylinders using a variety of methods, from a boundary layer code with a turbulence model to a full, time accurate, Navier–Stokes solver. The results have been validated by comparison with those from experiments. It has been found that there are major differences between the flow on a cylinder and the equivalent flow on a flat plate. The wall shear stress tends to a constant mean value downstream, with the flow near the surface independent of the downstream coordinate. The outer part of the boundary layer continues to evolve, with the boundary layer growing in thickness as the square root of the distance. Calculations of the power spectral density of the surface pressure fluctuations show that the noise generated by the turbulence initially increases as the radius of the cylinder is decreased, but eventually decreases as the radius is decreased further.

Near Critical Unsteady Three-Dimensional Triple Deck Flows

FM2L_11084
Thu • 09:30 • 309

Stefan Braun, Alfred Kluwick
Institute of Fluid Mechanics and Heat Transfer, TU Vienna, Vienna, Austria

In a number of cases interactive solutions for steady two-dimensional laminar triple deck boundary layer flows are known to exist up to a critical value α_c of a controlling parameter α (e.g. ramp angle of subsonic corner flows) only. In the present paper we investigate three-dimensional unsteady perturbations of such boundary layers assuming that the basic flow is almost critical, i.e. in the limit $\alpha - \alpha_c \to 0$. It is then shown that the interactive equations governing such perturbations simplify significantly allowing, among others, a systematic study of blow-up phenomena as observed also in related investigations of marginally separated boundary layers. Specifically it is found that solutions leading to the formation of finite time singularities can be continued beyond the blow-up time thereby generating moving singularities which can be interpreted as vortical structures quite similar to those emerging in direct numerical simulations and experimental observations of transitional separation bubbles.

Discontinuous Solutions of the Boundary-Layer Equations

Anatoly I. Ruban
University of Manchester, Manchester, UK

FM2L_11397
Thu • 09:50 • 309

Since 1904, when the boundary-layer equations were formulated by Prandtl, it was always assumed that, due to the viscous nature of the boundary layers, the solution of the Prandtl equations should be sought in the class of continuous functions. Meanwhile, there are clear mathematical reasons for discontinuous solutions to exist. In fact, under certain conditions they represent the only possible solutions of the boundary-layer equations. In this presentation two examples of such flows will be discussed. The first one represents an unsteady analogue of the well known two-dimensional laminar jet. We assume that the jet emerges from a narrow slit which was initially closed. The results of the numerical solution of the boundary-layer equations show that the jet has a well established front which propagates through initially stagnant fluid with a finite velocity. The second part of the talk deals with hypersonic flow past a delta wing.

The Development (and Suppression) of Very Short-Scale Instabilities in Buoyant Boundary Layers

James P. Denier[1], Peter W. Duck[2], Jian Li[1]
(1) *The University of Adelaide, Australia*
(2) *The University of Manchester, United Kingdom*

FM2L_10103
Thu • 10:10 • 309

This talk will present some new results on the development of algebraically growing disturbances in mixed forced-free convection boundary layer flows. Such disturbances have been conjectured as playing an important role in transition to turbulence in a wide variety of fluid flows. In the present case they are intimately linked with the development of streamwise grid-scale oscillations that arise in the numerical solution of the boundary-layer equations. Methods for the suppression of such instabilities will also be discussed.

Extending the Generalized Logarithmic Law to the Wall

Matthias M. Buschmann[1], Mohamed Gad-el-Hak[2]
(1) *TU Dresden, Institute of Fluid Mechanics, Dresden, USA*
(2) *Virginia Commonwealth University, Richmond, USA*

FM2S_10948
Thu • 14:30 • 308

An advanced, Reynolds-number-dependent, logarithmic law for the overlap region of the canonical turbulent boundary layer is presented. The law includes an additional constant in the argument of the logarithm, which extends the profile toward the buffer layer, but precludes a straight-line in a semi-log plot of the profile. As compared to either the traditional log law or power law, the generalized log law exhibits a superior fit to existing experimental data and DNS results. For practical applications, such as calibration of certain near-wall probes and appropriate construction of CFD codes for turbulent boundary layers, it is desired to derive an analytical relation for the velocity profile that would extend all the way to the wall. Employing a “mixing length approach”, we extend the generalized log law down to $y = 0$. Unlike some previous attempts, our approach is designed to have the physically correct y^{+3} dependence for the Reynolds stress.

Sub- and Supersonic Shapes without Separation and Cavitation

Ihor Nesteruk
Institute of Hydromechanics NASU, Kiev, Ukraine

FM2S_11017
Thu • 14:35 • 308

The slender body theory was applied to calculate axisymmetric bodies with the given pressure distribution on the surface and to investigate the principal problem of hydrodynamics: can the pressure gradient be positive on the body surface to ensure an unseparated flow pattern and to improve cavitation inception characteristics? Methods of calculating of axisymmetric and plane shapes in ideal compressible fluid, based on the potentials of sources and doublets located on the axis of symmetry are proposed. Analytic formulae for streamline functions and calculations results for different Mach numbers are presented.

The obtained shapes with specific pressure distribution ensure the flow without boundary-layer separation and without cavitation inception for bodies moving in water at high velocities. The axisymmetric supersonic form of minimal pressure drag was obtained. Results of experimental investigations of axisymmetric shapes without separation are rewiewed. Some of such forms ensure unseparated flow pattern at relative small Reynolds numbers. Since the origin of cavitation on a smooth shape is connected with separation, presented bodies could ensure the flow of liqiud without cavitation.

Long Layers Exhibiting Local Jumps, in Industrial and Biomedical Applications

FM2S_11210
Thu • 14:40 • 308

Frank T. Smith
Mathematics UCL, London, UK

In various interesting flow configurations, the long-scale thin layer problem interacts with the local property-jumping problem. First is that of modelling ground effect for cars. In two or three dimensions the boundary layer system over the scale of the car body and wake cannot be solved without the short-scale leading edge quasi-jump, and vice-versa. The second setting concerns modelling of multi-blade-and-wake behaviour for rotor performance. The short-scale response is again centred on the leading edge, while the long-scale response has interactive boundary layer form but (unusually) over the entire blade and wake. Third is branching flows, with application to cardiovascular, respiratory, cranial branchings and networks. Short-long analysis agrees with direct simulations. Recent developments (with Bowles, Dennis, Jones, Ovenden, Purvis, Tadjfar, J Engineering Mathematics, J Fluid Mechanics, 2001-2003) will be described throughout.

Secondary Instability of Stationary Vortex Packets in a Swept Wing Boundary Layer

FM2S_11339
Thu • 14:45 • 308

Valery G. Chernoray(1), Alexander V. Dovgal(2), **Victor V. Kozlov**(2), Lennart Löfdahl(1)
(1) *Thermo and Fluid Dynamics, Chalmers University of Technology, Goteborg, Sweden*
(2) *Institute of Theoretical and Applied Mechanics, 630090 Novosibirsk, Russia*

The presentation is focusing on the coherent features of a swept wing boundary layer. The three-dimensional flow of a swept wing is highly unstable with respect to longitudinal streamwise vortices, which, in turn, are subject to the secondary instabilities. The fact is that stationary vortex packets are most likely to be generated under natural flight conditions on the wing and these disturbances lead to breakdown the fastest. A detailed experimental study on the formation of crossflow vortex mode packets and their secondary instability in a swept wing boundary layer was carried out. Different methods of controlled excitation are used so that the crossflow vortex packets are generated by surface roughness elements and by localized continuous suction. The secondary instabilities investigated were those originated 'naturally' and forced in a controlled manner. Therefore, the characteristics of secondary instability obtained include phase information, growth rates and the development of nonlinear harmonics.

Boundary Layer Development in Unsteady Flows

FM2S_11479
Thu • 14:50 • 308

Andrei Camyshev, Andrei Kolyshkin, Inta Volodko
Riga Technical University, Riga, Latvia

The paper is devoted to the study of rapidly changing unsteady viscous flows in cylindrical channels of constant cross-section. Applications include flows in water supply systems, natural gas pipelines, blood flow in arteries. Suppose that an infinitely long horizontal cylinder of constant cross-section is filled with a viscous incompressible fluid. The flow is assumed to be fully developed. Starting from time $t = 0$ the flow is rapidly decelerated. The sudden change in pressure generates additional vorticity near the wall. As a result a boundary layer starts to develop near the wall. The method of matched asymptotic expansions is used to construct an approximate solution for the velocity distribution. Methods of linear and weakly nonlinear stability theory under a quasi-steady assumption are used to investigate stability characteristics of the flow. It is shown that the evolution of the most unstable mode is governed by the complex Ginzburg-Landau equation.

New Numerical Method for Complex Interacting Flows

FM2S_11780
Thu • 14:55 • 308

Vladimir B. Zametaev, Marina A. Kravtsova
TsAGI, 140180 Zhukovsky, Russia

New numerical method of second order accuracy for solving the boundary layer equation with interaction is suggested. It is well known that a given displacement thickness defines solution of 2D boundary layer equation by the only way. This

function is considered as the only unknown grid function in the problem. As a result amount of unknowns equals to number of nodes along X-axis. The main problem is to create a set of equations which define this grid function. Such set of equations may be formulated as zero difference between pressure gradient computed from BL calculation and pressure gradient found from interaction law. Introduced implicit set of equations is solved by Newton method which gives high convergence. Flow past a weak corner of a body contour was computed first. Second solved problem with using of proposed method is a mixing of boundary layers flowing from the edge of a wing.

Statistical Features and Levels of Natural Disturbances at Transition in Supersonic Boundary Layer

FM2S_11874
Thu • 15:00 • 308

Aleksander Kosinov, Aleksander Semisynov
ITAM SB RAS, Novosibirsk, Russia

The experiments on natural disturbance development in a boundary layer on a flat plate are executed at Mach number $M = 2$. Modified Kovasznay's method is applied for pulsation decomposition in compressible flow. It is shown that, the method is more suitable for measurement by a constant temperature hot-wire anemometer and increases accuracy of estimations. Dimensionless values of mass flow and temperature fluctuations and their relation are obtained depending on a Reynolds number in transition region of the supersonic boundary layer. The study of the statistical characteristics of natural pulsations in supersonic boundary layer is carried out. Linear and nonlinear regime of transition is determined. Statistical diagram of pulsations from laminar to turbulent stage is obtained. Bicoherence data indicates on the quadratic phase coupling of unstable waves. The quadratic interaction is decreased for low frequency waves in the last stage of transition. The activity is executed at support of RFBR, grant 03-01-00164.

Two-Fluid Jets and Wakes

FM2S_11984
Thu • 15:05 • 30_8

Patrick Weidman(1), Andrzej Herczynski(2), Georgy Burde(3)
(1) *University of Colorado, Colorado, USA*
(2) *Boston College, Massachusetts, USA*
(3) *Ben Gurion University, Israel*

Analytical solutions for laminar, horizontal, two-fluid jets and wakes are derived in the boundary-layer approximation, using a nonstandard similarity solution *ansatz* to account for interface deflection in the presence of gravity. Planar and axisymmetric fan jets, and classical and momentumless planar wakes, are considered. A statically stable system of lighter fluid 1 residing above heavier fluid 2, taken to be a liquid, is assumed. Velocity profiles for the jets and the classical wake depend on the parameter $\chi = \rho_1\mu_1/\rho_2\mu_2$, where ρ_i and μ_i are the respective fluid densities and viscosities. The momentumless wake profile depends on the parameter $\Omega = \rho_1\mu_2^3/\rho_2\mu_1^3$. All interfaces deflect from horizontal except the fan jet. However, while the interface for the classical planar two-fluid wake is never flat, interfaces for the planar jet and the momentumless wake become flat when $\mu_1 = \mu_2$. Velocity profiles illustrating the strongly asymmetrical jet and wake profiles that arise in air-over-water, oil-over-water, and air-over-oil flows are presented.

The Trailing Edge Problem for Mixed Convection Flow Past a Horizontal Plate

FM2S_12030
Thu • 15:10 • 308

Herbert Steinrück, Ljubomir Savic
Vienna University of Technology, Austria

The influence of buoyancy onto the boundary-layer flow past a horizontal plate aligned parallel to a uniform free stream is characterized by the buoyancy parameter $K = \mathrm{Gr}/\mathrm{Re}^{5/2}$ where Gr and Re are the Grasshof number and the Reynolds number, respectively. An asymptotic analysis of the complete flow field including potential flow, boundary layer, wake and interaction region near the trailing edge will be given for small buoyancy parameters and large Reynolds numbers in the distinguished limit $K\mathrm{Re}^{1/8} = O(1)$. The focus will be the numerical solution of the interaction problem at trailing edge. The interaction law is given by $p = K\mathrm{Re}^{1/8}A - \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{A'(\xi)}{\xi - x}\,d\xi$, where the first term takes the buoyancy effects into account. The solution will be discussed and analogies and differences to the interaction problem of a plate with a small angle of attack in an uniform free stream will be pointed out.

Experimental and Theoretical Study of Heated Coanda Jet

FM2S_12062

Thu • 15:15 • 308

Tomas Vít(1), František Maršík(2)

(1) *TU Liberec, Czech. Rep*

(2) *Acad. of Sciences, Inst. of Thermomechanics,Czech Rep.*

The results of the experimental and analytical study of the effect of temperature and temperature gradient on the stability of the boundary layer of air flow along the curved wall are presented. The transition from laminar to turbulent flow occurs for a certain magnitude of the Reynolds number in the case of plane wall jet as well as curved wall jet. The transition in the case of curved wall jet is well observed owing to the tendency of the laminar flow to separate from the wall. On the other hand the turbulent flow has a strong tendency to remain attached to the surface. The results of the experiments together with the analysis carried out on the basis of the similarity solution show the stabilizing effect of the heated wall on the boundary layer.

FM3

Combustion and flames

Chairpersons: N. Peters (Germany), P. Wolanski (Poland)

A Nearly 1-D Non-Premixed Flame Near Extinction. Cell Formation and the Effect of the Direction of Bulk Flow

FM3L_10918
Fri • 09:30 • 134

David Lo Jacono[1], Paul Papas[1], Moshe Matalon[2], Peter A. Monkewitz[1]

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(2) *McCormick School of Engineering and Applied Sciences, Northwestern University, Evanston, USA*

A unique burner has been constructed to realize experimentally a one-dimensional unstrained planar non-premixed flame, previously only considered in idealized theoretical models. One reactant flows vertically up towards the horizontal flame. The novelty of the design is the introduction of the other reactant from above through an array of 625 closely spaced hypodermic needles, such that its diffusion to the flame, against the upward product flow, is essentially 1-D, i.e. uniform over the burner cross section. The resulting flame is shown to be nearly unstrained and is used to study the effect of the nature of the fuel transport to the flame (convective fuel supply from the bottom versus diffusion of fuel from the top against the bulk flow) on the extinction limit of a CO2-diluted H2-O2 flame. In addition, first results on the formation of cellular structures near the extinction limit are presented.

Detonations of Hexane Vapor/Droplets – Air Mixtures

FM3L_12745
Fri • 09:50 • 134

Stanisław Cudziło[1], A. Kuhl[2], P. Wolański[3]

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(2) *Lawrence Livermore National Laboratory, California, USA*
(3) *Warsaw University of Technology, Warsaw, Poland*

Detonation characteristics of hexane droplets/vapor-air mixtures were determined on the basis of experiments in a vertical 13-m long detonation tube. Hexane droplets were injected at the top of the test section. The droplets moved down and – when first of them reached the bottom of the test section – a initiating shock wave entered the tube. Pressure histories, shock wave and flame velocities in the hexane droplet suspensions were determined on the basis of signals from pressure transducers, pressure switches and photodiodes located along the test section. The results obtained enabled us to state whether and under what conditions a detonation process of the droplet suspension occurs, what are the parameters of the detonation wave and how are they affected by the suspension parameters and the initiating shock wave pressure.

Experimental and Numerical Investigation of a Flameless Oxidation Combustor

FM3L_12348
Fri • 10:10 • 134

J. Melo[1], A. Yadav[1], J.M.M. Sousa[1], M. Costa[1], **P.J. Coelho**[1], Y. Levy[2]

(1) *Instituto Superior Tecnico, Lisboa, Portugal*
(2) *Israel Institute Technology, Technion, Hajfa, Israel*

The flow characteristics of a combustor model under non reacting conditions were investigated using LDA. Data is reported for mean and turbulent velocities as a function of the air mass flow rate. The main conclusions are as follows: i) a common feature to all test conditions is the establishment of a large recirculation zone and ii) mean and turbulent velocities increase within the recirculation zone as the air mass flow rate increases. The isothermal flow characterization was followed by combustion measurements at the exit of the combustor model. Measurements of mean gas species concentration (O2, CO2, CO, HC and NOx) are reported as a function of the equivalence ratio and thermal input. The main conclusions are as follows: i) combustion efficiency is highest (about 90%) for both low values of thermal input and equivalence ratio, ii) NOx emissions are very low over a large range of operating conditions.

Enhancement of the Impinging Diffusion Flame by Splash Plate

FM3S_10367
Thu • 14:30 • 308A

Ay Su(1), Ying-Chieh Liu(2)
(1) *Department of Mechanical Engineering, Yuan Ze University, Taiwan*
(2) *Chung-Shan Institute of Science and Technology, Taiwan*

It is clear that the potential core of the jet flow increases with the jet velocity. Similarity, the flame length of the jet flame also increases with jet velocity. Two opposing jets impinge together at an inclined angle, and form a mixing flow field illustrated in Fig. 1. During the impinging process, the jet flow velocities may decrease and attain a minimum at the impinging point. The momentum energy transfers to increase the flow intensities and mixing rate. Therefore, the combustion rates are accelerated as compared with a single jet flame. The research is focused on spreading out the flame stretch of the impinging flame by splash plate mechanism. Two types of the splash plate with flat plate and 60 degrees in sharp edge are conducted in this experiment. Slip condition occurs at the jet-to-jet impingement and no-slip condition takes place at the jet flow on the splash plate. A portion of the fluid energy will transfer to the radial direction by the no-slip condition. Therefore, it tends to overcome the flame stretch and spreads the impinging flame out. The fuel and air jets locate at opposite side, the result of the main reaction zone will concentrates at the fuel side. According to the distribution of the higher temperature region (above 1000°C), its combustion efficiency is higher than the results without the splash plate. The results of the splash plate with shape-edge indicate the fuel and the air entrain mutually. The higher temperature region spreads toward the air side.

Exothermic Explosions in a Slab: a Case Study of Series Summation Technique

FM3S_10747
Thu • 14:35 • 308A

Oluwole D. Makinde
Applied Mathematics Department, University of the North, S. Africa

This paper examine the steady-state solutions for the strongly exothermic decomposition of a uniformly distributed combustible material between symmetrically heated parallel plates under Bimolecular, Arrhenius and Sensitised reaction rates, neglecting the consumption of the material. Analytical solutions are constructed for the governing nonlinear boundary-value problem using perturbation technique together with a special type of Hermite-Pad approximants and important properties of the temperature field including bifurcations and thermal criticality are discussed.

Simulation of Flame Propagation in a Tube with Obstacles

FM3S_11031
Thu • 14:40 • 308A

Aidarkhan Kaltayev, Zhomart Ualiev
al-Farabi Kazak National University, Department of Mechanics, Almaty, Kazakstan

A fictitious domain method (FDM) is extended and implemented for time dependent combustion problems in non-regular closed domains. FDM allows to work in regular domains using regular meshes independently of the geometry of the actual domains. Up to now a FDM was used for solving the problems of physics with Dirichlet boundary conditions. In the paper a fictitious domain method is extended and implemented for combustion problems in non-regular domains. The propagation of 2D laminar methane-air flame in a tube with obstacles are simulated and studied.

Large Eddy Simulation of Piloted and Bluff-Body Diffusion Flame

FM3S_11888
Thu • 14:45 • 308A

Tim Broeckhoven(1), Sergey Smirnov(1), Chris Lacor(1), Eduardo Brizuela(2)
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LES appears to be a promising tool for the prediction of turbulent combustion processes. Combustion instabilities come with large coherent structures which are better predicted with LES and because the larger structures are computed explicitly in LES, the zones of fresh and burnt gasses are clearly identified, and combustion-turbulence interactions are described more accurately. LES appears to be a promising tool for the prediction of turbulent combustion processes. Combustion instabilities come with large coherent structures which are better predicted with LES and the zones of fresh and burnt gasses are clearly identified so combustion-turbulence interactions is described more accurately. In this paper results of two LES-simulations are presented and compared to the RANS-solutions and experimental results. The test cases are a piloted CH_4/air diffusion flame and a bluff-body burner with a central fuel jet of $50\%H_2/50\%CH_4$ by volume which intensively mixes in the recirculation zone with the co-flow of air. The combustion model implemented is the mixed-is-burnt model assuming infinitely fast chemistry. The structure of the diffusion flame is fully determined once the mixture fraction Z is known. To account for the turbulence a presumed pdf approach is used with a β-shaped probability density function determined by the mixture fraction and its variance.

Influence of the Subgrid Models on Combustion Modelling

FM3S_11914
Thu • 14:50 • 308A

Artur Tyliszczak[1], William P. Jones[2], Andrzej Boguslawski[1], Stanislaw Drobniak[1]
(1) *Częstochowa University of Technology, Poland*
(2) *Imperial College London, UK*

Turbulent flows with combustion are among the most difficult problems occurring in nature and in industrial applications. A common appearance and importance of such flows require their correct prediction allowing for their optimization and control. The unsteady character of the turbulence implies the use of LES method which in turn allows to obtain time dependent solutions. This work concerns the analysis of the influence of subgrid models (subgrid viscosity) used within a framework of the LES method of turbulence/combustion modelling. To be able to perform such research it is necessary to exclude the effect of the numerical dissipation and its possible influence on the subgrid viscosity. The high order compact differences/pseudospectral numerical discretization method applied in computations allows for such an analysis and also guarantees very accurate results. The governing equations applied in this work are based on the low Mach number approximation while the combustion modelling is performed using a flamelet approach. The computations are performed for diffusive Sandia D flame and the results are compared with experimental data.

Chemical Aspects of the Flameless Oxidation Applied for GasTurbine Combustor

FM3S_12199
Thu • 14:55 • 308A

Yeshayahou Levy, Valery Sherbaum, Vladimir Erenburg
TECHNION, Hajfa, Israel

Low pollutant emissions became the basic issues in new combustion technologies concept. The present work aimed to find the performance characteristics of a gas turbine combustor operating in the flameless oxidation the specific operating conditions of gas turbine combustor with recirculating flue gases. Chemkin 3.7 code with applications “AURORA” for “PSR” and “PLUG” for chemical reaction calculations were applied. The following main results were obtained: 1. NO_x formation is governed mainly by combustion temperature, almost does not depends on recirculation ratio, but depends on combustion pressure. 2. Combustion delay time and minimum combustion temperature (for a given residence time) depends on combustion pressure and for a given pressure it depends slightly on flue gases recirculation ratio.

Simulation of Ram Accelerator with PETN Layer

FM3S_12843
Thu • 15:00 • 308A

Arkadiusz Kobiera, Piotr Wolański
Warsaw University of Technology, Warsaw, Poland

Simulation of a ram accelerator busted by PETN layer is the subject of the paper. There is described an idea of ram accelerator with a high explosive layer on tube walls. The layer is an additional source of chemical energy and enhances the acceleration of projectile. The paper presents numerical model of such device. The model includes submodels: gas flow and chemical reactions model, gas-wall heat transfer model and model of ignition of PETN layer. The models are interconnected by boundary conditions. Such approach was successfully used in simulation of ignition of high explosive layer by detonation wave. These results are used in model of ram accelerator. Simulation shows that it is possible to obtain several percent higher trust comparing to traditional ram-accelerators. Analysis of results shows the main limitations of the modified device and point out ways of improving it.

Simple Model of a Detonating Gas for use with the Direct Monte-Carlo Simulation Technique

FM3S_12911
Thu • 15:05 • 308A

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(3) *Institute of Industrial Organic Chemistry, Warsaw, Poland*

The research on gaseous detonation has recently become a very important issue because of increasing importance of gaseous fuels. We propose to use the Direct Monte-Carlo Simulation technique, which is a very powerful tool for solving complex flow problems. We propose a very simple model of a molecular collision, which makes it possible to increase the thermal energy of a gas, which is similar to the processes in the flame. We show then, that this model can produce the wave, which has all the features, characteristic for a detonation wave.

FM4

Complex and smart fluids

Chairpersons: B. Khusid (USA), A. Yarin (Israel)

Field-Induced Dielectrophoresis and Phase Separation in Suspention

FM4L_10753
Mon • 16:00 • 144

Dawn J. Bennett[1], **Boris Khusid**[1], Conrad D. James[2], Paul C. Galambos[2], Murat Okandan[2], David Jacqmin[3], Anil Kumar[4], Zhiyong Qiu[4], Andreas Acrivos[4]

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We report observations of a new electric field- and shear-induced many-body phenomenon in the behavior of suspensions whose origin is dielectrophoresis accompanied by the field-induced phase separation. As a result, a suspension undergoes a field-driven phase separation leading to the formation of a distinct boundary between regions enriched with and depleted of particles. The theoretical predictions are consistent with experimental data even though the model contains no fitting parameters. It is demonstrated that the field-induced dielectrophoresis accompanied by the phase separation provides a new method for concentrating particles in focused regions and for separating biological and non-biological materials, a critical step in the development of miniaturizing biological assays.

Modeling DNA Separations in Self-Assembled Magnetic Arrays: Comparison of Theory and Experiment

FM4L_11209
Mon • 16:20 • 144

Kevin D. Dorfman, Nicolas Minc, Claus Fuetterer, Jean-Louis Viovy

Institut Curie, Paris France

Self-assembled magnetic matrices, formed by applying a magnetic field to a suspension of superparamagnetic particles, are a simple, low-cost solution for the rapid separation of long DNA. We present a theoretical model of macroscopic DNA transport in the device, where the fundamental geometric and transport parameters are either determined experimentally or from a microscale model. Using simple models for the collision probability and retention time, we predict that the mean velocity and dispersivity scale linearly with the applied field, the band broadening scales inversely with the field, and the separation resolution is independent of the field. The scaling results are confirmed experimentally. We achieve reasonable quantitative agreement between theory and experiment with an experimental measurement of the average trapping time.

Particle Manipulation in Microfluidics: the Role of Dielectrophoresis, Electrohydrodynamics and AC Electrokinetics

FM4L_12437
Mon • 16:40 • 144

Antonio Castellanos[1], Antonio Ramos[1], Antonio Gonzalez[1], Nicolas G. Green[2], Hywel Morgan[2]

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(2) *University of Glasgow, UK*

The movement of particles suspended in aqueous solutions subjected to non-uniform ac electric fields is examined. The ac electric fields induce movement of polarizable particles, a phenomenon known as dielectrophoresis. The high strength electric fields often used in separation systems can give rise to fluid motion, which results in viscous drag on the particle. The electric field generates heat, leading to volume forces in the liquid. Gradients in conductivity and permittivity give rise to electrothermal forces; gradients in mass density to buoyancy. In addition, non-uniform ac electric fields produce forces on the induced charges in the diffuse double layer on the electrodes. This gives a fluid motion termed ac electroosmosis. The effects of Brownian motion are also discussed in this context. The orders of magnitude of the various forces experienced by a particle are discussed in relation to experiments and the relative influence of each type of force is described.

Ferrohydrodynamic Hele-Shaw Cell Flows and Instabilities with Simultaneous DC Axial and In-Plane Rotating Magnetic Fields

FM4L_12662
Mon • 17:00 • 144

Scott E. Rhodes, Juan A. Perez, Shihab M. Elborai, Se-Hee Lee, Markus Zahn
Massachusetts Institute of Technology, Cambridge, USA

New flows and instabilities are presented for a ferrofluid drop contained in glass Hele-Shaw cells with simultaneously applied in-plane clockwise rotating and DC axial uniform magnetic fields. When a ferrofluid drop is stressed by a uniform DC axial magnetic field, up to ∼250 Gauss in 0.9–1.4 mm gap Hele-Shaw cells, the drop forms a labyrinth pattern. With subsequent application of an in-plane uniform rotating magnetic field, up to ∼100 Gauss rms at frequency 20–40 Hz, smooth spirals form from viscous shear due to ferrofluid flow. If the rotating magnetic field is applied first, the drop is held together without a labyrinth. Gradual increase of the DC axial magnetic field, to a critical magnetic field value, results in an abrupt phase transformation from a large drop to many small discrete droplets. A preliminary minimum magnetization and surface energy analysis is presented to model the phase transformation.

The Giant Electrorheological Effect in Suspensions of Nanoparticles

FM4L_11165
Mon • 17:20 • 144

Ping Sheng[(1)], Weijia Wen[(1)], Xianxiang Huang[(1)], Shihe Yang[(2)], Kunquan Lu[(3)]
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(3) *Institute of Physics, Chinese Academy of Sciences, China*

Electrorheology (ER) denotes the control of material's flow properties (rheology) through electric field. We have fabricated ER suspensions of coated nanoparticles that exhibit electrically controllable liquid-solid transitions in which the solid state can reach a yield strength of 130 kPa, breaking the theoretical upper bound on conventional ER static yield stress that is derived on the general assumption of linear dielectric and conductive responses of the component materials. This giant electrorheological (GER) effect displays near-linear variation of the static yield stress versus the electric field, in contrast to the quadratic variation usually observed. Our GER suspensions display low current density over a wide temperature range of 10–120°C, with a reversible response time of <10 ms. Finite element simulations, based on the model of saturation surface polarization in the contact regions of neighboring particles, yield predictions in excellent agreement with the experiment. *W. Wen, X. Huang, S. Yang, K. Lu, Ping Sheng, Nature Materials 2, 727-730 (2003).

Spray Impact on Solid Walls of Non-Newtonian Fluids, Including Yield Stress and Thixotropic Behavior

FM4L_12254
Mon • 17:40 • 144

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In a variety of applications the interactions of sprays with solid walls play an important role. The fluid may be pseudoplastic, possessing a non-vanishing yield stress, and thixotropic, with a viscosity showing a time-dependency, in addition to the shear-rate-dependency. Spray impact of thixotropic fluids with yield stress onto a dry smooth solid wall is investigated numerically. The rheological behavior of the fluids is modelled by a stationary flow curve, completed by a Quaak model for the time-dependent change of the viscosity. A commercially available code, based on the volume-of-fluid method is used. The code has been verified for fluids with yield stress and thixotropy, respectively, in viscosimetric flows and in impact processes of single drops. Calculations are performed for thixotropic fluids with yield stress of practical relevance. The results are compared with cases without thixotropy. They provide initial conditions for the subsequent evolution of the coherent fluid film.

Electrospinning of Nanofibers from Polymer Solutions

FM4L_10932
Fri • 09:30 • 226

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A straightforward, cheap and unique method to produce novel fibers with diameter in the range of 100 nm and even less, is related to electrospinning. For this goal polymer solutions, liquid crystals, suspensions of solid particles and emulsions are electrospun by a field of about 1 kVW/cm. The electric force results in an electrically charged jet of polymer solution outflowing from a droplet tip. After the jet flows away from the droplet in a nearly straight line, it bends into a complex path and other changes in shape occur, during which electrical forces stretch and thin it by very large ratios. After the solvent evaporates, solidified nanofibers are left. Nanofibers of ordinary, conducting and photosensitive polymers were electrospun. The present work deals with the mechanism and electrohydrodynamic modeling, experimental realization and a number of applications. In particular, we developed a unique electrostatic field-assisted assembly technique with the aim to position and align individual conducting and light-emitting nanofibers in arrays, crossbars and ropes. These structures are of potential interest in development of novel polymer-based light-emitting diodes, diodes, transistors, photonic crystals and flexible photocells. We also discuss our experiments on electrospinning of nanofibers reinforced by carbon nanotubes, and on coelectrospinning, which yields core-shell nanofibers and nanotubes.

Capillary Microfluidics for Viscoelastic Fluids

FM4L_10140
Fri • 09:50 • 226

Konstantin G. Kornev, Gerardo Callegari, Alexander V. Neimark
TRI/Princeton, New Jersey, USA

In conventional microfluidic devices, fluids are pumped by applying either pressure drop or temperature or voltage differences. In biomedical technologies dealing with fluids of a complex rheology, the forced fluid transportation is sometimes hardly applicable. We present a new principle of controlled fluid transport at micro- and nanoscale. This approach is based on the phenomenon of spontaneous absorption of wetting fluids by porous materials. That is, capillarity drives the droplet self-propulsion without the need for any additional external mean. We study viscoelastic fluids and develop some theoretical and experimental approaches to tackle this problem. Aqueous solutions of polyacrylamide (PAM), polyethyleneoxide (PEO) and lambda-DNA are taken as model polymeric fluids.

Break up of Polymer Solution Drop Impacting a Small Target

FM4L_11954
Fri • 10:10 • 226

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To investigate the effects of high molecular polymeric additives on the splashing of a drop impacting a solid, we used small disk-like targets. Such type of impact allows to “switch off” the viscous friction between the liquid and the solid and therefore to observe the drop splashing with a minimal number of influential factors. It was found that the polymeric additives suppressed the drop disintegration into secondary droplets because of the formation of thinning filaments between the droplets and the main drop, which prevented the droplets from detaching and forced them to coalesce back with the main drop. A splashing threshold criterion could be derived from the balance between the liquid inertia, the capillary forces and the liquid elasticity.

Electrospinning of Liquid Jets

FM4S_11184
Tue • 14:30 • 304

Slawomir Blonski[1], Anna Blasinska[2], Tomasz A. Kowalewski[1]
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A very thin liquid jets can be obtained using electric fields. The electrically-driven bending instability of the jet enormously increases the jet elongation path and effectively leads to its tinning by very large ratios and can be used to produce nanofibres. The mechanism of electro-thinning of liquid jets, discovered almost one century ago, is yet not fully understood. In the following study detailed experimental data are collected for electrospinning of different liquids in the purpose to correlate these data with the existing models describing basic mechanisms responsible for the electrospinning.

Contact Angle Dynamics of Droplets Impacting on Flat Substrates

FM4S_11603
Tue • 14:35 • 304

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Department of Mechanical and Industrial Engineering, University of Illinois, Chicago, USA

An experimental study is presented on contact angle dynamics of water droplets striking orthogonally smooth surfaces with widely disparate wetting characteristics (wetting to non-wetting). Fundamental information related to the relation between apparent (macroscopic) contact angle θ and contact line speed V_{CL} is presented. The impact conditions correspond to

$Re = O(100)-O(1000)$, $We = O(10)$, $Ca = O(0.001)-O(0.01)$, $Oh = O(0.001)$ and $Bo = O(0.1)$. In this parameter regime, inertial, viscous, and capillary phenomena act simultaneously to influence contact line motion and arrest. The combined molecular-hydrodynamic theory of contact line speed dependence of the contact angle was found to fit the experimental θ vs. V_{CL} data yielding physically reasonable molecular-kinetic parameters for wetting and partially wetting surfaces. Impact on non-wetting surfaces is followed by rebound, and reveals that both advancing and receding contact angles do not change with contact line speed. The combined molecular-hydrodynamic theory could not predict the experimental data for non-wetting surfaces. Contact angle hysteresis was detected on each surface, however it was found to be minimum on the non-wetting surface. Moreover, impact with lower initial velocity on the non-wetting surface showed more elastic rebound than impact with higher initial velocity. It is concluded that droplet impact at moderately high Weber numbers on surfaces of varying wetting characteristics does not support a simple relation between apparent contact angle and contact-line velocity.

Dissipation Features at Nonlinear Pulsations of Bubbles in Viscoelastic Fluids

FM4S_11648
Tue • 14:40 • 304

Semyon P. Levitsky, Jehuda Haddad
NACE, Beer-Sheva, Israel

Nonlinear interaction of heat-conducting gas bubble with viscoelastic liquid in a sound field of small but final amplitude is described. The liquid phase is treated as non-Newtonian fluid following Oldroyd type rheological equation. Solution of the problem is received within the volume approach in quadratic approximation with respect to the incident wave amplitude. Resulting relation for the scattered wave intensity is studied numerically with the emphasis on the dissipation features. The study is motivated by the problem of acoustic control of microbubbles trapping in flows of smart fluids with memory.

Effective Magnetoviscosity for Ferrofluid Planar Couette Flow

FM4S_11982
Tue • 14:45 • 304

Xiaowei He, **Markus Zahn**
Massachusetts Institute of Technology, USA

Ferrofluid spin velocity, shear stress, and magnetoviscosity are calculated for a planar duct Couette ferrofluid flow, with an applied uniform DC magnetic field transverse to the duct axis using Shliomis' first magnetization relaxation equation, generally valid for low magnetic fields. For simplicity, we take the ferrofluid to be linearly magnetizable with constant magnetic susceptibility χ_0. The solution for the axial flow is then while the spin velocity is spatially constant, where both and the change in viscosity, η, due to the magnetic field obey a 5th order algebraic torque equation. This analysis generalizes earlier analyses which had a 3rd order algebraic torque equation, and shows the importance of specifying the magnetic field source in order to best choose or as the independent variables describing the ferrofluid flow spin velocity and change in magnetoviscosity. The best choice magnetic field independent variable does not depend on ferrofluid magnetization or spin velocity.

Nanowires Assembly Using Microfluidic: an Experimental Investigation

FM4S_12319
Tue • 14:50 • 304

Wael Salalha, **Eyal Zussman**
Technion – I.I.T, Hajfa, Israel

Nanowires are common building blocks for the bottom-up assembly of electronic and photonic devices. A significant challenge is to introduce the individual building block in an oriented assembly in order to express its unique anisotropic properties or to create a nano-device. In this work we focus on fluidic alignment of nanowires suspended in an incompressible liquid. The approach is based on manipulation of a micro droplet with suspended nanowires in a confined shape, such as a micro-channel. These nanowires are eventually deposited on patterned surfaces forming parallel arrays. We report on alignment results of nanowires using Poiseuille flow and also report on the motion of the nanowires, in the vicinity of the dynamic contact lines, which follow non-closed spirally shaped streamlines and in certain case, the streamlines of sink- or source-like flows.

Ferrohydrodynamic Jets, Sheet Flows and Instabilities

FM4S_12676
Tue • 14:55 • 304

Thomas A. Franklin, John W.M. Bush, Markus Zahn
Massachusetts Institute of Technology, Cambridge, USA

We investigate vertical ferrofluid jets of initially circular cross-section striking a solid circular impactor to create a radially expanding sheet flow in the presence of a magnetic field. With no magnetic field, the expanding sheet is circular.

When a horizontal magnetic field transverse to the vertical jet axis is applied, the jet cross-section changes from circular to approximately elliptical with long axis in the direction of the magnetic field. The expanding sheet also becomes approximately elliptical but with long axis perpendicular to the magnetic field. If a nozzle of elliptical cross-section is used with non-magnetic fluid, the expanding elliptical sheet also has long axis perpendicular to the jet cross-section long axis. If the applied magnetic field is vertical, and thus perpendicular to the sheet interfaces, the expanding sheet radius decreases with increasing magnetic field. We demonstrate that in this geometry, the magnetic field destabilizes the sheet through amplification of the Kelvin-Helmholtz instability.

Ferrofluid Meniscus Shape in an Applied Uniform Horizontal or Vertical Magnetic Field

FM4S_12689
Tue • 15:00 • 304

Ronald E. Rosensweig[(1)], Shihab M. Elborai[(2)], **Se-Hee Lee**[(2)], Markus Zahn[(2)]
(1) *Exxon Corporate Research (retired), Summit, USA*
(2) *Massachusetts Institute of Technology, Cambridge, USA*

The classic analysis of the shape of a meniscus due to fluid wetting a vertical wall, including the influence of fluid weight and interfacial surface tension, is extended to ferrofluids stressed to magnetic saturation by a horizontal or vertical uniform magnetic field. This analysis is the first step in a larger analysis to calculate the magnetic surface force due to ferrofluid surface shapes altered by magnetic fields and forces that cause surface driven flows in rotating magnetic fields. Bernoulli's equation, including "magnetic pressure" together with the interfacial force balance due to pressure, surface tension and jump in Maxwell stress, leads to a second-order non-linear differential equation for the solution of interfacial displacement. Solutions show that a horizontal magnetic field raises, while a vertical magnetic field lowers, the meniscus height. Preliminary optical experiments are presented which measure meniscus height and shape using narrow light beam reflections from the meniscus as a function of horizontal magnetic field.

Non-Newtonian Effects of Ink-Jet Printed Droplets

FM4S_12894
Tue • 15:05 • 304

Paul C. Duineveld[(1)], J.F. Dijksman[(1)], H. Huang[(2)]
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(2) *York University, Toronto, Canada*

The influence of non-Newtonian effects on the droplet formation in an ink-jet printer has been investigated both experimentally as well as with a simple theoretical model. For the experiments, Newtonian liquids and model systems of solutions of flexible polymers (PEO, polyethylene oxide) and stiff polymers (Xanthan Gum) were used. The non-Newtonian effects were modeled by only taken into account the influence of the elongational viscosity and not the stress history effect. It is shown that the elongational viscosity in itself is not sufficient to understand the filament formation; the stress history effects can not be neglected.

Conditions for Creating Thin Liquid Layers at the Contact Surface of Two Other Liquids

FM4S_12910
Tue • 15:10 • 304

Agnieszka Slowicka, Zbigniew A. Walenta
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The design of new technologies, for manufacturing the nanostructured materials is one of the important tasks of the contemporary materials science. The use of emulsion droplets as templates for producing nanostructures out of solid particles, suspended in the liquid phase is already under development. In the present work we investigate the possibility of using a liquid film instead of solid particles. To simulate the behaviour of the liquids we apply the Molecular Dynamics simulation technique.Since the behaviour of the liquids depends mainly on the interaction potentials of the molecules, we look for combination of the interaction potentials, which might produce the required liquid film at the surfaces of the emulsion droplets.

FM5

Compressible flow

Chairpersons: H. Hornung (USA)

Hysteresis-Related Phenomena in Shock Wave Reflection

FM5L_10531
Wed • 08:30 • 206

Mikhail Ivanov, Dmitry Khotyanovsky, Alexey Kudryavtsev, Stanislav Nikiforov, Anatoly Trotsyuk
Institute of Theoretical and Applied Mechanics, Novosibirsk, Russia

Our presentation is focused on recent advancements in investigations of shock wave reflection. The hysteresis in the transtion between steady regular and Mach reflections, which was observed in 1995 in numerical simulations and wind-tunnel experiments, aroused a renewed interest in this old problem. We consider various aspects of hysteresis-related shock reflection phenomena including 1) experimental demonstration of the hysteresis in a low-noise wind tunnel where flow disturbances are minimum; 2) numerical simulations of the transition induced by artificial disturbances, especially by blast waves caused by laser energy deposition; 3) existence of shock-wave configurations with a reflected shock wave of a strong family upon asymmetric shock wave interaction; 4) Mach reflections in a chemically reacting gas mixture with a standing detonation wave as a Mach stem; 5) hysteresis in the transition between regular and Mach reflections of steady bore waves on shallow water. The universal character of the hysteresis in flow discontinuity interactions in different physical systems is emphasized.

Nonclassical Dynamics of Laminar Dense Gas Boundary Layers

FM5L_10789
Wed • 08:50 • 206

Mats Kinell, **Alfred Kluwick**
Institute of Fluid Mechanics and Heat Transfer, TU Vienna, Austria

While inviscid flows of dense gases have been studied intensively in the past, viscous effects have received much less attention so far. It is the aim of the present study to show that the observed unconventional gasdynamic behaviour may strongly influence the properties of laminar boundary layers in both accelerated and decelerated external flows. For example, by studying linearly retarded flows it is found that the formation of an unsurmountable separation singularity can considerably be delayed or even avoided by exploiting dense gas effects. A marginal separation singularity then occurs as a limiting case. Its formation is studied both numerically and analytically and traced back to the non-monotonous Mach number variation in the external inviscid flow.

Unsteady Drag Force Measurements of Shock Loaded Bodies Suspended in a Vertical Shock Tube

FM5L_11049
Wed • 09:10 • 206

Kazuyoshi Takayama[(1)], Mingyu Sun[(1)], Koji Tamai[(1)], Tsutomu Saito[(1)], Hiroyuki Tanno[(2)], Joseph Falcovitz[(3)]
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(2) *Kakuda Space Propulsion Research Center, Japan*
(3) *Institute of Mathematic, Hebrew University of Jerusalem, Israel*

Paper deals with experimental and numerical works of drag force measurements over a 80 mm diameter sphere. Test models were suspended in a 300 mm $\times$ 300 mm cross sectional vertical shock tube. Unsteady drag forces were measured directly with accelerometers installed inside the test models. Flow visualizations of individual shock/model interactions were visualized quantitatively with double exposure holographic interferometry and sequentially with high-speed video recording. Shock Mach number was 1.2 in air. Measured unsteady drag forces of individual bodies were compared with numerical results by solving the Euler equations and the Navier–Stokes equations with meshes of level four refinements. In addition to appearance of peak drag forces, negative drag forces appear when the transmitting shocks merge at bodies rear stagnation points.

Shock Wave Reflection in a Non-Circular Inlet

Beric W. Skews, Jithin A. Mohan, Nankishore Menon
University of the Witwatersrand, South Africa

FM5L_11072
Wed • 09:30 • 206

The flow between two finite wedges placed symmetrically in a supersonic flow with one or both sides capped with a semi-cone thereby forming a non-circular inlet is studied. In some cases one semi-cone is removed as an aid to visualisation and tunnel start-up. Imaging with laser vapour screen and shadowgraph techniques is conducted. The objective of the work is to examine transition between regular and Mach reflection in three-dimensional flows. The experimental results can give images that are difficult to interpret and which appear aphysical. Shocks appear to bifurcate and then rejoin on the symmetry plane; there is a very abrupt transition from the side conical incident wave to Mach reflection; and then a gradual reduction in stem height back to regular reflection. Clarity on these flows is obtained through further experimentation and CFD simulation.

The Mach Reflection of Weak Shocks

John K. Hunter, Allen M. Tesdall
University of California at Davis, USA

FM5L_11730
Wed • 09:50 • 206

We present numerical solutions of the steady and unsteady transonic small disturbance equations that describe the Mach reflection of weak shock waves. The solutions contain a complex structure consisting of a sequence of triple points and tiny supersonic patches directly behind the leading triple point, formed by the reflection of weak shocks and expansion waves between the sonic line and the Mach shock. The presence of a supersonic patch and an expansion fan at each triple point resolves the 'von Neumann triple point paradox', as was suggested by Guderley. The numerical results and theoretical considerations suggest that there is an infinite sequence of triple points in an inviscid weak shock Mach reflection.

Shock Wave-Boundary Layer Interaction Control by Streamwise Vortices

Piotr Doerffer, **Ryszard Szwaba**
IMP PAN, Gdańsk, Poland

FM5L_12202
Wed • 10:10 • 206

In many applications shock waves induce separation, which often leads to unsteady effects. Such interactions are hard to investigate and difficult to control. It is proposed to use streamwise vortices for this interaction control. The most useful method of the streamwise vortex generation is by air jets (AJVG), because it allows a simple method of switching it on and off. This paper presents our first experimental results which allow displaying the advantages of the AJVG's in the shock wave boundary layer control. Chosen Mach number cases cover the range from not separated to strongly separated flows. It was decided that the stagnation pressure of air jets was equal to the stagnation pressure of the main stream. Hence, there is no need for any driving system for jets. Obtained results show that the AJVG reduce the scope of separation area and that unsteady effects induced by the interaction are considerably dumped.

Pulsations of Pressure at a Cylinder in a Subsonic Stream of Gas.

Alexander Shvets
Moscow State University, Institute of Mechanics, Moscow, Russia

FM5S_10453
Thu • 14:30 • 219B

The distribution of root-mean-square values and spectral characteristics of pulsations of pressure at a cross flow of the cylinder in a subsonic stream of gas (M = 0.44–0.88) are investigated. At small subsonic speed (M = 0.44) there are two field of the increased root-mean-square value of pulsations of pressure ($\varphi = 50$–120°) owing to initial and rear separates a boundary layer, at big subsonic speed (M = 0.88) – on a field $\varphi = 90^\circ$ – owing to formation of a local supersonic zone with closing shockwave. At spreading a stream from a forward point speed is increased, that is accompanied by decrease of frequencies of pulsations. In a range of small subsonic speeds decrease of numbers Sh is observed at values of angle $\varphi = 40$–60°. At M = 0.54 frequencies rais up to $\varphi = 120$, then are a little bit reduced, and at M = 0.9 the increase of frequencies up to a back point of the cylinder is observed.

Analytical Models for Shocks in Compressible Flow

Helmut Sobieczky
DLR German Aerospace Center, Gottingen, Germany

FM5S_10945
Thu • 14:35 • 219B

Analytical flow models frequently are not seen useful anymore for the acceleration of design processes in aerospace technology. Because of at least two reasons we defend the suitability of the classical knowledge base using mathematical models

for compressible fbw: This contribution is pleading for a modern view on fbw models, with a timely extension by computer aided animation of complex fbw patterns. The understanding of local shock dynamics via analytical model functions has clarifi ed some seemingly contradictory requirements in the past, but nowadays computerized mapping techniques and fast graphic visualization will do this job effi ciently. A strong educational aspect is an academic reason for maintaining this approach. Some examples for the local and global structure of transonic and supersonic shock waves will be illustrated. Such models give valuable hints for a suitable confi guration parameterization incuding target pressure distributions for inverse design without an excessive number of optimization runs, a very practical reason to use model functions.

LDA Investigation of a Transonic Bump Flow

FM5S_10984
Thu • 14:40 • 219B

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The transonic fbw over a circular arc bump has been investigated in a blow-down wind-tunnel. A variety of shock strengths between M=1.2 and M=1.48, depending on the experimental confi guration, have been achieved. In all cases separation was observed at the trailing edge of the bump, whereas shock induced separation was present only in fbws with shock strengths above M=1.3. Laser Doppler Anemometry has been used to gather detailed information on turbulent fbw properties. Good quality information was obtained as close to the wall as 0.1 mm. The results highlight the effects of favourable and adverse pressure gradients on turbulence properties, in particular the influence of shock waves and separation / reattachment. The recovery of the boundary layer downstream of re-attachment is also discussed. The data can help the understanding of shock / boundary layer interactions and the development of turbulence models for numerical simulations.

Turbulent Effects in Type4 Shock Interactions

FM5S_11229
Thu • 14:45 • 219B

Josef Ballmann, F. Bramkamp, B.U. Reinartz, J. van Keuk
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Type4 shock interactions in hypervelocity fbws are investigated numerically using two different codes: The well-known structured DLR FLOWer-code extended by different upwind formulations and non-equilibrium chemistry as well as the new fbw solver QUADFLOW, which is an unstructured code with grid adaptation controlled by multi-scale analysis. Main focus of the paper is the correct prediction of the high heat loads for the contour caused by Type4 shock interactions compared with experimental data. In previous works assuming laminar fbw the numerically predicted heat flux was always lower than experimentally observed. So in this paper the influence of turbulent effects on the heat flux is investigated. Furthermore, the possible improvements using the adaptive fbw solver on the one hand and considering of chemical non-equilibrium on the other hand on the quality of the results is assessed.

Numerical Optimization of 2D Scramjet Inlets

FM5S_11560
Thu • 14:50 • 219B

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A scramjet engine is viewed as a promising propulsion system for a spaceplane, and signifi cant research is in progress worldwide on scramjet engine design and performance. An automated design optimization process for hypersonic inlets was developed and validated. The test case for the process was the evolution of an optimimal design for hypersonic inlets, where optimality was based on the maximization of the total pressure recovery at the isolator exit. This optimization process links together an optimizer with a full Reynolds Averaged Compressible Navier–Stokes solver into an automated optimization loop. This paper presents the implementation of these new design techniques and their application to hypersonic inlet case in flight condition of Mach 8. The improvements obtained using the optimizer are presented and compared. Results indicate the development of the geometric perturbation and a consequent increase in total pressure recovery during the convergence to the optimal geometry.

Effect of Surface Roughness on Mach Reflection

FM5S_11864
Thu • 14:55 • 219B

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It has long been believed that the oblique shock reflection is a self-similar phenomenon, and the analysis have been based on this assumption so far. However, recently non-self-similar behavior of oblique shock reflection has been observed under atmospheric pressure conditions. There are two possible reasons for the non-self-similarity: transport properties (viscosity or thermal conductivity) and surface roughness, both of which bring characteristic length into the system, and break the self-similarity. In the present paper, the effects of surface roughness and transport properties have been compared experimentally for Mach reflection. The surface roughness was given by pasting a piece of sand paper (#60 and #240) on the model surface. The results were compared with those for smooth surfaces. As the effect of surface roughness turned out to be small compared with viscosity effect, it was concluded that the effect of transport properties is dominant in the non-self-similar phenomena.

On the Theory for Subsonic, Transonic and Supersonic Flows in Water with Supercavitation

FM5S_12066
Thu • 15:00 • 219B

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The aim of this investigation is to improve the understanding of physical and mathematical aspects of hydrodynamics of flows at super high speeds, typically at sonic speed of water, which is of the order of 1500 m/s. Super high speed motion in water is realized with the help of lunching small axisymmetric projectiles of $\sim 0.2--0.7$ kg mass with initial speeds of $\sim 1000--2000$ m/s and by following its stable motion under inertia. Under these conditions the body is totally surrounded by a vapor filled cavity, which prevents direct contact of the projectile with the liquid fluid. Therefore, the viscous losses are considerably reduced, which implies the potential to achieve a very low total drag, comparable to that of high speed motion in air. Following the classical incompressible supercavitation modelling, the linearized approach, based on the Slender Body Theory, the Matched Asymptotic Method and by using simple heuristic models, together with integral conservation laws, and similarity consideration are applied for this analysis. With respect to the existence of a considerable more extended transonic regime in water flows, as compared to the classical case of air/gas flows, special attention is paid to the investigation of singularities of transonic water flows. As a result of the development of the second order theory a number of simple solutions have been found that give the possibility to analyze compressibility effects for super high speed motion in water as a whole.

Mathematical Modeling of Turbulent Supersonic Flows in Inlets with Rotating Cowl

FM5S_12144
Thu • 15:05 • 219B

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Methods of physical experiment and mathematical modeling have been used to study the properties of flows in adjusted inlets designed to operate in a wide range of Mach number. The variation of inlet geometry was performed by cowl rotation. The experimental investigations have been carried out in the blow-down wind tunnel at Mach numbers from 2 to 6 and in the hot-shot wind tunnel at Mach numbers from 5 to 8. The computations were performed on the basis of the full Navier–Stokes equations and the two-equation turbulence model by Wilcox. The experimental pressure distributions along the inlet walls were used for the verification of simulation results. Comparison have shown a good agreement. Computations within the wide range of flow and geometric parameters help to carry out the experiments and provide a basis for the choice of optimum configurations and explanation of flow features.

Correlation of Nearfield Pressure with Mixing Layer Velocity in a Supersonic Jet

FM5S_13016

Thu • 15:10 • 219B

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A series of experiments have been performed to investigate the possibility of using a linear stochatic estimation to reconstruct the three dimensional turbulence field of an isothermal supersonic jet using only a limited series of nearfield pressure measurements. To this end synchronous measurement of the nearfield pressure and the mixing layer velocity field has been effected, using a two-component LDV system in parallel with 39 pressure transducers arranged along the jet. Pressure-pressure and velocity-pressure correlations are obtained for an extensive range of locations in an isothermal jet with a Mach number of 1.4. Additional pressure measurements are performed in a region where the energy of the hydrodynamic and acoustic fields are of similar order, and preliminary results clearly identify both convective and propagative trends. This database will be used to reconstruct the temporal evolution of the three dimensional velocity field and also to filter and separate the acoustic and hydrodynamic components of the nearfield pressure.

Interaction of Supersonic Flows in an Ejector

FM5S_12219

Thu • 15:15 • 219B

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The article deals with experimental, theoretical and numerical study of the interaction of supersonic flows on the trailing edge of the primary flow nozzle of a supersonic ejector. The mechanism of mutual deflection of supersonic flows is explained. The results of the interaction are two shock waves or one shock wave and one Prandt-Meyer expansion. A shear layer and a wake occur downstream the trailing edge. The influences of back pressure ratio and stagnation pressure ratio on the interaction are presented. Recommendations for design and for operation of supersonic ejectors are formulated.

FM6

Computational fluid dynamics

Chairpersons: L. Kleiser (Switzerland), W. Schroeder (Germany)

Non-Reflecting Boundary Condition for Direct Aeroacoustic Computation

FM6L_10163
Mon • 16:00 • 327

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A new non-reflecting boundary condition (NSPML), based on perfectly matched layer concept applied to full compressible Navier–Stokes equations, is proposed for direct aeroacoustics computation. The boundary condition is designed to absorbs two-dimensional acoustic waves incident at all angles. The NSPML is validated with aeroacoustic flows of increasing complexity, namely a radially propagating Gaussian acoustic pulse, interaction of Gaussian pulse with a vortex in uniform flow and acoustic waves generated from an open cavity flow. In comparison with existing boundary conditions, it is found that the proposed NSPML provides higher non-reflectivity and generates significant less error waves, but at a much lower computational cost.

On Inflow Boundary Conditions for Large Eddy Simulation of Turbulent Swirling Jets

FM6L_11348
Mon • 16:20 • 327

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Three Large Eddy Simulations have been performed for an unconfined annular swirling jet with different inflow boundary conditions. The adequate specification of these conditions is a decisive issue for such computations. To validate the chosen approach it is usual to compare first and second order moments of the velocity field with the corresponding experimental data. By means of visualizations and frequency spectra we show that good agreement of mean and rms velocities is not, in general, sufficient for a realistic representation of the experimental conditions. The unsteady large-scale structures of the flow must also be taken into account. Also, for swirling jets, the simulation of the actual swirl-generating mechanism is not always needed. A less expensive strategy is proposed.

A Pressure-Correction Method for All Mach Numbers

FM6L_11602
Mon • 16:40 • 327

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We present a collocated finite-volume-based pressure-correction method, for all speed flows of a general fluid. Over the whole Mach number range, the algorithm shows an excellent efficiency and accuracy. Mach-uniform accuracy is obtained by applying the Advection Upstream Splitting Method (AUSM+) for the flux definitions, with adaptations for low Mach number stability. Mach-uniform efficiency is obtained by treating the convective phenomena and the acoustic/thermodynamic phenomena separately: a velocity predictor from the momentum equations, and a coupled solution of the continuity and energy equation for pressure and temperature corrections. Doing so, acoustics are treated implicitly and an acoustic CFL-limit is avoided. The algorithm finds its place in between a fully segregated and a fully coupled approach. It is valid for a general fluid, including special cases like a constant density fluid and an ideal gas.

Three-Dimensional Rayleigh–Bénard Instability in a Supercritical Fluid by Direct Numerical Simulation

FM6L_12123
Mon • 17:00 • 327

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(2) *CNES, France*

This paper describes the unsteady convective flow of a supercritical fluid in Rayleigh–Bénard configuration using direct numerical simulation. Two-dimensional earlier studies reported fast temperature equilibrium due to the piston effect and the development of a convective instability when the local Rayleigh number exceeds a critical value. In the present work, a high order 3D finite volume method has been developed and optimized, the code has been thoroughly validated, and to our knowledge, we show for the first time a three-dimensional convective instability in a supercritical fluid. Inspecting the time-evolution of temperature field patterns, we show the time-transition to convection-dominated flow causing the collapse of the boundary thermal layers, we exhibit corner effects and the three-dimensional behavior of the flow, and we show the heating intensity effects on the temperature field structure.

Commutator-Errors in Large-Eddy Simulation of Turbulent Flow

FM6L_13030
Mon • 17:20 • 327

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Commutator-errors in large-eddy simulation of incompressible turbulent flow arise from the application of non-uniform filters to the continuity – and Navier–Stokes equations. For non-uniform, high-order filters the order of magnitude of the commutator-errors is shown to be the same as that of the turbulent stress fluxes. Consequently, one can not reduce the size of the commutator-errors independently of the turbulent stress terms by some judicious construction of the filter operator. For situations in which the dynamical consequences of the commutator-errors are significant, e.g., near solid boundaries, explicit similarity modeling for the commutator-errors is proposed, including the application of Leray regularization. The performance of this commutator-error parameterization is illustrated for the one-dimensional Burgers equation. The Leray approach captures the filtered flow with higher accuracy than conventional similarity modeling, especially for large filter-width variations.

Multiscale Simulations Using Particles

FM6L_12583
Mon • 17:40 • 327

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We present multilevel particle methods with extended adaptivity in areas where increased resolution is required. We present two complementary approaches as inspired by r-adaptivity and adaptive mesh refinement (AMR) concepts introduced in finite difference and finite element schemes. For the r-adaptivity a new class of particle based mapping functions is introduced while for the particle-AMR mappings the methods use particle remeshing as a key element. The advantages and drawbacks of the proposed particle methods are illustrated on a number of applications. With the proposed techniques we show that rephrasing in terms of particle methods concepts inherited from adaptive finite-element or finite-difference methods can lead to methods that while keeping essential advantages of particle methods such as robustness when dealing with convection dominated problems may also maintain a high accuracy. Finally the implementation of particle methods for multiscale simulations as dictated by multiple physical phenoemena is discussed.

Treesph Simulations of Choked Flow Systems Using Smoothed Particle Hydrodynamics

FM6S_10857
Tue • 14:30 • 306

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Here we present exploratory two-dimensional calculations of the flow of a viscous, single-phase fluid through a wellhead choke of real dimensions using the method of Smoothed Particle Hydrodynamics coupled with a simple isothermal equation

of state for description of the flow. The results indicate that an approximate stationary flow pattern is rapidly established across the entire tube, with the density and pressure dropping and the flow velocity rising within the choke throat. If the downstream flow is inhibited at the outlet extreme of the tube, a pressure drop of about 20% occurs across the choke when the flow reaches an approximate steady state. If, on the other hand, the flow is not inhibited downstream, the pressure drop reduces to about 13% or less. The flow across the choke throat remains subsonic. We compare the results with experimental data.

Poloidal-Toroidal Decomposition in Cylindrical von Karman Flow

FM6S_10921
Tue • 14:35 • 306

Piotr Boronski, Laurette Tuckerman
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The goal of the VKS experiment is to observe a laboratory-scale dynamo effect in the cylindrical von Karman flow. Because there exists at present no complete numerical treatment of this configuration, we have developed an efficient three-dimensional pseudospectral code capable of solving the Navier–Stokes equations in a finite cylindrical geometry, to be coupled with the Maxwell equations. A poloidal-toroidal decomposition insures that fields are divergence-free by construction which is very important for applications to the magnetohydrodynamic case. The cylindrical domain is treated by using in the radial direction a polynomial basis which is regular at the domain axis. The satisfaction of high-order and/or coupled boundary conditions is guaranteed by the influence matrix method.

Calculation of Vortical Structure Evolution Using Combined Discrete Singularity and Boundary Element Method

FM6S_10958
Tue • 14:40 • 306

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Method of discrete vortices is a powerful tool for analysis of vortical structure evolution. However the method has several disadvantages, for example, incorrect calculation of interaction of discrete vortices on small distance and large computational errors in points near the boundary. To overcome of second difficulty the combined discrete vortex and boundary element method with integration along real boundary was proposed. Discrete singularity method generalizes discrete vortex, including also discrete sources, discrete dipoles, etc. It gives an opportunity to consider more complex flows. To avoid the first problem, different regularization schemes were developed. In the present work opposite idea of using of discrete vortical dipoles together with discrete vortices instead regularization in some specific cases is applied. It gives good results for calculation of vortical sheet behind thin airfoil under small attack angle. In general case, regularization schemes and scenarios of interaction are used in the present work. Computational stability of vortical structures is considered in the present work too. It is shown that a dipole can lead to destruction of even most stable vortical structures such as vortical rings. Interactions of vortical structures and dipole-vortical structures between themselves and with solid boundaries are numerically investigated too.

Numerical Simulation of the Backward-Facing Step in a Beowulf–Class Cluster

FM6S_11456
Tue • 14:45 • 306

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This present work proposal is to present a three-dimensional numerical simulation of the classical flow over a backward-facing step problem in a very fine mesh. The in-house parallel numerical code was written in Fortran 90 and has solved the Navier–Stokes Equations discretised by the FVM and has run in a Beowulf-class cluster of PCs. The flow Reynolds number was 28000, a LES turbulence modelling technique was employed with Smagorinsky's subgrid model. Several flow properties were analyzed, that is, the reattachment length,the velocity profiles, the stream and spanwise vorticities, and the Strouhal number in several points downstream the domain. The results were compared against the literature.

Development and Paractical Application of WENO Schemes for Compressible Fluid Flow Computations

FM6S_11485
Tue • 14:50 • 306

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Application of high-order shock-capturing schemes to numerical simulation of problems in supersonic aerodynamics is considered. Euler and Navier–Stokes solvers based on employing modern weighted essentially non-oscillatory (WENO) schemes are described. A new WENO scheme, which has an advantage when applied in general curvilinear coordinates, is constructed. A number of examples of numerical simulations of 2D and 3D shock-dominated flows with high-order schemes are given. They include shock wave propagation and diffraction, shock/shock and shock/boundary layer interaction, development of hydrodynamic instability waves in high-speed free shear flows, and the structure of imperfectly expanded supersonic jets. For some problems, high-quality numerical schlieren visualizations and interferograms are compared with experimental patterns. We demonstrate that high-order WENO schemes is a powerful tool for simulation of compressible fluid flow. They can be considered as a very promising candidate for DNS and LES of turbulent supersonic flows.

Numerical Analysis and Design Optimization of Lateral Jet Controlled Missile

FM6S_11569
Tue • 14:55 • 306

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The aerodynamic analysis and the aerodynamic optimization study have been performed for the lateral jet controlled missile system. For the numerical investigation, a three dimensional Navier–Stokes computer code (AADL3D) has been developed by incorporating the Spalart-Allmaras one equation turbulence model. The developed analysis code has been validated through several supersonic examples. The behavior of the normal force and the pitching moment characteristics have been investigated through the numerical analyses for the different jet flow conditions, angle of attacks, circumferential jet nozzle locations and spouting jet angles. The results show different behavior of the normal force and moment variation according to each parameter. Based on the results of the aerodynamic analyses of the supersonic flow around lateral jet controlled missile for various jet and flow conditions, pitching moment and normal force are selected as the objective and constraint functions, and the flight Mach number, the angle of attack and the spouting lateral jet angle are selected as the design variables. By implementing the genetic algorithm for the global optimum, and the response surface method, the design optimization of the lateral jet controlled missile has been performed to find out the most effective flight conditions for the missile control.

Numerical Prediction of Energy Dissipation in Condensing

FM6S_11576
Tue • 15:00 • 306

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In the presented work the analysis of losses (e.g. kinetic energy and entropy loss coefficients as well as an expansion line) in steam expansion flows will be carried out. The adiabatic flow, the flow with homogeneous and with heterogeneous condensation will be considered. The influence of the condensation phenomenon and steam impurity on the losses will be analyzed. The calculations of the steam flow through the Laval nozzle and LP steam turbine stages is going to be presented. The flow is governed by means of RANS equations. For modelling of the steam properties the IAPWS-IF'97 formulations are implemented. It allows to calculate the losses and expansion line for steam flow correctly. The set of governing equations is closed by a real gas equation of state. The numerical computations will be performed using an in-house multi-block code for the analysis of 3-D viscous, turbulent, condensing flows of ideal and real gas and commercial CFD code TascFlow.

Numerical Computation of Compressible Viscous Flow Through a Male Rotor-Housing Gap of Screw Compressors

FM6S_11702
Tue • 15:05 • 306

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Gas leakage is a phenomenon that has a lot of different features, many of significant importance. Compressor engineers are mostly interested in estimation for the mass flow rate. It has a great influence on the compressor performance, especially with regard to its internal efficiency. Therefore it is necessary to make reasonable estimates for mass flow rates or to

investigate the details of the leakage flow. The aim of this contribution is to show the numerical computation of compressible viscous fluid flow through a 2D model of the male rotor-housing gap in the srew compressor. Numerical solution of the nonlinear conservative system of the compressible Navier–Stokes equations is obtained by means of the cell-centred finite volume formulation of the explicit two-step TVD MacCormack scheme proposed by Causon on a structured quadrilateral grid. The viscous part is approximated by using a finite volume version with central differences.

Fast Numerical Method for the Boltzmann Equation on Nonumiform Grids

FM6S_11763
Tue • 15:10 • 306

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A new numerical method for the solution of the homogeneous Boltzmann equation on nonuniform grids is developed. The collision operator is written using the Fourier transform. This formulation and a special new discretization of the gain part allow for the fast numerical computations on nonuniform grids in velocity space. The computational cost of the algorithm is $O(N_v) + O(\sigma N^6 \log N)$ for a general model of interaction. Here N_v is the number of velocity points, N denotes the number of modes in the Fourier domain and $\sigma < 1$ is a small constant depending on the discretization. The results of some numerical test are presented.

Computation of Viscous Vortices with Fully Meshless Method

FM6S_11937
Tue • 15:15 • 306

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Computing the interaction of viscous vortices using traditional CFD methods is severely hindered by numerical diffusion. In general, the vortices diffuse too rapidly to properly capture the details of their interaction with each other or with structures. To deal with this problem, a fully mesh-less method has been developed, which is characterized by non-diffusive truncation errors. It is a new formulation of the vortex particle method, using the core spreading scheme for viscous effects, and a mesh-less spatial adaption technique based on radial basis function (RBF) interpolation. Numerical experiments have demonstrated increased accuracy in comparison with the standard approach of remeshing with high-order kernels. Validation has been performed using a quadrupole-perturbed Gaussian monopole, which exhibits a quasi-steady tripole state that decays in the viscous time scale. The method has been implemented in parallel using the PETSc library, and a new application is being developed to study the viscous interaction of co-rotating vortices.

Dirichlet/Dirichlet and Neumann/Neumann Parallel Non-Overlapping Domain Decomposition Method

FM6S_12076
Thu • 14:30 • 307

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The paper presents solution of two-dimensional Helmholtz equation using spectral non-overlapping domain decomposition method on parallel computer. The Chebyshev tau method was used for discretization of the subdomain problems, and the diagonalization technique was used for solution of local system of equations. The novel feature of the paper consists of solution of the 2-D Helmholtz equation using the new iterative method. Efficiency of the method proposed was compared to the other iterative methods i.e. Zanolli as well as Louchart and Randriamampianina algorithms. It was shown that using the method proposed a smaller number of iterations was needed to obtain converged solution compared to the other iterative schemes if higher number of subdomains was considered. The improvement is mainly caused by solution of the common system of equations at the correction stage of the iterative process, which take into account the patching conditions at all interfaces.

Distributed Simulation of Transitional Nanoscale Channel Flows by a DSMC Method with an Enhanced Reliability.

FM6S_12248
Thu • 14:35 • 307

Vladimir P. Memnonov
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Vladimir P. Memnonov St.Petersburg State University, Math. and Mech. Dept., St.Petersburg, Russia Transitional flows in very narrow channels were studied in the paper with the help of distributed simulation by DSMC method on several

parallel clusters for reduction of statistical scattering in order to resolve low flow velocities. By employment additionally a coupled at the boundaries finite element solution of the Navier–Stokes equations for the outer flow important features of a complex channel flow, which models the flow in Winchester-type disc storage devices, were established. The two new developed fault tolerant algorithmic procedures for diminishing bad consequences of possible node and link failures in this complicated computational systems essentially increased reliability of such distributed simulations and were applied to a filter problem which was simulated with the help of a metacomputing scheme.

CFD Methods in Industrial Applications Vehicle External Aerodynamics and Aerodynamic Interaction of Moving Vehicles

FM6S_12337
Thu • 14:40 • 307

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The paper deals with the properties of 3-D flow around a moving vehicle during the aerodynamic interaction with its environs. The models of rail vehicles intended for the public mass transport (fast trains, sub-urban trains units, underground and municipal railways trains) are simulated. Driving speeds of those vehicles are supposed in the range of 80–220 km/h. The computer simulations contribute to understanding and summarising the complex description of aerodynamic load of rail vehicles during various running regimes and situations, important aerodynamic effects occur during the passing of vehicles and/or under side wind. Simulations are carried out by means of commercial CFD code. Aerodynamic load is modelled as a special boundary condition in form of aerodynamic effect models. Those models describe (and to calculate) aerodynamic and interaction effects onto vehicles during passing and under side-wind and include time-dependent and space-dependent values of load. The studies allow to increase efficiency and accuracy of computer simulations.

A Computational Model for the Si/C/N Nanopowder

FM6S_12356
Thu • 14:45 • 307

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The growing interest in the synthesis of Si/C/N nano-sized powders can be further highlighted by the fabrication of materials that offer a large scale of properties. The powder must have a high purity and specific morphological characteristics depending strongly on the employed experimental process. Several methods are employed to produce ceramic powders from vapour phase reactants. These include flows through a tube furnace, Rf-heated and plasma arc. The presence of hot walls in these methods is undesirable since they can act as heterogeneous nucleation sites and sources of unwanted contamination. Furthermore, the thermal profiles within the reaction zone of these methods are often complex and give rise to non-uniform nucleation and growth, inducing irregular characteristics. To overcome this problem a new method was recently developed in the Massachusette Institute of Technology. An infrared CO2 laser beam is used to heat gas by absorption of radiation. The principle reason for this is due to the small size of the reaction zone minimizing the contamination area. In this work laser-heated gas-phase synthesis process is considered. The laser beam and gas stream interacts in orthogonal direction (cross flow). The precursor gas is continuously injected into a reaction chamber, which after reaching a threshold temperature of approximately 600°C reacts and decomposes thermally. The central inner jet is bounded by a coflowing annular inert gas (argon). It is interesting to note that the laser energy is not directly used to heat the argon gas. This is due to the fact that argon does note absorb the line emitted by the laser. The aim of this investigation is to develop an improved fundamental understanding of the heat and mass transfer during the synthesis of nanopowder ceramics. One aspect of this understanding consists to, determine 3D distribution of temperature and species, coupled to the fluid flow in the reactor. A numerical model is developed and simulations are conducted by using CFX5 CFD software based on finite volume approximation. It was also hoped that this study would allow a better understanding for the particles formation, in order to achieve the ultimate goals of an ideal powder synthesis.

Numerical Error Evaluation for Tip Clearance Flow Calculations in Centrifugal Compressor

FM6S_12510
Thu • 14:50 • 307

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This paper focuses on the evaluation of numerical errors due to grid resolution. Since rigorous numerical error assessment requires important computational resources, an attempt is made to obtain a numerical solution which is locally mesh independent. The proposed method is applied to the tip clearance flow region of a centrifugal compressor solution obtained with a the commercial RANS code Fine/Turbo. First, the design of experiment method is used to identify mesh parameters having a dominant influence on the tip clearance flow. The results ensure that refining the computational grid only in the tip region is sufficient to obtain a "local benchmark". The computed solutions on the refined grids then show a qualitative convergence of the shroud friction coefficient. Then, the different solutions allow a numerical error evaluation for the friction coefficient on the shroud surface. Thus, the main advantage of the proposed method is an affordable way to define local mesh requirements, that will still have to be fulfilled when global independence is the concern.

Simulation of a Viscous Flow Past a Three Dimensional Obstacle Using Vortex Particles

FM6S_12565
Thu • 14:55 • 307

Piotr Duszyński, Marta Poćwierz, **Andrzej Styczek**, Jacek Szumbarski
Dept. Aerodynamics, WUT, Warsaw, Poland

The new formulation of the lagrangian vortex method for viscous flow simulations is presented.The vorticity field is approximated by the large ensemble of vortex particles. These objects move with the fluid and perform the random motion modeling diffusion of the vorticity. The contribution of each particle to the vorticity field is exactly divergence-free. The no-slip boundary condition is ensured by auxiliary potential components and the vortex induction. At each time, two classes of the particles exist: those created in the past and the new particles introduced on the boundary to cancel tangent component of the velocity. Details of the method, the numerical implementation and sample results concerning the velocity and vorticity patterns, aerodynamics forces and pressure field are presented.

Investigation of WENO Scheme for 3D Unstructured Grids

FM6S_12618
Thu • 15:00 • 307

Jerzy Majewski, Robert Wieteska
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The paper presents a comparison of WENO (Weighted Essentially Non Oscillatory) reconstruction applied within two common approaches to Finite Volume Method (FVM), i.e. Cell Centered (CC) and Vertex Centered (VC) method, which are used for simulation of compressible inviscid flows. The subject of our interest was the reconstruction algorithm based on WENO scheme for 3D meshes.This kind of reconstruction allows keeping high order also in the vicinity of strong discontinuities (shock waves) without introducing oscillations. The CC and VC methods were subject to comparison in order to assess their quality with regards to accuracy of the scheme and to the computational cost. The CC method was found producing more accurate results than VC method but it was obtained at higher computational cost. The detailed analysis will be presented for 3D supersonic flow in a chanel and for the Onera M6 wing.

Numerical Study of the Dynamics of Coalescence of Two Bubbles of Air in a Water Column at Rest

FM6S_12985
Thu • 15:05 • 307

Jean M. Martinez, Xavier Chesneau, **Belkacem Zeghmati**
Université de Perpignan, France

The research of optimization, dimensioning or the implementation of a hydraulic system often reveals nondesired phenomena such as early erosion, the loss of output or the irregularity of the flows due to the presence of bubbles. The experimental study of the flows with bubbles being very complex, it appears paramount theoretically to analyze the transfers which are carried out with the interface of one or more bubbles of air and their medium. We present a numerical study of the dynamics of coalescence of two bubbles of air in a water column at rest. We used the PLIC-VOF method developped by Hirt & Nichols to analyse the change of topology with the surface tension force variation. The resolution of the Navier–Stokes equations is carried out by using a Projection method with a significant pression dependance in time. The use of a time pressure correction permit to change initial pressure and the behaviour of a rise bubble is more accuracy well predicted. For the study of coalescence between the rises of two bubbles we developped a new approach of the calculation of the voluminal force of surface tension, as well as an evolution of the resolution of the equation transport of the function of phase f(x, y, t). The results are presented in the form of curves and succession of images and show a very good behavior of the algorithms in front of the tests of validation as well as a better estimate of the force of surface tension. The evolution of the contour and the fields speed room of two bubbles in interaction is modelled and presented in the form of a succession of images representing the approach and coalescence in 2d of two bubbles for different Reynolds number and of Jump.

FM7

Convective phenomena

Chairpersons: G. De Vahl Davis (Australia), K. Zhang (UK)

Cellular Compressible Magnetoconvection: a Machanism for Magnetic-Field Amplification and Structuring

FM7L_10306
Tue • 17:00 • 226

Alexander V. Getling[1], Wolfgang Dobler[2]
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The amplifi cation and structuring of magnetic fi eld by cellular compressible magnetoconvection in a plane horizontal fluid layer heated from below is studied using numerical simulations. The cases of both horizontal and inclined initial magnetic fi elds are considered. A bipolar structure superposed with fi ner details (which is typical of solar magnetic regions) develops from a horizontal initial fi eld. If the initial fi eld is inclined, such a structure coexists with a strong unipolar concentration of magnetic flux. Convection cells form such structures over a fairly wide region in parameter space, and this property seems to be inherent in the very topology of the cellular fbw. These new effects are complemented with the well-studied sweep of the vertical magnetic fi eld to the cell boundaries and with a strong concentration of the horizontal magnetic fi eld near the bottom boundary of the layer (so-called topological pumping)

Large-Scale Semi-Organized Structures in Geophysical Turbulent Convection

FM7L_11053
Tue • 17:20 • 226

Tov Elperin[1], Nathan Kleeorin[1], **Igor Rogachevskii**[1], Sergej Zilitinkevich[2]
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(2) *Uppsala University, Uppsala, Sweden*

A new mean-fi eld theory of turbulent convection is developed by considering only the small-scale part of spectra as turbulence, whereas the large-scale part is treated as a mean fbw, which includes both, regular and semi-organized motions. In a shear-free turbulent convection the theory predicts the convective wind instability which causes formation of large-scale semi-organized fluid motions in the form of cells. The theory predicts also the convective-shear instability in a sheared turbulent convection which results in appearance of large-scale semi-organized convective rolls. This instability can cause also a generation of helical convective-shear waves which propagate perpendicular to convective rolls. The increase of shear promotes excitation of the convective-shear instability. Predictions of this theory are in a good agreement with the modern knowledge about the atmospheric convective boundary layer and observed semi-organized large-scale structures: three-dimensional Bénard-type convective cells (cloud cells) and convective rolls (cloud streets) stretched along the mean wind.

Experimental Studies of Planetary Core Convection and Dynamo Processes

FM7L_11440
Tue • 17:40 • 226

Jonathan M. Aurnou
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The magnetic fi elds of the terrestrial planets are generated by convectively-driven dynamo processes occurring within the electrically-conductive fluid regions of planetary cores. Present experimental approaches are focusing on two complementary methods for understanding core dynamo processes: mechanically-driven dynamo experiments and buoyancy-driven convection experiments. In the mechanically-driven experiments, energy is pumped into the velocity fi eld via impellers or pumps. Although the fbws produced are not necessarily geophysically accurate, dynamo action may result, thereby producing a system of both physical and geophysical interest. In buoyancy-driven rotating magnetoconvection experiments, energy is pumped predominantly into the externally-imposed magnetic fi eld. The buoyancy-driven fbws, acted upon by strong Coriolis and Lorentz forces, are interesting analogues to core convection; the velocities, however, are far too small to generate dynamo action. Here we will review the latest mechanically-driven dynamo experiments and then discuss the results of buoyancy-driven rotating magnetoconvection experiments relevant to core convective processes.

Sea Convective Motions Driven by Random Buoyancy Inputs

FM7L_11972
Tue • 18:00 • 226

Vanda Bouché
Physics Department, "La Sapienza" University, Rome, Italy

A numerical and analytical model for dynamics of dense water plumes in a homogeneous and a stratified sea initially at rest, suddenly perturbed on the air-sea surface by a series of space and time random buoyancy inputs localized on small space and time scales, due to strong transverse winds, is presented here. The conditions for their generation are identified. A Lagrangian rapresentation allows the time evolution for a set of perturbed by the Coriolis force, single, not entraining, plumes, able to carry down dense water mass, to be obtained. Their separate evolution till the initial collective rotating chimney formation phase is observed. Scaling laws depending on the surface air-sea interaction statistics involved and on the forcing time scale, are examined; their dependence on buoyancy fluctuations more than mean values is shown.

Thermochemical Convection in Two Superimposed Miscible Viscous Fluids

FM7L_12126
Tue • 18:20 • 226

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Marginal stability analysis and laboratory experiments have been performed to investigate thermal convection in two superimposed layers of miscible fluids. Four dimensionless numbers characterize the dynamics of the system: the viscosity ratio, the layer depth ratio, the Rayleigh number and the buoyancy number, ratio of chemical stabilizing density anomaly and thermal destabilizing density anomaly. Two different regimes are observed: an oscillatory doming regime for small B, where the interface deforms in large domes moving up and down quasi-periodically; a stratified regime for large B, where convection develops in the two superimposed layers, separated by a relatively undeformed interface. The critical buoyancy number determined by the marginal stability analysis agrees well with experimental results. We also propose scaling laws for domes direction of spouting, size, speed and periodicity. Such an experimental model has direct implications for the Earth's mantle dynamics: the oscillatory doming regime could explain the present-day observations.

Nonlinear Convective Patterns in Spherical Rayleigh–Bénard Systems

FM7L_12168
Tue • 18:40 • 226

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Nonlinear thermal convection in a spherical fluid layer in the presence of spherically symmetric gravity, spherical Rayleigh–Bénard convection, is investigated. At the onset of spherical Rayleigh–Bénard convection, there exists the (2l+1)-fold degeneracy of the linear solution, where l is the degree of a spherical harmonics. Nonlinear convection is studied through fully three-dimensional numerical simulations. Several new spherical patterns of nonlinear convection are found. In particular, a steadily drifting pattern in the form of a single giant spiral roll covering the whole spherical surface without defects is discovered for various Prandtl numbers for the first time.

Visualization of the Flow Structure and Temperature Field in the Region of Mixed Convection

FM7L_12173
Thu • 09:30 • 315

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The results of experimental simulation of mixed convection in the process of single-crystal growth by Czochralski method are presented. Visualizations were done by dispersed encapsulated liquid crystals, which enable simultaneous measurements of the velocity and temperature fields. Experimental analysis was done for the cylindrical vessel kept in the isothermal conditions. The temperature difference occurred between the rotated crystal simulating ring and the melt. The experimental conditions depended on the non-dimensional parameters like Prandtl number, Reynolds number and Grashof number. The velocity fields showed appearance of vertical structures, whose number, shape and movement depend strongly on the Reynolds number. Velocity vectors maps are compared with the isotherms.

Large Eddy Simulation of Rayleigh–Bénard Convection in an Infinite Fluid Layer

FM7L_12220

Thu • 09:50 • 315

Anne Sergent(1), P. Joubert(2), P. Le Quere(1)
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(2) *LEPTAB, Université la Rochelle, France*

A numerical study of Rayleigh–Bénard convection in an infinite fluid layer (Pr=0.71) is performed using large eddy simulation (LES) of the Navier–Stokes equations with the Boussinesq approximation. We present results in a 'hard turbulence' regime ($2.10^5 < Ra < 2.10^9$). The LES modelling uses the mixed scale diffusivity model, that we have originally developed in the case of the differentially heated cavity. This original subgrid diffusivity model is based on its own time-scale, so that the Reynolds analogy is not needed to be assumed. The main observation is the ability of the computations to reproduce the 2/7 scaling behavior over a large Ra range ($2.10^5 < Ra < 2.10^8$) despite of the LES modelling. Moreover the regime transition towards the 'ultra-hard regime' is observed at $Ra = 2.10^9$.

Thermal Buoyancy Convection in Systems with Deformable Interfaces

FM7L_12344

Thu • 10:10 • 315

Dmitriy V. Lyubimov(1), Nicolay I. Lobov(1), Tanyana P. Lyubimova(2),
Nikita A. Ospennikov(1), Sergey V. Shklyaev(1)
(1) *PSU, Perm, Russia*
(2) *ICMM UB RAS, Perm, Russia*

Thermal convection in a two-layer system with deformable interface heated from below is studied. Generalized Boussinesq approximation allowing correct accounting for the interface deformations in the case of fluids with close densities is used. In the framework of linear stability theory long wave and cellular perturbations are studied, parameter ranges where different perturbations are most dangerous are found. Non-linear amplitude equation describing long wave perturbations with large amplitude is obtained and analyzed. Numerical investigation of developed regimes of convec-tion is performed by the Level Set method. The situations are discovered when the development of instability results in the splitting of one of the layer into the drops.

Bifurcation of Steady Thermo-Capillary Flows of a Binary Mixture

FM7S_10322

Thu • 14:30 • 219A

Vladimir A. Batischev
Rostov State University, Russia

We study a branching of axially-symmetric thermo-capillary flows of a binary mixture in a Prandtl's boundary layer on a horizontal rigid wall. We reduce the governing system to a boundary-valuer problem for ODE system. We get a number of main regimes numerically and identify the parameter domain where the main regime is not uniquer. We examine the branching of main regimes with the use of branching equations. The bifurcation curves were found numerically. We show that a generic bifurcation creates two secondary counter-rotating flows, while in the case of degeneration two-side bifurcations generate four secondary regimes. The secondary regimes were constructed analytically in the small neighborhoods of the bifurcation points and continued numerically on the exterior of the neighborhoods.The study was supported by RFBR, grant 02-01-00226.

Scaling Laws for Thermal Convections

FM7S_10438

Thu • 14:35 • 219A

Martin P. King(1), M. Wilson(2)
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We begin with the derivation of various scaling laws for Rayleigh–Bénard convection using a combination of dimensional considerations and phenomenological models in the spirit of Castaing et al(J. Fluid Mech., 1989). Other than being simple, these models also offer an intuitive understanding of the connection between certain flow behaviours and the corresponding scaling laws. Castaing et al only applied their model to obtain the $Nu \sim Ra^{2/7}$ scaling. We show that this model, with some minor changes, can also produce other scalings which have been derived using more sophisticated methods and measured recently in experiments. Similar techniques are then applied to the analysis of heat transfer in an enclosure with an inlet and an outlet for cooling air flow. The results are summarised in a regime diagram delineating different types of convection and correlation scaling. The similarities between these with heat transfers from a flat plate will be highlighted. It will be thus shown that the method can be applied to both internal (e.g. in a sealed or unsealed box) and external (e.g a flat plate) flows.

On Features of Magnetic Convection in Ferrofluid

FM7S_10538

Thu • 14:40 • 219A

Aleksandra A. Bozhko, Ekaterina N. Beresneva, Gennady F. Putin
Perm State University, Perm, Russia

Magnetically driven convection in nonconducting fluids is actively investigated last years due to uses in the field of materials processing including crystal growth from protein solution and insulating paramagnetic melts. However, the pondermotive forces exerted in natural media by typical magnets are very weak. Therefore ferrofluid – colloidal suspension of monodomain particles – well approaches for modeling of magnetoconvection.The experiment was performed to examine the influence of external homogeneous magnetic field on the convection instability, heat transfer and flow patterns in ferrofluid. Both driving force connected with a spatial variation in magnetization and comparatively weak suppressive force arising due to interaction between applied field and distortions of magnetization induced by flow were studied. It was revealed that the competitive action of density gradients of thermal and concentration nature results in spatiotemporally chaotic convection. Concentration heterogeneities arise due to settling of magnetic particle aggregates in gravity field.

Multiplicity of Patterns in Cylindrical Convection

FM7S_10914

Thu • 14:45 • 219A

Katarzyna Boronska, Laurette Tuckerman
LIMSI-CNRS, Orsay, France

The experiments of Hof, Mullin and Lucas on Rayleigh–Bénard convection in a cylindrical system are simulated numerically using a pseudospectral three-dimensional code. We confirm that for their parameter values, there exist multiple stable solutions. Starting from a perturbed conductive state, we obtain different final patterns, depending on the Rayleigh number. We then use these flows to initialize the simulations for other Rayleigh numbers. In this way we obtain many different stable solutions for the same Rayleigh number – two, three or four parallel rolls, a three-spoke pattern and even an axisymmetric state.

Natural Convection for Anomalous Density Variation of Water – Numerical Benchmark

FM7S_11160

Thu • 14:50 • 219A

Tomasz Michałek[1], Tomasz A. Kowalewski[1], Bozidar Šarler[2]
(1) *Institute of Fundamental Technological Research PAS, Poland*
(2) *Nova Gorica Polytechnic, Nova Gorica, Slovenia*

A steady state natural convection in a differentially heated cavity for temperatures in a vicinity of the freezing point is used to investigate and compare performance of four different numerical methods: finite differences, finite volume, finite elements and mesh-free diffuse approximation method. A primary aim of the exercise is to define a new numerical benchmark solution for natural convection problems, which includes challenging configuration of strongly non-linear buoyancy term. This configuration is used to test performance of two popular commercial codes (Fluent and Fidap) and to compare them with two "classical" finite difference codes and the new promising mesh-free implementation.

3D Flow Transition Behind a Heated Cylinder

FM7S_11251

Thu • 14:55 • 219A

Maosheng Ren, **Camilo C.M. Rindt**, Anton A. van Steenhoven
Eindhoven University of Technology, the Netherlands

In the present study the 3D transition behind a **heated** cylinder subjected to a horizontal cross-flow is investigated at low Reynolds numbers: $Re = O(100)$. For a Richardson number $Ri \geq 1.0$, the 3D transition manifests itself in the form of escaping thermal plumes, which have a spanwise distance of around 2d (d is the cylinder diameter). To understand the flow structures observed from the experiments, Spectral Element calculations are carried out, providing more detailed insight into the occurrence of the 3D transition. For $Re = 85$ and $Ri = 1.0$, pairs of counter-rotating vortices appear close behind the cylinder. The counter-rotating vortices also have a spanwise distance of around 2d. A detailed study on the origin and evolution of the counter-rotating vortices in the near wake and the thermal plumes in the far wake will contribute to a better understanding of 3D transition behind heated bluff bodies.

Penetrative Convection in Stratified Fluids: Velocity Measurements by Image Analysis

FM7S_11673
Thu • 15:00 • 219A

Antonio Cenedese, Massimo Miozzi, Monica Moroni
DITS-University of Rome, Rome, Italy

Models of the structure of stratified oceans and lakes as well as the atmosphere use bulk parameters to predict a variety of processes that control the ecology of natural systems. The success of such approach in predicting even small scale phenomena has not a parallel in modeling turbulent. Particularly the interaction of convective turbulence and the density interface is not well understood. Analytic solutions for such turbulent motion are not available and there appears to be little hope of finding such solutions in the near future. The present experiments simulate the deepening of a convective mixed layer in a stratified lake. LIF visualizations, temperature measures and velocity field detection through Particle Tracking Velocimetry and Feature Tracking were employed to examine the effect of convective-driven perturbation at the mixed layer when no vertical shear occurs. The model used for laboratory experiments is a tank with glass sidewalls of dimension $40\times40\times41$ cm^3 in the two horizontal and vertical directions respectively. The working fluid is distilled water. Pollen is used as passive tracer. A stable stratification, e.g. a positive vertical temperature gradient, is generated by means of two connected tanks. After being stratified, the chamber is heated from below, to simulate the solar radiation effects and to cause penetrative convection. Temperature profiles are measured inside the tank by mobile thermocouples.

Experimental and Numerical Studies of Convection Flow in a Cylindrical-Conical Fermenting Tank

FM7S_11905
Thu • 15:05 • 219A

Heiko Meironke, J.A. Szymczyk
FH Stralsund – Department of Thermofluiddynamics and Turboma Machines, Straslund, Germany

In this paper the experimental and numerical investigations of the convection flow in a real cylindrical-conical fermenting tank of beer manufacturingare described. The experimental investigations in a cylindrical-conical fermenting tank was conducted using a two-dimensional ultrasonic Doppler velocity measurement method to measure the flow field during a real fermentation process in a opaque wort. In a further investigations the fermentation process was simulated with a model-fluid by heating and cooling the outside of the fermenter. In this work the proceeding of measurements, the experimental-setup and the measured flow fields are presented. In a numerical study the convection flow of the simulated fermentation process was analysed. Comparison of the numerical results with the experimental data of simulated and real flow shows for the first time a good prediction of the simulated flow of the model-fluid.

The Influence of Translational Vibration of Circular Polarization on Fluid Convection Stability and Flow Patterns

FM7S_12267
Thu • 15:10 • 219A

Aleksander A. Kozlov, Igor A. Babushkin, Gennady F. Putin
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Experiments were performed to examine the influence of nonlinear vibrations on thermogravitational convection. The results of the experiments indicate that the mentioned force field essentially influence on stability of mechanical equilibrium and the structures of liquid currents. A number of regimes of convection, e.g. rolls, cells and zipper-state were observed.

Natural Convection of Pseudoplastic Fluids

FM7S_12708
Thu • 15:15 • 219A

Tomasz Strek, Anita Uscilowska
Poznań University of Technology, Poznań, Poland

The numerical experiment of the transient natural convection in two-dimensional cavity with non-Newtonian fluid is presented. In non-Newtonian viscosity models it is assumed that the laminar viscosity can be expressed as a continuous function of the strain rate. The present work is based on the power law model, which is the most popular non-Newtonian viscosity models. The results of numerical experiments of natural convection in two-dimensional cavity with Newtonian or non-Newtonian are presented.

Convective Phenomena in Rotating Annuli Heated on Periphery

FM7S_12730
Thu • 15:20 • 219A

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Results of time-accurate numerical simulation of 2D and 3D unsteady buoyancy-induced convection in rotating annular air-filled cavities heated on the periphery and cooled at the inner radius are presented. The cavity radial aspect ratio is equal to 0.35, the centrifugal Rayleigh number is ranged from 5E04 to 5E07. It has been established that at the Rayleigh numbers ranged from 2E05 to 2E06 stable flow regimes with two, four or six vortices can be obtained with the 2D formulation for an unlimited annulus. In a 3D configuration with two bounding adiabatic discs (axial ratio is equal 0.34), the two-vortex regime is inhibited, and possible regimes with four-vortex or six-vortex large-scale structures manifest a pronounced chaotic behavior at Ra>1E06. For the 3D configuration, the Nusselt numbers are by 3 to 5% lower that for correspondent 2D solutions. The Nusselt numbers computed are in a good agreement with the experimental correlation.

On the Rayleigh–Bénard Problem in the Continuum Limit

FM7S_12850
Thu • 15:25 • 219A

Avshalom Manela, Itzchak Frankel
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The transition to convection in the Rayleigh–Bénard problem at small Knudsen numbers is studied via a linear temporal stability analysis of the compressible ‘slip-flow’ problem. No restrictions are imposed on the magnitudes of temperature difference and compressibility-induced density variations. The dispersion relation is calculated by means of a Chebyshev collocation method. The results indicate that occurrence of instability is limited to small Knudsen numbers (Kn<0.03) as a result of the combination of the variation with temperature of fluid properties and compressibility effects. Comparison with existing DSMC and continuum non-linear simulations of the corresponding initial-value problem demonstrates that the present results correctly predict the boundaries of the convection domain. The linear analysis thus presents a useful alternative in studying the effects of various parameters (e.g. temperature ratio) and models of molecular interaction on the onset of convection, particularly in the limit of arbitrarily small Knudsen numbers.

The Influence of Vibration on the Onset of Marangoni Convection in Horizontal Fluid Layer

FM7S_13005
Thu • 15:30 • 219A

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The influence of oscillations of hard or “soft” (free undeformable) wall on the onset of Marangoni convection in horizontal layer of viscous incompressible fluid with deformable boundary is considered. The oscillations are assumed to be translational and harmonical with frequency ω and amplitude a. Two cases were studied: 1) oscillations of arbitrary direction, large frequency ω and small amplitude $a = O(1/\omega)$; 2) vertical oscillations of finite frequency and amplitude. In the first case by application of averaging method it was shown that oscillations of any other direction than longitudinal smoothen the free boundary. In the second case the stability analysis of the quasiequilibrium was carried out utilizing Floquet theory. Continuous fractions method was applied to obtain the dispersion equations for computing the critical parameter values for main types of loss of stability – synchronous, subharmonic and quasiperiodic. Neutral curves $Ma(k,\omega)$ (k is the wave number) were computed for the case of weightlessness.

Air Convection in a Cubic Enclosure with Laterally Shifted Electric Coil without a Gravity Field

FM7S_13022
Thu • 15:35 • 219A

Tomasz Bednarz(1), Toshio Tagawa(1), Masayuki Kaneda(1), **Hiroyuki Ozoe**(1), Janusz S. Szmyd(2)
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(2) *AGH University of Science and Technology, Poland*

Numerical computations were carried out for magnetizing convection of air in a cubic enclosure with laterally shifted coil at various elevations. Air is known as a paramagnetic substance and its magnetic susceptibility varies with temperature due to the Curie’s law and the convective motion is driven by the magnetic buoyancy force. Magnetic field was generated by an electric current through a coil which was laterally shifted in the X direction and placed at various elevations Z_c. The heat transfer rate was mostly enhanced for the coil shifted horizontally to have a close location of the coil with the hot wall. This work shows that character of convection and the average Nusselt number depends strongly on the horizontal position of the coil and the heat transfer rate is controlled by the magnetic field.

FM8

Drops and bubbles

Chairpersons: J. Eggers (UK), A. Prosperetti (USA)

Theoretical Studies of Flow-Induced Coalescence

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FM8L_11289
Thu • 11:00 • 327

We study the dynamics of collision and film drainage that leads to coalescence of two drops in a flow. The objective is comparison with experimental observations from our laboratory. The basis is to study head-on collisions with a time dependent force along the line of centers of the drops that varies with time in the same way that the force along line of centers varies with time in a "normal" glancing collision. Experiments carried out with a computer-controlled version of the 4-roll mill demonstrate that the coalescence process in such a head-on collision is identical to that in the corresponding glancing collision for low capillary numbers. The focus on head-on collisions allows a much greater degree of spatial resolution than is possible in a fully 3D collision. Two kinds of theory are discussed: thin-film theory based on the asymptotic limit Ca $\ll 1$; and boundary integral calculations.

Atomization of an Undulating Liquid Sheet

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FM8L_11317
Thu • 11:20 • 327

This paper presents an experimental study devoted to the understanding of break-up mechanisms of liquid sheets. The studied sheet is formed by the normal collision of a round jet on a solid rod which can oscillates vertically. The liquid expands radially in air initially at rest. A shear instability develops at the interface liquid/gas resulting in an undulated motion of the liquid sheet. Because of the velocity contrast between the liquid and the surface waves, the liquid is submitted to transient accelerations as it moves through the undulations. This situation trigs a Rayleigh–Taylor instability leading to azimuthal thickness modulations. The thickness profile governs the free rim shape and therefore the drops formation. A model including the development of both instabilities allows us to predict the sheet and drops sizes.

Evaporation-Driven Assembly of Colloidal Particles

Eric Lauga, Michael P. Brenner
Division of Engineering and Applied Sciences, Harvard University

FM8L_11330
Thu • 11:40 • 327

In a recent experiment by Manoharan et al. (2003, Science, vol. 301), a small number N of spherical particles located at the surface of a droplet self-assemble due to the droplet evaporation. Such process leads to final packings of spheres which are unique and, for N less than 11, equivalent to the minimal second moment clusters as studied by Sloane et al. (1995, Discrete Comput. Geom., vol. 14). We first use numerical simulations to reproduce the packings of Manoharan et al. We then study theoretically the packing selection problem. We show that at the smallest droplet volume below which the droplet can no longer remain spherical, the packing of spheres on its surface is unique and independent of the liquid-solid contact angle. We then use a perturbation analysis to characterize the rearrangement of the spheres at this point and we show that for N less than 18, the rearrangement of the sphere is unique and purely geometric.

Molecule Configurations in a Droplet Detachment Process of a Semdilute Xanthan Solutions

FM8L_11462

Thu • 12:00 • 327

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The detachment process of a droplet of an elastic liquid is characterized by the suppression of the pinch off finite time singularity and the formation of a cylindrical filament between the droplet and the nozzle. The flow in this filament is purely elongational. The resistance to such a flow is macroscopically described by the elongational viscosity. However, a sound understanding of the functional connection between the microscopic configurations of the macromolecules and the macroscopic flow is still missing. We present birefringence data that are taken simultaneously to the macroscopic flow measurements. By changing the ionic strength of the solvent we can tune the flexibility of our polyelectrolytic macromolecules and correlate them with the microscopic polymer configurations and the measurements of the elongational viscosity.

Numerical Simulation of Liquid–Gas Interfaces with Applications to Atomization

FM8L_11723

Thu • 12:20 • 327

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We investigate the two-phase mixing layer between high speed liquid and gas jets. This flow leads to the breakup of the interface into small droplets and is the basic mechanism in atomization processes. We use Volume of Fluid methods to investigate this flow numerically. Some recent versions of the Volume of Fluid method conserve momentum exactly, which is an advantage for the robust simulation of very small droplets. To validate the use of these methods for the computation of the instability, we have investigated in depth the linear stability theory. Good agreement is obtained between simulations and stability theory. We then report simulations of the non-linear development of the instability in 3D. We use boundary conditions that allow the study of the spatial development of the instability. The simulations show the convective character of the instability and the influence of small upstream perturbations on droplet formation.

Evolution of a Pair of Spherical Bubbles Rising Side by Side at Moderate Reynolds Number

FM8L_11911

Thu • 12:40 • 327

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The three-dimensional incompressible flow past two identical spherical clean bubbles moving side by side in a viscous fluid is studied numerically, allowing us to describe the interaction between the two bubbles over a wide range of Reynolds number and separation distance. The results enlighten the role of the vorticity generated at the bubble surface in the interaction process. When vorticity remains confined close to each bubble, the interaction is dominated by an irrotational mechanism and yields an attractive transverse force. In contrast, when viscous effects are sufficiently strong, the vorticity field about each bubble interacts with that about the other bubble, resulting in a repulsive transverse force. Using these computational results we show that, depending on their initial separation, freely-moving bubbles may either reach a stable equilibrium separation or move apart from each other up to infinity, which strongly contrasts with the conclusions of the potential flow approximation.

Cavitation Inception on Micro-particles: a Self Propelled Particle Accelerator

FM8L_11999

Fri • 11:00 • 327

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Corrugated, hydrophilic particles with diameters between $30\,\mu$m and $150\,\mu$m are found to cause cavitation inception at their surfaces when they are exposed to a short, intensive tensile stress wave. The growth of cavity and its interaction with the original nucleating particle is recorded by means of digital imaging. The growing cavity accelerates the particle into translatory motion until the tensile stress decreases, and subsequently the particle separates from the cavity. The cavity growth and particle detachment are modeled by considering the momentum of the particle and the displaced liquid. The analysis suggests that all particles which cause cavitation are accelerated into translatory motion, and separate from the cavities they themselves nucleate.

A Long-wavelength Model of Viscous Entrainment

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FM8L_12429
Fri • 11:20 • 327

When a large air bubble rises in syrup, it often leaves behind a thin trailing tendril in which air is entrained into the syrup. This is a familiar example of how viscous entrainment can create a long and slender structure on a liquid surface. We derive a simplified model of viscous entrainment in the limit when the entrained fluid is far less viscous than the entraining fluid. Results suggest there exists a class of macroscopic conditions which allow local, scale-invariant entrainment dynamics, thus raising the possibility of that infinitely thin liquid spouts in the continuum model are realizable in practice.

Lift force on Bubbles and Particles in a Rotating Cylinder

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FM8L_12769
Fri • 11:40 • 327

We report on lift and drag coefficient measurements of bubbles and particles in a vortex flow. The Strouhal number Sr and Reynolds number Re are $0.1 < Sr < 1$ and $0.01 < Re < 100$ based on the typical bubble radius R_b about 1 mm. An increased drag is found in accordance with numerical experiments in linear shear flow. Negative lift coefficients are found for $0.1 < Re < 3$.

Low-Reynolds-Number Motion of a Drop Beween Two Parallel Plane Walls

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FM8L_12741
Fri • 12:00 • 327

The motion of a deformable drop between two parallel plane walls in Poiseuille flow at low Reynolds number is examined using a novel boundary-integral method. Instead of the more commonly employed free-space Green's function, the Green's function for a point force between two infinite plane walls is utilized, which permits direct incorporation of the wall effects without discretization of the walls. Three-dimensional results are presented for neutrally-buoyant spherical and deformable drops of arbitrary fluid-to-drop viscosity ratio, drop size, and position within the channel. For spherical drops, the decrease in translational velocity from the undisturbed fluid velocity increases with drop size, proximity of the droplet from one or both walls, and drop-to-fluid viscosity. For off-centerline placement of deformable drops, lateral migration trends are given as a function of capillary number and viscosity ratio.

Singular Droplets

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FM8L_13025
Fri • 12:20 • 327

We study droplets of complex fluids, having either surfactants or polymers dissolved in the fluid. We study the spreading at low Reynolds number. It turns out that both polymers and surfactants slow down the spreading. A special type of surfactants (trisiloxanes), however, leads to superspreading, in which the droplet spreads out orders of magnitude quicker than with usual surfactants. We provide quantitative explanations for the slowing down of the spreading; however, the mechanism of the speeding up remains a puzzle. At high Reynolds number, we study the impact and subsequent retraction of aqueous droplets on hydrophobic surfaces. Here, the polymer and surfactant additives slow down the retraction, leading to improved deposition. The mechanisms are however very different: the surfactantants act on the surface tension, whereas the polymers change the bulk rheology.

High-frequency Linear Viscosity of Emulsions Composed of Two Viscoelastic Fluids

FM8L_11411
Fri • 12:40 • 327

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The high-frequency linear response to an oscillatory flow is studied for an emulsion of viscoelastic droplets suspended in another viscoelastic fluid. Our analysis applies when the frequency of the imposed flow is much higher than the inverse capillary-relaxation time of the drops. However, the imposed frequency can be comparable to the inverse timescales associated with the response of the component fluids. In our approach, the complex, frequency-dependent effective viscosity of the emulsion is described using the Bergman spectral representation. It allows us to characterize the response of the system in the complex domain by a single real function, i.e. the spectral density. Moreover, the spectral representation enables construction of rapidly converging continued-fraction approximations. We find that the emulsion response is accurately described by several coefficients of the expansion. Numerical results for the spectrum and the continued-fraction coefficients are presented at different volume fractions for emulsions of randomly distributed drops.

Method for Solving Nonlinear Problems on Unsteady Free-Boundary Flows

FM8S_10580
Tue • 14:30 • 315

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A direct method of finding a flow potential of 2-D inverse boundary-value problems is proposed. The method makes it possible to construct the expressions of a complex velocity and a derivative of the complex potential defined in the parameter domain. These expressions contain in explicit form the functions determined from boundary conditions. They are the time dependent functions of the velocity modulus and the velocity angle to the boundary including the free surface. The dynamic and kinematic boundary conditions lead to a system of the integral and integro-differential equations for determination of these unknown functions. The method has been evaluated when solving the new self-similar water impact problems: vertical entry of an asymmetric wedge; oblique entry of a wedge; oblique entry of a flat plate, a liquid wedge impacting the solid wall.

Viscous Extensional Flow and Drop Break-Off Under Gravity

FM8S_11855
Tue • 14:35 • 315

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Smooth honey dripping from a spoon is an everyday example of a viscous fluid in a long filament-like extensional flow which may eventually break up into drops. Similar filament or drop forming flows are important in modern technologies including ink-jet printing, molten metal processing, polymer and glass fibre spinning, and for rheological measurement. We study here finite drops of very viscous Newtonian fluids falling under gravity in an extensional flow, starting from rest in contact with a solid boundary. We emphasise the role of initial conditions and the geometry of the original drop boundary, together with balances between forces such as inertia, gravity, viscosity and surface tension. For example, under gravity and viscosity alone, break-up occurs in finite time, but inertia makes that time formally infinite, and surface tension will further modify this conclusion. A slender-filament theory is used to illustrate these effects.

Spreading Behavior of Single and Multiple Drops

FM8S_10981
Tue • 14:40 • 315

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This paper describes experimental and numerical work relevant to the impact of single and multiple drops onto various solid substrates. The experimental methods are based on visualization techniques such as high speed cinematography and phase controlled ultra short snap shots of the impact process. The single drop spreading transients are modelled using the variational principle and a modified commercial code and they allow to obtain transient diameters, heights and profiles of the drop. Comparison between experimental and numerical results demonstrate quite fair agreement. The collision of two drops is then considered focusing on the case of one drop impinging onto another initially at rest. The preliminary experiments, performed at low enough velocities to avoid splashing, show that after coalescence of the two drops the

swelling behavior of the liquid mass is very much alike that of a single drop. These results lead to a simple model able to describe the axisymmetric collision of drops and the extension of the model to other forms of coalescence is discussed.

Bubble Wall Interaction and Bubble Pairs Motion Using Potential Flow Theory

FM8S_11026
Tue • 14:45 • 315

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In this paper the fbw of bubbles near a wall at high Reynolds and low Weber number fbws. Under this conditions bubbles can be modelled as spherical ones, and the potential fbw approach can be used. There are experiments that confi rm this approximation(Duineveld, 1995). Two cases are studied, fi rst the fbw of two bubbles moving along a same axis (colineal case), and secondly a fbw of two bubbles moving in paralel. This is equivalent to the fbw of a bubble near a wall. The velocity potential can be calculated using a series aproximation in spherical harmonics (Van Vijngaarden, 1982). Lagrange equations are used to obtain the motion of the bubbles near a wall, and graphics of the velocity and displacement are obtained. In the colineal case, the simulations showed that two bubbles in potential fbw can collide with fi nite velocity. This confi rm the fi rst aproximations made by Kumaran (1992). Then the motion of a bubble ascending near a wall is analyzed.

Locomotion of a Viscous Drop, Induced by the Internal Secretion: Boundary Effects

FM8S_11250
Tue • 14:50 • 315

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When a dissolved substance is secreted from an internal source within a drop that is embedded in an immiscible viscous fluid, concentration variations at the surface result in interfacial stress gradients that ultimately induce surface motion and the locomotion of the drop. We have studied this type of motion when the drop is located near a solid wall or non-deformable liquid–liquid interface. The cases of plane and spherical boundaries have been considered. The dependence of the drop migration velocity on the location of the source and on the separation distance between the drop and the outer boundary as well as on the physical parameters of the system is reported. The dynamics of the drop is studied in the case of a fi xed location of the source inside the drop, and in the case when it moves passively with the internal circulation.

Occurrence of Micro-Bubbles During the Coalescence of Two Bubbles

FM8S_11299
Tue • 14:55 • 315

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A new method is proposed to estimate hydrodynamic interactions among deformable gas-bubbles in a viscous liquid at low Reynolds numbers. This superposition method of Oseen's fbw fi els succeeds to estimate the approaching motions of two equal-sized gas-bubbles located vertically in series in the viscous liquid. On relation to this subject the following interesting phenomena are newly recognized by using high-speed video-cameras and microscopes: (1) an occurrence of several number of micro-bubbles during the coalescent motions of two bubbles, (2) an occurrence of micro-bubbles during coalescent motions of two bubbles between two sheets of vertically set parrarel two plates in a viscous liquid, and (3) an occurrence of several micro-water-drops and micro-bubbles in a bursting motion of a single air-bubble at water surface.

Experimental and Theoretical Description of a Rotating Liquid Jet

FM8S_11405
Tue • 15:00 • 315

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The industrial process of prilling, which is used in the manufacture of small pellets, involves liquid jets emerging out of holes on the surface of a rotating cylinder. These jets are curved because of the rotation and gravity, and breakup into droplets because of surface tension. The dynamics of a curved liquid jet is examined both experimentally and by using a mathematical model. The breakup is discussed for inviscid, viscous and non-Newtonian liquid jets, in a vacuum and in air. Convective and absolute instability is examined.

Bubble Formation in a Co-Flowing Air–Water Stream

FM8S_11448

Tue • 15:05 • 315

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The formation of bubbles in a co-flowing jet has been investigated in the present work. It has been determined that the outer shear layer caused by the difference of velocity between the outer water stream and the stagnant water of the reservoir can trigger the formation of bubbles when the outer diameter of the co-axial nozzle is not sufficiently larger than the inner one. In addition, the characteristic of an air-water stream under the assumption of infinitely large outer to inner jet diameter ratio has also been studied. Under those conditions, two different regimes were described, namely bubbling regime, characterized by a periodic bubble formation and jetting regime, characterized by a long, stable gas jet forming inside the core of the liquid. Furthermore, similar to what happens in a water hammer phenomenon, it has been shown that the bubbling regime is initially influenced by the overpressure generated by the rapid pinch-off of the previous bubble. The analytical results have been satisfactorily compared with the experimental ones.

Spreading and Retraction of Impacting Drops

FM8S_11614

Tue • 15:10 • 315

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We consider theoretically and numerically the axisymmetric dynamics of drop impacts on a hydrophobic solid surface. For reasonable Weber and Reynolds numbers the dynamics shows an initial spreading of the drop on the substrate followed by a retraction phase due to capillary forces. We perform a parametric study to investigate both capillary and viscosity influences on this dynamics. We particularly focus on the film thickness during the spreading. At early times of impact the ejected liquid lamella is determined for low Weber number by the capillary length. On the contrary for large Weber numbers we observe that the residual liquid film in the center of the impact at maximum spreading is controlled by viscous effects. The retraction dynamics is also captured and is clearly dependant on the liquid film thickness at the center. A simple Taylor-Cullick theory for receeding liquid film on solid substrate will be derived and compare to the numerical results for this hydrophobic case. More general situations with non trivial contact angle will be discussed.

Main Factors Controlling the Emulsification Process under Turbulent Conditions. Experiment and Data Interpretation

FM8S_11669

Tue • 15:15 • 315

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We present a systematic experimental study of the effects of surfactant type and concentration on the mean drop size during emulsification in turbulent flow. The electrolyte concentration is also varied to clarify the role of the electrostatic repulsion between the droplets. The experimental results are analyzed by considering the processes of drop breakup and drop-drop coalescence. We found that the drop size at high surfactant concentration is determined mainly by the equilibrium interfacial tension (which is a characteristic of the used surfactant) and by the density of power dissipation in the emulsification chamber. In this "surfactant-rich regime", the measured values of d32 are described very well by the Kolmogorov-Hinze theory of emulsification, which indicates a negligible contribution of drop-drop coalescence. In contrast, at low surfactant concentration, the mean drop size is strongly affected by coalescence. The theoretical analysis and the experimental results show that two qualitatively different cases can be distinguished: (1) For emulsions with suppressed electrostatic repulsion, the mean drop size is determined by a certain critical value of the surfactant adsorption, above which the drop coalescence is hindered. (2) In the presence of significant electrostatic repulsion, the drop coalescence and the mean drop size are governed by the electrostatic repulsion between the drops.

Water Mist Behavior as Flame Supressant

FM8S_11670

Tue • 15:20 • 315

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The present work focuses on the numerical simulation of the interaction of a water spray barrier and a premixed methane-air flame inside a closed tube. The water mist is modelled as an uniform cloud of monodispersed droplets. The principal mechanisms of interaction of the water spray against the flame are: the break-up, drag, heating and evaporation of the droplets. The work presents an overview of these models. It is analysed the behaviour of the barrier and identified the

different vaporization regimes: diffusive and boiling. The results let identify the main mechanisms of break-up from the range of variation of the Eotvos and Weber Numbers. It is compared the propagation of an adiabatic flame with the one of a flame interacting with a water mist. The efficiency of water barriers of different diameters and liquid volume fractions is analysed as a function of the propagation velocity of the corresponding perturbed flames.

On the Numerical Simulation of Two Phase Liquid-Vapor Phenomena

FM8S_11979
Thu • 14:30 • 315

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The computation of boiling phenomena raises several difficult issues, one of them being the necessity of accounting for both incompressible and compressible phases in the same computational domain. We have developed two different numerical approaches for dealing with such a situation. One of them makes use of a single pressure which has the status of a thermodynamic pressure and obeys a Helmholtz type equation. The other method is of the Low Mach number type where the pressure is split into a mean thermodynamic pressure defined in the gas phase, and an additional field which ensures mass conservation and which obeys a Poisson equation with an inhomogeneous source term in the gas. These two methods are compared in two simplified configurations consisting of an enclosure subjected to sudden heating at its walls and initially containing either solely a perfect gas or a combination of both an incompressible liquid and a perfect gas.

Level-Set Simulations of Shear Flow with Inertia Pas a Droplet Adhering to a Wall with Moving Contact Lines

FM8S_12106
Thu • 14:35 • 315

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A level-set method for the numerical simulation of incompressible two-phase flow is developed for flows with moving contact lines. The method is used to study shear flow past a two-dimensional droplet that adheres to a solid substrate. Cases with pinned and moving contact lines can be simulated. Previous work on this problem assumed Stokes flow, whereas the present method is suitable for flow with significant Reynolds number. Results were found to agree well with those published previously for creeping flow. The wake formed at intermediate Reynolds numbers is located at some distance behind the droplet, because the fluid rotates in the same direction inside the wake as inside the droplet. If the contact lines are allowed to move, the wake moves with the droplet. Results will be presented for critical dimensionless parameters, beyond which part of the droplet is sheared off.

Modelling Surface Tension Using a Ghost Fluid Technique within a Volume of Fluid Formulation

FM8S_12163
Thu • 14:40 • 315

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Ghost fluid methods (GFM) are a viable approach for imposing sharp boundary conditions on interfaces that are arbitrarily embedded within the computational mesh. All GFM to date are formulated with an interface distance function that resides within a level-set (LS) framework. Recently we proposed a technique for reconstructing distance functions from volume fractions. This technique enables the exploitation of GFM within a volume of fluid formulation for modeling an interfacial phenomenon like surface tension. Combining GFM with a volume of fluid (VOF) formulation is attractive because of the VOF method's superior mass conservation and because of the ability of GFM to maintain sharp jump conditions. The continuum surface tension force (CSF) method, however, has the propensity to produce smooth jump. In the following, the combined VOF-GFM and more classical VOF-CSF formulations are compared and contrasted. Static and dynamic numerical results are used to illustrate our findings and support our claims.

Dynamics of Bubble Supercompression in Organic Liquids

FM8S_12190
Thu • 14:45 • 315

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Theoretical research of vapor bubbles in deuterated acetone and benzol is conducted. On the basis of the developed models of a single bubble and bubble cluster the dynamics of bubbles formed during maximum rarefaction in the liquid is investi-

gated. It is shown that during the rapid contraction of a bubble a shock wave is formed inside it. Shock wave focusing in its center leads to violent rise in density (10^4 kg/m^3), pressure (10^{10}–10^{11} bar) and temperature (10^8–10^9 K), high enough to produce nuclear reactions. The diameter of the neutron emission zone is about 100 nm. It has been found out that the intensity of the bubble collapse and the number of emitted neutrons increase if one varies the phase of nucleation, the positive pressure wave amplitude, the liquid temperature, and when one switches on the mechanism of bubbles coagulation in the cluster during its simultaneous explosion.

Hydrodynamics of Gas Bubbling through Organic Liquids

FM8S_12311
Thu • 14:50 • 315

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The bubble diameter values were calculated from theoretical model. The model has been based on the original approach by Prince and Blanch. It assumes an equilibrium between the coalescence and redispersion processes, and uses a simplified method of solution of the population balance equations. The experiments were carried out with different organic liquids in two bubble columns: – a glass laboratory column 9 cm diameter and 200 cm high with different gas distributors (porous gas distributor and spargers with holes) operated at atmospheric pressure and low temperature, with seven liquids: acetaldehyde, acetone, cyclohexane, isopropanol, methanol, n-heptane and toluene. – a stainless steel pilot plant column 30.4 cm diameter and 400 cm high (gas distributor – spargers with holes) operated at elevated pressure (up to 1.1 MPa) and temperature (up to 160oC), with cyclohexane as a liquid. Good agreement was found between calculated and experimental values.

Surfactant Effects on Buoyancy-Driven Coalescence of Spherical Drops

FM8S_12329
Thu • 14:55 • 315

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Collision efficiencies are calculated by a trajectory analysis for two contaminated spherical drops in buoyancy at low Reynolds number with arbitrary surfactant surface coverage. The time-dependent convective-diffusion equation is solved for the bulk-insoluble surfactant concentration on the drops' surfaces by expansion in spherical harmonics with Lamb's singular series used for the velocity field. A series of nonlinear ordinary differential equations results which is solved numerically with fast-convergent, biconjugate-gradient iterations at each time step. To determine the many requisite trajectories with maximum efficiency, rotational reexpansions of Lamb's series are employed. It is anticipated that, under conditions when the surfactant concentration remains nearly uniform when the drops are well separated, significant deviation in coverage may occur in the region of close approach for weak diffusion, causing the interfaces to become immobile. Film drainage would be retarded, considerably decreasing the collision efficiency from spherical-drop results for nearly uniform coverage.

Static Shapes of Levitating Viscous Drops

FM8S_12388
Thu • 15:00 • 315

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We consider the levitation of a drop of molten glass above a spherical porous mould, through which air is injected with a constant velocity. In the present context, we assume that the glass is so viscous compared to the air that we can neglect the motion in the drop. Therefore, if static shapes of the drop exist, these shapes are completely determined by the coupling between the equations of motion in the air cushion and the Young–Laplace equation. Assuming that the pressure applied on the upper surface of the drop is atmospheric, this sessile solution is computed. A lubrication model for the thin air film is used to find static shapes of the lower surface of the drop. Then a comparison with full Navier–Stokes simulations is presented, and an argument is given about the stability of these solutions.

Entrainment of Air Bubbles During Strong Vorticity-Free-Surface Interaction

FM8S_12547
Thu • 15:05 • 315

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The air entraiment induced by vorticity–free-surface interaction is here numerically investigated with the help of a two-fluid model which describes the flow in air and water as that of a single incompressible fluid whose density and viscosity

vary smoothly across the interface. The numerical approach is used for the simulation of a viscous vortex pair vertically rising toward the free surface and comparisons are established with results available in literature obtained by boundary-fitted numerical approach. A validation of the model is carried out in a mild vorticity–free-surface interaction and a rather good agreement is achieved. For a stronger interaction, air entrainment is found, in contrast with available results. A deeper verification is undertaken aimed at understanding the reasons for such disagreement.

Spreading of Charged Microdroplets

FM8S_12548
Thu • 15:10 • 315

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We consider the spreading of a charged conducting droplet on a flat dielectric surface. Two forces drive the spreading: surface tension and electrostatic repulsion. By using the lubrication approximation we derive a fourth order nonlinear partial differential equation that describes the evolution of the height profile. We find that the equation has a two-parameter family of selfsimilar solutions. Some of the solutions are explicitly computed while the other solutions are studied numerically. We show that the solutions have moving contact lines and the radius of the drop is a power law of time with exponent one-tenth. We also construct explicit solutions corresponding to non-circular drops, whose interfaces are ellipses with constant focal length.

Multiple Bubbles Dynamics Using Level Set Indirect Boundary Element Method

FM8S_12596
Thu • 15:15 • 315

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We present a new method for simulating bubble dynamics called Level Set Indirect Boundary Element Method (LSBEM). This method tries to combine the advantages of LSM with BEM. As we know, the Level Set Method (LSM), which is a long-familiar computational technique used for tracking a propagating interface over time, has the strength in accurately handling topological complexities and changes. The Boundary Element Method (BEM), on the other hand, is known to serve well in conserving computational effort by reducing the dimensions of the problem by one. The novelty of this work is that while keeping this advantage of BEM, LSBEM simplifies the representation of the interface of multi-bubbles by using LSM. Thus advantages from both methods are conserved. A number of techniques are applied to ensure solution convergence and numerical accuracy. For instance, effort is made to avoid singularities in calculation by defining two sets of source and control points on the mesh which will never overlap one another; also work is done to ensure solution accuracy by reinitializing the level set function using Fast Marching Method (FMM) after every two timesteps.

Optimal Splashing

FM8S_12806
Thu • 15:20 • 315

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Keywords: drops, instability, atomization, experiment, passive flow control, scaling theory Abstract: The splashing process that occurs when a droplet impacts on a solid surface with sufficient speed was studied. The objective was to determine the conditions at which the splashing is optimal, i.e. as a means of atomizing the primary drop into many small secondary drops. The splashing process was studied experimentally by a liquid jet impinging on a rotating disk. Atomization efficiency and secondary droplet size distribution were measured using a photographic method. Measurements were analyzed in a dimensionless form suggested by scaling theory. It was found that secondary droplet size distribution and atomization efficiency could be described as a family of curves that depend on only two dimensionless groups. The analysis demonstrated that viscous-, inertia- and surface tension forces are important, as well as details of the topography of the solid surface. It is demonstrated at which conditions more than 75% of the primary drop can be atomized in many, very small, secondary droplets.

Thermodynamic Parameters of Vapour Bubble Growth by Image Analysis

FM8S_12873

Thu • 15:25 • 315

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Using high speed video camera and numerical processing of the digital images transient description of the geometry and the interface velocity for vapour bubble growing at the heated surface is achieved. Particle Image Velocimetry and Thermometry are applied to obtain details about velocity and temperature in the surrounding fbw fi eld. The whole bubble growth from time inception to lift-off from the wall and bubble collapse can be observed. Time history of the geometric parameters of the bubble such as equivalent diameter, base diameter and height of bubble center have been evaluated and compared with theoretical prediction obtained by a simple mathematical model.

FM9

Environmental fluid dynamics

Chairpersons: H. Huppert (UK), R. Narasimha (India)

The Growth and Structure of Double-Diffusive Cells Adjacent to a Side-Wall in a Salt-Stratified Enviroment

FM9L_10366
Wed • 11:00 • 124

O.M. Phillips(1), L. Malki-Epshtein(2), H.E. Huppert(2)

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Measurements are reported of the rate of horizontal extension of the cells in tanks of different lengths with a range of initial salinity gradients and cooling rates (which determine the vertical height of each cell). A simple model for the cell evolution is developed. It predicts that cell growth is dependent on tank length. The mean rate of increase of cell length decreases linearly in time, as does the density gradient inside the cells, supported by both temperature and salinity gradients. The results are found to agree quantitatively with the measurements.

Free Surface Behavior in Turbulent Open-Channel Flows

FM9L_11164
Wed • 11:20 • 124

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Laboratory experiments were conducted to investigate characteristics of the free surface behavior and its influences on turbulence structures in an open-channel shear flow. A simultaneous image measurement method was used to measure instantaneous velocity vectors and the corresponding water surface profile in a vertical cross section of the open-channel flow. The proper orthogonal decomposition of the water surface fluctuations successfully reveals that most of the principal components are sinusoidal wave shapes. Then, interactions between the predominant surface fluctuations and the turbulence structures are examined by calculating their space correlations. The result shows that there is a thin surface influence layer near the water surface, and also that there is the specific interaction between the water surface fluctuations and the large-scale turbulence structures having the same longitudinal scale. Moreover, the streamwise spectrum of the water surface fluctuations and the influence range of the free surface are discussed in detail.

Integral and Laboratory Modelling of Sedimentation from Turbulent Buoyant Jets

FM9L_11182
Wed • 11:40 • 124

Gregory F. Lane-Serff

Manchester Centre for Civil and Construction Engineering, UK

An integral model is developed to describe sedimentation from a turbulent, particle-carrying, buoyant jet injected at an angle to the vertical into stationary fluid. Sediment is assumed to fall from the jet where the outward component of the fall velocity normal to the jet boundary exceeds the inward entrainment velocity. The sedimentation can be characterized in terms of a non-dimensional fall-speed: the ratio of the particle fall-speed to a typical entrainment velocity. An important result is that this ratio is independent of the source flow rate (above a minimum value). Particles remaining in the jet beyond the near-source region are deposited when the jet spreads horizontally as a radial gravity current once it reaches the free surface, and this deposition is also modelled. The model results are compared to laboratory experiments and show good agreement.

Experimental and Numerical Simulation of Dense Water Overflows on a Continental Slope

FM9L_12410

Wed • 12:00 • 124

Sabine Decamp, Joel Sommeria
LEGI / Coriolis, Grenoble, France

A gravity current flowing down a uniform slope in a stratified or homogeneous media in rotation is analyzed. This configuration represents the descent of dense water over a sill (like in the Denmark strait) which controls the global density structure of the ocean interior. This study aims to determine experimentally the principal characteristics of such a current like its position, width, thickness, velocity, or development of periodic instabilities and to measure effects of bottom friction, mixing and entrainment in a rotating system. Gravity currents obtained in experiments performed on the large Coriolis turntable (Grenoble) are strongly influenced by rotation and still fully turbulent, in dynamical similarity with oceanic cases. Laboratory facilities provide high resolution velocity fields from image correlation measurements, and accurate density profiles from conductivity probes. Those experimental results are compared with oceanic numerical models to test the influence of parameterizations.

Formation and Rapid Expansion of Double Diffusive Layering in Lake Nyos

FM9L_12626

Wed • 12:20 • 124

Alfred Wuest, Martin Schmid
Applied Aquatic Ecology, Kastanienbaum, Switzerland

No signs of double-diffusive convection have been reported from Lake Nyos since the catastrophic CO2 eruption in 1986. In December 2002, however, 26 well mixed layers with thicknesses of 0.2 to 2.1 m and sharp interfaces were discovered. Such fascinatingly pronounced steps are characteristic of double-diffusive convection. It was probably triggered by an exceptional cooling in early 2002. The double-diffusive heat fluxes, calculated by heat budgeting, agree within the uncertainties with laboratory-based flux-laws. The heat fluxes increased by an order of magnitude since the establishment of double-diffusive convection and reached values of the heat input of the deep and warm CO2-enriched source water at maximum lake depth. Because the double-diffusive heat fluxes are higher in the upper part of the double-diffusive zone, the temperature gradient doubled, whereas the salinity gradient remained almost constant. This process reduces the staircase stability and leads to rapid expansion of the double-diffusive zone

An Alternative Model for “Pingo” Formation in Permafrost Regions

FM9L_12072

Wed • 12:40 • 124

James G.A. Croll
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Pingos are a characteristic geomorphologic feature of certain Arctic regions in which dome-shaped dimples can form in the permafrost layers of otherwise flat landscapes. It is widely accepted that the formation of a “pingo” results from the development of an excess pore water pressure in the unfrozen ground, the “talik”, underlying the permafrost layer. This paper argues that these prevailing models for pingo formation contain some serious mechanical inconsistencies. An alternative model is postulated. It relies upon the development of high levels of in-plane compressive stress in the permafrost layer. These compressions would arise from the restraint to the expansions otherwise occurring when in a thickening of the permafrost layer water turns to ice and/or when the ice in the permafrost layer is subject to a seasonal increase in temperature. An upheaval buckling under these conditions is consistent with the local dimples associated with pingos.

Parametrization of the Micrometeorological Tower’s Data Through Similarity Theory Of Monin–Obukhov and by Gradient and Profiles Methods

FM9S_10651

Tue • 14:30 • 237A

Jose F. de Oliveira Junior(1), Ramon H.V. Raimundo(2), Veronica T. Gomes(2)
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Up on the present research was made a Superficial Boundary Layer (SBL) parametrization through a micrometeorological tower’s data on Burgos (Spain).For this study was used the Monin-Obukhov’s theory (M-O), and the gradient and profiles methods. One intends, through profile methods, to esteem z0 and to obtain the atmosphere stability’s regime. So far, we have identified the contribution of both thermal (q) and dynamics (U) terms up on (Ri)B, where we found out a big variation on the two geometric levels, with relation to the stability transition regime, and 1.5 m level presents a stability regime and to 5.2 m level an instability atmospheric condition was observed.Was esteemed the fm (x) and fh (x) functions for the experiment using the gradient method for the two cases. We evaluated the atmospheric stability regime by the gradient

method end was identifi ed atmospheric stability regime on the 1.5 m level and on the 5.2 m level was observed a variation between both stability and instability regimes.The information obtained here showed signifi cant results, check the important role of the parametrization of meteorological data made through hypothesis, and the gradient and profi le methods carry out on the SBL characterization.

Flow and Dispersion in the Atmospheric Boundary Layer Investigation by Physical Modelling

FM9S_10467
Tue • 14:35 • 237A

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(2) *J. Heyrovsky Institute of Physical Chemistry, AS CR*

The method of physical modelling belongs to the power tool for environmental and wind engineering tasks. The principle of physical modelling consists in analogy between a boundary layer formed over the fbor of a wind-tunnel working section and the Atmospheric Boundary Layer. The method has been adopted and a new environmental wind tunnel was designed at the Institute of Thermomechanics AS CR. To investigate fbw and dispersion characteristics in aerodynamic wind tunnel, it was necessary to develop some methods of measurement. First of all, there was demand for fbw visualisation for fbw and dispersion qualitative assessment. The turbulence characteristics of the fbw fi eld were measured by LDA system and the slow FID is used for mean concentrations measurements. Some examples of results are demonstrated: air pollution due to traffi c inside a street-canyon, plum of smoke spreading over complex terrain, the surface mean concentrations of lead from point source assessment.

Computational Modeling of the Emission and Distribution of Gaseous Toxic Matters in the Atmosphere

FM9S_12590
Tue • 14:40 • 237A

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Physical, mathematical models and numerical calculation algorithm of toxic gas dispersion in an atmosphere were developed. They take into account air motion, gravity, complex relief, gases thermodynamics properties and presence of toxic matters variable source. The complete system of equations, describing the time-dependent three-dimensional two-component gas mixture fbw, is written down in Cartesian co-ordinates. These equations are the conservation laws of gas mixture mass, impulse and energy and of gas admixture mass. The system of equations is complemented by equations determining heat-transfer properties of the gas mixture components. Set of the fbw parameters in domain is calculated by means of the integral-interpolation Godunov's method. Developed computer system allows carry out effectively the engineering three-dimensional analysis of gas-dynamic mixing processes, to predict further distribution of gas mixture in open air or apartment with ventilation, and also to forecast the concentration of toxic gas across space.

Dynamics of Separation Zone behind the 2D Hill in Oscillating Incident Wind.

FM9S_12266
Tue • 14:45 • 237A

Alicja Jarza, **Jaroslaw Ciechanowski**
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The experimental and numerical simulation of the unsteady wind phenomena around the 2D hill has been performed for different parameters of infbw periodicity. The modelled hill has been immersed in the boundary layer fbw formed over the terrain of moderate roughness. To study the effect of periodical disturbances of the approaching wind the oscillating component superimposed on the mean velocity profi le has been introduced. Experimental test has been done in wind tunnel equipped with fast-scanning acquisition system of X array hot-wire signal and devices generating unsteady wind boundary layer and . They numerical simulations, guiding the experimental tests programme, have been performed by the use of phase averaged form of RNG version of $k-\varepsilon$ turbulence model. The main fi nding of the simulations reveal the strong dependence between the characteristics of infbw periodicity and vorticity structure of separation region.

Joint Urban 2003 Surface Energy Budget Measurements and Analysis

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FM9S_12738
Tue • 14:50 • 237A

Understanding of the surface energy balance is a critical component for correct modeling of flow in an urban environment. During the Joint Urban 2003 field campaign, extensive data were collected of the components of the surface energy. These data were analysed in an attempt to close the surface energy budget and to gain an understanding of energy partition.

High Resolution Modelling of Atmospheric Flow over Southern Poland

Jakub Krawczyk(1), Mirosław Andrejczuk(1), **Zbigniew Piotrowski**(1), Joanna Strużewska(2), Bogumił Jakubiak(3), Szymon Malinowski(1), Lech Łobocki(1)
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(2) *Institute of Environmental Engineering Systems, Warsaw University of Technology, Poland*
(3) *Interdisciplinary Centre for Mathematical and Computational Modelling, Warsaw University, Poland*

FM9S_12592
Tue • 14:55 • 237A

A nonhydrostatic model of atmospheric flows EULAG is set up over southern Poland on a grid with 1 km horizontal resolution. The goal is to test a short-term numerical weather prediction over complicated topography with explicit treatment convective processes. Boundary and initial conditions are interpolated from routine mesoscale hydrostatic UMPL model running at 17 km resolution. The case study of evolving fonvection forced by topography will be presented.

Nocturnal Temperature Inversions Under Calm Clear Conditions: an Analytical Study

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TIFR Centre, Indian Institute of Science, Bangalore, India

FM9S_12980
Tue • 15:00 • 237A

The knowledge of inversion height in the nocturnal boundary layer (NBL) under calm clear conditions is crucial in determining the fate of chemical pollutants that are (accidentally or otherwise) released into the atmosphere. A new analytical expression for temperature profiles over bare soil surfaces under calm clear conditions is used to study inversion height and intensity as a function of surface parameters like ground emissivity and cooling rates. Previous analytical expressions available in the literature have ignored these parameters.

Modified Shallow Water Equations for Inviscid Gravity Currents

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FM9S_11294
Tue • 15:05 • 237A

To analyze the motion of gravity currents, a common approach is to solve the hyperbolic shallow water equation together with the boundary conditions at both the current source at upstream and the current front at downstream. The use of the front condition is to account for the resistance from the ambient fluid, which, nevertheless, is missed in the shallow water equation. The present study starts from the continuity and inviscid momentum equations and applies the shallow water approximation to derive the so-called modified shallow water equation, in which the ambient resistance is accounted for by a nonlinear term so that the use of the front condition becomes non-necessary. This equation is highly nonlinear, which, under the assumption that the gravity current moves with a constant speed, can be solved by a similarity transformation. Qualitatively, the similarity solution ends up with a gravity current of a profile being close to those observed in experiments and being in a much better shape than those obtained by solving the traditional shallow water equation. Quantitatively, the similarity solution can be converted into a relation in terms of a parameter used in the front condition, which turns out to be exactly the same with that obtained by previous studies using both theoretical as well as experimental approaches. These comparisons support that the present modified shallow water equation can properly govern the motion of inviscid gravity current when the ambient resistance is concerned.

The Propagation of Viscous Gravity Currents over a Rigid Conic Surface

FM9S_11703
Tue • 15:10 • 237A

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Asymptotic models of a thin-film flow of highly viscous heavy fluid with mass supply on a curved rigid surface with small and finite inclination angles of the surface generatrix to the horizontal are constructed. The existence of a steady-state solution for the free-surface shape (absent in the case of a horizontal plane) is demonstrated. The solutions obtained are generalized for the case of viscoplastic fluid. A 3D hydrodynamic model of lava dome growth on a slightly non-axisymmetric conical surface is constructed. For finite inclination angles of the surface generatrix to the horizontal, an evolutionary first-order partial differential equation for the free-surface shape is obtained. For point mass supply at the apex of the conical surface and a power or exponential dependence of the entire liquid volume on time, an unique self-similar solution for the free-surface shape and the law of flow front propagation is found analytically. The families of self-similar solutions describing flows with mass sources or sinks at the flow front are also obtained. Non-self-similar regimes of flow on a conical surface with small inclinations to the horizontal are studied numerically. The solutions obtained can be used for describing extrusive and effusive volcano eruptions on curved substrate surfaces. The work received financial support from the RFBR (project 02-01-00067) and from the grant for Leading Scientific Schools (project 1697.2003.1).

Lobe and Cleft Formation at the Head of a Gravity Current

FM9S_12396
Tue • 15:15 • 327A

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Department of Applied Mathematics and Theoretical Physics, University of Cambridge

Gravity current experiments were carried out in which the formation, and subsequent evolution, of lobes and clefts was examined in detail. This was achieved by calculating the curvature of the level-set of first-arrival times. The results show that there is a weak dynamical linear instability when the radius curvature of the front is similar to the height. The formation and evolution of the clefts is then a nonlinear kinematic phenomenon, caused by the front propagating with a roughly constant normal velocity. Three different mechanisms for the initial instability are discussed and the subsequent evolution of the front is explained in detail.

Experiments on Up-slope to Down-slope Transition in an Inclined Box Filled with Water

FM9S_10576
Tue • 15:20 • 327A

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(2) *EFDP, Department of Mechanics and Aerospace Engineering, Arizona State University, USA*

Summary The natural convection of water in inclined side-heated rectangular box is investigated experimentally and numerically. The aim is to demonstrate existence and features of the convective front formation typical for the evening transition of the atmospheric boundary layer on gentle slopes. Particle image velocimetry and thermometry allows for quantitative analysis of the temporary velocity and temperature fields generated in a small scale laboratory model. The laboratory experiment is compared with numerical simulations performed with Fluent. Observations confirmed predictions of the evening transition front described for the atmospheric flows by Hunt et al [1].

Dam-Break Flow for Arbitrary Slope of the Bottom

FM9S_11346
Tue • 15:25 • 327A

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ETS Ingenieros Industriales, University of Malaga, Spain

The dam-break flow problem in the shallow-water approximation on an inclined bed for arbitrary slopes of the bottom is considered. An analytical solution for the spreading of the water fronts at the initial stages after the catastrophic failure of the dam is given. A self-similar solution asymptotically valid for large times is also found in a simple closed form. For intermediate times the problem is solved numerically by the method of characteristics.

The Formation of the Hail and the Newlycome Snow

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State Engineering University of Armenia, Gyumri, Campus

FM9S_11537
Tue • 15:30 • 327A

The principally new approach of the hail formation is given in [2]. The existence of the hail is conditioned by the fact that the clouds are charged, especially when they are highly charged [2]. According to the existent viewpoint, the base of hail consists of a little ice-crystal, which then during eddy motion rolls up with the layers of frozen water, which is formed, from the clouds around. By the way, the formation of ice-crystals is not explained, yet. But the real structure of the hail that has a big, solid nucleus 5 mm cannot be explained by the existent explanation. And there is a real contradiction when egg-sized hailstone falls. It is also well known, that the hail is always accompanied with powerful thunders, which, naturally, is connected with the charged-ness of the clouds. Basing on this viewpoint, the hail formation is explained in the following way: the formation of the drop from smallest drops brings to the fact, that the charge density exceeds a certain critical value on the influence of Coulomb forces a rapid removal of the exterior layer of the drop takes place, which leads to the formation of a big, solid, icy nucleus of the hail. The formation of newlyfallen snow is the result of the cavitations in the domain of the clouds. In the basis of the formation of the newlyfallen snow is the cavitation in the clouds. The newlyfallen snow generally comes in early spring and in a warm late autumn. In that period the ground is still warm, but in the domain of the clouds it is already cold but not much enough to become snow, the powerful convective streams bring to cavitations inside the clouds, and in the formed cavities the temperature briefly reduces and the newlyfallen water is formed. The lightness and the porosity of the newlyfallen snow can be explained by the cavitations.

Extended Nonlinear Theory for Topographic Rossby Waves

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FM9S_11433
Tue • 15:35 • 327A

The nonlinear-dispersive theory is proposed for topographic Rossby waves of small but finite amplitude for the case when external conditions (Coriolis parameter and ocean depth) are changed mainly along one direction, and wave is propagating along the orthogonal direction. The theory is based on the asymptotic procedure applied to hydrodynamic equations of frictionless, vertically homogeneous, incompressible, rotating fluid. The procedure includes series expansions of hydrodynamic fields by small parameters of nonlinearity and topographic dispersion. As a result, temporal evolution and spatial transformation of Rossby wave field is described by nonlinear evolution equation of second order in small parameters.

FAST FER TRAFFIC AS A NEW FORCING FACTOR OF ENVIRONMENTAL PROCESSES IN NON-TIDAL SEA AREAS

Tarmo Soomere
Marine Systems Institute at Tallinn Technical University

FM9S_12099
Tue • 15:40 • 327A

The impact of wake wash from high-speed ferries on the coastal environment is analysed in terms of wave energy and power, and properties of the largest waves. Shown is that hydrodynamic loads caused by heavy high-speed traffic may play a decisive role in certain non-tidal areas with high wind wave activity. The main reason of concern is the long periods of wake waves. The leading waves typically have a height of about 1 m and a period of 10–15 s. They cause unusually high hydrodynamic loads in the deeper part of the nearshore. The fast ferry traffic is thus a qualitatively new forcing component of vital impact on the local ecosystem.

Effects of Curvature in Avalanche Deflecting Dams

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FM9S_12270
Tue • 15:45 • 327A

Curved deflecting dams are an effective protection against avalanches. Three different models are applied for evaluating the effects of curvature in natural and artificial avalanche tracks. The NIS model is a continuum model for simulating dense snow avalanches, incorporating centrifugal forces in two planes, and a procedure for displacing the centre line of the flow according to these. The Schieldrop model is based on the Voellmy-Perla equations, and computes the trajectory of the centre of mass of avalanching material arbitrarily hitting a plane deflecting dam. The quasi-static approach is based on an ideal fluid in stationary flow along a curved channel. The models are applied on data from observed avalanches, to find out how curvature influences run-up, and how the models handle these effects. The NIS model provides velocities for the other two models. The models may be used to evaluate run-up on deflecting dams, providing guidelines for design.

Analysis of Double-Free Surface Flow through Gates Using Element-Free Galerkin Method

FM9S_10733
Tue • 15:50 • 327A

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In the analysis of free surface flows under gates, computational difficulties arise not only from the non-linear nature of the boundary conditions but also from the fact that the boundary is not known a priori. There are additional difficulties when the problem involves two highly curved unknown free surfaces and arbitrary curved shape boundaries. The goal of the present work is to develop a suitable and accurate numerical procedure based on moving least square method (MLS) and element-free Galerkin method (EFG) for the computation of free surface profiles, velocity and pressure distributions and flow rate in a two-dimensional gravity fluid flow through a radial gate. The results of the calculations are compared with those obtained from a hydraulic model test. It is found that the method can be successfully used in the analysis of free surface flow through the radial gates and locating two free surface profiles. It converges almost rapidly and the results obtained are in good agreement with the experiment.

FM10

Experimental methods in fluid mechanics

Chairpersons: A. Leder (Germany), J. Westerweel (Netherlands)

HPIV using Polarization Multiplexing Holography in Bacteriorhodopsin (bR)

FM10L_11899
Thu • 09:30 • 206

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Abstract Holographic particle image velocimetry (HPIV) is a three-dimensional flow measurement technique that can determine all fluid velocity components volumetrically (Hinsch 2002, Barnhart et al 2002). This paper demonstrates the use of bacteriorhodopsin (bR) as the holographic recording medium for a (HPIV) system. Using an off-axis hologram in bR, forwardly scattered double exposed images of particles in a turbulent flow are recorded. Bacteriorhodopsin, a polarization sensitive holographic recording material, has the ability to alter the polarization of the reconstruction beam, possibly resulting in the reconstruction of the original object polarization. Therefore, by using polarization multiplexing, two time separated holograms can be multiplexed in a single bR film, thereby allowing directional ambiguity in the HPIV flow data to be eliminated (Koek et al 2004, Chan et al 2004). For the first time, we successfully demonstrated this idea in a HPIV system by using a sequential holographic read-out method, to retrieve the two holograms independently.

Void Collapse and Jet Formation: The Impact of a Disk on a Water Surface.

FM10L_11909
Thu • 09:50 • 206

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Faculty of Science and J.M. Burgers Center for Fluid Dynamics, University of Twente, Enschede, Netherlands

The formation and collapse of the void created by the impact of a disk onto a water surface is investigated experimentally and numerically. The experiments are performed using a linear motor to precisely control the disk velocity; the simulation is based on a boundary integral formulation. The numerical results for the void shape are found to be in excellent agreement with the experimental observations. The cavity closes by the radial convergence of the liquid onto the symmetry axis. The resulting impact gives rise to two jets of water, one shooting up straight into the air, and one down piercing the void enclosed by the collapse. Both experiment and simulation show that the depth of the point where the cavity closes divided by the disk radius is proportional to the square root of the Froude number.

Experimental Detection of the New Phenomenon of Turbulent Thermal Diffusion

FM10L_12070
Thu • 10:10 • 206

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A new phenomenon of turbulent thermal diffusion, which was predicted theoretically by Elperin et al. (1996), has been detected experimentally in oscillating grids turbulence with an imposed mean temperature gradient in air flow. This effect implies an additional mean flux of particles in the direction opposite to the mean temperature gradient and results in formation of large-scale inhomogeneities in the spatial distribution of particles. We used Particle Image Velocimetry to determine the turbulent velocity field and an Image Processing Technique to determine the spatial distribution of particles. Analysis of the intensity of laser light Mie scattering by particles showed that they are accumulated in the vicinity of the

mean fluid temperature minimum due to turbulent thermal diffusion. In a flow with unstable stratification (heated bottom and cooled top walls of the chamber) the turbulent thermal diffusion coefficient was larger than that for a flow with a stable stratification.

On the Evaporation of a Monodisperse Droplet Stream at High-Pressure

FM10S_10445
Tue • 14:30 • 305

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A new experimental facility has been developed aimed at investigating the evaporation of free falling droplets at high pressure. A monodisperse droplet stream is generated in the upper part of the test rig and is embedded in a gas flow. The droplet speed is determined by means of a video technique and a stroboscope lamp. The droplet size is determined by means of the low-angle light scattering technique. The method consists in detecting the light scattered by an ensemble of particles at small angles in the forward direction. As detector device, a common CCD camera has been employed, thus resulting in an increased angular resolution and sensitivity when compared to standard photodiodes arrays. Promising results have been obtained in the case of iso-propanol droplets with an average nominal diameter of 54 micron.

Time-resolved Wall Shear Stress Measurements using MEMS

FM10S_11455
Tue • 14:35 • 305

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(3) *Signals, Sensors and Systems, Microsystem Techn., Royal Institute of Techn., 10044 Stockholm, Sweden*

MEMS (Micro Electro Mechanical Systems) wall mounted hot wire sensors have been developed at the Thermo and Fluid Dynamics department (TFD) at Chalmers University of Technology, and final design and production was performed by the KTH group. The sensors were used to investigate the fluctuations of the velocity within the viscous sublayer of a zero-pressure-gradient turbulent boundary layer flow. The particular aim of the experiments was to increase the accuracy of using MEMS in turbulent flow by incorporating new features such as temperature compensation. The measurements were performed at Reynolds numbers, R_θ ranging from 1000 to 15000. The relative intensity of the streamwise wall shear stress fluctuations was the property of primary interest and the results achieved were compared to other relevant, reliable data collected from literature. From this study the limiting value of turbulence intensity at the wall was found to range between 0.3 and 0.5 with an appropriate approximation being the 0.4 value that is quoted in most literature.

Experimental Study of a Supersonic Mixing Layer with an Estimation of Acoustic Radiation

FM10S_11505
Tue • 14:40 • 305

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The study of turbulent compressible flow is the object of a particular interest in this last decade. The striking attract is that many phenomena become very important with the effect of compressibility. Indeed, the structure of turbulence changes drastically and depends essentially on the convective Mach number Mc, i.e. the Mach number based on the velocity difference between the large eddies and the external flows. One flow where the effect of compressibility on turbulence appears at relatively low Mach number is the plane mixing layer. The study of a supersonic mixing layer on self preservation was investigated in paper. In order to accomplish these investigation we have got a large test section in a wind tunnel. The setup of an isobaric mixing layer was obtained by a judicious downstream conditions in the diffuser. The mean field profiles were measured and correspond to similarity solutions. The estimation of the acoustic radiation shows that this term is insignificant against the production of turbulence.

Comprehensive Experimental and Computational Investigations of the Unsteady Flow in an Axial Flow Low Speed Compressor Stage

FM10S_11916
Tue • 14:45 • 305

Andrzej S. Witkowski, Tadeusz J. Chmielniak, Mirosław M. Majkut, Michał D. Strozik, Jacek M. Żukowski
The Silesian University of Technology, Gliwice, Poland

The objective of the study is experimental and computational investigation of the unsteady flow in the axial flow low speed compressor stage with the use of two systems based on totally different principles: – A 2-sensor fast response straight and 90 degree triple split fiber probes (TSFP) and, – Commercially available three-dimensional Laser Doppler Anemometer (3D-LDA) system. To account for the uniformity of the rotor absolute inlet flow field, measurements will be made at six tangential locations in the absolute frame equally spaced over one inlet guide vane (IGV) pitch. Using two measurement systems, one being intrusive and the other non-intrusive, in the same complex flow field gives the opportunity for: – Study of the structure and decay characteristics of turbulence downstream of the rotor and at the rotor-stator blade row spacing, – Investigations of three-dimensional unsteady flow field in rotor blade-to blade passages, – To understand the propagation of the IGV wake through the rotor at different relative positions of the rotor with respect to the IGV, – A concerted application of experimental (LDA) and computational fluid dynamics (CFD) calculations as well as basis for verification of computational results.

3D Vortices Structure Monitoring in Turbulent Flows by Digital Speckle Photography

FM10S_12213
Tue • 14:50 • 305

Nikita A. Fomin, Andrey V. Krauklis, Elena I. Lavinskaya
HMTI, Minsk, Belarus

3D vortices structure in complex turbulent flows is reconstructed using computerized speckle tomography. Multiprojectional digital speckle photography (DSP) is based on the computer aided acquisition and evaluation of time evolution of dynamic speckle patterns and allows the instantaneous quantitative derivation of a 2D map of deflection angles of the light passing through the flow under study. Both macro and micro scales of vorticity in compressible flow are visualized and quantitatively characterized with the applied DSP techniques. The macro structures are reconstructed using Radon integral transform. The microscale turbulence structures are determined by using the 3-D density correlation functions evaluated with Erbeck-Merzkirch integral transforms. With high density speckle photography data the precision of the turbulence microscale determination using this integral transform for the isotropic turbulence is rather higher. For non-isotropic turbulence the evaluation would require a more correct conversion using multi-angular probing and convolution of Radon and Erbeck-Merzkirch integral transforms.

Single-View Super-Resolution Whole-Field Velocity and Scalar Mapping Technique

FM10S_12403
Tue • 14:55 • 305

Vladimir M. Zubtsov, Aleksey V. Mikheev
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Innovative technique consists of two major components. First, a new algorithm, which relies on the accurate recovery of location, diameter and intensity provided by each individual tracer particle image spot has been proposed and experimentally demonstrated. Second, a novel single-view particle tracking velocimetry technique enhanced by pairs matching based on tracer particle random size variety has been established and experimentally demonstrated. Feasibility, limitations and most attractive embodiments of this technique are evaluated. Employing mask-free defocusing for pure 3-D volumetric visualization, it is an attractive alternative not only to well-established stereoscopy, recently developed defocusing by aperture masking digital particle image velocimetry, but also to holography, tomography, magnetic resonance imaging, etc., for a number of particular applications ranging from micro fluids to large scale industrial facilities. Adding two-color pyrometry for whole-field velocimetry/thermometry, it is a competitive alternative for more sophisticated technologies (e.g. filtered Rayleigh scattering, Coherent anti-Stokes Raman Scattering, etc.).

Thermal-wave Resonator Cavity: Modelling and Applications for Water Mixtures

FM10S_12719

Tue • 15:00 • 305

Anna Matvienko, Andreas Mandelis

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A novel technique for ultra-high resolution thermal diffusivity measurements of liquid mixtures was developed. In this technique, a thermal-wave cavity containing a liquid sample is utilized. A thermal-wave generator (TWG) and a pyroelectric sensor bound the liquid layer from both sides. The TWG converts the optical energy of a broad modulated laser beam into thermal waves. The induced temperature oscillations are conducted into the liquid and are detected by the sensor producing an output signal. The high sensitivity of the method is due to the exponential dependency of the output signal on the thermal diffusivity of the liquid. To achieve ultra-high sensitivity, we applied a novel signal baseline suppression scheme known as “common-mode rejection demodulation”. Frequency scan experiments with liquid samples were also performed. A theoretical model of the one-dimensional thermal-wave fi eld within the cavity was developed and compared with experiments, showing good agreement.

Optical Diagnosis Systems for Measuring Thermofluiddynamicals Phenomena in Liquid Biosystems Under Ultra High Pressure

FM10S_12720

Tue • 15:05 • 305

Antonio Delgado, Ozlem Ozmutlu, Christoph Hartmann, Albert Baars

Technische Universitat Munchen, Germany

In modern bioprocess engineering, novel visualization systems for investigating thermofluiddynamical processes, particularly, phase transition phenomena occurring when liquid systems are pressurized up to 10000 bars are presented. In contradiction to literature, the results found show conclusively that neither the assumption of homogeneity nor of pure diffusive transport in a resting liquid holds. Rather, they clearly demonstrate the heterogeneity of temperature distribution in the liquid phase during pressure induced phase transition of water, even “cold spots” are observed. The existence of this phenomenon is not only a result of thermal diffusion but mainly of convective transport. In fact, during melting, Ice I moves up because its density is lower than that of water. These movements of the ice block forms two counter rotating vortices in the water layer below it. As biosystems could react extremely sensible against mechanical and thermal heterogeneities, published results up today worth to be checked carefully.

Particle Image Velocimetry (PIV) for Cloud Droplets – Laboratory Investigations

FM10S_12855

Tue • 15:10 • 305

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Interaction between small-scale turbulence and cloud particles is a key issue in warm rain formation mechanism, which is an important meteorological and climatological challenge. We investigate this interaction observing turbulent motion of cloud droplets in a laboratory chamber (1 m deep, 1 m wide and 1.8 m high) by means of Particle Image Velocimetry (PIV). A specially developed multi-scale PIV algorithm is used to retrieve two components of velocity of cloud droplets.

FM11

Flow control

Chairpersons: J. Freund (USA), M. Gad-el-Hak (USA)

Response on the Near Wall Turbulence to Localized Unsteady Blowing Periodical and Dissymetric in Time

FM11L_11394

Tue • 11:00 • 306

Sedat Tardu, Olivier Doche

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The effect of a localized unsteady blowing on the near wall turbulence structure and the drag is investigated experimentally and through direct numerical simulations. Localized time dependent blowing is either sinusoidal or dissymmetric in time with a rapid acceleration phase followed by a slow deceleration phase. The flow is partly relaminarized during the oscillation cycle because of an induced positive spanwise vorticity layer that dilutes the negative vorticity existing near the wall whose diffusion is constrained into the low buffer layer with limited effect of turbulent mixing, when the frequency of the oscillating blowing is large. Thus, in case of sinusoidal blowing the vorticity concentrates, becomes compact and rolls-up into a coherent spanwise vortex at approximately the beginning of the low buffer layer. The unsteady periodical blowing dissymmetric in time prevents the destabilization and the set-up of the spanwise vortex that causes the drag increase. These results point at possible alternate ways of drag management.

Passive Control of Turbulent Flow behind a Model Vehicle for Drag Reduction Using Wake Disrupter

FM11L_11636

Tue • 11:20 • 306

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Both wind-tunnel experiment and large eddy simulation (LES) are carried out to examine the applicability of a new passive device, wake disrupter, to flow over a model vehicle for drag reduction. The wake disrupter is a small-size rectangular body attached to a part of the trailing edge of the model vehicle, designed to perturb an essentially two-dimensional nature of wake. A pair of wake disrupters is mounted on the mid-span at the upper and lower trailing edges. Experiments are performed at the Reynolds numbers of 20000, 40000 and 80000 based on the free-stream velocity and vehicle height. From the parametric study, it is found that the increase in the base pressure is about 20% with an optimal wake disrupter. From LES, it is shown that the wake disrupter significantly changes the wake structures and increases the base pressure of the model vehicle.

On the Possibility and Prospects of Turbulent Flow Noise Control

FM11L_12156

Tue • 11:40 • 306

Victor F. Kopiev

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The main problem of realizing the idea of active noise control rests on the absence of conceptual study of the reduction strategy itself and this, in its turn, reflects our insufficient understanding of the principal mechanisms of noise generation by turbulence. The mechanism of noise generation for supersonic jets is essentially clear and is connected mainly with instability waves developing downstream from the nozzle. Two strategies for noise control in supersonic jet are considered: non-adaptive and adaptive. The first is based on instability wave coupling and transformation of modes in the initial part of slowly corrugated supersonic jet due to small deformation of nozzle. The second one based on new experimental technique on multi-channel signal decomposition, giving the example of active action on the radiating part of turbulence but not control of the all manifold of turbulence disturbances. This situation is quite different from that for subsonic flows, where a complete understanding of noise radiation mechanisms is yet absent.

A Singular Value Analysis of Boundary Layer Control

FM11L_12013

Tue • 12:00 • 306

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Several approaches for boundary-layer control are analyzed from a linear system point of view. The singular value decomposition (SVD) is applied to the linearized Navier–Stokes system in the presence of control. The performance of control is examined in terms of the largest singular values, which represent the maximum disturbance energy growth ratio attainable in the linear system. The maximum growth ratio is shown to be less in controlled systems than in the uncontrolled system only when control parameters are within a certain range of values. The SVD analysis of various controls shows a similarity between the trend observed in the SVD analysis (linear) and that observed in direct numerical simulations (nonlinear), thus reaffirming the importance of linear mechanisms in the near-wall dynamics of turbulent boundary layers. The present study illustrates that the SVD analysis can be used as a guideline for designing controllers for drag reduction in turbulent boundary layers.

Optimal Energy Growth and Optimal Control of the Swept Attachment-Line Boundary Layer

FM11L_12305

Tue • 12:20 • 306

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The amplification of perturbations near the leading-edge of swept wings is known to play a major role in boundary layer transition. Optimal perturbations and their optimal control in swept attachment-line boundary layers are addressed in the context of the swept Hiemenz base flow, under the Görtler–Hämmerlin assumption. An adjoint formulation is used to determine the initial condition that experiences the strongest energy growth over a given time interval; amplification as high as one thousand is observed at high Reynolds numbers. The optimal control sequence of wall-normal blowing and suction leading to the lowest energy at a given time is then computed by implementing an analogous adjoint method. Optimal control leads to a drastic reduction of the maximum energy by several orders of magnitude. Two-dimensional mechanisms are found to be responsible for most of the transient energy amplification. Control inhibits energy amplification at a given time by accelerating these processes.

Feedback Control of Vortex Shedding in a Separated Diffuser

FM11L_12387

Tue • 12:40 • 306

Tim Colonius, Takao Suzuki, Douglas G. MacMartin

Division of Engineering and Applied Science, California Institute of Technology, Pasadena, USA

We propose a closed-loop control algorithm for vortex shedding in a separated diffuser. We introduce pulses of zero-net-mass injection (consecutive blowing and suction) based on estimates of the circulation of a vortex in the separated region. The circulation is determined with an inverse detection algorithm based on pressure at a limited number of observer points at the wall. The closed-loop algorithm attempts to time the pulse so that the vortex is pinched off with an optimal size (determined through modeling and open-loop forcing). We investigate the performance of both open and closed-loop control in a simplified two-dimensional diffuser flow by using direct numerical simulation. We examine robustness by introducing high frequency disturbances upstream of the separation point. The disturbances significantly reduce the effectiveness of open-loop control compared to the case where no external disturbances are added. By using feedback control, performance is again recovered in the presence of disturbances.

Separation Control by Stationary and Time Periodic Lorentz Forces

FM11L_12068

Thu • 09:30 • 306

Tom Weier, Gunter Gerbeth, Gerd Mutschke

Forschungszentrum Rossendorf, Dresden, Germany

Stationary and time periodic wall parallel Lorentz forces in streamwise direction have been used to control the suction side flow of NACA 0015 and PTL IV hydrofoils. Experimental results, consisting of flow visualizations and force measurements in the low Reynolds number range $Re = 0.5 \ldots 1.5 \times 10^5$ will be presented. A stationary Lorentz force may increase lift by two mechanisms: 1) reattaching the separated flow and therefore increasing the critical angle and 2) introducing circulation due to acceleration of the attached suction side flow. Periodic excitation by oscillatory Lorentz forces near the leading edge

is able to reattach the separated flow with much less momentum input then required for stationary forcing. However, to increase the maximum lift gain requires a comparable expenditure for both methods. The action of a wall parallel Lorentz force compares well to that of momentum input by blowing.

Model-Based Control of Shear Flows Using Low-Dimensional Galerkin and Vortex Models

FM11L_12624

Thu • 09:50 • 306

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(4) *Institute of Combustion Engines and Basics of Machine Design, Poznań University of Technology, Poland*

The present study proposes a model-based flow control strategy using low-dimensional coherent-structure representations. This strategy is applied to the suppression of a von Kármán vortex street and the mixing enhancement of a wall-bounded shear-layer. Here, low-dimensional Galerkin and vortex models are used as a ‘plant’ for controller and observer design. The control approach is validated against direct numerical simulations.

Numerical Analysis of the Wake Control behind a Circular Cylinder with Oscillatory Rotation

FM11L_12736

Thu • 10:10 • 306

Marek Morzyński(1), Sophie Goujon-Durand(2), Bernd R. Noack(3), Jose E. Wesfreid(2), Benjamin Thiria(2)

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(3) *Hermann-Fottinger-Institut fur Stromungsmechanik, Technische Universitat Berlin, Germany*

In this study, the wake flow is controlled via open-loop oscillatory rotation of a circular cylinder. The Karman vortex street is suppressed with this method of control, both, in experiment and in simulation. The results of natural and actuated numerical flow simulations are used as the input for POD analysis. With this approach the spatial distribution of empirical eigenmodes are elucidated. Actuation pushes the Karman mode downstream if the amplitude and frequency of the rotation are adequately chosen. Thus, the modal energy contains only a fraction of it original value of natural shedding.

Liquids: The Holy Grail of Microfluidics Modeling

FM11S_10128

Tue • 14:30 • 307

Mohamed Gad-el-Hak
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Interest in microelectromechanical systems (MEMS) has experienced explosive growth during the past few years. Such small devices typically have characteristic size ranging from 1 mm down to 1 micron, and may include sensors, actuators, motors, pumps, turbines, gears, ducts and valves. Microdevices often involve mass, momentum and energy transport. Modeling gas and liquid flows through MEMS may necessitate including slip, rarefaction, compressibility, intermolecular forces and other unconventional effects. The continuum-based Navier–Stokes equations-with either the traditional no-slip or slip-flow boundary conditions-work only for a limited range of Knudsen numbers above which alternative models must be sought. These include molecular dynamics simulations (MD), Boltzmann equation, Direct Simulation Monte Carlo (DSMC), and other deterministic/probabilistic molecular models. The kinetic theory of gases defines well the boundaries for which the no-slip Navier–Stokes equations can accurately model the flow of a dilute gas. The same cannot be said about dense-gas and liquid flows where intermolecular interactions play a dominant role. Neither type of fluid has a well-advanced molecular-based theory, as is the case for dilute gases. The concept of mean free path is not very useful for liquids and the conditions under which a liquid flow fails to be in quasi-equilibrium state are not well defined. Such complex fluids can only be treated via hybrid continuum-molecular approaches, which approaches are still far from satisfactory at the present time. The present talk will address such issues and outline a blueprint for future developments.

Active Control of Shock/Boundary Layer Interaction in Transonic Flow Over Airfoils

FM11S_10872

Tue • 14:35 • 307

Ramesh K. Agarwal, Jose L. Vadillo
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The objective of this paper is to show, via numerical simulation, the feasibility of weakening the shock wave(s) and reducing the pockets of supersonic and separated flow regions on airfoils in transonic flow at small angles of attack using an active control device such as a synthetic jet or a spark-jet actuator. A large number of numerical simulations are performed for transonic turbulent flow past a NACA 0012 airfoil and a Boeing 767 airfoil at small angles of attack (cruise flight condition) by varying various parameters of the synthetic jet such as amplitude of the jet velocity, jet width, momentum coefficient, frequency, and jet location on the airfoil surface. Detached Eddy Simulation(DES)modification of Menter's two-equation Shear Stress Transport(SST)model is employed in the computations.It is shown that the maximum value of the Mach number in the supersonic region decreases resulting in reduced drag with minimal change in lift for suitably selected parameters of the synthetic jet.

Manipulating a Vee-Shaped Bluff Body Wake Using a Fluidic Oscillator

FM11S_11043

Tue • 14:40 • 307

Rong F. Huang, Kuo T. Chang
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The vee-shaped bluff body was re-designed by employing the unsteady Coanda effect to induce self-sustained, periodically oscillating jet. The oscillating jet was expelled through narrow passages and injected into the near wake of the vee-shaped bluff body to modify the wake characteristics. Behaviors and frequency characteristics of the slit-jet in the oscillation cavity as well as the turbulence properties in the wake were studied experimentally in a wind-tunnel by using the smoke-wire flow visualization technique, hot-wire anemometer, and PIV. The oscillation frequencies of the presently developed jet-injection vee-gutter were about 25 to 40 times higher than that of the conventionally used fluidic flowmeter. The integral length scales of turbulences of the jet-injected vee-shaped bluff body were significantly smaller than their counter parts of the conventional bluff body, which indicated that large effect of vortex stretching was induced by the periodic jet injection. Modifications of turbulence properties were presented and discussed.

Control of Internal Supersonic Flow Separation

FM11S_11918

Tue • 14:45 • 307

Andrzej Szumowski, Jan Wojciechowski
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Supersonic internal flow separation at a cylindrical convex contour was controlled by means of obstacles and swirling jets used to excite the turbulent boundary layer. In the former case a row of oblique half-cylinders paired in a form of V-letters were stuck to the wall. In the latter case the jets from orifices in the wall were injected into the boundary layer. They were strongly swirled to induce the vortex brake down phenomenon. In this effect the air of the jets spreads around orifices and disturbs only the flow region close to the wall. In the supersonic flow the boundary layer separation is accompanied by a shock wave. It was noted in the present experiments that the shock wave displaces remarkable downstream when the boundary layer is excited. The separation is delayed due to streamwise vortices downstream of obstacles and swirling jets which enhance mixing of retarded and fresh air particles.

Control of Flow Oscillations over a Cavity by Means of a Spanwise Cylinder

FM11S_12244

Tue • 14:50 • 307

Illy Herve, Philippe Geffroy, Laurent Jacquin
DAFE-ONERA

This study deals with an experimental investigation of the passive control of a flow over a cavity. The control system is based on the introduction of a spanwise cylinder in the boundary layer upstream of the cavity. This simple device leads to elimination of the low frequency cavity tones. This suppression is related in the literature to the cylinder wake which forces at high frequency the shear layer over the cavity. The mean velocity profile is changed and the flow stabilized. The low frequency tones are replaced by low energy oscillations at the cylinder frequency. The aero-acoustic loop, which leads to the flow oscillations described by the Rossiter's model, is broken down by the cylinder wake whose dynamics does not feel the forcing by the cavity acoustics. The cylinder imposes its own dynamics to the mixing layer in a way we try to explain.

Synthetic Jet Actuation at the Resonance Frequency

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(3) *Technical University of Eindhoven, Dept. of Mech. Eng., Divison of Thermo Fluids Engineering, Eindhoven, The Netherlands*

FM11S_12258
Tue • 14:55 • 307

An air round jet was generated by means of a zero-net-mass-flux actuator. Generation (synthesis) of the jet flow was tested experimentally by smoke visualization and hot-wire anemometry, and a satisfactory function was confirmed. The choice of suitable operating frequency was found by means of theoretical as well as experimental approach: the resultant 75 Hz was found near the theoretically derived resonance frequency as well as near the maximum measured time-mean velocity. The hot-wire data were decomposed using the phase-averaged technique. The experiments present a formation of the synthetic jet when fluid puffs travel downstream and the periodic component of the velocity gradually diminishes. The investigated, originally pulsatile jet resembles a conventional jet for the axial distance greater than 20 diameters from the orifice, where the streamwise decay of the centerline time-mean velocity is described by the proportionality with the exponent -1.04.

Reduction of Aerodynamic Noise Induced by Flow over a Cavity

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Department of Mechanical Engineering, Tohoku University, Japan

FM11S_12491
Tue • 15:00 • 307

An experimental study to develop effective methods to reduce the aerodynamic noise induced by a turbulent flow over a cavity at low Mach numbers is carried out. It is shown that noise reduction can be achieved by both an active flow control method using piezo-ceramic devices and a passive control method inserting a thin plate into the cavity. In the active flow control case, it is shown that the piezo-ceramic actuators are capable of modifying the phase of the oscillatory flow fluctuation leading to noise suppression. It is also shown that for noise suppressing purposes, the passive method to simply insert a thin flat plate in to the cavity can be more effective. However, by carrying out the experiments in two different sized facilities, it is found that the sound suppressing efficiency depends on the scale of the flow field.

Control of Turbulent Streaks by Active Wall Movement

Philippe Konieczny(1), Alexis Renotte(2), Bertrand Nogarede(2), Alessandro Bottaro(1)
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FM11S_12602
Tue • 15:05 • 307

Experimental results on the near-wall structures of turbulent boundary layers subject to a dynamic deformation of the wall are presented. The movement of the wall is based on computational evidence showing that a spanwise forcing in the form of a standing or travelling wave of the right amplitude, wave length and frequency can produce a significant turbulent drag reduction. This action is supposed to act on the near-wall coherent structures, whose dynamics controls the turbulence production. The control is first tested on a model of the near-wall turbulent boundary layer, streamwise vortices and streaks are produced artificially by an array of roughness elements in a Blasius boundary layer. The control in the form of a standing wave has been tested and work is in progress to appraise the effectiveness of a spanwise travelling wave. So far, it has been found that the most effective excitation wave has a period of oscillations close to 50 viscous units of time, in agreement with experimental and theoretical results on similar configurations. Future work will consider the effect of the actuation module in turbulent flows.

FM12

Flow in porous media

Chairpersons: A. Mojtabi (France), V. Nikolaevskiy (Russia)

Plastic Mass Flow of Sand Under Action of Pore Pressure Gradient

FM12L_11109
Tue • 17:00 • 327

Victor N. Nikolaevskiy
Head of Laboratory on Geomechanics of Schmidt Institute, Russia

Fundamental principles of elastic-plastic mechanics of soils and rocks are given on the base of the author original publications (1971) where non-associated fbw rule was developed for solid friction and dilatancy effects in now well-known form. Here the model of poroplasticity is suggested for fluid-saturated materials. The model generalizes the Frenkel–Biot poroelasticity but the solid matrix equilibrium is determined by the effective Terzaghi stresses. As usual, additional terms and equations are used for pore (fluid) pressure field. To illustrate the theory possibilities, some practical solutions for failure and mass sand fbw, driven by the pore pressure gradient, are selected. The sand production of oil/gas wells, disposal of wastes into weak artesian seams and computer design of the fracpack operation are discussed. The generalization of the Dupuit formulae is given for stationary regimes of well production. The self-similar solutions are permissible for basic unsteady regimes because the plasticity effects do not increase the physical dimensions of the problem.

Onset of Convection for a Miscible Fluid in a Porous Medium

FM12L_12617
Tue • 17:20 • 327

Robert Behringer, Michael Carey, Mark Steen, Laurens Howle
Duke University

We describe experiments and simulations for convection of a binary mixture saturating a porous medium. We consider negative separation ratios, ψ. Theory predicts oscillations at the onset of fbw. We have carried out experiments using Magnetic Resonance Imaging and shadowgraph techniques with high precision heat transfer measurements. In all cases, we observe a backwards bifurcation to steady convection rather than to oscillatory convection. Through modeling, we have investigated whether these observations are explained by enhanced mixing. Using a truncated version of the full equations, we find that for sufficiently strong enhanced mixing, the bifurcation changes from Hopf-like to backward (with a steady convective fbw at onset). We directly measure the strength of the enhanced mixing using NMR, and we find that it is much too small to account for the observations. Hence, the explanation for the difference between theory and experiment must be sought elsewhere.

Fractional Model for Solute Spreading in Randomly Heterogeneous Porous Media

FM12L_12376
Tue • 17:40 • 327

Kira Logvinova, **Marie-Christine Neel**
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Classical experimental results show that spreading of passive tracers in very heterogeneous soils does not always obey Fourier's law. A fractional partial differential equation is proposed for spreading of matter in a saturated porous medium, starting from precise hypotheses concerning the medium itself. Solute is assumed to spread according to Fick's law in intertwisted tubes whose slope and cross-section are randomly distributed. Then, the averaged concentration evolves according to a modified heat equation, including a non local operator which is a time derivative of fractional order, combined with a space derivative. The fundamental solution of the fractional equation has a second moment which is not proportional to time.

Dissolution in Porous Media: Upscaling, Instabilities and Heterogeneity Effects

FM12L_10234
Tue • 18:00 • 327

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Dissolution mechanisms in porous media are of paramount importance in many practical situations. This is the case, for instance, when considering acid injection in reservoirs, or NAPL (Non-Aqueous Phase Liquid) pollutant dissolution in aquifers, salt formation dissolution, ... When trying to model those phenomena, several important theoretical questions must be answered. The major question concerns the possibility of representing by macro-scale equations mass and momentum transfer in such systems. Because dissolution patterns are greatly affected by heterogeneity effects at all scales (pore-scale and small-scale heterogeneities leading to wormholing, large-scale heterogeneities, . . .), and because the dissolution process itself leads to transient evolution of the geometrical characteristics of the system, there is a great potential for non-local behavior in space and time. These questions are reviewed on the basis of recent theoretical, experimental, and numerical evidence. The status of Darcy-Scale and Core-Scale models is discussed based on: – theoretical arguments using averaging techniques, – direct numerical simulation of pore-scale and Darcy-scale problems, – experimental evidence (acid injection, salt dissolution, NAPL dissolution). It is shown that Darcy-Scale models have a sufficient potential for reproducing even unstable dissolution patterns in porous media, as well as some quantitative characteristics such as the optimum flow rate leading to the longest wormhole for a minimum acid consumption. Based on numerical results, the possible features of large-scale models is investigated. Finally, a weak solution to the problem of the impact of large-scale heterogeneities on dissolution models is presented in the case of NAPL dissolution.

Microscopic Simulations of the Dissolution of Rock Fractures

FM12L_11994
Tue • 18:20 • 327

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The results of numerical simulations of dissolution in fractured rocks are reported. The model is microscopic, with a detailed representation of the topography of the fracture. The velocity field in the fracture is assumed to be Stokes flow and is efficiently calculated with an implicit lattice-Boltzmann technique. The transport of dissolved species in the pore spaces is modelled by an innovative random walk algorithm that incorporates the chemical kinetics at the solid surfaces. The simulated morphological changes in a complex fracture are compared with laboratory experiments.

Numerical Investigation of Convective Regimes in a Planar Filtrational Convection Problem

FM12L_10199
Tue • 18:40 • 327

Vasiliy N. Govorukhin, Igor V. Shevchenko
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One-parameter families of steady-state convection regimes developing in the Darcy plane convection problem in a rectangular vessel are investigated numerically with increase of filtrational Rayleigh number and various aspect ratios of the container. The reason of the existence of these families is the cosymmetry. We consider Galerkin systems of various dimensions (up to 1000) for PDE approximation. The qualitative repetition of the bifurcations and consistency of the bifurcation parameter values was established by investigation of Galerkin's models of increasing dimensions for each set of the physical parameters. The loss of stability on a primary family, bifurcations of equilibrium families, periodic and chaotic regimes are studied. The fluid motion and heat transfer by convective regimes are also investigated.

Infiltration into Inclined Fibrous Sheets

FM12L_10671
Fri • 09:30 • 327

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Most medical absorbents, e.g. sanitary towels, incontinence pads and wound dressings, consist of fibrous sheets. We describe a detailed theoretical and experimental study of the capillary driven and source driven flows, through an inclined fibrous sheet. Fluid transport is modeled using Richards' equation which employs experimentally determined closure relations between pressure, moisture and permeability. Similarity and numerical solutions for the rate of spreading of wetted

regions and the moisture profiles are developed and agree with experimental measurements. The spread fluid from a point source on an inclined sheet may be described, for short time, by a similarity solution, with the down and cross slope width spreading in a diffusive manner. But for large time, we must appeal to numerical solution and an approximate model, which shows a pronounced asymmetry with down and cross-slope spreading. Extensions of the analysis and experiments to inhomogeneous layered and rewetting are described.

Confined Air-Liquid Drainage: Local Analysis and Invasion Percolation Model

FM12L_11343
Fri • 09:50 • 327

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This paper studies drainage of a wetting liquid by non wetting air between two confined rough solid surfaces. We focus on the limit of small Reynolds and capillary numbers. In this limit the viscous pressure drop is negligible and the pressure inside the liquid and the air is uniform. In this case the invasion process is controlled by the liquid-gas interface curvature, in keeping with Laplace law. The invasion of air in complicated geometries, is controlled by bottom-neck constrictions that the uniform pressure inside the air finger has to overcome. From convergence of asymptotic, numerical and experimental analyses, we found simple expressions for the air finger width and total curvature invading a single saddle-point as a function of its aspect ratio. The result of this local analysis is applied to a new invasion percolation numerical model which is compared to experiments involving drainage between complicated rough surfaces.

Double-Porosity Soils with Highly Conductive Inclusions: Modeling of Water Flow in Unsaturated Conditions

FM12L_11059
Fri • 10:10 • 327

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The paper presents a macroscopic model of water flow in an unsaturated double-porosity soil. The soil consists of highly conductive inclusions embedded in a much less conductive matrix. The flow at local scale in both sub-domains is governed by a nonlinear diffusion-type equation (Richards equation) for the capillary pressure. Application of the homogenization method by the asymptotic expansion leads to a one-equation macroscopic flow model with two effective parameters. The effective water capacity depends on the specific water capacities of the matrix and inclusions and their volumetric fractions. The effective conductivity tensor depends on the conductivity of the porous matrix and its local geometry. It is not influenced by the conductivity of inclusions. The domain of validity of the model is defined. An example of numerical simulation (REMOL_1D) is presented for the macroscopically 1D infiltration into an initially dry soil. The results obtained by homogenization are in good agreement with a fine scale solution where the local 2D heterogeneous structure is explicitly represented (SWMS_2D).

Instability and Dynamic Chaos of Non-equilibrium Filtration of Gaseous Liquid

FM12S_10548
Tue • 14:30 • 308

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In our paper we discussed stability conditions of stationary filtration below bubble point pressures in the case of non-monotonous dependence of the relative phase permeability of fluid on the gas saturation. This non-monotonic manifests itself in abrupt increase of relative permeability of the liquid phase when gassing starts to evolve. It was shown the existence of regular auto oscillations evolving into deterministic chaos through the induction and degradation of quasi-regular flow.

P-Waves Behavior at Transition from Liquid to Gas-Saturated Porous Media

FM12S_11115
Tue • 14:35 • 308

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According to the Frenkel-Biot theory, two P-waves can propagate in saturated porous medium. The 1st wave is faster wave and has small attenuation. The 2nd wave is slower, extremely damped wave. But, for gas-saturated media the situation can be changed. As Nikolaevskiy had shown, the 2nd wave is determined mainly by rock matrix deformation. For liquid

saturated media, a porous matrix deforms only if saturating fluid may flow through a pore system. The Darcy resistance creates extremely high attenuation. However, the saturating gas has high compressibility and therefore the matrix volume deformation becomes possible without gas flow. Correspondingly, such 2nd wave can have small attenuation. On the base of full linear dynamical equations of poroelasticity, the comparison of P-wave behavior for water and gas saturated media was performed. This confirms that for gas-saturated media the 2nd wave has low attenuation, but the 1st wave is extremely damped. Moreover, for gas-saturated media at low frequencies the wave dispersion radically differs from ones for liquid-saturated media. It is shown, such P-waves transformation happens if gas pressure exceeds some threshold value.

Nonstationary Flow of Stokesian Fluid through Elastic Skeleton with Hierarchical Structure

FM12S_11248
Tue • 14:40 • 308

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The aim of this contribution is to study the problem of nonstationary flow of Stokesian fluid through linear elastic porous skeleton. The novelty of the paper consists in that the skeleton is deformable and possesses a hierarchical structure. For simplicity, it is assumed that the porous matrix is characterized by two well-separated scales, namely ε and ε^2, where ε is a small parameter characteristic for the double-periodic microstructure. Two well-separated scales are typical for fractured reservoirs The homogenization method is based on multi-scale convergence, in this case three-scale convergence. Passing with ε to zero in the sense of this convergence we get the macroscopic relationships, included the generalized Darcy law. The last involves both scales and is nonlocal in time.

Non-Stationary Heat and Liquid Transport in Capillary-Porous Materials During Intensive Microwave Heating

FM12S_11323
Tue • 14:45 • 308

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The differential equations system for non-stationary moisture transport in capillary-porous materials during intensive microwave heating based on multiphase filtration law, Kelvin, Clapeyron-Clausius formulas, desorption isotherms of wet materials, Debye relaxation model is offered. The results of numerical computer simulation are submitted to show the time evolution of temperature, moisture content, vapor pressure and strength of microwave in sample.

Non-Stationary Flow of Flexible Chain Polymer Solutions in Porous Medium

FM12S_11342
Tue • 14:50 • 308

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Theory of elastic deformation effects for the flow with stretching of flexible chain polymer solutions predicts a higher degree of porous medium inclusion to be achieved by non-stationary flooding of polymer solution into it. In order to justify this prediction water solutions of polyethilenoxide were studied under conditions of non-stationary flow with stretching. Conducted experiments proved the accuracy of theoretical prediction.

A Joule-Thomson Process of a Wetting Fluid Near Saturation

FM12S_11487
Tue • 14:55 • 308

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The flow of a fluid with a positive Joule-Thomson coefficient through a porous membrane is considered. Upstream of the membrane, the fluid is in the state of saturated vapor. Downstream of the membrane there is cooler, unsaturated vapor. Because a saturated vapor cannot simply cool down without condensation, fronts of phase change occur. The process is described assuming local thermodynamic equilibrium and an ideally wetting liquid phase. For a sufficiently small permeability of the membrane the fluid condenses fully at the upstream front of the membrane. Liquid flows through the membrane and evaporates completely at a front within the membrane. For very small permeabilities the fluid condenses upstreams and a liquid film forms in front of the membrane. Characteristic quantities are the critical permeability, $\kappa_c = \nu_l T_1(v_g - v_l)k_l/\Delta h^2_{lg}$, and a capillary number, $\mathrm{Ca}_{JT} = \mu_{JT}(\mathrm{d}p_s/\mathrm{d}T)(\Delta p_{12}/\Delta p_{cap,c})$.

Advances in Mathematical Modeling of Hydraulic Stimulation of the Hot Dry Rock Geothermal Reservoir

FM12S_12456
Tue • 15:00 • 308

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Hydraulic stimulation is an effective method of enhancing hot dry rock geothermal system productivity. The 3D structure of the fractured rock is approximated by the network model of “fractal geometry”, which is generated by distributing fractures randomly in space and assuming the fractal power-law equation for correlating the number of fractures and fracture length. This procedure makes it possible to characterize the geothermal reservoirs using parameters measured from field data. The proposed mathematical model accounts for normal and shear stresses in the rocks, fluid pressure variation and fracture dilation caused by fracture shear offset. Along with the fractal-type distribution of the fracture lengths, the fracture surfaces are also assumed to follow fractal geometry. Taken together, these tools permit the approximate engineering resolution of the multi-parametric, highly complex mechanical problem. The reliability of the developed model was validated by comparisons with the experimentally determined data for the Hijiori Deep Reservoir, Japan.

Oscillatory Modes of Adsorption in the Flow of Multicomponent Systems

FM12S_12528
Tue • 15:05 • 308

Liana Kovaleva, Marat Mavletov
Bashkir State University, Russia

The flow of a multicomponent hydrocarbon system, including n surface-active components, diffusing in the porous space of a medium and simultaneously adsorbing on its surface is considered. Experimental investigations of adsorption phenomena in multicomponent systems show the presence of competing effects, which lead to a mutual influence of the components on the degree of adsorption of each of them. An equation of sorption kinetics, which describes a series of oscillatory modes for certain values of the original parameters, is suggested. The formulated problem was solved numerically by a difference method and using the checkerboard scheme. All the results obtained can be divided into two classes: (1) solutions of the traveling concentration wave type, and (2) solutions corresponding to the various oscillatory processes. Regions of existence of solutions (1) and (2) was found

Extended Description of Pore Space Structure and Fluid Flow through Anisotropic Porous Materials

FM12S_12611
Tue • 15:10 • 308

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This work concerns modelling of mechanical behavior of fluid in porous materials with anisotropic pore space structure. A new macroscopic description is proposed in which the motion of fluid in anisotropic pore space of skeleton is considered as a motion of material continuum in Minkowski (anisotropic) metric space. The applied model of pore space enabled obtaining an extended and self consistent description of pore structure and precise definition of its scalar and tensorial parameters. The formulated balance equations and constitutive relations for stress tensor in fluid and interaction force with skeleton allowed one to derive the generalized equations for wave propagation and the generalized Brinkman and Darcy equations describing fluid flow in porous materials with extended characteristics of pore structure anisotropy and nonsymetric filtration properties.

FM13

Flow instability and transition

Chairpersons: P. Monkewitz (Switzerland), P. Huerre (France)

Travelling Waves and Transition to Turbulence in Pipe Flow

FM13L_10313

Wed • 08:30 • 315

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At critical Reynolds numbers as low as 1250 3-d travelling wave solutions have been found in pipe flow. The waves are dominated by pairs of downstream vortices and associated streaks. The wave with the lowest critical Reynolds number has 3 pairs, but others with 2 to 5 pairs have been found as well. The states are unstable, but can be detected in direct numerical simulations and seem to be responsible for the formatin of a chaotic saddle that dominates the transition to turbulence. In particular, the life time of perturbations show strong fluctuations, and can well be described by an exponential distribution, in agreement with the chaotic saddle picture. The median life time increases rapidly and becomes inaccessibly large for Re about 2250.

Stability of Flow in a Rough Channel

FM13L_10489

Wed • 08:50 • 315

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Stability of a two-dimensional flow in a channel with distributed surface roughness is considered. The reference geometry is defined as two-dimensional channel with one rough wall. The roughness is represented by a Fourier expansion. Explicit results are given for two case studies, i.e., roughness represented by a single Fourier mode (wavy wall model) and roughness in the form of spanwise grooves (grooved wall model). It is shown that the critical roughness wave number decreases from about 35 at roughness amplitude 0.001 to about 10 at roughness amplitude 0.01 in the case of wavy wall model. Analysis of grooved wall model shows that a very good approximation of the critical Reynolds numbers can be determined using only the dominant Fourier mode used to represent roughness geometry. Measurements carried out in the wavy wall case confirm theoretical predictions.

Stability of Lagrangian Ideal Flows

FM13L_10525

Wed • 09:10 • 315

Stephane Leblanc
LSEET, Université du Sud Toulon-Var, France

A general method is presented to investigate the stability of ideal incompressible flows described in Lagrangian representation. Based on the theory of short-wavelength instabilities, the problem is reduced to a transport equation which involves only the distortion matrix of the equilibrium flow. Theory is applied to Gerstner's rotational free-surface gravity waves. It is shown that they are three-dimensionally unstable when their steepness exceeds 1/3.

Instability Thresholds of Flow Between Exactly Counter-Rotating Disks

FM13L_10640

Wed • 09:30 • 315

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(2) *Université d'Evry, Evry, France*

The von Karman flow engendered by the differential rotation of the upper and lower bounding disks of a cylinder exhibits a large variety of phenomena, and depends on three parameters, an angular velocity ratio, an aspect ratio and a Reynolds

number. This flow is of growing interest to fluid dynamicists, but its three-dimensional patterns and transitions have as yet been explored for only a few parameter combinations. We present the linear three-dimensional instabilities of the flow between exactly counter-rotating disks for height-to-radius aspect ratios between 0.5 and 3. The lowest Reynolds number threshold always corresponds to a non-axisymmetric and stationary eigenmode and the critical azimuthal wavenumber is approximately proportional to the radius. The axisymmetric instabilities are quite complicated, and are organized around various codimension-two points.

Transient Growth in Developing Plane and Hagen Poiseuille Flow

FM13L_10916
Wed • 09:50 • 315

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The problem of the stability of developing entry flow in both two-dimensional channels and circular pipes is investigated. The basic flow is generated by uniform flow entering a channel/pipe, which then provokes the growth of boundary layers on the walls, until (far downstream) fully developed (Poiseuille) flow is attained; the length for this development to be O(Reynolds number) $\times$ the channel/pipe width/diameter. This enables the use of high-Reynolds-number theory, leading to boundary-layer-type equations; as such there is no need to impose heuristic parallel-flow approximations. The resulting flow is shown to be susceptible to significant, three-dimensional transient (initially algebraic) growth in the streamwise direction, and as such large amplifications to flow disturbances are shown to occur (followed by ultimate decay far downstream). It is suggested that this initial amplification of disturbances is a possible mechanism for flow transition, with steady disturbances being the most 'dangerous'.

Three-dimensional Global Modes in Spatially Varying Rayleigh–Bénard–Poiseuille Convection

FM13L_11186
Wed • 10:10 • 315

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Above their critical threshold, the thermo-convective instabilities rising in a laminar Poiseuille flow heated from below by a two-dimensional bump of temperature may self-tune to precise temporal frequencies despite the spatially varying base flow. In cases where these variations are slow, such instabilities are analytically sought as travelling rolls with slowly spatially varying amplitudes and wavevectors. Furthermore, the existence of turning points where the group velocity of an unstable mode vanishes yields an analytical selection criterion for these instabilities and their respective frequencies. The most unstable linear modes and their critical conditions obtained by this method are compared with the results of direct numerical simulations of the Navier–Stokes equation under the Boussinesq approximation. The issue of the nonlinear behaviour of these instabilities is then addressed.

Elliptical Instability in a Rotating Spheroid

FM13L_11396
Wed • 11:00 • 315

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This study concerns the elliptical instability of a flow in a rotating deformed sphere. The aim of our work is to observe and measure the characterics of this instability in experiments and to compare them with theorical predictions. For this purpose, an elastic and transparent hollow sphere has been moulded. The flow is visualised using Kalliroscope flakes as the sphere is set into rotation and compressed by two rollers. The elliptical instability occurs by the appearance of the so-called 'spin-over' mode whose growth rates and saturations are measured for different Eckman numbers by video image analysis. These growth rates compare avantageously to theoretical calculations which are performed using classical asymptotic expansions. The linear analysis is then completed by a non linear model which predicts correctly the asymptotic regimes for high Eckman numbers.

The Instability of a Localized Vortex Disturbance in Uniform Shear Flow

FM13L_11461

Wed • 11:20 • 315

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The objective of the present numerical (and theoretical) study is to examine the capability of a simple model of interaction, between a localized vortical disturbance and laminar uniform unbounded shear fbw, to reproduce the generation mechanism and characteristics of the coherent structures (streaks and hairpin vortices) that naturally occur in turbulent (and transitional) bounded shear fbws. The results demonstrate that a small amplitude initial disturbance eventually evolves into a streaky structure, whereas a large amplitude disturbance evolves into a hairpin vortex, independent of its initial geometry. Main non-linear effects are: relative movement of the vortical structure, destruction of its streamwise symmetry, and its alignment with the vorticity lines (which in the linear case is poor). The optimal spanwise spacing (producing the maximal transient growth) between two concentrated vorticity regions (expressed in wall units) corresponds well to the spacing of streaks in turbulent boundary layers. Finally, the numerical results will be discussed with respect to relevant theories.

Subcritical Transition to Turbulence in Plane Couette Flow

FM13L_11647

Wed • 11:40 • 315

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We present results of numerical simulations of a model of plane Couette fbw derived from the Navier–Stokes equations by truncation of an appropriate Galerkin expansion. The model mimics its basic properties, especially conservation of kinetic energy by nonlinear terms, linear stability for all Reynolds numbers and direct transition to turbulence beyond some global stability threshold. Simulations using a pseudo-spectral numerical scheme have been performed in a large enough periodic box. Here we focus on the nucleation and development of turbulent domains from spots around that threshold. Before merging into featureless turbulence, they form oblique turbulent stripes well separated from laminar domains by propagating sharp fronts, thus giving insight in the transition to turbulence via spatio-temporel intermittency in extended subcritical systems.

Three-Dimensional Vortex Breakdown in Swirling Jets and Wakes

FM13L_11995

Wed • 12:00 • 315

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Vortex breakdown of nominally axisymmetric, swirling incompressible fbws with jet- and wake-like axial velocity distributions issuing into a semi-infi nite domain is studied by means of direct numerical simulations for a two-parametric initial velocity profi le. Highly swirling fbws at large Reynolds numbers exhibit bubble, helical or double helical breakdown modes. It is shown that a transition from super- to subcritical fbw, as defi ned by Benjamin (1962), accurately predicts the parameter combination yielding breakdown, if applied locally to fbws with supercritical infbw profi les. The basic form of breakdown is found to be axisymmetric, and a transition to helical breakdown modes is shown to be caused by a suffi - ciently large pocket of absolute instability in the wake of the bubble, giving rise to a self-excited global mode. Two distinct eigenfunctions corresponding to an azimuthal wavenumber m=-1 and m=-2 have been found to yield a helical or double helical breakdown mode, respectively.

By-pass Laminar–Turbulent Transition of the Wind-Driven Free Surface Flow

FM13L_12233

Wed • 12:20 • 315

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The laminar-turbulent transition of wind-induced spatially developing surface boundary layer in water at the entrance of a water tank is investigated experimentally. Observations of the velocity fi eld were made both by fbw visualisation techniques using dye injection and laser Doppler velocimeter measurements. Two stages in the development of the perturbations have been clearly identifi ed. First, a slow growth of streamwise longitudinal vortices embedded into the laminar fbw is followed by a rapid development of secondary instabilities till to breakdown. The picture is similar to the by-pass transition to

turbulence of a rigid plate boundary layer. At the second stage, peculiar to this flow, an explosive deepening of the boundary layer and fast development of inflexional instabilities occur. The critical fetch, where the shear boundary layer collapses and the first turbulent spots appear, is not linked to any critical Reynolds number but was found to be inversely proportional to the friction velocity squared.

Large-Eddy Simulation of the Transitional Flow in Natural Convection in a Horizontal Annulus

FM13L_12250
Wed • 12:40 • 315

Elie L.M. Padilla, **Aristeu Silveira-Neto**
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Three-dimensional analysis of the transitional flow in natural convection in horizontal cylindrical annulus was performed, using Large-Eddy Simulation methodology with dynamical sub-grid scale model. The finite volume method is applied in cylindrical coordinates with an staggered grid. The second order Adams-Bashforth temporal scheme and the second order central-difference spatial scheme were used. The governing equations were solved with a fractional time-step method, employing the following boundary conditions: non-slipping and impermeability in the radial direction and periodicity in the tangential and axial directions. The time-step is conditioned by the CFL criterion. The beginning of the transition process and the beginning of turbulent regimes is indicated. The characteristics of the oscillatory and the influence on heat transfer coefficient were analyzed. The results showed that coherent structures exist in this type of flow.

On Instability Mechanisms in a Separating Boundary-layer Flow

FM13L_12372
Thu • 11:00 • 315

Matthieu Marquillie, **Uwe Ehrenstein**, François Gallaire
Lab. J.A. Dieudonné, Université de Nice-Sophia Antipolis, France

The stability of separating boundary-layer flow at the rear of a bump mounted on a flat plate is numerically investigated. It is shown that a geometrically controlled, short separation bubble exhibits a global instability consisting of self-sustained two-dimensional saturated perturbations oscillating at a well defined frequency. Local stability analyses confirm that this instability is triggered by a transition from local convective to local absolute instability in the separation bubble. Solving the three-dimensional Navier–Stokes equations, the flow field is shown to exhibit a three-dimensional steady structure well below the critical Reynolds number for the onset of two-dimensional self-sustained oscillations. Regions subject to centrifugal instability due to streamline curvature are detected, considering the Rayleigh discriminant: some evidence is given that the counter-rotating three-dimensional streamwise vortex structure originates from a potentially unstable region nearby the bump-summit.

Spiral Vortex Breakdown as a Global Mode

FM13L_12425
Thu • 11:20 • 315

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Non-axisymmetric vortex breakdown states observed in the numerical simulations of Ruith, Chen, Meiburg and Maxworthy (J. Fluid Mech. 486: 331-378, 2003) are interpreted as the result of local instability of the unstable axisymmetric breakdown serving as spatially varying baseflow. A local stability analysis demonstrates that the azimuthal mode m=1 is absolutely unstable in the wake region of the breakdown bubble. The corresponding frequency at the convective-absolute transition location is in excellent agreement with the naturally selected frequency obtained in the direct numerical simulations. This suggests that the breaking of symmetry of vortex breakdown may be interpreted as a nonlinear steep global mode in the wake of the bubble.

Computational Study of Turbulent–Laminar Bands in Couette Flow

FM13L_12431
Thu • 11:40 • 315

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Recent experiments by Prigent and Dauchot have shown that the remarkable spiral turbulence state of Taylor-Couette flow also occurs in plane Couette flow. In both cases, a pattern of alternating turbulent and laminar bands appears at a well-defined Reynolds number. The pattern is tilted with respect to the streamwise (or azimuthal) direction and its wavelength is much larger than the gap; the angle and wavelength depend systematically on Reynolds number. We have numerically simulated these turbulent-laminar patterns for plane Couette flow. In our computational approach, we replace the very large lateral dimensions of the experiment by a narrow and periodically repeating rectangle which is tilted with respect to the streamwise direction. In this way we determine which angles and lengths support turbulent bands.

A Generic Mechanism for By-Pass Transition in Vortices

FM13L_12483
Thu • 12:00 • 315

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Vortices are common structures that can be found in a wide variety of flows, ranging from industrial to geophysical ones. There has been in the literature several studies investigating the instabilities of vortices induced by the presence of an external strain field or an axial jet in the vortex. Yet, the only studies concerning an isolated vortex (axisymmetric monopole) all seemed to predict the damping of disturbances injected in such a swirling flow and long-time re-axisymmetrization of the vortex, though rare but violent disruptions cases have been reported. In a recent paper, we have shown the possibility for an azimuthal wavenumber-one (m = 1) spiral-shaped disturbance lying in the periphery of a vortex to be amplified and capable of contaminating the core of the vortex, producing a strong bending wave. In the present work, we will investigate $|m| \neq 1$ optimal perturbations, whose linear growth via the Orr mechanism is associated with the transient production of a multipolar strain field in the core region. The nonlinear evolution and the possible secondary instability leading to transition will also be sketched.

Acoustic Field Generated by Instability Waves in the Transonic Regime

FM13L_12509
Thu • 12:20 • 315

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We consider the problem of acoustic radiation generated by a spatial instability wave on a weakly-developing two-dimensional mixing layer. Assuming a WKBJ approximation for the instability wave, we compute the far pressure field by using a Fourier transform along the streamwise direction. Approximations for this pressure field are obtained by a steepest descent method when the WKBJ parameter goes to zero. A branch cut and several saddle points are shown possibly to contribute to the approximation. A detailed analysis of these contributions is provided when the instability wave is close to transonic near its maximum amplitude. This permits to explain the modifications of the far pressure field observed during a subsonic-supersonic transition.

Nonlinear Transition of a Flow Driven by a Rotating Magnetic Field

FM13L_12542
Thu • 12:40 • 315

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Non-normal nonlinear transition of a linearly stable liquid metal flow driven by a rotating magnetic field is simulated numerically. Three dimensional Navier–Stokes equations are solved by a highly accurate spectral methods. Response of the flow to noise is simulated introducing a random body force. We observe four flow regimes. At a low control parameter the flow response does not differ from the response of a fluid at rest. In the second regime the amplitude of response is considerably higher though it scales linearly with the noise amplitude. Nonlinear intermittent outbursts are observed in the third regime. Duration of outbursts increases with noise amplitude until they merge in a continuous series in the fourth regime. We demonstrate that direct numerical simulation of the flow response to random forcing can uncover mechanisms which lead to transition in linearly stable flows.

Stability of Stratified Shear Flows with a Monotonic Velocity Profile without Inflection Points

FM13S_10917
Tue • 14:30 • 327

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In the two-layer model of a stably stratified medium we investigate the stability of flows without inflection points on the velocity profile, which monotonically increases from zero at the bottom ($y = 0$) to the maximum value of U_0 (when $y \to \infty$).

It is shown that in general, instability sets in at an arbitrarily small density difference, and perturbations of all scales grow simultaneously. With an enhancement of the stratification, the real part c_r of the phase velocity of unstable perturbation increases. The upper boundary of the instability region is determined by the fact that c_r reaches U_0, the perturbation becomes out of the phase resonance with the flow and transforms to a neutral oscillation of the medium. An analysis is made of the role of the neutral modes associated with null-curvature points on the velocity profile in the formation of the instability region configuration.

Shear Layer Instability and Frequency Modes Inside an Open Cavity

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FM13S_10188
Tue • 14:35 • 327

The dynamic behaviour of the vortex structures occurring in a cavity in interaction with an upstream boundary layer, drives the flow confinement inside the cavity. The vortex structures present small scales as well as large scales related to the instability of the shear layer which connects the main flow to the cavity flow. However, the frequency modes measured also depend on the characteristic sizes of the cavity. This presentation concerns the coupling between the mechanisms of shear instability and the mechanisms of frequency selection depending on the size of the cavity. The analysis is based on an experimental exploration of the flow (LDV, PIV) and on numerical simulations.

A New Convective Instability with Growth Normal to a Boundary Layer

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FM13S_12150
Tue • 14:40 • 327

Lingwood's (1995) Briggs-Bers spatio-temporal instability analysis of the rotating disc boundary layer has been repeated in the inviscid limit. For long enough waves, we find that one spatial branch crosses both the real and imaginary axes of the complex wavenumber plane. Such waves have exponentially diverging eigenfunctions in the wall-normal direction. A saddle-point analysis has been developed describing the behaviour of disturbances in the wall-normal direction which predicts a new type of convective instability in which the disturbance grows as it propagates normal to, i.e. out of, the boundary layer. But surely such modes are unphysical as they don't satisfy homogeneous boundary conditions. A numerical integration of inverse Fourier transforms of an impulsive forcing has been carried out, with integration countours chosen such that all modes decay exponentially. Nonetheless, their collective behaviour produces exponential growth in the wall-normal direction.

Fully Nonlinear Global Modes and Transition to Turbulence in Open Flows

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FM13S_12711
Tue • 14:45 • 327

The fully nonlinear theory of global modes in open flows, proposed in recent analyses of amplitude equations, is extended to the case of Navier–Stokes equations using direct numerical simulations. The basic flow under consideration is in a first time, a parallel wake in a finite domain generated by imposing the wake profile at the inlet boundary and by adding a body force to compensate the basic flow diffusion. The link between the global bifurcation, the absolute or convective nature of the local linear instability, and the theory of speed selection for the front separating an unperturbed domain of the flow from a fully saturated solution is elucidated. New scenarii involving secondary absolute instability are proposed and compared to the dynamics of mixing layers simulations conducted in the same spirit as for the wake.

On the Nature of Virial Liapunov Functional in Hydrodynamic Instability

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FM13S_11971
Tue • 14:50 • 327

There is a persistent myth of 'irrationality' of 'virial' Liapunov functionals used in proofs of fluid instability. The aim of the paper is to address that issue and to produce the unifying and systematic concept on introducing of 'virials'. Our 'virial' can be introduced via the second variation of Lagrangian, and correspondent 'virial equality' is closely linked to the Jacobi equation for deviations of geodesics. This link explains the nature of 'virial' as Liapunov functional. It may be considered as the 'distance' between two geodesics corresponding to the main flow and perturbed flows. New applications of 'virials' to instabilities both states of rest ('converse Lagrange theorems') and flows ('horseshoe instability' and 'Arnold's instability') are considered and further perspectives are discussed.

Nonlinear Stability of Rotating Channel Flow

FM13S_12291
Tue • 14:55 • 327

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The stability of Poiseuille flow in a channel subject to a system rotation about a spanwise axis has been considered. Linear stability results show that the basic flow first loses its stability to a two-dimensional streamwise-independent disturbance. We have found two-dimensional nonlinear secondary flows, and have analysed their stability. The secondary flow may lose stability to a variety of secondary disturbance modes including two-dimensional steady Eckhaus modes, and three-dimensional travelling-wave modes, which do not exist for the equivalent Couette problem. We proceed to find three-dimensional nonlinear travelling-wave tertiary flows which bifurcate from the secondary flows upon the loss of their stability. We succeeded in finding three distinct classes of these flows, including flows which resemble the twisting vortex flows observed in previous experimental and direct numerical simulation (DNS) studies.

Stability of Plane Poiseuille Flow and Energy Growth in the Case of a Bingham Fluid

FM13S_12766
Tue • 15:00 • 327

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The present work examines the stability of three-dimensional pertubation of Poiseuille flow of Bingham fluid. The principal characteristic of the basic flow is the presence of the plug zone, which moves as a rigid solid. The movement of the interface between the yielded and the unyielded zones depend only on the shear stress in the yielded zone. A Chebychev collocation method is applied within a temporal stability framework to compute eigenvalues and maximum transient amplification factor. It is found that Poiseuille flow of Bingham fluid is linearly stable, and for sufficiently large Reynolds, the least stable mode is an interfacial mode. Due to the non-normality of the operators, transient amplification of the disturbance kinetic energy is observed. The results show that amplification factor decreases with increasing the Bingham number B. Conditions for no energy growth are then determined. When B»1, it is shown that the critical Reynolds number increases as the square root of B. This result is compared with the conditional stability based on an energy method (Nouar and Frigaard in 2001).

Influence of Swirl Vibrations on Flow in Long Cylinder

FM13S_12280
Tue • 15:05 • 327

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The object of our consideration is linear stability of azimuthal flow of incompressible viscous fluid within an infinitely long cylinder subjected to swirl vibrations. The boundary velocity varies harmonically with time at a moderate frequency. In this system the most excitable perturbations are found to be axisymmetric at low and moderate (up to frequencies providing the oscillatory Stokes layer thickness $\simeq 1/10$ cylinder radius) frequencies. At the high-frequency limit and at large enough moderate frequencies, non-axisymmetric perturbations uniform along cylinder axis are most excitable. The Floquet solutions are proved to be able to have a negative multiplier only as the particular case of a pair of complex multipliers, and in this case the negative multiplier is doubly degenerated. The perturbations are classified with respect to their solution spatial and temporal symmetry properties; and the different parametric resonances are found to correspond to most effectively exciting perturbations of the different classes.

Nonlinear Mechanics of Wavy Instability of Steady Longitudinal Vortices and Drag Rise in Boundary Layer Flow

FM13S_10487

Tue • 15:10 • 327

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Wavy secondary instability of steady longitudinal vortices in boundary layer flow is studied. The nonlinear interaction problem is parabolized through scaling obtained from observations. Emphasis is placed on the nonlinear modification of the steady, averaged problem by the Reynolds stresses of the wavy disturbance. It is found that the skin friction in such a modification process increases well above the local turbulent boundary layer value.

Gortler Vortex Secondary Stability: Varicose Mode

FM13S_12381

Tue • 15:15 • 327

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The growth of Goertler vortices in boundary layers over concave surfaces is responsible for the strong distortion of the velocity profile in the normal and spanwise directions. The resulting inflectional velocity profiles are subject to secondary instability which may result in the development of horseshoe vortices. This type of secondary instability is known as the varicose mode. In the present study the varicose mode is investigated using direct numerical simulation. The governing equations based on the vorticity-velocity formulation are solved using compact finite differences in the normal and longitudinal directions. In the spanwise direction the flow is assumed periodic. A Runge-Kutta time marching scheme was use to integrate in time. The results obtained were compared with secondary stability theory results from other authors, and with experimental results. The results were in good agreement with secondary stability theory and experimental data.

Instabilities in a Taylor–Dean Open Flow

FM13S_10185

Tue • 15:20 • 327

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The flow studied hereafter is produced in a system of two coaxial circular cylinders azimuthally opened. It is a combination of the inner cylinder rotation and a flow provided in the gap by external pumping. Our observations, however, indicate that the flow possesses certain distinctive features not present in the pure rotation of closed cylinders (Taylor-Couette flow) neither in the pure pumping (Dean flow). During the laminar-turbulent transition, for a wide range of τ, the ratio of pumping and rotation flow rates, the flow undergoes a series of instabilities giving rise for local or global patterns. These new regimes will be presented.

Global Stability of the Flow Induced by Wall Injection

FM13S_12508

Tue • 15:25 • 327

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The linear stability study of the Taylor flow is led with perturbations evolving in two space directions, corresponding to the stream-plane, instead of the usually used single direction for stability study. Thanks to this approach, the spectrum of the stability modes is found to be discrete what allows a better comprehension of the thrust oscillations of large solid propellant motors, whose internal flow can be represented by the flow induced by wall injection of fluid, since particular frequencies are established. The eigenfunctions exhibit particular points, comparable to amphidromic points when studying the tide of the seas. These points may be a reason of the quasi-exponential spatial growth of the perturbations (unstable flow) and whose presence may be due to the curvature of the streamlines of the Taylor flow.

Instability of the Far Wake Behind a Wind Turbine

FM13S_13019

Tue • 15:30 • 327

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A stability analysis of the far wake behind a N-bladed wind turbine has been carried out. In conflict with experimental data, previous studies based on stability analysis of point vortices predicted instability at all operating conditions. In the present study the wake description is based on a $(N+1)$-vortex model consisting of N helical tip vortices and a hub vortex, exposed to a constant axial velocity field. An algebraic solution is obtained that provides for an efficient analysis of motion and stability of the $(N+1)$ vortex systems covering a range of helical pitch variations. The stability properties depend basically on vortex strength, helical pitch and vortex core radius. To relate these properties to the operating conditions of a wind turbine, they are approximately expressed in terms of thrust coefficient and tip speed ratio. In accordance with experiments, the far wake is shown to consist of both stable and unstable flow regimes.

Scaling with Freestream Fluctuations in the Laminar–Turbulent Transition Process

FM13S_10952

Tue • 15:35 • 327

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It has been known for a century now that transition to turbulence is delayed when background disturbances are decreased. In boundary layers in quiet tunnels, the transition onset Reynolds number and the amplitude of freestream disturbance are related by a power law, with an exponent of -1. Recent experiments in pipe flows too show a power-law relationship between these two quantities, with the same exponent. We investigate here the relationship between background disturbance amplitude and the critical Reynolds number for a precursor to transition onset, namely, secondary disturbance growth in a channel. For each primary mode, the Reynolds number for a given secondary growth rate is found to obey a power-law with a frequency and growth-dependent exponent. The exponents are negative with magnitudes less than 1; the envelope of instability has an exponent close to -1. We conlude with the surprising observation that critical Reynolds numbers defined using the *disturbance velocity magnitude* as scale, are constant in all these cases.

Linear Stability of the Incompressible Swept Hiemenz Flow: a 2D Model

FM13S_12653

Tue • 15:40 • 327

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Swept attachment-line linear stability cannot be handled with a parallel theory. A more complex approach is undertaken which leads to an eigenvalue problem, written as a partial differential equations system. Discretization is based on a spectral collocation method in two directions and an Arnoldi iterative algorithm is used in order to obtain the eigenvalues. The classical Goertler-Haemmerlin (GH) mode is retrieved as the most amplified one. A series of least amplified modes, alternately even and odd, close to the GH mode, is mentionned in previous works. The sensitivity of these modes to outflow boundary conditions and towards chord computational domain are discussed.

Supersonic Boundary-Layer Response to Freestream Disturbances

FM13S_12598

Tue • 15:45 • 327

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The prediction of the location and extent of boundary layer transition is a major issue for the design and control of supersonic flight vehicles. Blunt bodies generate detached bow shocks thereby adding complexities to the flow field. The resulting high pressure gradient and entropy layer change the characteristics of the boundary layer and the dynamics of shock-boundary layer interactions. Our presentation consists of three parts: computation of steady base flow, linear stability analysis, and receptivity simulations. The steady viscous flow field around a blunt flat plate at $M_\infty = 2.5$ is numerically simulated by solving the full Navier–Stokes equations using a multi-domain spectral collocation method. Linear stability analysis is carried out on the steady base flow. Receptivity simulations are related to planar freestream fast acoustic disturbance waves, which are imposed on the steady base flow. The analysis covers the interaction of disturbances with the shock wave and the receptivity of the boundary layer.

FM14

Flow in thin films

Chairpersons: N. Aksel (Germany), V. Shkadov (Russia)

Effect of Bottom Undulations on the Stability of Film Flow Down Inclined Planes

FM14L_10642
Tue • 11:00 • 315

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We study the effect of bottom undulations on the stability of a stationary film flow down inclined planes. Allowing for rather moderate bottom variations, we carry out a linear stabil-ity analysis and show how the wavy bottom affects the instability. Contrary to results for weakly undulated bottoms described in literature, where the instability is identical to that over a flat incline, we obtain an increase of the critical Reynolds number and a smaller un-stable frequency spectrum with respect to the flat bottom in accordance with experimental observations.

Hydrodynamics of the Solitary Waves Travelling Down a Liquid Film

FM14L_12656
Tue • 11:20 • 315

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The regular solitary waves on the surface of a liquid film flowing down an inclined stationary plate were excited by means of the flow rate pulsations. The direction sensitive, two-segment electrodiffusion probe was flush mounted into the wall to measure the fluctuating wall shear rate. The results of electrodiffusion measurements provided some basic characteristics of the wavy flow regime and confirmed the existence of a small backflow region located just in front of the solitary wave. To confirm independently this finding, the high-speed camera together with microscopic objectives was installed to carry out the particle tracking velocimetry inside the flowing liquid film. The visualization of small particles motion in the near-wall region revealed that the capillary waves provoke strong pulsations of the near-wall flow velocity. These successively growing flow pulsations finally result in the short-time flow reversal, which has the duration of a few milliseconds.

Solitary Waves on Liquid Film Flowing Along a Periodic Wall

FM14L_10557
Tue • 11:40 • 315

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The characteristics of solitary waves, travelling along a wall with orthogonal corrugations at right angles to the flow direc-tion, are studied experimentally and are set in perspective with their counterparts over a flat wall. Large disturbances are introduced at the inlet, and lead to the formation of more ordered wave trains. The shape of each solitary hump is influenced by the periodicity of the wall, through its interaction with the statically deformed free surface that corresponds to the base flow without waves. At high Re, travelling waves recede in favor of a stationary three-dimensional free surface structure, consisting of transverse series of depressions along the corrugation troughs. This phenomenon has no counterpart in film flow along a flat wall.

Hydraulic Jumps and Resonance in Gravity-Driven Flows of Liquid in Inclined Wavy Channels: Transition and Hysteresis

FM14L_10928
Tue • 12:00 • 315

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We study the flow of a viscous liquid down an inclined channel with a sinusoidal bottom profile of moderate waviness. At low inclination angles, where basins form due to non-monotonous falling bottom slopes, we observe the formation of stationary hydraulic jumps in the form of shock fronts and surface rollers. There exists a bistable region in which both jump

phenomena, shock fronts and surface rollers, can occur. At the low end of the bistable region, an instationary regime of a shock with a fingering-like lateral modulation is found. At higher volume flux and inclination angles, the hydraulic jump is suppressed by a standing wave that is generated by a resonance between gravity waves and the wavy bottom. At the transition between surface rollers and standing gravity-waves, periodic switching between the two occur.

Drifting and Merging Collars in Liquid-Lined Tubes

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FM14L_11799
Tue • 12:20 • 315

Lubrication theory is used to describe the evolution under surface tension and viscosity of an axisymmetric air-liquid interface in a long, liquid-lined tube. Growing liquid collars of baselength pi are formed, and are separated by draining lobes (baselength < pi). These structures and their interactions are investigated, leading to a new similarity solution to the thin-film equation. The presence of this similarity solution suggests that a draining lobe may sometimes act as a barrier, prohibiting the free flow of fluid between the two collars and hindering any potential merging of the collars. The similarity solution is investigated both numerically and analytically, and an approximate asymptotic prediction of the draining lobe is constructed. We also show that the direction of drift of a single fluid collar is dependent on the minimal height at the collar's edges, with the collar drifting in the direction of the greater minimal height.

Hydrodynamic Theory of De-Wetting

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FM14L_11089
Tue • 12:40 • 315

A prototypical problem in the study of wetting phenomena is that of a solid plunging into or being withdrawn from a liquid bath. In the latter, de-wetting case, a critical speed exists above which a stationary contact line is no longer sustainable and a liquid film is being deposited on the solid. Demonstrating this behavior to be a hydrodynamic instability close to the contact line, we provide the first theoretical explanation of a classical prediction due to Derjaguin and Levi: instability occurs when the outer, static meniscus approaches the shape corresponding to a perfectly wetting fluid.

Layer Thickness Distribution of Thin-Film Ink-Jet Printed Structures.

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FM14L_11509
Wed • 11:00 • 306

We studied the layer formation process of sessile droplets of a colloidal suspension, deposited by piezo-electric ink jet printing. An approximate numerical model was developed, together with scaling laws. The model solves the convection-diffusion equation for a drying droplet, assuming the liquid–air interface has the shape of a spherical cap. The number of input parameters in the model was kept to a minimum, still describing the relevant physical phenomena for a range of materials. The numerical predictions and underlying assumptions of the model were compared with experiments, using a water-based colloidal silver suspension. They were found to be in reasonable agreement with each other. Based on experiment and simulation, different drying regimes were distinguished. The approximate model and scaling laws provide useful quantitative insight into the drying process of ink-jet printed droplets. This can be used for manufacturing of printable inorganic conductors.

Long-Wave Marangoni Instability in Binary-Liquid Films with Soret Effect

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FM14L_10543
Wed • 11:20 • 306

We study the Marangoni instability in binary-liquid films in the presence of Soret effect. Linear stability analysis shows that both monotonic and oscillatory long-wave instabilities are possible depending on the value of the Soret number. Sets of long-wave nonlinear evolution equations are derived for both types of instability. In the case of poorly conducting boundaries both monotonic and oscillatory instability modes exist. Bifurcation analysis in the monotonic case for large

Prandtl number yields amplitude equations for roll-, square- and hexagon patterns. Squares are stable in the physically relevant limit of large inverse Lewis number. Hexagons bifurcate transcritically and steady stable hexagonal patterns are possible. In the case of oscillatory instability travelling waves are stable. If finite deformations of the interface are allowed binary-liquid films rupture in both settings of prescribed temperature distribution and temperature gradient at substrate. The behavior of the film near rupture is investigated.

Surfactant-Induced Fingering Phenomena in Thin Liquid Films

FM14L_11404
Wed • 11:40 • 306

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The Marangoni-driven spreading of a surfactant droplet on a thin liquid film is accompanied by an instability, which manifests itself via the formation of fingering patterns. These patterns localise near the foot of the droplet behind an advancing front that forms at the surfactant leading edge. We have developed a theory based on the lubrication approximation to explain the physical mechanism responsible for this fingering instability. This theory elucidates the dependence of the pattern wavelength on system parameters such as the ratio of the thickness of the underlying film to that of the droplet, surfactant solubility and the form of the surfactant equation of state. The patterns obtained from our numerical simulations bear a striking resemblance to those observed experimentally.

The Slopped Falling Films with Surfactants: Instability and Nonlinear Waves

FM14L_10616
Wed • 12:00 • 306

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The film flow of a weak solution of a soluble volatile surfactant in liquid is considered. Diffusion of the surfactant to the film surface from the bulk solute, its evaporation to the gas phase and the adsorption-desorption processes in the near-surface layer are taken into account. The full Navier–Stokes formulation is reduced to the system of nonlinear evolutionary equations. A model for the dynamic surface tension is appropriate for the transition of the freshly formed surface to the old surface to be investigated. A steady state solution for film flow along a slopped wall and instability of the flow are considered for the simultaneous action of the body forces, capillary pressure and Marangoni stresses. The nonlinear effects for the hydrodynamic and diffusion instability modes for non-equilibrium adsorption kinetics in the sorbed sublayer are investigated. The work was financially supported by RFBR (Grants 00-01-00645, 03-01-00042)

Dynamics of a Reactive Falling Film at Large Peclet Numbers

FM14L_10220
Wed • 12:20 • 306

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We study the dynamics of a vertically falling film in the presence of a first-order (exothermic or endothermic) chemical reaction. Our analysis is based on a long-wave expansion (LWE) and an integral-boundary-layer (IBL) approximation of the equations of motion, energy/concentration and associated free-surface boundary conditions. We also develop a hierarchy of IBL models starting from a simplified Shkadov approach to large IBL systems based on high-order Galerkin projections. Particular emphasis is given to permanent-form solitary waves. We contrast the solitary wave solution branches obtained from LWE and IBL and we show that LWE leads to branch multiplicity and limit points while IBL predicts the continuing existence of solitary pulses for all Reynolds numbers. We also demonstrate that for large Peclet numbers the inclusion of the heat/mass transport convective effects can make the solitary waves dispersive. For large dispersion and for a sufficiently large region of Reynolds numbers, the liquid layer can be excited in the form of non-dissipative solitary pulses which close to criticality assume the form of KdV solitons.

Gravity- and Shear-Driven Thin Films Flow on Heated Hicrostructured Walls

FM14L_12293
Wed • 12:40 • 306

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Evaporation of thin falling films and shear-driven films is widely used for cooling of electronic devices and other components, for powders production in chemical and food industry and for other technological processes. Using microstructured

wall surfaces may improve the performance of the evaporator and prevent film dryout. We develop a model which describes the hydrodynamics and heat transfer of the gravity- and shear-driven liquid films on microstructured surfaces. We investigate the hydrodynamic stability of the film flow using the long-wave theory. It is shown that the longitudinal grooves stabilize the film flow both when the wall is completely or only partially covered by the film. The influence of the Marangoni effect on the film shape and velocity field has been analyzed in the framework of the long-wave theory and using the volume of fluid method.

Liquid Film Flow in Conical Capillary

FM14S_10059
Tue • 14:30 • 305A

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The phenomenon of two-side filling with some liquids of conical capillaries was established in 1989. During the last years comprehensive experimental data concerning this phenomenon were obtained. But till the present time there is a lack of its theoretical description. Theoretical model based on mathematical description of gas-vapor diffusion and phase transition (evaporation–condensation) in the cone's channel, which was presented at 19th ICATM in Kyoto, can't explain experimental results. Mathematical theory of the phenomenon based on liquid film flow along the capillary channel is presented in this paper. It is established that the mechanism of the phenomenon can be explained by a liquid film flow caused by the difference of capillary pressures at two liquid columns and stabilized by disjoining pressure in the liquid film. All main qualitative regularities of the process following from this theory are in a good correspondence with experimental results.

Linear Response of a Viscous Liquid Sheet

FM14S_11413
Tue • 14:35 • 305A

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The paper to be presented investigates the propagation of disturbance signals in a uniform thin viscous liquid sheet of infinite extent which is in contact with a passive ambient medium. The disturbances are induced by moving local external pressure perturbations on the sheet interfaces. The tool of analysis is the Fourier-Laplace transformation of the linearized perturbation equations, and the inverse Fourier-Laplace transform for the reconstruction of the signal, the amplitude of the interface deflections. The response is determined by the shape of the disturbance and by the intrinsic response properties of the viscous sheet, codified in its dispersion functions which determine the singularities of the Fourier-Laplace integrand. Symmetric (varicose) and antisymmetric (sinuous) disturbances are investigated in the long time limit by numerical signal evaluation. The exact disturbance responses are compared with their longwave approximations and with experiment.

Experimental and Numerical Study of Marangoni-Natural Convection

FM14S_11477
Tue • 14:40 • 305A

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An experimental and numerical study of steady thermal Marangoni-natural convection was carried out to examine the flow behaviour under various conditions of liquid layer depth and heating temperatures. Silicone oil was used as the working fluid in a cylindrical glass container heated on its free surface in the centre. To minimize natural convection effects and to allow Marangoni convection to dominate, layer depths in the order of milimetres was studied. Particle Image Velocimetry (PIV) was used to visualize the flow both qualitatively and quantitatively. FLUENT V6 was used to create a numerical model to provide comparison with the experiment. The numerical model assumes the Boussinesq approximation with steady, axisymmetric, laminar flow. The agreement between the experimental and numerical results is good. The liquid free surface shape due to the presence of menisci is shown to be important in the validation of the results.

Amplification of Nonlinear Disturbances on a Falling Liquid Sheet

FM14S_11739
Tue • 14:45 • 305A

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We analytically examine behavior of a liquid sheet falling under the action of gravity when liquid viscosity and inertia of surrounding fluids are ignored. Analysis is made based on a set of nonlinear equations for the sheet in the gravitational

field derived under the membrane approximation. We numerically find a particular boundary condition for the steady flow whose velocity increases and thickness decreases monotonically as it goes downstream. Weakly nonlinear analysis for unsteady modulational waves shows that only antisymmetric mode of disturbances propagating downstream is amplified and otherwise decayed. Numerical analysis shows that the symmetric mode is locally induced on the antisymmetric mode and it is expected that this induced mode leads to the breakup of the sheet.

Hydrodynamics of Particle-Stabilized Thin Liquid Film

FM14S_11996
Tue • 14:50 • 305A

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Thermodynamic and hydrodynamic properties of thin liquid films stabilized by colloidal particles are investigated theoretically and numerically. A thermodynamic description of the film is formulated, in which the system is treated as an effective two-dimensional medium. Equilibrium equations of state were evaluated via a Monte-Carlo method for a film stabilized by a suspension of hard spheres. Our results provide basis for quantitative description of stepwise structure of films with coexisting regions of different thickness. We also evaluated the effective viscosity coefficients for two-dimensional compressional and shear flows of a film and the self and collective mobility coefficients of the stabilizing particles. The hydrodynamic calculations were performed using a multiple-reflection representation of Stokes flow between two free surfaces. In this approach, the particle-laden film is equivalent to a periodic system of spheres with a unit cell that is much smaller in the transverse direction than in the lateral direction.

Thin Film Flows Near Isolated Humps and Interior Corners

FM14S_12155
Tue • 14:55 • 305A

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We examine the surface-tension-driven redistribution of a Newtonian liquid film following a sudden change in the shape of its substrate, which is assumed to form an isolated hump or interior corner. The flow is modelled with an evolution equation derived from lubrication theory, extended for corner flows via fully nonlinear expressions for interfacial curvature and volume conservation. We employ numerical simulations and asymptotic analysis to describe the film dynamics. For sufficiently large humps and sharp corners, the film pinches off to form an effective contact line separating a quasi-static puddle from a wave-like disturbance that propagates into the far field. We show that this effective contact line drifts slowly to a limiting position dictated by the transient dynamics. Flows off humps with maxima less than a critical height do not exhibit pinch-off and are captured by one of two possible branches of similarity solutions of the thin-film equation.

FM15

Fluid mechanics of materials processing

Chairpersons: F. Dupret (Belgium), R. Moreau (France)

Analysis of Flow-Induced, Step-Bunching Instabilities During the Growth of Crystal from Liquid Solutions

FM15L_10363
Fri • 11:00 • 144

Bing Dail, Yong-Il Kwon, **Jeffrey J. Derby**
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The growth of crystals from a supersaturated liquid is widely employed to produce large, single crystals or many crystals in crystallization separations processes. Crystal quality is often compromised by morphological instabilities, such as macrosteps, step bunches, and inclusions, which arise from the coupled effects of fluid dynamics, mass transport, and the growth of atomic layers (steps) across a vicinal crystal surface. We present a novel multi-scale model that couples bulk fluid dynamics with surface step growth to analyze these instabilities. The surface kinetic model rigorously accounts for the interactions of discrete growth steps through surface diffusion fi elds, adsorption and desorption events, solute incorporation, and surface convection due to step motion. This model is self-consistently coupled with a bulk model that describes the fluid fbw and its effects on the convection and diffusion of solute to the surface. The governing equations are solved numerically by an effi cient, moving-boundary, fi nite element method.

Relevance of Alfven Waves in Process Metallurgy under a High Magnetic Field

FM15L_10860
Fri • 11:20 • 144

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Under the strong DC magnetic fi eld now available with super-conducting magnets, the Alfven waves transit time becomes shorter than their damping time and makes these waves observable. An experiment has been performed with liquid gallium. The waves are excited at the free surface of a vertical cylinder, where an AC electric current is forced between two electrodes. The whole cell is located within a vertical coil delivering a 10 Tesla vertical DC magnetic fi eld and the waves are detected by a pressure sensor located at the bottom wall. A linear theoretical attempt allows to interpret those observations and yields some criteria such that the waves reach the far end of the experimental

3D Computer Simulation of Time-Depended Solutal Convection

FM15L_11893
Fri • 11:40 • 144

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The paper deals with computer simulation of natural convection in multicomponent solution. Three-dimensional calculations have been done to study the onset of convective motion and correspondent fbw patterns. The process has been considered for Rayleigh number in range $1*10^3$–$4*10^4$. Numerical simulation confi rm the existence of convective motion at Rayleigh numbers less than critical one predicted by stability analysis. The planform of subcritical convection and fbw direction agree with theoretical data. The evolution of the fbw pattern at Ra above the critical value is also consistent with theoretical predictions and experimental results. The numerical procedure is reliable and allows to perform long-time computer simulation of the convective motion in a wide range of operating parameters.

Convective Instabilities in Czochralski Model

FM15L_11929
Fri • 12:00 • 144

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Instabilities are the main reason of the striation defects in crystals grown by Czochralski method (pulling crystal growth from the melt), which is widespread in crystal growth technology. The paper contains direct numerical simulation of the axisymmetric, 3D flows and linear stability analysis of the 3D instabilities in hydrodynamic (or so-called idealized) Czochralski model for buoyancy-driven and thermocapillary convection on the basis of Navier–Stokes equations (Boussinesq approach). Comparison of the nature of the buoyancy-driven and Marangoni instabilities for high and low Prandtl numbers, impact of the thermal boundary conditions on the melt surface and overview of the critical Mn and Gr numbers for the parameters of the benchmark configuration are done. Possibilities for control of the temperature oscillations in the melt are discussed. This work was supported partly by the Ministry of Science and Technology of the Russia and by grant RAS Parallel computing using multi processor computational systems and the work of NVN – by RFBR grant 02-01- 00492.

New Possibilities for Velocity Measurements and Model Experiments in Liquid Metal Processing

FM15L_12349
Fri • 12:20 • 144

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A serious deficit in technologies involving liquid metals or semiconductor melts consists in the difficult access to velocity measurements. We report on a new level of velocity resolutions in model experiments with liquid metals, and on various magnetic field solutions for a tailored flow control. Potential difference probes (PDP) as well as the Ultrasonic Doppler Velocimetry (UDV) have been deployed in flows driven by an alternating respectively rotating magnetic field. With the PDP it was possible to resolve velocities as low as in the laminar regime. Not thus sensitive but delivering spatio-temporal data from the velocity field as a complete profile along the sound beam, the UDV measurements permit mapping of the mean flow distribution and the turbulence degree. Further, UDV was proven to suffice for a spectral decomposition of the velocity fluctuations in the case of the alternating magnetic field driven flow.

Dynamic Simulation of the Entire Crystal Growth Process: Multi-Scale Analysis of Melt Flow Transients

FM15L_12591
Fri • 12:40 • 144

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This paper investigates the transient melt flow evolution during a complete Czochralski crystal growth process. Two basic time scales are considered. The short scale concerns the basic transients associated with flow oscillations at different process stages. Accurate understanding of the flow mechanisms at this scale is required to develop an average axisymmetric flow model for complete dynamic simulations. The long time scale is associated with the transients caused by the slower system evolution occurring during the complete growth process. In order to focus on the fundamental effects governing the flow, a model problem is considered where the liquid is placed into a possibly rotating container while a disk of smaller diameter rotates on its top surface. Both the container and the disk are isothermal. Several transient effects are investigated including the effect of disk radius increase or decrease, and abrupt changes of disk or container temperature or rotation rate.

Flow and Crystallization of Holey, Compound, Optical Fibers

FM15S_10440
Tue • 14:30 • 337A

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A model of the flow, thermal field and crystallization of slender, axisymmetric, slender, holey, compound optical fibers is developed by means of asymptotic methods based on the slenderness ratio. The model accounts for the crystallization kinetics and molecular orientation through generalized Avrami and Kikutani equations and their effects on the momentum equations through a dynamic viscosity law that depends on the temperature in an Arrhenius fashion and exponentially on the degree of crystallization. For small Biot numbers, it is shown that the fiber's geometry, axial velocity component, temperature, molecular alignment and crystallization are governed by one-dimensional equations, whereas, at high Biot numbers, the thermal field is two-dimensional and the fiber's geometry and axial velocity component depend on the cross-

section integrals of the viscosity. It is also shown that the fiber's necking, viscosity and molecular orientation increase whereas the crystallization decreases as the activation energy of the viscosity law is increased.

Effect of Thermal Boundary Modulation in a Restricted Fluid Domain of a 3D Vertical Bridgman Apparatus

FM15S_11386

Tue • 14:35 • 337A

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Fluids heated from below provide non linear behaviour very rich and interesting in many scientific fields. The classic Rayleigh–Bénard problem offers a first approach to this complexity of flow evoluting from a conductive to convective regime and a first predictive way of coupling with solid/liquid transition. Stable dynamic solutions are of interest in practice because of their impact on the constitution control. For example, in electronic applications, growth involves convection dominating dopant segregation and influencing interface shape. 2D models are used for predictive investigation of directional solidification configurations based on thermal or solutal control, under full or low gravity conditions. Heating conditions varying with time interacts with flow characteristics and the unsteadiness thresholds, such situations are encountered for example for electronic component energized inducing unsteady generation of heat. The heat and mass transfer regarding the amplitude and the frequency of a given oscillation imposed to the hot wall exhibits a particular behaviour when compared to the configuration without modulation. Starting with the steady regime for a given low Rayleigh number, modulation can activate a resonant state for which it is possible to predict the next oscillatory state that the system can reach without modulation but only with increasing the intensity of the convection (higher Ra). In this paper we will investigated the effect of wall temperature modulation, for the 3D case, on the flow and heat transfer.

Liquid and Gas Jets Impinging on a Moving Wetted Surface

FM15S_11903

Tue • 14:40 • 337A

Anh V. Nguyen, **Geoffrey M. Evans**

University of Newcastle, Callaghan, Australia

This paper contains the theoretical development and predicted results for both analytical and computational models of a combined liquid and gas jet wiping system designed to remove cooling liquid from the surface of a continuous moving strip. An analytical approach was used to determine the average cooling liquid height on the moving strip upstream of the jetting assembly. A momentum balance was applied to determine if the combined liquid and gas jet momentum were sufficient to prevent the cooling liquid from traveling downstream with the strip. CFD modelling of the jetting system was successfully developed based on the VOF technique. It was found that when no gas jet was applied a thin film of liquid remained, where the thickness of the film was most strongly influenced by the liquid jet incident angle. When the gas jet was applied the liquid film was removed in all cases.

Sensitive Regions and Optimal Perturbations in the Floating Zone Using the Adjoint System

FM15S_12636

Tue • 14:45 • 337A

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Thermocapillary convection arises in free surface systems, particularly in non-isothermal cylindrical liquid bridges. The floating zone process is used as a containerless crystal growth process to produce high quality material, but defects can appear in the crystal when the flow is unsteady. In this study, the geometrical configuration is 2D axi-symmetric. The parameters of the model are the Prandtl number, the Marangoni number and the aspect ratio. The mechanisms of the growth of instabilities are analyzed using an adjoint technique. It allows to determine the most sensitive regions of the flow to local perturbations. As far as we know, this work is the first attempt to identify the region of the steady thermocapillary flow where a local disturbance has the largest response, by the use of the adjoint technique. This is also the first application of this method to a highly confined geometrical configuration. The most sensitive regions to thermal perturbations are presented.

FM16

Fluid mechanics of suspension

Chairpersons: R. Bonnecaze (USA), E. Guazzelli (France)

Velocity Fluctuations in Non-Brownian Suspensions Undergoing Simple Shear Flows

FM16L_10361
Mon • 16:00 • 124

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The velocity fluctuations present in macroscopically homogeneous suspensions of neutrally buoyant, non-Brownian spheres undergoing simple shear flow, and their dependence on the microstructure developed by the suspensions, are investigated in the limit of vanishingly small Reynolds numbers using Stokesian dynamics simulations. We show that, in the dilute limit, the standard deviation of the velocity fluctuations (the so-called suspension temperature) is proportional to the volume fraction, in both the transverse and the flow directions, and that a theoretical prediction, which considers only the hydrodynamic interactions between isolated pairs of spheres, is in good agreement with the numerical results even up to volume fractions of the order of 10%.

The Collective Dynamics of Self-Propelled Particles

FM16L_10603
Mon • 16:20 • 124

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Self-propelled particles, such as spermatozoa, bacteria and other microorganisms, exhibit several intriguing features in the collective dynamics, such as the spontaneous formation of spatio-temporal patterns, convection cells etc. In this study, we propose a method that can be used for the dynamic simulation of a collection of self-propelled particles. In our descritpion, each particle is treated as a rigid sphere with a force dipole of constant magnitude. In isolation, it would move at constant velocity set by the magnitude and direction of the force dipole. When it coexists many such particles, its hydrodynamic interaction with other particles rotates it and therefore change its direction of motion, and also induces an additional stresslet on it. The velocity distribution differs significantly from the Guassian, and the collective motion of the particles is diffusive at long time.

Microstructure of a Dilute Sedimenting Suspension

FM16L_10993
Mon • 16:40 • 124

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The slow sedimentation of a dilute disordered non-Brownian suspension in a viscous,incompressible fluid described by the Stokes equation is studied. Starting from the Liouville equation, we derive the BBGKY (Bogolubov–Born–Green–Kirkwood–Yvon) hierarchy of equations for particles interacting via long range hydrodynamic interactions. This hierarchy determines the time evolution of the reduced distribution functions. Assuming next low particle concentration we determine the particle distribution which for stationary state assures finite correlations despite multi-particle hydrodynamic interactions. Results are discussed.

Numerical Simulations of Particle Suspensions in a Rotating Flow

FM16L_11418
Mon • 17:00 • 124

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We have developed an algorithm to simulate the motion of suspended solid particles in a rotating cylinder. The hydrodynamic interactions are calculated from the flow fields generated by point forces, with a Green's function that enforces

a zero-velocity boundary condition on the surface of the cylinder. We have implemented a parallel version of the algorithm, which also scales linearly with the number of particles. For the time scales of interest, typically of the order of 100-200 rotations of the tube, simulations of a few thousand particles per processor are feasible. The code has been applied to the investigation of pattern formation in a rotating suspension. In these experiments a cylinder filled with a suspension of heavy particles is rotated about a horizontal axis, and a number of different phases or particle patterns have been observed and characterized experimentally. We plan to use numerical simulations to elucidate the hydrodynamic mechanisms leading to pattern formation.

The Effect of Different Particle Contacts on Suspension Rheology

FM16L_11473
Mon • 17:20 • 124

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Experiments involving a sphere travelling down an inclined plane in a viscous fluid at low Reynolds numbers have shown that the sphere and plane have irreversible interactions at an apparent contact height that depends on the inclination angle of the plane. In this paper we consider several models of contact roughness, some previously studied, others new in this work, which are capable of reproducing these experimental results. In particular, we consider particles with microscopic asperities causing contact at a fixed nominal separation, particles with microcopic asperities of two different heights, and particles having a thin, soft asperity layer that deforms under compression. We use the Stokesian Dynamics method to simulate the flow of large populations of particles with microscopic surface roughness, and hence investigate numerically the effect of contact on the rheology of a suspension of identical rough spheres in shear. The irreversible contact interactions lead to normal stress differences and also generally lower the suspension viscosity, due to the roughness elements preventing very close approach and lowering viscous lubrication effects.

Evolution of Suspension Sedimenting in a Container Bounded by Horizontal Walls

FM16L_11480
Mon • 17:40 • 124

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Evolution of large-scale disturbances in sedimenting suspension is studied. The rectangular container is bounded by rigid walls in vertical direction and periodic in horizontal direction. Analytical solution is obtained for particle concentration and fluid velocity fields based on the continuum model of particle transport and linear-perturbation theory. The concentration inhomogeneities and velocity fluctuations are shown to decay with time. The decay is due to decrease of particles' number because of their deposition on the bottom wall and the variation of sedimentation-front shape. Calculated velocity fluctuations and correlation functions agree qualitatively with experimental values. Fluctuations evaluated in the middle of the cell grow linearly with the height of a cubic container, but saturate or even decrease as the container width grows and the height is fixed. The research was supported by Russian Foundation for Basic Research (Grant No. 02-01-00149).

Slip and Flow in Pastes

FM16L_12574
Tue • 11:00 • 124

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Concentrated dispersions and pastes of soft particles are ubiquitous in everyday life (mayonnaise), in biology (biological fluids and tissues) and in geology (lava and mud). These materials display many fascinating bulk properties such as yield stress, shear thinning, aging and memory. In practice however, their motion is often dominated by wall slip, with dramatic effects when they move within confined smooth surfaces. Slip in soft particle pastes is dominant at low shear rates. By directly imaging the flow of pastes using video-microscopy, we show that slip is characterized by universal properties, which depend on solvent viscosity, bulk elasticity and particle size. A generic slip model based on elasto-hydrodynamic lubrication between the squeezed particles and the wall explains these properties quantitatively. Our results offer new routes to predict the bulk non-linear rheology of pastes.

Inertial Migration of Rigid Spherical Particles in Poiseuille Flow

FM16L_11850

Tue • 11:20 • 124

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A neutrally buoyant particle in pipe flow is known to undergo a radial migration for finite Reynolds number flows. This effect was first observed by Segre and Silberberg, who noted a radial equilibrium position at a radius r= 0.6R in a pipe of radius R, in conditions of finite but low Re. These results have been extended to show that the equilibrium position of the particles is moved toward the wall as Re increases. Moreover a new equilibrium position closer to the center was observed to become dominant at elevated Re. A comparison with asymptotic theories is provided.

Segregation of Suspended Particles in a Rotating Fluid-Filled Horizontal Cylinder – Experiment and Theory

FM16L_11884

Tue • 11:40 • 124

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A dilute suspension of particles in an almost inviscid fluid that fills a rotating horizontal cylinder has recently been observed to segregate into well-defined periodic vertical bands. We present the results of an extensive experimental investigation into the main features of this phenomenon, including the dependence of the periodic spacing between bands on the tube length and a previously unreported phenomenon of oscillations between two interleaving band patterns. A theoretical approach to the banding mechanism, assuming very small Ekman and Rossby numbers, is presented whereby the gravity-induced motion of the suspended particles excites inertial waves, whose flow pattern leads to the observed axial segregation. The experimental results agree well with the theory with no adjustable parameters. We shall also discuss some effects of viscosity and non-linearity which were neglected in the theory.

Migration of Buoyant Mono- and Bi-Disperse Suspensions in Low Reynolds Number Pressure-Driven Pipe Flow

FM16L_11991

Tue • 12:00 • 124

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Suspensions of neutrally buoyant particles in low Reynolds number, pressure-driven flows migrate from regions of high to low shear. When the particle density does not match that of the suspending fluid, buoyancy forces as quantified by a dimensionless buoyancy number, determines the particle distribution. We use electrical resistance tomography (ERT) to visualize and quantify particle migration in pressure-driven pipe flow of monodipserse suspensions of dense or light particles and bidisperse suspensions of heavy and almost neutrally buoyant particles. The images reveal greater particle segregation at higher buoyancy numbers for the suspensions. Experiments with bidisperse suspensions reveal enhanced resuspension of the heavier particles. In addition for some flow conditions an adverse density gradient is observed with heavy suspension above light. Additionally, ERT imaging captured the developing concentration profile, revealing a complex evolution to fully developed flow. The particle distributions are reasonably well-predicted by a suspension transport model.

Dynamic Simulations of the Instability of Sedimenting Fibers

FM16L_12005

Tue • 12:20 • 124

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The concentration instability of sedimenting fiber suspensions under gravity at zero Reynolds number is investigated by means of large-scale numerical simulations. Periodic boundary conditions are used to simulate an infinite suspension. Far-field hydrodynamic interactions are modeled using slender-body theory, and the lubrication approximation is used for short-range pairwise interactions. A fast summation algorithm is implemented to compute the hydrodynamic interactions, allowing the simulation of systems of several hundred fibers. Using very wide boxes we are able to observe several high density streamers in the lateral direction, and show that the wavenumber selection is determined to a large extent by low-wavenumber concentration fluctuations in the initial distribution, which create backflows in the disturbance velocity field. We also study the dynamics of clusters inside these vertical streamers, and observe a mechanism during the transient phase of the instability by which small clusters merge into larger ones.

Spreding Fronts and Fluctuations in Sedimentation: Part II Computer Simulations

FM16L_12345

Tue • 12:40 • 124

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Following on from the experimental Part I, Part II uses computer simulations to examine the spreading of the front and the velocity fluctuations, and how these depend on the concentration and size of the container.

Effective Viscosity of an Inhomogeneous Dilute Suspension Flowing Along a Wall

FM16S_10248

Tue • 14:30 • 308A

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The classical result of Einstein for the effective viscosity of a dilute suspension of solid spheres in an arbitrary infinite Stokes flow is extended to account for the effect of a nearby wall. It is found theoretically that the presence of a wall amounts to a slip velocity for the suspension on a macroscopic scale. This slip velocity is obtained in term of the stresslet on a sphere, which is calculated analytically with the method of bipolar coordinates. Because of walls, the effective viscosity is reduced in a homogeneous suspension, in qualitative agreement with experiments. For a bounded suspension, the expression for the viscosity depends on the flow field, even in the first order in volume fraction. Moreover, the sensitivity of the effective viscosity to the inhomogeneity of the suspension is higher for a Poiseuille flow than for a shear flow.

Hydrodynamic Interaction of a Spherical Particle in Poiseuille Flow Between Planar Walls

FM16S_10565

Tue • 14:35 • 308A

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By using a two-dimensional Fourier representation of the Green tensor for Stokes flow between parallel walls, we calculate all friction and mobility functions for a single spherical particle moving between two walls subject to Poiseuille flow. The method readily generalises to N particles. For a channel narrow with respect to particle size, superposition of one-wall results is not an accurate approximation for the two-wall problem. Translation-rotation coupling is significant and changes its sign as the lateral position of the particle ranges across the channel. We illustrate these two-wall effects by calculating the trajectories of a magnetic colloid particle in Poiseuille flow subject to an external magnetic field.

Sedimentation of Dilute Suspensions

FM16S_11236

Tue • 14:40 • 308A

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In the theory of sedimentation of dilute disordered suspensions the calculation of the mean speed of sedimentation and of the variance of the speed is problematic. For a random distribution of particles the variance of the speed diverges with the number of particles. Therefore one must take account of the ordering of particles caused by sedimentation. We show that for a class of sedimentation states, corresponding to definite values of the mean sedimentation velocity and of the horizontal and vertical velocity variance, the static structure factor and the velocity correlation functions of the suspended particles exhibit screening. The mean velocity and the variances, as well as the density and velocity distribution functions, are calculated in continuum approximation for given parameters characterizing the distribution in configuration space, and compared with experiment.

Relaxation Time for Sedimenting Spheres of a Suspension with Periodic Boundary Conditions

FM16S_11409

Tue • 14:45 • 308A

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A system of spheres sedimenting in low-Reynolds-number fluid flow, with periodic boundary conditions, is simulated numerically for different classes of initial positions of the spheres, (1) chosen at random, (2) slightly and randomly perturbed

from cubic lattice, and (3) randomly grouped into close pairs distributed at random. The numerical algorithm is based on the Stokes equations. The mobility coeffi cients are evaluated by the multipole method, corrected for lubrication. The equations of motion are integrated with the fourth-order Runge-Kutta algorithm. The mean sedimentation velocity and the mean velocity fluctuations are evaluated as functions of time. The averaging is performed over the particles and over random initial confi gurations, separately within classes listed above. It is analyzed how fast a steady state is reached and how the relaxation time depends on initial positions of the spheres, for a fi xed low volume fraction.

A Mode-Mode Coupling Scheme of Colloidal Electrolyte Friction

FM16S_11431

Tue • 14:50 • 308A

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The self-diffusion of spherical colloidal polyions (i.e., macroions) immersed in an electrolyte solution depends on electrostatic, excluded volume and solvent-mediated hydrodynamic interactions between the ionic species. The electro-hydrodynamic coupling of the electrolyte and counter-ions to the macroion motion gives rise, in particular, to an additional contribution to the macroion friction coeffi cient. On the basis of the primitive model of asymmetric electrolytes and the generalized Smoluchowski diffusion equation for Brownian spheres, a simplifi ed mode-mode coupling scheme is solved for quantifying this electrolyte friction effect. The influence of the fi nite sizes of the small electrolyte ions is accounted for using mean spherical approximation expressions of static pair correlation functions for unequal sizes. The importance of hydrodynamic interactions is assessed by comparing results obtained with and without hydrodynamic interactions included.

Spreading Fronts and Fluctuations in Sedimentation: Part I Experiments

FM16S_11588

Tue • 14:55 • 308A

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The problem of velocity fluctuations in a sedimenting suspension is still unresolved. In this paper, we examine by laboratory experiments how the sedimentation front spreads and how this affects the velocity fluctuations. The influence of the size of the container is also investigated.

Constant Force and Constant Velosity Momentum Tracers in Concentrated Suspensions

FM16S_11725

Tue • 15:00 • 308A

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Here we report on the results of experiments designed to compare constant force and constant velocity experiments for test spheres translating through suspensions of non-colloidal, neutrally-buoyant spheres dispersed in viscous Newtonian fluids. Measurements were made of the apparent viscosity of a suspension using either a settling ball or momentum tracer animated by a constant gravitational force or a towed ball translating with a constant velocity. In all of the suspensions, the apparent viscosity in the constant velocity experiments was found to be signifi cantly larger than that in the constant force experiment. Thi s ratio increases linearly as the solid fraction increases. In all of the dilute suspen sions, and in concentrated suspensions with very narrow size distributions, both viscosities were found to be independent of the size and the velocity of the test sphere. In concentrated suspensions with broad particle distributions, both apparent viscosities are found to be shear thinning.

Flow of a Concentrated Suspension Down a Rough Plane

FM16S_11749

Tue • 15:05 • 308A

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Submarine landslides have a great importance in geophysics because of their consequences (submarine canyons, tidal waves). They occur when a large amount of granular material (sand) fbws downslope. But the rheology of the sand and water mixture is still not well understood. We lead experiments of submerged granular fbws in a water tank. The particles are spherical glass beads and fbw down a rough inclined plane from a reservoir with a controlled opening. Thickness, velocity and interstitial fluid pressure of the avalanche are measured, as well as the deposit thickness when the fbw is over.

Results show that the flow behavior changes abruptly for a small angle variation. Indeed, for a small variation of inclination angle above 36 degrees, the avalanche velocity increases rapidly. We suspect that a transition between a contact regime and a suspension regime occurs.

The Role of Cohesive Forces on the Fluidization Behavior of Fine Powders

FM16S_12438
Tue • 15:10 • 308A

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Gas-fluidized beds are suspensions of particles in an upward gas flow. They display three main regimes of behavior: bubbling, fluidlike, and solidlike. At large gas velocities there is a continuous bubbling process in which the bed looses memory of previous states. If the gas velocity is decreased below a critical value bubbles disappear and the bed acts as a low viscosity liquid. Due to interparticle attractive forces, particles aggregate and aggregates interact hydrodynamically with the gas. By means of settling experiments we characterize aggregates. Optical probe measurements reveal the existence of mesoscale pseudoturbulent structures, responsible for an enhanced effective diffusion process, and short-lived voids. As the gas velocity is decreased there comes a point at which aggregates are brought together to a loose packing structure and the bed gets a solidlike appearance. The extension of the fluidlike regime decreases as particle size is increased and shrinks to zero when the particle weight is comparable to the interparticle attractive force.

Single Particle Motion in Colloidal Dispersions

FM16S_12452
Tue • 15:15 • 308A

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The motion of a particle of size *a* due to an imposed external force through a suspension of colloidal particles is investigated analytically and numerically. The particle's translational velocity is determined by a balance between the imposed force and the reactive force of the colloidal dispersion, which consists of the viscous Stokes drag and a Brownian force caused by the microstructural deformation. The Peclet number (Pe = Fa/ kT), the ratio of the external force (F) to the Brownian force (kT/a), governs the distortion of the microstructure. At small Pe the response is viscous, with a linear relation between the imposed force and the particle velocity. As the Peclet number is increased the particle's velocity decreases with increasing Pe until a viscous plateau is reached at infinite Pe. This 'shear thinning' of the particle's velocity is reminiscent of the shear thinning of the dispersion's viscosity.

Gravity Waves in Fluidized Suspension

FM16S_12585
Tue • 15:20 • 308A

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A suspension of solid particles fluidized in a liquid is classically described as an effective fluid. With this description, a solid liquid fluidized bed consist of a light fluid over a denser and more viscous one. In the case of two real fluids, the waves generated at their interface are damped. We generate such waves in a Hele-shaw cell, and study the attenuation rate and the phase velocity of the waves as functions of concentration of solid phase of the suspension, and for different viscosities of fluid phase. The results are compared to theoretical predictions obtained with the use of the Navier–Stokes–Darcy equation. In particular, an estimation of the effective viscosity is obtained from the attenuation rate measurements.

Mobility of Membrane-Trapped Particles: Protrusion into the Surrounding Fluid

FM16S_12056
Tue • 15:25 • 308A

Howard A. Stone
Harvard University, Cambridge, USA

Rheological and transport studies of model thin films and membranes, often inspired by biological systems, make use of translational or rotational motion or diffusion of particles trapped in the surface film. Here, the mobility of a disk-shaped particle, trapped in a Newtonian surface film, which is bounded on one side by a viscous Newtonian fluid, is considered for the case that the particle protrudes into the subphase. The finite protrusion of the membrane-bound particle into the subphase is the unique contribution of this work. Both the subphase and surface film contribute to the resistance on the particle and the relative contributions are calculated as a function of the degree of protrusion as well as the viscosity contrast between the surface film and the surrounding liquid. Experiments consistent with the theoretical results are discussed.

FM17

Granular flows

Chairpersons: R. Behringer (USA), I. Goldhirsch (Israel)

Gravity Flow of a Densely-Packed Granular Material

FM17L_10959
Tue • 17:00 • 309

Jean Rajchenbach
Université de Nice-Sophia Antipolis, Nice, France

We present experimental results concerning the rapid flow of a densely-packed grain collection down a bumpy inclined channel. We show that the results do not agree with the predictions of the standard kinetic theory, relying on the binary collision hypothesis. Emphasizing the role played by multicontact collisions in the dense limit, we propose a new approach relying on a long range dissipation scheme. Our model succeeds in accounting qualitatively and quantitatively for the linear profile of velocity found in experiments on dense gravity-driven flows.

Velocity Profiles During Granular Avalanches

FM17L_13029
Tue • 17:20 • 309

Marc Rabaud[1], **Sylvain Courrech du Pont**[1], Philippe Gondret[1], Bernard Perrin[2]
(1) *FAST, Orsay, France*
(2) *LPMC de l'ENS, Paris, France*

Instantaneous velocity profiles of grain motion during glass beads avalanches are obtained with a high speed camera and by Particle Image Velocimetry (PIV) in a rotating drum set-up. When the pile is seen from above the surface velocity profile is curved with a strong slip on the two lateral smooth walls. When observed from the side, the in-depth velocity profile at the wall is found exponential with a characteristic length of two grain diameters. These profiles are time resolved (1/250 sec.) and show that their shapes are determined as soon as the avalanches start. Velocity measurements are in good agreements with global flow rate measurement deduced from the pile angle decrease.

Evolution of Internal Structure of Sheared Dense Granular Flows: Crystallization and History-Dependent Final States

FM17L_12445
Tue • 17:40 • 309

J.C. Tsai[2], J.P. Gollub[1]
(1) *Haverford College, Haverford, USA*
(2) *University of Pennsylvania, Philadelphia, USA*

Simultaneous measurements of internal structure, granular volume, and boundary shear force are reported for dense granular packings steadily sheared under a fixed normal load. We identify important consequences of the crystallization transition for deep flows, whose height-dependent local mean velocity spans more than five orders of magnitude. The structural change is accompanied by a significant decrease of granular volume and shear force, and dramatic change of the internal velocity field. Boundary conditions can have a profound influence on the crystallization of the entire layer. Furthermore, for given boundary conditions and long-term shearing, the evolution can depend on the prior history of the shearing process. A few cycles of initial oscillatory shearing can favor ordering, while compaction due to unidirectional shear can stabilize the disordered state. These experiments raise interesting questions about incorporating internal structure into theories of granular flow.

Granular Flows on a Heap

FM17L_11775
Tue • 18:00 • 309

Pierre Jop, Yoel Forterre, Olivier Pouliquen
IUSTI, Université de Provence, Marseille, France

Flow of granular material on a heap is experimentally investigated. A layer of granular material is flowing from a hopper on top of a static pile in a channel. We study the role of the side walls and show that it has a dramatic influence on the

dynamics of the flow. First, we show that the angle of the free surface increases with flow rate for narrow channel but remains constant when the side walls are far enough. This result is explained by the additional solid friction induced by the side walls. We also study systematically the velocity profiles at the side walls using PIV and compare these measurements with estimations of flow depth far away from the walls.

Undulations and Ripples of a Thin Granular Layer Due to Vertical Vibration

FM17L_11883
Tue • 18:20 • 309

Akiko Ugawa, Osamu Sano
Tokyo University, Tokyo, Japan

An experimental study is performed on quasi-two dimensional waves in a thin granular layer of thickness h induced by vertical vibration with frequency f and amplitude a under atmospheric pressure. We used sesame of oval shape as well as different sizes of spherical glass, lead, and steal particles. Irrespective of the container size L, “ripples” are observed in a thin layer which consists of spherical particles for relatively small acceleration of external forcing. On the other hand “undulations” are observed in a thicker layer, which consists of sesame as well as spherical beads, for larger accelerations. In the latter, several eigen modes are observed, which is reminiscent of bending waves in an elastic rod. Continuum model is shown to explain the observed modes.

Impact

FM17L_10253
Wed • 11:00 • 309

Detlef Lohse, Raymond Bergmann, Rene Mikkelsen, Christiaan Zeilstra, D. van der Meer, Michel Versluis
University of Twente, Enschede, The Netherlands

A lot of information on impacts of solid bodies on planets has been extracted from remote observations of impact craters on planetary surfaces; experiments however with large enough impact energies as compared to the energy stored in the ground are difficult. We approach this problem by downscaled experiments and by corresponding discrete particle numerical simulations: The idea is to fully decompactify very fine sand which then at impact of a steel ball behaves fluid-like. The series of events is as follows: On impact of the ball, sand is blown away in all directions (“splash”) and an impact crater forms. When this cavity collapses, a granular jet emerges and is driven straight into the air. A second jet goes downwards into the air bubble entrained during the process, thus pushing surface material deep into the ground. The entrained air bubble rises slowly towards the surface, causing a granular eruption. In addition to the experiments and discrete particle simulations, we present a simple continuum theory to account for the void collapse leading to the formation of the upward and downward jets. We show that the phenomenon is robust and even works for oblique impacts: the upward jet is then shooting backwards, in the direction where the projectile came from.

Collapse, Growth and Merging of Cavity Regions in a Granular Material due to Viscous Flow

FM17L_11876
Wed • 11:20 • 309

O. Sano[(1)], Y. Kaneko[(1)], G.P. RajaSekhar[(2)]
(1) *Tokyo University of Agri. Technology, Tokyo, Japan*
(2) *Indian Institute of Technology, Kharagpur, India*

Experimental and theoretical studies of viscous flow are made on the effect of macroscopic cavity regions in an otherwise homogeneous granular material. The presence of a cavity enhances volume flux and magnitude of velocity in the cavity, which amount to two[three] times and three[six] times, respectively, of the undisturbed flow in a circular [a spherical] cavity. The increment of the magnitude of flow causes collapse of the cavity boundary above a certain critical velocity. The fluidized region develops towards upstream direction, which changes flow field in and around it. Interaction of two circular cavities becomes largest at a certain arrangement, which leads to faster collapse and merging of the boundaries. In the case of many cavities, they develop into network formation of fluidized region, as well as macroscopic sheet-like cavity region, the latter of which is considered to be one of the mechanisms of the onset of landslide.

Granular Column Collapse

FM17L_10524
Wed • 11:40 • 309

Gert Lube[1], **Herbert E. Huppert**[2], R. Stephen Sparks[1], Mark A. Hallworth[2]
(1) *Department of Earth Sciences, Bristol University, Bristol, UK*
(2) *Institute of Theoretical Geophysics, DAMTP, CMS, Cambridge, UK*

The talk presents experimental observations of the collapse of vertical columns of small grains. Some flows were analysed using high-speed video, from which sequences will be shown. Three regimes dependent on the aspect ratio a=hi/ri exist, where hi and ri are initial height and radius of the column. In all cases a central, conical region remains undisturbed throughout the motion. The final extent of the deposit and the time for emplacement are systematically collapsed independent of any friction coefficients. Along with kinematic data for the rate of spread of the front, this is interpreted as indicating that frictional effects between individual grains in the bulk of the flow only play a role in the last instant of the flow, as it comes to an abrupt halt. Insights and conclusions gained from these experiments can be applied to a wide range of industrial and natural flows of concentrated particles.

Kinetics of Weakly Frictional Granular Gases

FM17L_12308
Wed • 12:00 • 309

Isaac Goldhirsch, S. Henri Noskowicz, O. Bar-Lev
Tel-Aviv University, Tel-Aviv, Israel

Although all macroscopic grains are frictional, most of the theoretical studies of granular gases have focused on models of frictionless spheres. The success of these models in explaining many experimental results raises the question of the role of frictional restitution in the dynamics of granular gases. The weak frictional limit is explored here. Using the pertinent Boltzmann equation we derive hydrodynamic equations of motion (as it turns out one needs to extend the list of hydrodynamics fields in this case) and study some of their consequences. One of these consequences is that the homogeneous cooling state is highly non-Gaussian. Another consequence is the long memory associated with the rotational degrees of freedom, when weakly coupled to translation.

Extended Granular Temperature

FM17L_12399
Wed • 12:20 • 309

Lou Kondic[1], Robert P. Behringer[2]
(1) *New Jersey Institute of Technology, Newark, USA*
(2) *Duke University, Durham, USA*

We consider the role of elastic energy in the context of granular materials undergoing shear flow. Depending on the ratio of pressure to Young's modulus of the material from which grains are made and the typical velocity of shearing, there is a transition from a regime in which the fluctuations of kinetic energy are dominant to the regime where the fluctuations of elastic energy are dominant. This regime has likely been reached in recent experiments. We then consider a generalization of the granular temperature that includes both types of energy fluctuations and that changes smoothly from one regime to the other. We conclude by discussing related energy distributions and the degree to which the zeroth law of thermodynamics is satisfied by this new generalized temperature.

Pore Pressure Relaxation During Granular Compaction

FM17L_11751
Wed • 12:40 • 309

Maxime Nicolas, Max Belzons, Olivier Pouliquen
CNRS-Polytech Marseille, Marseille, France

The compaction of a granular assembly immerged in a fluid implies complex interactions between viscous forces and grain contact forces. We present the study of the compaction under tapping of a granular packing fully immerged in water. In order to follow the interaction between the grains and the fluid, we measured the pore pressure at the base, related with suspended particles in the packing. A simple model is proposed to understand the time relaxation of the pore pressure.

Transverse Motion, Segregation and Rotations in 2D Granular Flows

FM17S_12883
Thu • 14:30 • 337A

Renauld Delannay[1], Alexandre Valance[1], Patrick Richard[1], Weitao Bi[1], Gaelle Berton[2], Nicolas Taberlet[1]
(1) *Université Rennes, Rennes, France*
(2) *Université de Tours, Tours, France*

We present experimental studies of two dimensional dense flows consisting of both monodisperse and bidisperse disks. We compare results obtained from chute flow experiments to those produced on an air table with the same kind of particles. In both cases experiments are recorded by a high speed video camera. Image processing software computes the exact position of the center of the disks and their rotation angle, allowing one to extract the trajectories and kinematic properties. We observed fully developed, dense shear flows of constant packing fraction. We present here the general features of monodisperse and bidisperse flows in terms of average and variance of the distribution of velocity (angular and center velocities). We discuss the concept of granular temperature, introduced in the kinetic theory, relatively to the lack of equipartion of energy. We analyze in detail the transverse motion of particles and segregation process through the transverse motion of the small particles.

Species Segregation Driven by a Granular Temperature Gradient

FM17S_12073
Thu • 14:35 • 337A

Janine E. Galvin, Steven R. Dahl, **Christine M. Hrenya**
University of Colorado, Boulder, USA

Rapid granular flows are often polydisperse and consequently have a tendency to de-mix or segregate. Based on kinetic theory, several driving forces for this segregation have been previously identified. These analyses, however, have included an equipartition assumption. When this assumption is lifted, another driving force arises, namely one which includes the gradient of species temperature. To determine the magnitude of this driving force relative to the other driving forces, MD simulations of binary mixtures are examined. The system under consideration is characterized by zero mean flow between two, impenetrable boundaries of constant, unequal granular temperatures. Consistent with findings of previous researchers, all particle types segregate toward the lower temperature region, with the more massive particle having a higher affinity. Furthermore, the simulation results indicate that the non-equipartition effects are non-negligible. Another interesting observation is that the more massive particle may have a lower species temperature than its lighter counterpart.

Arching in Granular Media

FM17S_12790
Thu • 14:40 • 337A

Radoslaw L. Michalowski[1], Namgyu Park[2]
(1) *University of Michigan, USA*
(2) *Texas A&M University, USA*

Arching in sand piles can cause a counterintuitive stress depression (a “dip”) at the center of a conical or a wedge-shaped pile. However, predictions of the degree to which the granular material will arch are not easily made. A framework of plasticity analysis is used to shed some light on the issue of arching in granular media. Arching is characterized by a stress distribution where the load is transferred from softer to stiffer regions of a structure, forming a stable configuration. Since it is a stable “arrangement”, arching is not a typical limit state problem. However, it can be formulated in a manner that allows using the static theorem of limit analysis to assess the likelihood of arching. The theorems of limit analysis can be rephrased to indicate when arching may, and when it will not occur. Radial stress fields are constructed to search for stress distributions that promote arching. Governing equations are derived for radial stress distributions with regions varying from the yielding stress state to the elastic stress state. The stress fields with an elastic core promote arching, whereas the field where all material is in the active limit state does not support arching. Characteristics of arching in sand piles do not confirm the stereotypical view that arching is associated with a transfer of load from yielding parts of the structure to the stiffer parts. It appears that equally plausible arching stress fields are ones where the load is transferred over the sand that has not reached the yield state.

Maximum-Entropy Estimates and Virtual Thermomechanics for Granular Assemblies

FM17S_10371
Thu • 14:45 • 337A

J.D. Goddard
University of California, San Diego, USA

This is an extension of previous works, dating back some thirty years on more, on maximum-entropy estimates of the statistical distribution of quasi-static contact forces in granular assemblies. The precise form of the probability density is shown

to depend on the statistical weight assigned to elements in the state space of contact forces or displacements. A brief review is given of comparisons with experiment and computer simulations. The formal methods of statistical thermodynamics are employed to establish a virtual thermomechanics. without reference to a granular temperature. This leads to an elastoplastic work function, of the type appearing in various phenomenological models of complex solids and fluids. The possibility of non-convexity, leading to continuum- and meso-scale material instability, is discussed.

The Role of Multiple Shear Bands in Deformation of Granular Materials

Danuta Lesniewska
Polish Academy of Science, Institute of Hydro-Engineering, Gdańsk, Poland

FM17S_12817
Thu • 14:50 • 337A

The patterning of shear bands in granular materials is subject to extensive research nowadays, as one of the fundamental features of their behaviour. There is no agreement between many researchers, what are the physical reasons for this kind of localised deformation and how it should be modelled in theory. Existing experimental data are often difficult to interpret and new experimental ideas are necessary to explain the phenomenon in a proper way. Some such ideas are proposed to be discussed and compared with previously used techniques. Assumptions of several theoretical models, used to describe strain localisations, are also discussed in this light.

Dynamics of Driven Granular Gases in Periodic Structures

Umberto M.B. Marconi
Phys. Dept. Univers. Camerino, Italy

FM17S_12198
Thu • 14:55 • 337A

The behavior of a driven granular gas in a container consisting of M connected compartments is studied employing a microscopic kinetic model. After obtaining the governing equations for the occupation numbers and the granular temperatures of each compartment we consider the various dynamical regimes. The system displays interesting analogies with the ordering processes of phase separating mixtures quenched below the their critical point. In particular, we show that below a certain value of the driving intensity the populations of the various compartments become unequal and the system clusterizes. Such a phenomenon is not instantaneous, but is characterized by a time scale, τ, which follows a Vogel-Vulcher exponential behavior. On the other hand, the reverse phenomenon which involves the “evaporation” of a cluster due to the driving force is also characterized by a second time scale which diverges at the limit of stability of the cluster.

Flow Dynamics of Dense Granular Materials Subjected to Vertical Vibration

Azita Soleymani(1), **Vesa Tanskanen**(1), Piroz Zamankhan(1), William Polashenski, Jr.(2)
(1) *Lappeenranta University of Technology, Finland*
(2) *State College, USA*

FM17S_10969
Thu • 15:00 • 337A

Results are presented from a numerical study examining the flow dynamics of dense granular materials in a narrow gap between two concentric cylindrical buckets subjected to sinusoidal oscillation in the vertical direction $z = A\sin(\omega t)$, where the parameter $\Gamma = A\omega^2/g$ exceeds a critical value Γ_c, above which the system becomes fluidized. Using a recently developed expression for the stress tensor of dense granular materials, a set of conservation equations were derived for the particle and fluid phases interacting via an interfacial drag force. Numerical integration of the equations for the granular material in buckets revealed that above Γ_c, granular materials may exhibit liquid-like behavior and convection can occur creating a heap similar to that previously observed experimentally.

Morphology and Scaling of Impact Craters in Granular Media

Amanda M. Walsh, **John R. de Bruyn**
Memorial University of Newfoundland, Canada

FM17S_12338
Thu • 15:05 • 337A

We study the size and morphology of impact craters formed when a steel ball is dropped into a container of small glass beads [1]. We find that both the depth (measured from the original surface) and diameter of the crater are proportional to the 1/4 power of energy. This is as expected if the energy of impact goes into excavating the crater and material strength is unimportant. We observe a variety of crater morphologies as a function of impact energy and grain size: simple craters, craters with a central peak, craters with slump terraces around the perimeter, and multi-ringed craters. The progression of these changes in morphology is similar to that observed in lunar craters.

1. A.M. Walsh, K. Holloway, P. Habdas, and J.R. de Bruyn, Phys. Rev. Lett. 91, 104301 (2003).

Particle Image Velocimetry Analysis of Granular Material Flows

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(2) *IPPT PAN, Warsaw, Poland*

FM17S_11169
Thu • 15:10 • 337A

Digital Particle Image Velocimetry (DPIV) technique, well know in fluid mechanics, has been applied to evaluate main fbw characteristics for granular material (amarantus seed) sliding between parallel walls of a Plexiglas model of a silo. The development and evolution of the consecutive stages of the fbw will be demonstrated. The vertical velocity functions on the horizontal sections of the model are used to describe different fbw regimes. Velocity fi elds are used to calculate particle tracks, lines representing main fbw structure.

FM18

Low-Reynolds-number flow

Chairpersons: R. Davis (USA), C. Pozrikidis (USA)

Free Surface Deformation in Suspensions Near a Rotating Rod

FM18L_10983
Thu • 09:30 • 123

L.A. Mondy[(1)], R.R. Rao[(1)], M.M. Hopkins[(1)], S.A. Altobelli[(2)]
(1) *Sandia National Laboratories, USA*
(2) *New Mexico Resonance, USA*

We have incorporated a model based on the shear-induced particle migration arguments into a massively parallel, three-dimensional, general purpose, multi-physics, finite element computer code developed at Sandia. In addition to solving the coupled heat and momentum transport equa-tions, the code supports fully coupled free-boundary parameterization. To validate the treatment of free-surface problems involving suspensions, we have studied the free surface near a rotating rod. Experimental data was taken with magnetic resonance imaging, which allows the visualization of suspended particle concentration profiles as well as detailed views of the free surface profile. Concentrated suspensions of up to 50 per cent by volume of spheres were subjected to a variety of rod rotation rates. The results show that the interface dips near the rotating inner rod, in agreement with earlier studies, and that our model captures this normal-stress induced behavior.

Microcavitation and Detachment of a Stokes Particle in Near-Wall Slow Motion

FM18L_11460
Thu • 09:50 • 123

A.N. Prokunin
Moscow State University, Moscow, Russia

A near-wall slow motion of a spherical particle along the wall in a fluid is studied with the reference to an example of gravity-driven sliding of the particle down an inclined surface of a tube. The particle was several millimeter in diameter with varying roughness of its surface. It was revealed experimentally that for fairly small roughnesses: (i) the particle may travel without contact with the wall under the action of lifting force of non-inertial nature (not the Magnus force); (ii) a small air cavity is formed in the narrow particle-wall gap; (iii) particle motion depends on atmospheric pressure and the liquid-air surface tension. The mechanism of appearing the cavitation lifting force for contactless motion of the sphere is as follows: in studying Stokes motion of the particle along the wall it was revealed that between the particle and the wall directly ahead the pressure is positive and behind it can be negative. When cavitation takes place, negative pressure is not realized and lifting force arises.

Particles Located on a Planar Free-Surface-Hydrodynamic Interactions in Quasi-Two-Dimensional System

FM18L_11300
Thu • 10:10 • 123

Bogdan Cichocki[(1)], Maria L. Ekiel-Jeżewska[(2)], Gerhard Nägele[(3)], Eligiusz Wajnryb[(2)]
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(3) *Institut fur Festkorperforschung, Forschungszentrum Julic, Julic, Germany*

The system of many spherical particles, which are suspended in a quiescent fluid and which touch a planar free surface is considered. A method to evaluate the friction and mobility matrices for such a quasi-two-dimensional system is developed. In this approach, the irreducible multipole expansion is applied. Moreover, the free surface boundary conditions are taken into account with the use of the method of images. The essential element of this scheme is construction of an operator, which determines reaction of a single sphere (located at the free surface) on an external ambient fluid flow. This quasi-two-dimensional one-sphere resistance operator is next calculated numerically. The long-distance leading terms of the two-sphere quasi-two-dimensional mobility matrix are evaluated up to the terms of the order of $1/r^3$, where r is the interparticle distance.

Radially Symmetric Polar Ice Sheet Flow with Evolving Anisotropic Fabric

FM18S_10297
Thu • 14:30 • 304

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(2) *University of East Anglia, Norwich, UK*

A radially symmetric, gravity-driven, steady flow of a grounded polar ice sheet with a prescribed temperature field is considered. The ice is modelled as an incompressible, non-linearly viscous and anisotropic fluid with evolving orthotropic fabric. To describe the evolution of the fabric as an initially isotropic free surface ice descends to depth in an ice sheet, a constitutive law relating the deviatoric stress to the strain-rate and strain is applied. The solution is constructed as a leading order approximation derived from asymptotic expansions in a small parameter that reflects the small ratio of stress and velocity gradients in the longitudinal direction to those in the thickness direction. Results of calculations show the effects of a bed topography on the ice sheet thickness profile and the velocity components. Additionally, the influence of the temperature field and the free surface snow accumulation rates on the flow is illustrated.

Two-Layer Stagnation Point Flows

FM18S_10766
Thu • 14:35 • 304

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(1) *University of East Anglia, Norwitch, England*
(2) *University of California, San Diego, USA*

Exact solutions of the Navier–Stokes equations are presented for orthogonal and oblique stagnation-point flow against a flat film resting on a plane wall. The viscosity and density of the fluid film and the superposed fluid are generally different. At zero Reynolds number, the solution may be written down in closed form. The solution for orthogonal flow at non-zero Reynolds numbers adopts a structure which is similar to that of the classical Hiemenz flow of a homogeneous fluid toward a plane wall. For oblique flow, the structure is similar to that for a single fluid presented by Stuart (1959) and Dorrepaal (1986). The problem reduces to solving a pair of partial differential equations involving one spatial coordinate and time, together with an evolution equation for the position of the interface. Only a minor modification is required to compute solutions for two-layer axisymmetric stagnation point flow.

Optimal Lift Force on Vesicled Near a Defomable Subtrate

FM18S_11239
Thu • 14:40 • 304

Julien Beaucourt, Thierry Biben, Chaouqi Misbah
Université Joseph Fourier (CNRS), Grenoble, France

We investigate the effects of a deformable substrate on the dynamics of a vesicle in a shear flow. This system can be viewed as a zeroth order model for studying the complex coupling between blood cells and the glycocalyx layer which covers the internal part of microvessels. More precisely, we show that the lift force on spherical vesicles (a model for the leucocytes) exhibits a maximum for a rigidity of the substrate which lies in the physiological range. In the case of unswelled vesicles (for red blood cells), the maximum tends to disappear and the lift force is constant below this value, which appears now as a limit between two different regimes.

Flow Visualization Experiments of Cellular Stokes Flows Induced by Rotation of a Cylinder Variously Positioned Inside Channels

FM18S_11915
Thu • 14:45 • 304

Emin F. Kent
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In this work, flow visualization experiments of cellular Stokes flows induced by rotation of a circular cylinder variously positioned inside channels of different shapes have been performed. Flow visualization experiments have been carried out inside wedge-shaped and rectangular channels. These channels are filled with silicon rhodorsil oil of different viscosities and CMC. The motion is generated by the uniform rotation of a circular cylinder positioned at different locations inside these channels. Flow visualization experiments are carried out using solid tracers of magnesium for the Newtonien fluid and Rilsan for CMC. They are illuminated by a thin sheet of light coming from a laser device and the visualization photographs are obtained by means of long time exposure photography. A series of experiments have been performed at different rotational speeds and viscosities. High quality visualization photographs have been presented. The inner cylinder is positioned at different locations inside these channels and many interesting flow patterns have been visualized. The shape of the separating streamline and recirculating eddies are clearly seen and compared for the channels.

Many-Sphere Hydrodynamic Interactions: Weak Convective Inertia Effects

FM18S_11922

Thu • 14:50 • 304

I.T. Pienkowska

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Oseen flows past a finite number of rigid spheres are considered in the régime of low Reynolds numbers. The many-sphere hydrodynamic interactions are described in terms of the multiple scattering processes. The hydrodynamic forces, experienced by the spheres, are expressed in the form of the infinite series, presenting the dependence of these forces on the spatial configuration of the spheres and on the convective inertia of the fluid. The obtained solutions to the Oseen boundary value problem are applied to examine the solutions to the analogous Navier–Stokes boundary value problem, at small data, in the sense of Finn (Robert Finn, ARMA 19, 363 (1965)).

Viscous Eddy Structures in an Oscillating Cylinder with Sharp Corners

FM18S_12164

Thu • 14:55 • 304

M. Branicki, H.K. Moffatt

University of Cambridge, Cambridge, UK

The two-dimensional flow of a viscous fluid contained in a cylinder which is subjected to rotational oscillatory motion is considered. The instantaneous flow relative to the cylinder is driven by a Poincaré-type force which provides a uniform rate of production of vorticity. The problem may be linearised when the viscosity is sufficiently large and the amplitude of oscillations is sufficiently small; the Reynolds number of the instantaneous flow relative to the cylinder is then small, and the Strouhal number is large. If the cross-section of the cylinder has any sharp corners, the nature of the flow near these corners may be analysed through comparison of the 'driven' component of the flow, and the eigenfunction ingredients of the corresponding homogeneous problem which are inevitably present. A sufficient condition for the appearance of oscillatory eddy structures emerging from the corners is obtained and confirmed numerically for various geometries of the boundary.

Transient Squeeze Flow of Viscoplastic Liquids

FM18S_12859

Thu • 15:00 • 304

G. Karapetsas, N. Chatzidai, M. Pavlidis, J. Tsamopoulos

University of Patras, Greece

We examine the axisymmetric squeeze-flow, under creeping flow conditions, of viscoplastic materials placed between two parallel disks using the continuous constitutive model suggested by Papanastasiou and, more recently, the discontinuous Bingham model. This is the first transient simulation of such liquids and allows us to also determine the shape of the liquid/air interface, initially located inside the disks, as it is displaced towards their edge. We employ the mixed finite element method coupled with a quasi-elliptic mesh generation scheme in order to follow these large deformations. The material yields in part of the domain as the disks approach each other, departing from the corresponding Newtonian solution. Unyielded material arises around the two stagnation points of flow at the disk centers verifying previous steady state calculations. The unyielded region increases with the Bingham number, but decreases with time. If wall-slip is present, the unyielded region decreases significantly and may even totally disappear.

Slow Rotation of a Double Sphere in a Viscous Fluid

FM18S_12981

Thu • 15:05 • 304

D. Palaniappan

The University of the West Indies,Trinidad and Tobago

The problem of slow steady rotation of a double sphere in a viscous fluid in the limit of low-Reynolds number is addressed. The geometry of the double sphere is assumed to be formed by two overlapping spheres of radii a and b cutting at an angle $\frac{\pi}{n}$, n an integer. The classical method of electrical inversion, also known as Kelvin's inversion, is utilised to obtain an exact solution for the axisymmetric rotation of the double sphere in the Stokes/creeping flow approximation. The exceedingly simple nature of the method leads to the representation of the solution in terms of elementary Green's functions for rotational flow, namely, the rotlets (or couplets). The image system for this case contains a finite number of rotlets all aligned parallel to the axis of rotation and located at the respective inverse points on the axis of symmetry. The strengths of those image rotlets depend on the two radii, distance between the centers of the two spheres and the angular speed. The couple/torque exerted on the double is extracted directly from the singularity solution without explicitly integrating the stresses on the surface. It is shown graphically that the vertex angle influences the couple significantly. It is observed that the torque is greater than the volume of a single sphere but less than the sum of the volumes of two spheres. This brings out an interesting inequality that provides an upper and lower bounds for the couple. The present solution may be conveniently utilised to study pair interactions of a double sphere with other axisymmetic bodies in the rotational motions. Furthermore, the exact results provided here could also be useful in validating numerical codes on merging objects in electrostatic and microfluidic environments.

FM19

Magnetohydrodynamics

Chairpersons: P. Davidson (UK), A. Thess (Germany)

Migration and Interaction of two Conducting Particles Freely Immersed in a Liquid Metal

FM19L_10025

Tue • 17:00 • 315

Antoine Sellier
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We determine the rigid-body motions of two solid and conducting particles $\mathcal{P}_1$ and $\mathcal{P}_2$ freely suspended in a liquid metal of uniform viscosity μ and conductivity $\sigma_l > 0$ when subject to uniform ambient electric and magnetic fields $\mathbf{E}$ and $\mathbf{B}$. The translational and angular velocities $\mathbf{U}^{(n)}$ and $\mathbf{\Omega}^{(n)}$ of the particle $\mathcal{P}_n$ with uniform conductivity $\sigma_n \geq 0$ are obtained without calculating the disturbed electric field and the liquid metal flow in the unbounded fluid domain. The advocated approach solely resorts to a few boundary-integral equations on the entire surface of the cluster. The work will successively establish the relevant boundary-integral equations and both propose and implement a suitable numerical strategy. Numerical results will be presented and discussed for a few two-sphere clusters of equal or inequal spheres for several settings $(\mathbf{E}, \mathbf{B})$ and $(\sigma_1/\sigma_l, \sigma_2/\sigma_l)$.

Complementary Experiments at the Karlsruhe Dynamo Test Facility

FM19L_10931

Tue • 17:20 • 315

Ulrich Mueller(1), Robert Stieglitz(2), Sandor Horanyi(3), Fritz Busse(4)
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The Karlsruhe Dynamo Experiments have demonstrated that a permanent magnetic field of dipole character can be generated by a proper arrangement of helical vortices in a container filled with liquid sodium employing forced flow in helical guide tubes. Moreover, it has been shown that the dynamo state originates from the hydrodynamic turbulent state of channel flow as an imperfect bifurcation. In a recent series of experiments the critical conditions for dynamo action as well as the supercritical dynamo behaviour were investigated with regard to a) variations of the electrical conductivity of the test fluid sodium (by varying the sodium temperature), b) time periodic variations of the volumetric flow rates at a period comparable with the magnetic diffusion time of the test module, c) the feedback of the dynamo field on the velocity in the guide channels of the module with the help of permanent magnet potential probes. The results and conclusions from these experiments may be presentet at the 21st ICTAM, 2004 WARSAW

Liqiud Metal Flow Under Inhomogeneous Magnetic Field

FM19L_11120

Tue • 17:40 • 315

Oleg Andreev, **Yurii Kolesnikov**, Andre Thess
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We present an experimental study of a liquid metal channel flow under the influence of inhomogeneous magnetic field. The problem is relevant to the electromagnetic braking of a molten metal in the process of continuous casting. It is shown that applied inhomogeneous magnetic field brakes an initial flow in its central part and transforms a nearly flat initial velocity profile into the M-shape one. Because of a stabilizing effect an intensity of velocity fluctuation decreases up to 8 times in the central part of the flow. The fluctuations do not develop in the side boundary layers until they flow inside the magnetic field. Contrary, downstream the magnet system the layers generate velocity fluctuations by intensity up to 27%. In a regime of weak instability the flow around a zone of applied magnetic field generates large-scale vortical structures confined in the space between inlet and outlet of magnetic field.

Small-Scale Motion in the Core of the Earth

FM19L_11124

Tue • 18:00 • 315

P.A. Davidson, F. Siso-Nadal
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In 1996 St. Pierre reported numerical simulations of a buoyant blob migrating across the earth's outer core and subject to the combined effects of rotation and an azimuthal magnetic field. He noted that the blob rapidly fragments into a series of plate-like structures. Quite independantly, in the mid 1990's, Davidson discovered a similar behaviour in the context of low-Rm MHD turbulence (in which the Coriolis force is absent) and showed that this phenomenon has its roots in the destruction of angular momentum by the Lorentz force. In this lecture we pull together these earlier studies and show that they are closely related. The implications for the structure of the small-scale motion in the core of the earth are also discussed.

Investigation of MHD Processes in Aluminium Reduction Cells

FM19L_11145

Tue • 18:20 • 315

Ivan D. Borisov, Sergey A. Poslavskiy, **Yuriy I. Rudnev**
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The MHD-processes in high-power industrial aluminium reduction cells are investigated. The effective numerical methods for the electric and magnetic fields for the steady flows of the molten aluminium and electrolyte as well as for determing steady metal-electrolyte interface shapes are developed. The two-parameter differential turbulence models in calculations for steady flows are used. The small oscillations of the melt in the vicinity the equilibrium state are studied. The numerical methods for obtaining values of electric current corresponding to regime of wave generation on the metal-electrolyte interface and the anode-cathode distance are developed. The mathematical models of nonlinear oscillations of the melt have been elaborated and calculations methods for obtaining frequencies and values of periodic oscillation amplitudes in overcritical domain depending on constructive parameters of reduction cells are proposed. The experimental investigation of MHD-processes occurring in physical models have been carried out.

Magnetohydrodynamic Instabilities of Astrophysical Jets

FM19L_11429

Tue • 18:40 • 315

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(3) *Institut de Mécanique des Fluides et de Solides, Strasbourg, France*

We present the main findings of recent studies using high-resolution magnetohydrodynamic (MHD) simulations of compressible shear flow layers. First, we show how initially weak magnetic fields ultimately control the non linear dynamics of Kelvin-Helmholtz instabilities in two dimensional single layers and jets. In particular, small-scale magnetic reconnection events are able to partially disrupt the Kelvin-Helmholtz vortices at different stages of the evolution, even in the presence of a strong large-scale coalescence. Second, we show that co-spatial shear flows and twisted magnetic fields are susceptible to different types of MHD instabilities in a three dimensional cylindrical jet, thus leading to a stabilizing mutual interaction. The consequences of these results could help to understand the remarkable stability of observed astrophysical jets.

Magnetohydrodynamic Motion of Toroidal Magnetic Eddies

FM19L_11458

Thu • 11:00 • 306

Y. Hattori[(1)], H.K. Moffatt[(2)]
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The magnetohydrodynamic evolution of magnetic eddies, within which the magnetic field is purely toroidal and the velocity field is poloidal, is studied analytically and numerically. A new contour-dynamics formulation is obtained by assuming piecewise constant distribution of B_θ/r and used for numerical simulation. Singularity which appears on the contour is removed by a standard regularization technique without damaging global motion. A family of exact solutions which includes Hill's spherical vortex as a limiting special case is found. The exact solution is (like Hill's vortex) unstable, a spike growing from the rear, while the spherical front is almost unchanged. When the velocity field is initially zero, the magnetic eddy first shrinks towards the axis of symmetry; then spherical heads form, which are well described by the exact solution; in consequence, the magnetic energy does not decay to zero, although the lower bound determined by the (zero) magnetic helicity is zero.

Large Eddy Simulation of Magnetic Damping of Jet

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(2) *Hyundai Mobis, Gyunggi-Do, Korea*

FM19L_11637
Thu • 11:20 • 306

In the present study, we perform large eddy simulations to investigate the effect of magnetic field on the flow characteristics of a round jet at Re=10000. A dynamic subgrid-scale model is used for large eddy simulation. We consider two different directions of magnetic field: one is the axial direction and the other is the transverse direction. With the axial magnetic field, the shear layer becomes thinner and the potential core becomes longer than those without magnetic field. In case of the transverse magnetic field, the jet progressively spreads along the direction of the magnetic field applied, and the negative axial velocity appears along the direction perpendicular to the magnetic field line.

Observations of the Magnetorotational Instability in Spherical Couette Flow

Daniel P. Lathrop
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FM19L_11681
Thu • 11:40 • 306

Experiments conducted in liquid sodium confined between a rotating inner sphere and a concentric stationary outer sphere show a host of MHD behavior. With a sufficiently strong external coaxial magnetic field, this system exhibits the magnetorotational instability. The primary instability shows a continuous bifurcation to a rotating m=1 pattern in the magnetic field, and concomitant oscillations in the velocity field. By varying both the rotation rate and the external magnetic field (made dimensionless as the magnetic Reynolds number and the Lundquist number respectively), we have navigated the parameter plane to observe a number of states with distinct dominant wavenumber and parity. The onset conditions compare favorably with expectations from linear stability calculations. This is remarkable considering the significant background turbulence (15% to 25% turbulent intensity) in the base state. Finally we have explored the suitability of spherical Couette flow to show dynamo action.

A Model for Liquid Metal Current Limiters

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FM19L_12090
Thu • 12:00 • 306

We present a simple model which describes the complex interplay between electromagnetic forces, inertia, and gravity in liquid metal current limiting devices utilizing the electromagnetic pinch effect. The dynamics of this system is described by a nonlinear differential equation for the fluid height. A bifurcation analysis of stationary states shows that for sufficiently high initial fluid levels the fluid height is a discontinuous function of the electrical current. The jump in fluid height above some critical current is accompanied by a strong increase of the total electric resistance of the system and results in the current limiting action of the device. An experimental study of the system confirms the predicted switching behavior. For low electric current the experiment is in quantitative agreement with the theory. Due to its conceptual and numerical simplicity our model enables us to isolate the pertinent parameters and scaling laws of liquid metal current limiters.

The Magnetohydrodynamic Couette Flow in a Plane and Spherical Geometries with Singular Hartmann Boundary Layers

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FM19L_12107
Thu • 12:20 • 306

A magnetohydrodynamic Couette Flow, meaning a flow between two boundaries one of which moves at a constant speed is considered in two geometries: Carthesian and Spherical. The solution is provided for a case of low Reynolds numer and Large Hartmann number. In both geometries the external magnetic field is chosen in such a way, that singular Hartmann boundary layers appear, where the component of the magnetic field which is perpendicular to the boundary vanishes. In this singular region the velocity of the fluid exeedes the velocity of the moving boundary due to strong currents leaving the singular Hartmann layer. This phenomenon of super-velocities was studied by E. Dormy, D. Jault and A.M. Soward (2001) where they resolved a case of spherical Couette Flow with insulating outer boundary. Following their ideas I found solutions for spherical and a plane Couette Flow with conductive boundaries. The influence of the conductivity of the boundaries on the super-velocities is discussed here.

Numerical Simulations of Dynamo Experiments

FM19L_12125

Thu • 12:40 • 306

Andreas Tilgner
University of Goettingen, Goettingen, Germany

Several experimental groups throughout the world have reproduced the dynamo effect on a laboratory scale or are preparing to do so. All experiments rely on numerical simulations, both in the design phase and for data analysis. This talk presents a few examples of how experiments and simulations interact, and where they agree and disagree, in particular for the Karlsruhe experiment. Possible implications for the geodynamo will also be discussed.

Stability of Liquid Metal Drops Affected by High-Frequency Magnetic Fields

FM19L_12290

Fri • 09:30 • 315

Vaclav Kocourek, Christian Karcher, Dietmar Schulze
Techniche Universitat Ilmenau, Ilmenau, Germany

The dynamic behavior of sessile liquid metal drops submitted to a high-frequency magnetic field is investigated experimentally. The drops are of Galinstan and placed on a curved glass plate. A ring-like inductor fed by an alternating electrical current generates the magnetic field. The free surface contour of the drop is observed using a high-speed camera system. In the experiment we vary the inductor current and the drop volume while the frequency is fixed. Upon increasing the inductor current static axisymmetric squeezing (0 < I < Ic) and following azimuthal waves (I > Ic) were observed.

Quasi-Geostrophic Dynamos

FM19L_12330

Fri • 09:50 • 315

Nathanaël Schaeffer, Philippe Cardin
LGIT, Université Joseph Fourier, Grenoble, France

Taking advantage of the properties of liquid metals and of rapidly rotating flows, we are able to compute dynamos at high Reynolds number ($Re > 10^5$) and low magnetic Prandtl number ($Pm < 10^{-2}$) We developped a numerical model that uses a quasi-goestrophic approximation to compute the flow (whithout subgrid scale model), leading to two-dimensional equations. The induction equation for the magnetic field is fully resolved in 3D, in a sphere. This approach proves quite efficient for low magnetic Prandtl number and suitable flows, for which there is a scale separation between magnetic field and velocity field, allowing to compute the magnetic field on a coarser grid and whith larger time steps than for the velocity field. We show results of these calculations applied on the turbulent flow produced by the destabilization of a Stewartson shear layer.

Dynamo Action in Steady Helical Pipe Flow

FM19L_12979

Fri • 10:10 • 315

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(2) *Imperial College London, UK*

This paper considers laminar flow of an electrically conducting fluid through a helical symmetric pipe driven by a steady pressure gradient. The possibility of spontaneous magnetic field generation is investigated. Two features of the helical geometry are favourable for dynamo action. Firstly, the helical symmetry automatically gives rise to a geometrical linkage akin to the alpha-effect, and secondly the steady pipe flow has a stagnation point structure in the secondary, cross-pipe component at moderate hydrodynamic Reynolds number. It is shown that growing modes, with the same helical symmetry as the underlying flow, can occur for moderate values of the magnetic Reynolds number, $R_m \simeq 100$. The structure of these modes is analysed asymptotically as $R_m \to \infty$, and found numerically. The calculations are continued into the nonlinear saturation regime. This is believed to be the first example of a steady, pressure-driven fluid dynamo. The work has relevance to contemporary experiments to construct a laboratory dynamo.

Bifurcation of Conical Magnetic Field

FM19S_10235

Thu • 14:30 • 306

Vladimir Shtern
University of Houston, USA

The appearance of a magnetic field in a magnetic-free flow of an electrically conducting fluid is an intriguing manifestation of symmetry breaking. It is shown that bifurcation of magnetic field (BMF) is typical of conical flows. The conical flows include the Schlichting, Landau and Squire swirl-free jets, the Long swirling jet, and many other jet-like flows. Some jet-like flows consist of not only outflow but also inflow regions, e.g., near accretion disks in cosmic jets and near the surface of electro-slag flows. The inflows being sufficiently strong overcome magnetic diffusion and accumulate the magnetic field in the similarity region where the magnetic induction behaves as velocity. The accumulation manifests as BMF in a conical model. We prove that BMF occurs in a flow with accretion and show a few examples which mimic cosmic and technological jets. Interestingly, the accretion enhances mostly the magnetic field rather than the jet velocity.

Fluid Dynamos and Precession Driving

J. Leorat
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FM19S_11621
Thu • 14:35 • 306

The successful fluid dynamo experiments of Riga and Karlsruhe in 1999 prompt to study the feasibility of a large scale MHD wind tunnel without internal walls, as in natural dynamos. Since precession motion imposed on a closed container is able to drive a flow at the largest available scale, a systematic test study has been undertaken, using a cylindrical container (28 litres). The main control parameter of the flow is the precession rate p (ratio of precession to rotation frequencies). A critical rate p* (showing hysteretic properties) clearly separates laminar flow (steady in the precession frame) and turbulence. The laminar domain may be considerably extended by adding radial blades at one container's end. The turbulent regime verifies Kolmogorov's scaling with a low power coefficient and MHD flows with magnetic Reynolds numbers of a few hundreds seems within reach. Extensions of this work are in progress (PIV and kinematic dynamo computations).

Simulating the Orszag-Tang vortex using RSPH

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(2) *Norwegian Defence Estates Agency, Oslo, Norway*

FM19S_11809
Thu • 14:40 • 306

The formation of the compressible Orszag-Tang vortex has become a standard test for multi-dimensional MHD codes. In the present work, the problem is studied using the Lagrangian method Regularized Smoothed Particle Hydrodynamics (RSPH). First, a brief introduction to RSPH is given together with the model equations. Then, test results are presented, both for the case of uniform and non-uniform resolution. The results fit well with earlier results and indicate that RSPH might be a fully competitive, Lagrangian alternative to traditional grid-based methods for this type of problem.

Homogenisation of Electrically Heated Glass Melts by Lorentz Forces

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FM19S_11906
Thu • 14:45 • 306

Key words: glass melts, homogenisation, Lorentz forces Abstract: In contrast to liquid metals which are generally turbulent, in glass melts occur only slow laminar flows due to their high viscosity and small Reynolds numbers ($Re \approx 1$). To obtain sufficient homogeneity plenty of time is required for processing. It is well known that the refining and mixing of glass can be supported by additional direct electrical heating. This causes stronger buoyancy due to the resistive heating of the melt mainly near the electrodes and enhances the temperature gradients. In addition to that, an imposed magnetic field perpendicular to the electric field generates Lorentz forces, which reinforce or counteract the temperature gradient driven convection. This work investigates the utilisation of this effect for the homogenisation of glass melts. We have performed several experiments characterized by different values of the heating electrical current and the intensity of the magnetic field in order to systematically study the influence of Joule heat and Lorentz forces on the homogeneity of glass melts. The investigation of material from specimens showed an improved homogeneity as a result of similar optical and physical properties. To verify the findings of the hot experiments we have also analysed model fluids at low temperatures to get visible information about the convective flow. Furthermore, numerical simulations and analytical modelling complete the research. The use of mixing effects caused by electromagnetic stirring may lead to new applications of magnetofluiddynamics in glass technology.

Mean Electromotive Force for a Ring of Helical Vortices

FM19S_12120

Thu • 14:50 • 306

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We study the dynamo mechanism for a fbw made of a ring of stationary helical vortices in an electrically conducting media. The choice of this fbw is related to the one obtained in thermal convection in a rotating shell which is also expected in the Earth's outer-core. This choice is also related to a sodium experiment, carried out in Grenoble, based on a spherical Taylor-Couette model. Applying the mean fi eld approach and relying on the second order correlation approximation we derive the mean electromotive force (e.m.f.) produced by such a fbw. We fi nd that such a ring of helical vortices may produce, from an azimuthal mean magnetic fi eld, an azimuthal mean e.m.f. leading to the generation of a poloidal magnetic fi eld.

Model of Gas Flow Inside a Plasma Thruster

FM19S_12363

Thu • 14:55 • 306

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Stationary Plasma Thrusters (SPT) are high-effi ciency electric rocket engines that are ideally suited to spacecraft orbit transfer and positioning missions. By harnessing the power resources available on-board to accelerate a plasma, these engines allow substantial savings on the propellant mass in comparison with chemical rocket engines. The dynamic of neutral particles (non-ionized propellant) is a key element in numerical simulations of SPT discharges. Yet, some important kinetic phenomena are often overlooked in the common macroscopic descriptions of such a collisionless fbw, namely: i) the fact that the ionization probability of slow neutrals is higher due to their longer transit time in the channel, ii) the fbw deceleration due to friction on the walls. Using a specifi c property of the distribution function of a collisionless fbw in the presence of ionization, an assumption on the velocity dispersion of a free fbw is proposed. Distinguishing then between a primary free fbw and a secondary fbw in thermal equilibrium with the walls, simplifi ed one-dimensional macroscopic equations are obtained. Stationary and transient test-cases highlight an excellent consistency between the results of the macroscopic model and exact kinetic solutions.

Subgrid-Scale Modeling of Anisotropic MHD Turbulence

FM19S_12379

Thu • 15:00 • 306

Oleg Zikanov, Anatoliy Vorobev
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We perform high-resolution direct numerical simulations of MHD turbulence at low magnetic Reynolds number. A forced fbw in a three-dimensional box with periodic boundary conditions is considered. The purpose of our simulations is to investigate fundamental properties of turbulent fluctuations affected by an imposed steady uniform magnetic fi eld and to develop an SGS (subgrid-scale) closure capable of accurate and physically adequate representation of anisotropic and intermittent MHD turbulence.

Numerical Study of the Flow in a Finite Cylinder Driven by a Rotating Magnetic Field

FM19S_12587

Thu • 15:05 • 306

Karel Frana, **Jorg Stiller**
Dresden University of Technology, Dresden, Germany

We present direct numerical simulations (DNS) of the fbw in a fi nite cylinder d riven by a rotating magnetic fi eld. Employing the rigid-body and low-frequency approximations the mathematical model reduces to the Navier–Stokes equations with a priori known Lorentz force. A sec ond-order fi nite-element method combined with Adams-Bashforth time integration i s used for discretization. The objective of this study is to identify the dominating structures and mechani sms in the transitional and early turbulent fbw regimes. The DNS cover a range up to 10T(ac), where Ta denotes the magnetical Taylor number. The most striking result of the study is the insight in the formation, evolution and fi nally dissipation of Taylor-Gortler-like vortices that clearly dominate t he turbulence physics and provide an effi cient mixing mechanism in this fbw. Moreover, large scale fbw variations in azimuthal direction could be identifi ed. However, these fluctuations do not contain any harmonic components even in nea r-critical fbw.

Interface Reconstruction in Cylindrical Two-Compartment-Systems Using Magnetic Field Tomography

FM19S_12605

Thu • 15:10 • 306

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In magnetic fluid dynamics appears the problem of reconstruction of free boundary between conducting fluids. The reconstruction problem of the interface between two conducting fluids with different conductivities using external magnetic fi eld measurements in the case of a highly simplifi ed model of an aluminium electrolysis cell has been investigated. In the paper, an interface reconstruction technique based on genetic algorithms is presented, and numerical simulations are compared with some magnetic fi eld measurements.

Contactless Inductive Flow Tomography: Theory and Experiment

FM19S_12613

Thu • 15:15 • 306

Frank Stefani, Gunter Gerbeth, Thomas Gundrum
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When a moving electrically conducting fluid is exposed to an applied magnetic fi eld, electrical currents are induced that give rise to an additional magnetic fi eld. The ratio of the induced fi eld to the applied fi eld is determined by the magnetic Reynolds number Rm. If Rm is not too small, the induced fi eld can be measured in the exteriour of the fluid. Applying the imposed magnetic fi elds in different directions and measuring the respective induced fi elds one can gather suffi cient information to reconstruct, at least approximatively, the velocity structure of the fluid. The theory of such a ontactless inductive fbw tomography (CIFT) is delineated, and its practical feasibility is demonstrated in a liquid metal experiment. Qualitative as well as quantitative changes of the fbw fi eld were resolved by the CIFT method in a reasonable and reproducible way.

FM20

Multiphase flows

Chairpersons: S. Balachandar (USA), J. Magnaudet (France)

Statistics and Preferential Distribution of Micro-Particles in Turbulent Boundary Layer: Implications for Resuspension Mechanisms

FM20L_13012
Fri • 09:30 • 309

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The distribution of inertial particles dispersed in turbulent flows is highly non-homogeneous and may exhibit a complex pattern which is driven by the structures of the turbulence field. We simulate a turbulent channel flow of air laden with a dilute concentration of inertial micro-particles for different values of their inertial parameter. We focus on the statistical description of particle velocity and distribution field and we specifically quantify particle deposition and resuspension in the near wall region. Direct Numerical Simulation of a turbulent boundary layer, calculated for a shear Reynolds number of 150, is used on a 128x128x129 grid and is coupled with Lagrangian particle tracking of 100.000 particle trajectories (Stokes number: 0.2, 1, 5, 25). Forces acting on particles are: drag and inertia. We also quantify the relative effects of gravitational and turbophoretic mechanisms in wall transfer of inertial particles for two different configurations: vertical upward and horizontal channel flow. We further examine the influence of one-way and two-way coupling assuumptions on particle statistics and transfer mechanisms.

Particle Turbulence Interaction

FM20L_12332
Fri • 09:50 • 309

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Here we present results from fully-resolved direct numerical simulations of turbulent multiphase flow. In addition to resolving the wide range of length and time scales associated with turbulence we also resolve all the length scales associated with the particle and the small-scale flow features generated by them. We present results for the interaction of a single spherical particle with ambient turbulence and consider the both isotropic freestream turbulence and wall-bounded channel turbulence. The key parameters of the problem are the ratio of particle size to Kolmogorov scale, the ratio of turbulence intensity to mean relative velocity, and the relative distance from the wall. We first study the effect of ambient turbulence on the mean and fluctuating components of drag and lift forces on the particle. We then study the effect of the particle on wall turbulence by focusing attention on the wake region of the particle.

Gravity Induced Mixing of Miscible Fluids in Vertical and Inclined Tubes

FM20L_12092
Fri • 10:10 • 309

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(2) *LPA, Département de Physique de l'ENS, France*

Gravity induced mixing of two miscible fluids in a long tube is studied as a function of the tube tilt angle from vertical θ and of the density contrast characterized by the Atwood number At. At high At values and/or low θ values, the relative concentration of the two fluids follows a macroscopic diffusion law characterized by a diffusion coefficient D increasing strongly with the tube tilting (by a factor of 100 between 0 and 70^o). At higher θ values and/or for low density contrasts, a segregation of the two fluids in the tube section is induced by gravity resulting in a stable counterflow with little mixing at the interface. The Atwood number corresponding to the transition between the diffusive and counterflow regimes increases strongly with the deviation angle from $At = 10^{-4}$ for $\theta = 0°$ to $At = 5 \times 10^{-2}$ for $\theta = 80°$.

Viscous and Viscelastic Potential Flow

FM20L_10843
Fri • 11:00 • 315

Daniel D. Joseph
University of Minnesota, USA

Recent results will be reviewed and new results presented which establish that in all cases in which potential flow satisfies the equations of motion for viscous (or viscoelastic) fluids, it is neither necessary nor useful to put the viscosity to zero. Stated more severely these results suggest that the inviscid part of potential flow theory may be deleted.

Oscillatory Motion of Freely-Moving Light Bodies: from Cylinders to Disks

FM20L_12139
Fri • 11:20 • 315

P. Cordeiro Fernandes, P. Ern, **F. Risso**, J. Magnaudet
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The oscillatory motion of flat cylinders rising freely in a slightly viscous fluid otherwise at rest was investigated experimentally. Original results concerning the translation and rotation of the body were obtained for a wide range of Archimedes numbers Ar (buoyancy vs. viscous effects) and diameter-to-height ratios d/h. Body inclination and velocity oscillate at the same frequency and have amplitudes that increase with Ar. However the dynamics are rather complex since the coupling between the body rotation and translation strongly depends on the body aspect ratio. When d/h increases, the amplitude of the oscillations of the body inclination reaches a constant value whereas that of horizontal velocity continues to increase. Moreover, the phase difference between the body velocity and inclination continuously evolves from about zero (bubble-like behavior) to a value close to 90 degrees (disk-like behavior). It also appears that the drag coefficient is strongly influenced by the oscillatory motion.

Non-Uniform Flow Hydrodynamics of Deformable Shapes

FM20L_12342
Fri • 11:40 • 315

T. Miloh
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We consider the practical case of a rigid or deformable body of arbitrary shape moving unsteadily with six degrees of freedom in an inviscid, incompressible and nonhomogeneous flow field possessing a uniform shear (vorticity) and fluid density gradient. By integrating the Euler equations, we derive analytic expressions for the pressure induced force and moment exerted by the fluid on the moving body which determine its spatial trajectories. A distinction is made between 2d and 3d flow geometries in the sense that in 3d the analysis is valid only during a short time interval after the body is introduced into the fluid as a result of vortex stretching effects. Nevertheless, it is demonstrated that the small-time 3d analysis can be also applied to viscous flows governed by the Navier–Stokes equations. Special attention is given here to the puzzling problem of self-propulsion of a general deforming shape (bubble, drop, elastic structure etc.) in the Eulerian realm resulting from non-linear coupling between body's shape modes and non-uniform flow parameters. Also considered is the feasibility for a Lorentz-type MHD self-propulsion mechanism of a non-rigid shape embedded in a conducting fluid due to controled resonant interactions between the applied magnetic field and body deformation in the limit of a small magnetic Reynolds number. Demonstrations are given for some time-dependent simple shapes embedded in a linear shear flow with a constant applied magnetic field and fluid density gradient in both unbounded or bounded flow domains.

Mean Motion Induced in a Liquid by Rising Bubbles

FM20L_12383
Fri • 12:00 • 315

Veronique Roig, Amaury Larue de Tournemine
Institut de Mécanique des Fluides, Toulouse, France

We report experiments on the mean motion generated by a uniform injection of bubbles in a uniform liquid flow. The Reynolds number of the relative motion is high, the Weber number is moderated and the void fraction is varied up to 15%. With a newly developed methodology, we estimate the statistics of the liquid velocity conditioned or not by the presence of the bubbles. We therefore discuss the displacement of liquid induced by the relative motion of the bubbles. We discuss drift flux models as developed by Kowe et al (1988) and more recently by Eames et al (2003). An attempt to take into account wakes effects in such models is also presented

Plane Couette Flow of Dense Liquid-Particle Suspensions

FM20L_12397
Fri • 12:20 • 315

Jos Derksen, Sankaran Sundaresan
Princeton University, Princeton, USA

We numerically study dense (26–59% solids volume fraction) neutrally buoyant solid-liquid suspensions undergoing shear at particle-Stokes numbers signifi cantly larger than 1, inspired by Bagnold's 1954 Couette fbw experiments. The three-dimensional, time-dependent simulations employ lattice-Boltzmann discretization of the Navier–Stokes equations to solve the fluid fbw in between the particles and to account for solid-liquid interaction; and hard-sphere and lubrication force interaction between the particles. The simulations show shear induced ordering which strongly depend on solids volume fraction and polydispersity. The scaling of the normal stresses indicates the presence of a granular fbw regime. So far, no evidence of a macro-viscous regime has been found.

The Effect of Bubbles on Developed Turbulence

FM20L_12440
Fri • 12:40 • 315

Stefan Luther, Thomas H. van den Berg, Judith Rensen, Detlef Lohse
University of Twente, Enschede, The Netherlands

We report on measurements of energy spectra, second and higher order structure functions in bubbly turbulence. The void fraction is up to 2.9% with an mean equivalent bubble size of 3–5 mm. We fi nd the results of [I. Mazzitelli, D. Lohse, F. Toschi, Phys. Fluids 15, L5 (2003)] qualitatively confi rmed, i.e. a more pronounced energy enhancement on small scales than on large scales due to the presence of the bubbles, leading to a less steep slope in the spectrum as compared to the Kolmogorov -5/3 law.

Large-Eddy Simulation of Particle Dispersion in the Duct with Fluid Injection

FM20S_10416
Thu • 14:30 • 307A

Konstantin N. Volkov
University of Central Lancashire, Preston, UK

The numerical calculations are performed by the Eulerian-Lagrangian approach for the fluid and dispersed phases respectively. The fluid fbw calculations are based on fi ltered Navier–Stokes equations. Subgrid turbulent viscosity is computed with the dynamic model. The solid phase is treated by the Lagrangian approach, which means that particles are followed in time along their trajectories through the fbw fi eld. At every given time step, the new position of the particles and the new translational velocity are calculated according to the forces acting on the particles. The influence of infbw conditions, size of particles and place of particles injection on their dispersion pattern in the turbulent duct fbw are investigated. The obtained results have a good agreement with the results computed on the base of Reynolds averaged Navier–Stokes equations and experimental data.

Sings of Flooding Instability in Inclined Liquid Films at High Pressure and Mass Transfer in High Density Gas Slugs

FM20S_10690
Thu • 14:35 • 307A

Maria J.F. Ferreira, Joao R.F. Guedes de Carvalho
FEUP, Department of Chemical Engineering, Porto, Portugal

The influence of gas density on fboding instability phenomena is investigated experimentally both in long gas slugs of CO2 rising in vertical tubes fi lled with water at pressures up to 5.2 MPa, and inside a rectangular column, with fht walls, positioned in the vertical and at 15ş, 45ş and 60ş from the horizontal, at absolute pressures up to 0.6 MPa with air and up to 1.5 MPa with argon, at Reynolds numbers for the water between 2667 and 26667. The experiments have shown, despite some scepticism about the possibility of occurrence of fboding instability at low gas velocities recorded, that there is a critical value of rg(u + ui)2 above which fboding instability sets in, for a given liquid at a given fbw rate in a given column (where rg is the density of gas, u the average velocity of gas and ui is the liquid velocity on gas-liquid interface).

Separation and Sorting of Heavy Particles Suspended in a Fluid by Settling in a Periodic Vorticity Field

FM20S_11189
Thu • 14:40 • 307A

Urbano Sanchez, Maria J. Moreno
Huelva University, Huelva, Spain

Processes involving separation and sorting of small particles from fluids are important in the environment and many industrial processes. For particles which density is much greater that the fluid density we have simulated a velocity fi eld generated by a 2D array of vortices periodically repeated in space. Firstly the neighbouring vortices were swirling alternatively cyclonically and anticyclonicaly. For small particle inertia the particles follow the flow streamlines surrounding the vortices, but for larger particle inertia the particles settle in the central region of low flow vorticity situated between two vertical rows of vortices due to an inertial bias. Secondly all the vortices were swirling anticyclonically. Surprisingly, for sufficiently great particle inertia some isolated curves appear, which limit some regions of low vorticity where particles can not enter and all the particles settle on those curves. As greater is the particle inertia greater is the width of those regions. Therefore if we know the particle inertia we will know the position in which it will settle and vice versa, so this fact suggest a mechanism to sort particles with different inertia values materializing the velocity field mentioned above.

Gas–Liquid Interfractial Distribution in Inclined Downward Pipe Flow

FM20S_11655
Thu • 14:45 • 307A

Elena Trostinetsky, Lev Shemer, Dvora Barnea
Tel-Aviv University, Tel-Aviv, Israel

Two-phase air-water flow experiments for a wide range of pipe inclinations and flow rates are reported. Digitial video camera connected to a boroscope is used to visualize phase distribution in the pipe cross-section illuminated by a laser light sheet. Advantages and limitations of the boroscope technique applied for two-phase flow are discussed. Simultaneously, wave gauges are used to measure the instantaneous surface changes. The main goal of this work is to investigate the transition from stratified to annular and to slug flow. Simultaneous video images and wave gauge records provide extensive information on the instantaneous and statistical properties of the phase distributions in the pipe.

Videogrametry in Fluidized Bed Reactors

FM20S_11745
Thu • 14:50 • 307A

Stanisław Anweiler, Roman Ulbrich
Politechnika Opolska, KTCiAP, Opole, Poland

Experiments were put on identification and evaluation of two phase gas-solid flow pattern in fluidized bed models with the use of videogrametry. Different fluidization columns with transparent walls were used. The main task was to develop method for evaluation of the homogeneity of the fluidized bed, based on image analysis. Various types of flow regimes were recorded with high speed CCD video camera, and frame sequences were put under digital image analysis. Dynamics of homogeneity changes have been expressed as change of grey level value of the image. Analyzing brightness level of each pixel of each image in the frame sequence, gives the grey level fluctuation function. It turned out that each two phase flow regime has its original grey level fluctuation pattern. The digital imaging of fluidization phenomena – videogrametry – provides non-invasive measurement tool for recognition of two phase flow structure, and evaluation of many features of fluidized bed reactor.

Proteus: a New Computational Method for Multiphase Flow

FM20S_11849
Thu • 14:55 • 307A

Zhi-Gang Feng, **Efstathios E. Michaelides**
Tulane University, New Orleans, USA

“Proteus” is a new computational scheme that combines several desired components of the Lattice Boltzmann Method (LBM) the Immersed Boundary Method (IBM) and the Direct Forcing Method (DFM) in order to solve fluid-particle interaction problems, including problems with deformable boundaries. The method uses a regular Eulerian grid for the flow domain and a Lagrangian grid to follow particles in the flow field. The velocity field of the fluid and particles is solved by adding a force density term into the LBM. The no-slip condition on the boundary of a moving particle is enforced by adding a forcing term in the momentum equations as in the case of the IBM. “Proteus” applies the direct forcing scheme and eliminates the need for the determination of the stiffness coefficient, a free parameter that requires trial and testing to select. This allows the enforcement of the rigid body motion of a particle in a more direct and efficient way. This novel method preserves the advantages of LBM in tracking a group of particles and, at the same time, provides an alternative and better approach to treating the solid-fluid boundary conditions. Proteus enables one to simulate problems with particle deformation and fluid-structure deformation. Here we present results on the validation of the method as well as the solution to a problem with 1234 spheres in an enclosure.

Production of Sound Self-Oscillations as a Result of Vapor Condensation

FM20S_12239

Thu • 15:00 • 307A

Serguei O. Makarov
Perm State University, Perm, Russia

Generation of spontaneous sound oscillations in an acoustic resonator in the case of condensation of vapor is investigated theoretically and experimentally. The experimental setup is a resonator with warmed cylindrical tank and cooled tube. The quantity of different fluids inserting into the tank is varied. It has been found experimentally that the condensation of vapor on the cold tubeis a necessary requirement of existence of sound oscillations in the system. Furthermore the character of vapor movement is visualized at sound initiation. The mathematical model of this phenomenon is developed. The full system of hydrodynamics equations for compressible fluid with heat transfer and kinetic equations is used. The analytical solution of linearized equations for normal disturbances is found. Neutral curves with regions of oscillating instability are constructed.

Dynamic Blocking at the Flow of Invert Water–Oil Emulsions

FM20S_12304

Thu • 15:05 • 307A

Alfir T. Akhmetov[1], Alexey G. Telin[2], Vladimir V. Glukhov[1]
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(2) *CID YUKOS, Ufa, Russia*

Experimental investigations were done with the multiphase systems – highly concentrated invert water-in-oil emulsions, stabilized by the emulsifier Neftenol and without it. Flow in the channels – in the cell of Hele-Show or in the capillary structure results in the considerable transformation of emulsion without Neftenol – major re-structuring. Flow rate of the emulsion was measured using the electronic scales HM-200, visual picture of flow was recorded using the digital camera. According to data from the scales full blocking at constant pressure drop, a surprising effect for the disperse liquid-in-liquid system, with careful study using the microscope showed presence of small flow of the fluid, which size is four orders less than initial. As the microflow of the emulsion is always present, we will call this effect effect of dynamic blocking. In the axisymmetrical flow the effect is also present, but in this case hydrodynamic flow turns into very slow creeping motion in the capillary.

Simulation of Planar Wave Instabilities in Liquid-Fluidized Beds

FM20S_12671

Thu • 15:10 • 307A

Jos Derksen, **Sankaran Sundaresan**
Princeton University, Princeton, USA

We have performed discrete particle simulations in a fully periodic domain at conditions that are representative for liquid fluidized beds. Our three-dimensional unsteady simulations employ lattice-Boltzmann discretization of the Navier–Stokes equations for solving the fluid flow. The particles interact with the fluid through hydrodynamic forces, and with each other via hard-sphere collisions and by the leading order term of the normal lubrication force. Starting from a case with a very high volume fraction of particles, we have examined the dynamics of the flow at progressively smaller solids volume fractions in the periodic domain. The simulation results show the experimentally observed transition from homogeneous fluidization to a planar wave regime. The wave speed corresponds nicely with experimental observations. The simulations reveal detailed information with respect to spatial variation of fluid-particle interaction, and particle phase pressure.

Image Processing Method in Estimation of Bubble Column's Work

FM20S_12886

Thu • 15:15 • 307A

Daniel Zajac, Roman Ulbrich
Technical University of Opole, Opole, Poland

This paper presents an experimental study of identification and analysis of two phase gas-liquid flow using image processing method. The process of two phase flow has been realized in bubble column. The continuous and dispersed phases were water and air, respectively. The gray level value of the obtained recordings from gas-liquid flow was the basic parameter for process investigation. Based on this parameter it was possible to calculate and determine many important statistical characteristics of two phase gas-liquid flow.

FM21

Solidification and crystal growth

Chairpersons: M. Worster (UK), M. Glicksman (USA)

Solidification and Compositional Convection of a Ternary Alloy

FM21L_11328

Mon • 16:00 • 123

Andrew F. Thompson[1], Herbert E. Huppert[2], M. Grae Worster[2], Anneli Aitta[2]
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(2) *Institute of Theoretical Geophysics, University of Cambridge, UK*

In an experimental study where an aqueous solution of potassium nitrate and sodium nitrate were cooled from below, two distinct mushy layers formed separated by a nearly horizontal interface. Fluid in the melt and the upper, primary, mush was kept well mixed due to compositional convection originating in the primary mush. Convection reduced the vertical concentration gradient in the primary mush layer allowing the cotectic mush to overtake the primary mush. At this point convection stopped and the growth of the single mush layer (cotectic) that remained was governed by diffusion. Concentration measurements showed good agreement with the evolution predicted by use of the linearized equilibrium phase diagram. We develop a global conservation model in this regime that accurately predicts the two mush interface positions when forced with empirical heat and solute fluxes. The identification of a density reversal in this system begins to address the complexities of solidifying multi-component alloys.

Directional Solidification of Pb-Sn Alloys Affected by a Rotating Magnetic Field

FM21L_12365

Mon • 16:20 • 123

Sven Eckert[1], Bernd Willers[1], Ulf Michel[2], Gustav Zouhar[2], Petr A. Nikrityuk[3], Kerstin Eckert[3]
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(2) *Institute of Material Science, Technische Universität Dresden, Dresden, Germany*
(3) *Institute of Aerospace Engineering, Technische Universität Dresden, Dresden, Germany*

An experimental and numerical study with respect to the influence of a rotating magnetic field (RMF) on the directional solidification of a Pb-Sn alloys is reported. A cylindrical crucible with a diameter of 50 mm was positioned on a water cooled copper chill thus inducing an axial heat transfer from the mold. The electromagnetically driven convection shows a distinct effect on the solidification parameters such as the cooling rate, the temperature gradient or the growth velocity of the liquidus isotherm resulting in significant modifications of the observed macro- and microstructures. The fluid flow promotes the heat transfer rate and decreases the temperature gradients in the melt. Analyzing the columnar-equiaxed transition (CET) a dependence of the CET position and shape on the applied Taylor number was demonstrated. The experiments also revealed that the permanent modification of the fluid volume due to the movement of the solidification front prevents the development of stationary flow pattern as known for the isothermal case.

Mushy Zone Evolution: Experimental and Theoretical Approach

FM21L_11472

Mon • 16:40 • 123

Afina Lupulescu[1], Martin E. Glicksman[1], **John Lowengrub**[2], Vittorio Cristini[2]
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(2) *Dept. of Mathematics and Dept. of Biomedical Engineering, CA, USA*

Melting and freezing phenomena play key roles in materials and biological sciences, and might also influence geophysical and nebular processes. To interpret microgravity melting experiments two of the authors (MEG/AL) recently developed a quasi-static model for the conduction-limited melting of prolate spheroids by solving the quasi-static moving boundary problem in the absence of capillarity, assuming that the ratio of major to minor axes, C/A, is constant. Capillarity, as observed in experiments, plays an increasingly important role in the late stages of melting as the curvatures diverge when a melting crystal nears extinction. The other authors (VC/JL) recently developed adaptive 3D boundary integral methods for quasi-steady solid/solid and solid/liquid phase transitions. Their numerical approach tests the assumption of shape-

constraint (prolate spheroids) and quantifies the effect of capillarity not yet included in the model. Using 3D adaptive boundary-integral methods, the authors are also simulating fragmentation dynamics during melting.

Nonlinear Oscillatory Convection in Mushy Layers

Peter Guba, M. Grae Worster
Institute of Theoretical Geophysics, University of Cambridge, UK

FM21L_11270
Mon • 17:00 • 123

We study the nonlinear development of an oscillatory convective instability in a two-dimensional mushy layer during solidification of a binary mixture. We adopt the near-eutectic limit, making the problem analytically tractable using standard perturbation techniques. We consider also a distinguished limit of large Stefan number, which allows a destabilization of the system to the oscillatory mode of convection. We provide a comprehensive investigation of the nonlinear stability of travelling and standing waves, including the relative stability between the two wave patterns. In addition to mapping out the location of different stable oscillatory patterns in the available parameter space, we give the detailed spatio–temporal structure of the corresponding thermal, flow and solid fraction fields within the mushy layer, as well as the local bulk composition in the resulting eutectic solid. The relevance of our results to recent laboratory experiments is also discussed.

Salt Precipitation in Geothermal Reservoirs

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(2) *BP Institute for Multiphase Flow, Cambridge, UK*

FM21L_11926
Mon • 17:20 • 123

We model the motion of the boiling front which develops when hot saline solution migrates towards a low pressure well from a geothermal reservoir which is initially saturated with hot saline solution. We derive a family of self-similar solutions which describe the motion of the liquid and vapour towards the well, as the boiling front migrates out into the reservoir. These solutions take into account the reduction in permeability and porosity due to salt precipitation at the boiling front. We find that for low reservoir pressure or small salt concentration there are two distinct branches of self-similar solutions. For each salt concentration, these branches coincide at a critical reservoir pressure. For larger reservoir pressure, the self-similar solutions cease to exist and we propose that in this regime, the pore space becomes fully clogged with salt precipitate.

Magnetic Resonance Imaging of Structure and Convection in Solidifying Mushy Layers

P. Aussillous[1], A.J. Sederman[2], L.F. Gladden[2], H.E. Huppert[1], M.G. Worster[1]
(1) *Institute of Theoretical Geophysics, Cambridge University, UK*
(2) *Magnetic Resonance Research Center, Cambridge University, UK*

FM21L_11320
Mon • 17:40 • 123

Using a powerful Magnetic Resonance Imaging technique, we present new high-resolution images of structure and convection inside a solidifying mushy layer formed from a binary alloy. We focus especially on systems in which chimneys are observed, which represent an unwanted and financially wasteful phenomenon in industrial casting. The experimental setup consists of a sucrose-water solution in a cylindrical tank, cooled at the top at -20C, well below the liquidus temperature. Once a mushy layer has formed, we observe the appearance of chimneys inside the mushy layer and resolve their internal structures and that of the ice platelets around them. The MRI technique allows us to measure the porosity and follow its evolution as a function of time and position. It also gives a measure of the convection in the chimneys, and we correlate the measured vertical mean fluxes through chimneys with the evolution of the spatial distribution of porosity.

A Semi-Sharp Phase Field Method for Quantitative Phase Change Simulations

Gustav Amberg
Dept. of Mechanics, Stockholm, Sweden

FM21L_12312
Fri • 09:30 • 123

The phase field method has become very popular for simulating solidification phenomena, such as the evolution of dendrites or other microstructures. The essential idea of the method is to treat the interface as having a finite width, represented as a rapid but continuous transition in a scalar variable. However, in order to connect the model parameters to the sharp interface parameters, the standard model requires an asymptotic analysis in a vanishing interface width, which has hampered the quantitative usefulness of the method. In this talk the method is simplified to the point that the relevant reduced problem can be solved analytically, allowing the sharp and phase field parameters to be identified, in principle without restrictions

on the model parameters. The scheme is tested for standard cases of two-dimensional solidification, showing excellent agreement with sharp interface kinetics. Further examples and applications are presented as time and results allow.

Cell Shapes in Directional Solidification: a Global Study

FM21L_12543
Fri • 09:50 • 123

Marc Georgelin, Alain Pocheau
IRPHE, Université Aix-Marseille, Marseille, France

This work is devoted to experimentally characterize the whole shape of growth cells in directional solidification, from their tip to their grooves, and in a large domain of control parameter. For this a library of cell shapes is determined and fitted to a class of definite shape functions that involves a minimum of fit parameters. All shape have been finely fitted this way with fit parameters showing meaningful variations with control parameters. This provides the first global characterization of cell shapes, both in the real space and in the control parameter space. Interestingly, no shape transition is found at the sidebranching transition. More generally, this geometrical determination of a whole cell library provides a firm ground for testing or improving theories or simulations of directional growth in the cellular to near dendritic regime.

Convection Driven by Tidal Heating: Numerical Model and Parameterized Theory

FM21L_12743
Fri • 10:10 • 123

Leszek Czechowski
University of Warsaw, Poland

Global volcanic and tectonic activity observed on some satellites of giant planets are probably a result of convection driven by tidal heating. To investigate the problem, 3D model of convection is developed based on the Navier–Stokes equation, the equation of thermal conductivity, the equation of continuity, and the equation of state. Using this model a number of numerical experiments are performed to determine properties of convection. The Nusselt number as a function of Rayleigh number is also found. Using this relationship a parameterized theory of convection driven by tidal and radiogenic heating in celestial bodies is developed and applied to medium size icy satellites. The results indicate that some of the satellites could exist in a few thermal states. Present volcanic activity of Enceladus as well lack of such activity on the other satellites could be explained on the basis of this theory.

Experimental Observations of Hydrate Formation in a Convection Tank

FM21S_11058
Tue • 14:30 • 307A

C.F. Chen, Cho Lik Chan
Dept. of Aerospace and Mechanical Engineering, University of Arizona, USA

Clathrate hydrates are crystalline compounds formed by cage-like structure of hydrogen-bonded water molecules enclosing a guest molecule of a hydrate-forming substance. Many substances such as gases and fluorocarbon refrigerants are hydrate formers. We carried out experiments to examine the hydrate formation process at the interface between water and the immiscible refrigerant R141b (CH3CCl2F). In this case, hydrate formation is possible if T is less than 281.5K and P is greater 0.04 MPa. Experiments were carried out both in quiescent and convection states. In the quiescent state at 2°C, a thin hydrate film first forms on the interface. Thereafter a mushy hydrate layer grows above the film in the water layer. In a test tank with copper sidewalls, hydrates also grow from these walls at a greater rate than those at the interface. Under the convection state, growth of the hydrate mushy layer is very much affected by the flow of water.

Morphological Stability of Directional Solidification under Temperature Modulations

FM21S_11208
Tue • 14:35 • 307A

C.A. Chung, K.H. Ho, W.Z. Chien
Dept. of Mechanical Engineering, National Central University, Taiwan

We study the instability of a planar solid-melt interface during directional solidification of a binary mixture. The molten zone is oscillated by an imposed temperature modulation. The basic state is solved analytically with the bulk melt quiescent by expanding the governing equations in terms of the small amplitude of modulation. A preliminary investigation on the morphological instability of the basic state is presented.

AHP Setup for Low Laminar Melt Flow Study in Crystal Growth

FM21S_11331

Tue • 14:40 • 307A

Michael A. Gonik[1], Janusz A. Szymczyk[2], Tomasz A. Kowalewski[3]
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(2) *University of Applied Sciences, Stralsund, Germany*
(3) *IPPT PAN, Warszawa, Poland*

For verification of numeric methods and development of experimental benchmarks for 2D and 3D models of heat and mass transfer in crystal growth, the experimental setup is designed. A novel AHP method of crystal growth, which makes possible to grow crystal from the thin melt layer employing submerged AHP-heater, was based on this setup. Laminar character of the flow and available data on temperature over all boundaries of melt-crystal system allows performing accurate computations. The setup is made for conducting experiments in crystal growth of NaNO3 and ice, and equipped with PIV and PVT visualizations systems to provide finding flow velocity field and temperature distribution in the fluid. Preliminary investigations conducted for NaNO3 solidification have shown good coincidence of calculated data on convection with those observed in the experiment, as well as possibility to suppress the natural convection and to create low laminar melt flow similar to micro gravity conditions

Optimization of the Growth Conditions of a Nd:YVO4 Cylindrical Bar

FM21S_11362

Tue • 14:45 • 307A

Liliana Braescu[1], Robert Szabo[2], Agneta M. Balint[2], Stefan Balint[2]
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(2) *Dept. of Mathematics, The West University of Timisoara, Timisoara, Romania*

The main purpose of this paper is to find those values of the growth process parameters (pulling rate v, temperature at the meniscus basis T0, die radius r0) which assure the growth of a Nd:YVO4 cylindrical bar with a prescribed diameter and for which the non-uniformities of the surface of the bar, due to small uncontrollable oscillations of the pulling rate and the melt temperature at the meniscus basis, are minimum possible. Numerical results are given for a Nd:YVO4 cylindrical bar of 5 [mm] diameter, grown in a furnace in which the vertical temperature gradient is k=33 (K/mm) for the following three types of uncontrollable oscillations: $\Delta v = 0.001$ (mm/s), $\Delta T = 1$ (K); $\Delta v = 0.01$ (mm/s), $\Delta T = 10$ (K) and $\Delta v = 0.02$‘(mm/s), $\Delta T = 20$‘(K), respectively.

Front Tracking Technique on a Fixed Grid in Modelling of Binary Mixture Soldification with Natural Convection

FM21S_11364

Tue • 14:50 • 307A

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A novel front tracking method is presented in calculations of binary mixture solidification driven by conduction and natural convection. The method, based on the local dendrite tip kinetics and tracking of mass-less marker particles within a control volume grid, enables the detection of the under-cooled liquid zone in front of the dendrite tips line. A classical single set of mass, momentum and energy conservation equations is used to get the velocity, pressure and temperature fields in solid, liquid and mushy zones, but the latent heat effect is considered by a careful definition of the source terms in the energy equation accounting for both: the advance of solidification front and subsequent thickening of the mushy zone within a control volume. The proposed model is verified and validated through detailed comparisons with both: the predictions of the enthalpy-porous medium model and the PIV experimental findings.

Boundary-Layer Analysis of Chimney Structures in Mushy Layers

FM21S_12276

Tue • 14:55 • 307A

Jacqueline Ashmore, M. Grae Worster
Institute of Theoretical Geophysics, University of Cambridge, UK

When a multicomponent fluid solidifies against a cooled boundary, morphological instability can lead to growth of dendritic crystals of one component that form a porous medium, with interstitial liquid that is rich in the other components. Convection driven by compositional buoyancy can subsequently dissolve the solid crystals in narrow channels, which are called chimneys. We study the structure of a steady-state chimney theoretically. This requires analysis of coupled nonlinear partial differential equations characterizing the solute concentration, temperature, solid fraction and the flow field. We use boundary-layer analysis and find similarity solutions that are valid in the vicinity of the chimney. As well as obtaining a prediction for the variation in the heat and solute concentration fields and the flow, we predict the mass and solute flux through the chimney and its width.

Travelling Magnetic Field Influence on Crystal Growth by Bridgman Method

Irina S. Fayzrakhmanova, Tatyana P. Lyubimova
ICMM UB RAS, Institute of Continuous Media Mechanics, Perm, Russia

FM21S_12278
Tue • 15:00 • 307A

The paper deals with the numerical investigation of axisymmetric travelling magnetic field (TMF) influence on crystal growth by vertical Bridgman method. Several types of material, two types of geometry and temperature distribution on ampoule lateral wall are studied. We have performed fully time-dependent simulation by finite difference method and obtained different characteristics of crystal growth process (stream function maximum and minimum, front deflection; dopant distribution, temperature and stream function fields in melt and in crystal) with and without TMF and analyze TMF influence on these characteristics. It is found that TMF induces meridional flow which could be easily controlled in magnitude and direction. As the calculations show, unlike static axial magnetic field, TMF even of small intensity makes significant influence on crystal/melt interface shape: depending on TMF propagation direction it can either decrease or increase front deflection. Thus, TMF application is promising method for growing of crystals with high quality.

Convective Heat and Mass Transport in Novel Bridgman Configurations for Cadmium Zinc Telluride Growth

Andrew Yeckel, Jeffrey J. Derby
Dept. of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, USA

FM21S_12687
Tue • 15:05 • 307A

We are studying the influences of convection on heat and mass transfer in vertical Bridgman (VB) systems used to grow cadmium zinc telluride (CZT), a ternary compound which is susceptible to constitutional supercooling. We have constructed transport models of two novel VB configurations. A top-seeded configuration has a destabilizing temperature gradient in the melt. The flows in this configuration are far more intense than occur in the stabilized bottom-seeded VB configuration. Better mixing reduces radial segregation for doped-semiconductor melts, results that we expect will extend to CZT melts. Interface shapes remain unfavorably concave, however. An alternative is a bottom-seeded VB system with submerged heater, which gives superior control of interface shape, but which has poor lateral mixing. This alternative requires active control to maintain a constant gap between the interface and the heater. We will compare these systems in terms of interface shape, morphological stability, segregation behavior, and thermal stresses.

Ternary Alloy Convection in Mushy Layers: Extended Summary

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(2) *Dept. of Mathematics, University of Tennessee, Knoxville, USA*

FM21S_12768
Tue • 15:10 • 307A

We consider solidification and convection in a ternary alloy system. We focus on growth conditions under which the solidification path (liquid line of descent) through the ternary phase diagram gives rise to two distinct mushy layers. A primary mushy layer, which corresponds to solidification along a liquidus surface in the ternary phase diagram, forms above a secondary (or cotectic) mushy layer, which corresponds to solidification along a cotectic line in the ternary phase diagram. These two mushy layers are bounded above by a liquid layer and below by a eutectic solid layer. This double mushy layer geometry provides an interesting setting in which to investigate potential convective effects. In this work we describe a model for the ternary alloy mushy layer system, characteristics of nonconvecting solutions, and an investigation of convective solutions and their stability properties.

Convective Instabilities During Solidification of a Mushy Layer

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(2) *School of Chemical Engineering, Seoul National University, Seoul, Korea*

FM21S_13008
Tue • 15:15 • 307A

During solidification of binary alloys, a mushy layer of dendritic crystals is often formed by constitutional supercooling. The convective instabilities in the mushy layer solidified from a bottom boundary are analyzed under linear stability theory. By using a similarity variable, the time-dependent disturbance equations for the liquid and mushy layers are transformed to the self-similar stability equations. The critical Rayleigh numbers based on the mushy-layer thickness are found numerically for various Lewis numbers, Darcy numbers, and superheats. The critical conditions at the onset of convection in the mushy layer are predicted for the solidification system of aqueous ammonium chloride solution.

FM22

Stirring and mixing

Chairpersons: H. Aref (USA), E. Villermaux (France)

Mixing in Multiconnected Planar Domains

FM22L_12442
Wed • 08:30 • 327

Philip Boyland
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We study the stirring of two-dimensional fluids in multi-connected domains with moving boundaries using analytic and numerical tools. A time-periodic Euler flows with typical initial vorticity is not chaotic, but for constant initial vorticity there are stirring protocols which always yield chaotic time-periodic Euler flows. These protocols generate flow maps in pseudoAnosov isotopy classes as defined in the Thurston-Nielsen theory. PseudoAnosov stirring protocols with generic initial vorticity always yield non-periodic solutions for which the sup norm of the gradient of the vorticity grows exponentially. For Stoke's flow numerical and experimental results have shown that the flow maps under pseudoAnosov protocols are very efficient stirrers appearing to lack elliptic islands on visible scales. Our explanation of this phenomenon uses the connection between Helmholtz' variational characterization of Stoke's flow and the quasiconformal distortion of the flow map. Minimization of the latter, under the appropriate conditions, is known to imply global hyperbolicity.

Chaotic Advection in a Mixer with Changing Geometry

FM22L_10497
Wed • 08:50 • 327

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Chaotic advection is examined in a mixer consisting of a circular vat full of fluid, stirred by an arbitrary number of stirring rods. The fluid is assumed to be highly viscous, and the corresponding Stokes flow two-dimensional. A series solution for the velocity field permits an extremely precise computation of the paths of passive fluid particles under motion of the stirring rods. Of particular note is the case of three or more stirring rods, which allows the generation of 'topological chaos' provided the stirring rods move with appropriate topology. To date, the stirring rods have had circular cross-section; it is shown here how the series-solution approach can be modified to accommodate other cross-sectional profiles, and that stirring can be made more effective using elliptical paddles rather than circular ones.

Evaluation of Transport Properties by Exchange Matrix Method

FM22L_12257
Wed • 09:10 • 327

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This work is devoted to the study of transport properties of materials in chaotic two-dimensional stirring using, Spencer & Wiley matrix method. This study is important for applying in problems of pollutants transport (such as petroleum patches) in tidal flows. In order to construct this special exchange matrix we use an approximation of such flows suggested by Zimmerman, who adopted the idea of chaotic advection, first put forward by Aref. Then for a quantitative estimation of the transport properties we explore a coarse-grained density description introduced by Gibbs and Welander. Such coarse-grained representations over an investigation area, show a "residence place" for the pollutant material at any instant. The exchange matrix can show transport of patches or particles from any place in the area under consideration to an arbitrary location in the tidal sea and time if it happens.

On the Design of 3D Micromixers Having the Bernoulli Property

FM22L_11293
Wed • 09:30 • 327

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In dynamical systems theory a hierarchy of characterisations of mixing exist Bernoulli -> mixing ->ergodic, ordered according to the quality of mixing (the strongest first). We consider micromixers whose flows take one of two forms: 2D blinking flows, or 3D duct flows. We show that these types of flows can be reduced to so-called linked twist maps (LTMs). LTMs can be shown to possess the Bernoulli property of mixing under certain conditions. Hence, conditions can be specified for a large class of micromixers guaranteeing the best quality mixing. Extensions of these concepts lead to first principle-based designs without resorting to lengthy computations.

Chaotic Advection and Mixing in Pulsed Source-Sink Systems

FM22L_12158
Wed • 09:50 • 327

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It is well-known that pulsing a source and a sink in the unbounded plane can produce chaotic advection. This knowledge provides motivation for mixing laminar flows in high-aspect-ratio volumes using an arrangement of sources and sinks. In contrast to the existing chaotic advection analysis, the actual system is bounded and the sources and sinks must operate in pairs in order to conserve volume. These are substantial changes that impact the extent and character of the chaos. Fortunately, analytic solutions exist for source-sink pairs in unbounded and various bounded domains. We will present the results of a chaotic advection analysis that identifies the optimal operating parameters for producing chaos in pulsed source-sink systems in unbounded, circular, and rectangular domains. Application of this approach to DNA microarray analysis demonstrates that a pulsed source-sink system can significantly enhance transport and mixing in high-aspect-ratio volumes.

Active Shear Superpositon Micromixer

FM22L_12761
Wed • 10:10 • 327

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We present a theoretical and experimental study of the mixing in a Micro Electro Mechanical System (MEMS). The mixer is an active micromixer. Its design consists of a main mixing channel where the main flow is perturbed by jet flows emanating from a series of secondary channels. The lateral flows oscillate in time and reorient the lamination of passive tracers from streamwise to cross-stream. The micromixer is a silicon-etched device where the main channel is 2h wide, 13h long and h deep (h = 100 microns). The secondary channels are 5h long and h/2 wide. The parameters (flow rate, frequency, and amplitude of oscillation) are accurately controlled. The mixing process is studied numerically and experimentally using flow visualizations techniques. The numerical simulations are performed for the 3-D flow. We present some flow properties using the Mixing Variance Coefficient (MVC).

Mixing Is an Aggregation Process

FM22L_12326
Thu • 09:30 • 327

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Experiments show how a stirred scalar mixture relaxes towards uniformity through an aggregation process. The elementary bricks are stretched sheets whose rates of diffusive smoothing and coalescence build up the overall mixture concentration distribution. The cases studied in particular include mixtures in two and three dimensions, with different stirring protocols and Reynolds numbers which all lead to a unique family of concentration distributions stable by self-convolution, the signature of the aggregation mechanism from which they originate.

Intermittent Distribution of Heavy Inertial Particles in Turbulent Flows

FM22L_12048

Thu • 09:50 • 327

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The phenomenon of preferential concentration of inertial particles is studied by following lagrangian trajectories. Elementary properties of the coarse-grained distribution of heavy particles in simple turbulent flows are investigated by direct numerical simulations. In the small Stokes number case, we compute the coarse-grained particle distribution, $\overline{n}_r$, and we demonstrate that the second moment $\langle \overline{n}_r^2 \rangle$ behaves as an approximate power law: $\langle \overline{n}_r^2 \rangle \sim r^{\alpha}$. The dependence of the exponent α as a function of the Reynolds and of the Stokes number is studied in the small Stokes number limit. Our results show a strong dependence of the level of fluctuation of the particle distribution as a function of the Reynolds number.

Front Propagation in Laminar Cellular Flows: an Experimental Study

FM22L_11190

Thu • 10:10 • 327

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We experimentally address the propagation of reaction fronts in laminar flows. This issue, which may be relevant to microfluidic, biophysical media or chemical engineering, raises the question of the interplay between the mixing property of flows and the propagative property of reactions. It is modeled experimentally here in a set-up which allows front propagation in a channel that involves cellular flows. Reaction is provided by an autocatalytic oxydo-reduction chemistry and flows are generated by thermal convection or by electroconvection. It is found that reaction propagates not as a wave (i.e. not as a global object) but as particles (i.e. as local front parts) and in a way that is very sensitive to the flow geometry. As a result, reaction ever finds the most efficient way to propagate, possibly by narrow paths. This picture is at a variance with the current statistical models of effective front properties.

Development of the Fractal Dimension of Material Elements in Homogeneous Isotropic Turbulence Using Kinematic Simulation

FM22S_10130

Thu • 14:30 • 305

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The evolution of the fractal dimension of material elements as a function of time in homogeneous isotropic turbulence is investigated using Kinematic Simulation. The fractal dimension of a 3D line is found to obey:

$$D = 1 + 0.088 (Re_{KS})^{\frac{1}{2}}\, t \frac{u'}{L}$$

where Re_{KS} is the KS equivalent Reynolds number. A comparison between ours and Villermaux's results leads to a relation between experimental and KS Reynolds numbers:

$$Re_{KS} = 30.25 \left(\frac{L}{\eta}\right)^{\frac{4}{3}}$$

We also study the evolution an initially horizontal square. Its dimension is found to increase with time as follows:

$$D = 2 + \frac{0.088}{2} (Re_{KS})^{\frac{1}{2}}\, t \frac{u'}{L}$$

Finally we use KS to track particles released from a cube and measure the fractal dimension of this set of particles as a function of time for different Reynolds numbers. The fractal dimension of the cube is found to decrease regularly towards 2. The cube's fractal dimension is found to be independent of the Reynolds number but function of the cube's initial size (S):

$$\frac{S(D-3)}{tu'} = 0.3 \left(\frac{tu'}{L}\right)^{-\frac{2}{3}}$$

Enhanced Mixing by Vortices

FM22S_10532

Thu • 14:35 • 305

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The advection of a passive scalar blob in the deformation field of an axisymmetric vortex is a simple mixing protocol for which the advection–diffusion problem is amenable to a near-exact description. It is investigated here both experimentally and theoretically. The blob rolls-up in a spiral which ultimately fades away in the diluting medium. The complete transient concentration field in the spiral is accessible from the Fourier equations in a properly chosen frame. The concentration histogram of the scalar wrapped in the spiral presents unexpected singular transient features and its long time properties are discussed in connection with mixtures from the real world. The merging of two vortices will also be addressed and compared to the mixing properties of two-dimensional turbulence.

Geometric Features of High-Schmidt Number Scalar Mixing

FM22S_10896
Thu • 14:40 • 305

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The mixing of passive scalars of decreasing diffusivity, advected in each case by the same three-dimensional Navier–Stokes turbulence, is studied within high-resolution direct numerical simulations. The mixing becomes more isotropic with decreasing diffusivity, as is manifest in the increasing symmetry of the probability density function of the scalar gradient and in approach to equality of box-counting results of level sets of scalar gradients of opposite sign. The local flow in the vicinity of steepest negative and positive scalar gradients are in general different, and its behavior is studied for various values of the scalar diffusivity. Mixing approaches monofractal properties with diminishing diffusivity. We consider these results in the context of possible singularities of scalar dissipation.

Chaotic Stirring of Passive Fluid by a Vortex Pair in Circular Domain

FM22S_12110
Thu • 14:45 • 305

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The advection problem of a passive fluid in 2D velocity field induced by two point vortex pair in an inviscid incompressible fluid inside a circular domain is considered. It is shown that the motion of fluid particles can demonstrate chaotic properties which result under certain initial conditions in an intensive stirring regime. Various criteria and methods were proposed in order to identify these regions, including: an analysis of phase trajectories, spectral and correlation analyses, construction of Poincaré sections, calculation of largest Lyapunov exponents. Some additional criteria are offered, namely: definition of the changes of length of border of investigated contours in time, analysis local stretching maps of passive contours and some statistical methods adapted to 2D fluid flows. Comparative analysis of various stirring criteria and methods in a velocity field induced by two and three point vortices in a circular domain is presented.

On Dissipative Structures of Stirring-Grids Turbulence

FM22S_12209
Thu • 14:50 • 305

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The spatiotemporal scalar and kinetic energy dissipation rates were measured in a stationary homogeneous turbulence generated by a pair of vertically stirring grids in a water tank using high-speed successive planar laser-induced fluorescence and particle image velocimetry techniques. Results reveal the complexity of the fine structures of both scalar and kinetic energy dissipation rate fields that contain line-like, blob-like, and sheet-like structures at which essentially all the dissipation is concentrated, a highly intermittent phenomenon. The diameter, size, and thickness of these fine structures are found ranging in scale from 0.4 to 5 Kolmogorov scale (LK) with a mean of about 1 LK and 3 LK for scalar and kinetic energy dissipative structures, respectively. These measurements are useful for understanding of some topological features of fine scale turbulence.

Stirring and Mixing Effects in Agglomerative Precipitation

FM22S_12415
Thu • 14:55 • 305

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Precipitation of solid products from liquid, ionic solutions including mixing, chemical reaction, nucleation, growth and

agglomeration of crystals is considered. Modeling of agglomeration that dominates the process at high supersaturation includes simulation of effects of bulk fluid motion, Brownian diffusion, colloidal forces and mixing. Modeling of particle collision is based on the convective-diffusion equation for the particle pair probability. Modeling of the relative particle motion includes effects of hydrodynamic interactions by employing the mobility functions. The colloidal interaction forces are calculated from the DLVO theory using the Gouy-Stern-Grahame double layer model and Nernst equation. Mixing controls distribution of supersaturation and affects electrical interactions between particles by affecting the local ion concentration. Mixing is modeled using PDF approach. Probability of agglomeration function is used to identify particle collisions leading to agglomeration, whereas multifractal formalism enables formulation of the subgrid closure for turbulent stresses. Results of computations are compared with experimental data.

Resonances and Mixing in Stokes Flows

FM22S_12439
Thu • 15:00 • 305

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In the present paper we study chaotic advection and mixing in a stationary incompressible Stokes flow between two coaxial counter-rotating cylinders. The velocity field of the flow is a result of a small perturbation of an integrable velocity field. Under arbitrarily small perturbations of a certain kind a domain of chaotic advection within the gap between the cylinders arises. We show that this phenomenon is a consequence of quasi-random changes in the adiabatic invariant of the flow, which occur as a streamline crosses the two-dimensional resonance surface of the unperturbed flow. We derive an asymptotic formula for the change in the adiabatic invariant due to the passages through the resonance and describe the diffusion of the adiabatic invariant due to multiple passages through the resonance.

Eulerian Measures for Lagrangian Stirring in a Thermally Driven Flow

FM22S_12545
Thu • 15:05 • 305

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Lagrangian stirring in a thermally driven rotating annulus is investigated numerically using a Navier–Stokes model and a two dimensional Runge-Kutta integration routine. The stirring is quantified using geometrical and dynamical Eulerian symmetry measures, as well as more commonly used Lagrangian measures, such as finite time Lyapunov exponents and box counting dimensions. The ability of the measures to identify transport barriers and regions of well and poorly stirred flow is investigated, and space and time averages of the Eulerian symmetry measures are compared to those of the Lagrangian measures for various flow regimes. The flow regimes considered include axisymmetric flow regimes with time dependent temperature forcing as well as more dynamically consistent three dimensional time dependent baroclinic wave flow regimes.

An Analysis of Mixing Process in a Static Mixer

FM22S_12610
Thu • 15:10 • 305

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In the present study flow mixing process in a static mixer for two immiscible viscous fluids has been treated numerically by a control volume method in connection with volume of fluids method(VOF). A comparison of numerical results and measured data for flow-mixing process in circular duct has been made to check the results of numerical simulations. Numerical analysis was applied to calculate flow pattern, pressure drop, resident time distributions and intensity of segregation in a mixing process for Newtonian fluids. In this study mixing efficiency function has been proposed and calculated. It shows that such function which connect pressure drop and intensity of segregation can be used for industrial process optimisation to obtain most efficient conditions for the mixing process.

Stirring by Blinking Rotlets in a Bounded Stokes Flow

FM22S_12633

Thu • 15:15 • 305

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We apply the blinking rotlet model to the analysis of stirring in a Stokes flow in rectangular containers. Specifically, we construct the rigorous analytical solution for the two-dimensional bi-harmonic equation in a rectangular domain $|x| \leq a$, $|y| \leq b$ with a rotlet placed at point $(0,c)$. The solution shows that for a certain position of the rotlet c_0 which depends on a and b, the flow has a stagnation point $(0,-c_0)$ symmetrically placed inside the rectangle. Thus the blinking rotlet model can be constructed for the rectangle in which the rotlet that is off does not disturb the flow. This model seems preferable to the classical blinking vortex flow when discussing chaotic advection by the Stokes flow. When the velocity field is accurately obtained, the detailed study of stirring any passive blob can be done by the adaptive boundary tracking algorithm. Quantitative measurements of stirring are developed and they provide the estimates for the goodness of mixing according to Danckwerts.

Weak Inertia and Mixing Between Rough Surfaces

FM22S_12731

Thu • 15:20 • 305

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Weak inertial effects in flows between two rough surfaces may lead to significant effects in various situations such as fracture flow or micro-fluidic. Recent experimental results have shown that proper surface patterning could produce vortex which are transverse to the longitudinal mean flow and could be used to produce chaotic stirring. The present study concerns the influence of weak-inertia effects produced by a smooth surface patterning on the flow field and the stream-line geometries. We describe an asymptotic treatment of the Navier–Stokes equation that leads to equations describing the inertial corrections to lubrication equations. These equations are solved with a high order spectral method and the results discussed with examples relevant for mixing describing the inertial influence on the flow field properties.

FM23

Topological fluid mechanics

Chairpersons: P. Boyland (USA), K. Ohkitani (Japan)

Eulerian–Lagrangian Analysis of Navier–Stokes Turbulence

FM23L_10938
Tue • 11:00 • 327

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A numerical study of Navier–Stokes turbulence is performed on the basis of Eulerian-Lagrangian formalism. This is a form of impulse formalisms augmented with viscous Weber formula. As in the case of previous numerical experiments on reconnecting vortices, the diffusive Lagrangian label requires resetting to keep its Jacobian matrix invertible. Associated with this near identity transformation of the label, a time scale is defined as resetting intervals. It is found to be at least as fast as Kolomogorov's time scale. Virtual velocity is a counterpart to initial velocity in inviscid Weber formula. It has two kinds of viscous terms in its time evolution; a diffusion term and a term related with geometrical property of particle paths. Using the latter connection term, a characterization is proposed as to the singular perturbation nature in the limit of vanishing viscosity.

Topological Chaos in Simple Mixers

FM23L_11060
Tue • 11:20 • 327

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Topological chaos is discussed in a two-dimensional batch mixer and a three-dimensional static mixer, under very viscous flow conditions. Topological ideas may be used to calculate a minimum stretch rate for certain flows, but cannot predict the size of the region in which this stretching is achieved. Numerical simulations of dye advection are used to test whether topological ideas can be used to practically enhance mixing quality. In two dimensions it is found that material stretch rates are in tight accordance with theoretically predicted values dependent on flow topology. Furthermore, effective mixing is readily achieved in a useful sized domain. However, in three dimensions we find flow features which make topological arguments less practical for improving mixing quality.

Generic Hydrodynamic Instability

FM23L_11677
Tue • 11:40 • 327

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Every fluid dynamicist knows that almost all 3-d steady incompressible inviscid fluid flows are unstable; however, very few rigorous results about generic instability exist. Our idea is to use the geometry of the flow domain as a parameter. We prove that for generic geometry, *all* of the curl-eigenfield solutions to the steady Euler equations on R^3 (with periodic boundary conditions) are hydrodynamically unstable (linear instability, L^2 norm), with the possible exception of the zero-eigenvalue solution. The proof involves a marriage of topological methods with the instability criteria of Lifshitz-Hameiri and Friedlander-Vishik. An application of a new homology theory in symplectic geometry is the crucial step.

Helicity Dynamics of Vortex Filaments

FM23L_12375
Tue • 12:00 • 327

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We study the singular filament solutions of the fluid equation obtained by requiring the fluid momentum to also be its vorticity. The Lagrangian in Hamilton's principle for this equation is the helicity: the linkage of the vorticity field. This fluid equation admits a Hamiltonian formulation that preserves the linkage of the curl of vorticity and has singular filament solutions on space curves $\mathbf{x} = \mathbf{R}(t,s)$ whose motion is described in the local induction approximation by a modified da Rios-Betchov equation $\dot{\mathbf{R}}(t,s) = (-c/4\pi)\hat{P}\mathbf{R}_{sss}$, where the projection $\hat{P}$ causes the motion to be transverse to the filament. Thus, we determine the Hamiltonian dynamics in the Lagrangian fluid description describing a massless filament of vorticity $\omega = \mathrm{curl}\,\mathbf{u}$ supported along a space curve $\mathbf{x} = \mathbf{R}(\mathbf{a},t)$ that moves without slipping in the incompressible flow induced by its own helicity.

Relation Between Mixing Efficiency and Geometrical Property of Stable Manifolds

FM23L_12484
Tue • 12:20 • 327

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We examine the mixing of fluids associated with the chaotic motion of fluid particles due to the time-periodic flow between two eccentric cylinders caused by the time-periodic slow rotation of these cylinders. We examine the relation between the geomtrical property of the stable manifold of the unstable periodic points of the Poincaré map and the efficiency of the mixing. We find that the maximum stretching rate of fluid elements in a short time is large in the region where the density of the stable manifold is high, and that this stretching rate is small in the region where the curvature of this manifold is large. We also find that small blobs initially located at the region of high density of the stable manifold are mixed well in a short time.

Particle Transport by a Vortex Soliton

FM23L_11660
Tue • 12:40 • 327

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Motions of fluid particles advected by a vortex soliton are studied. In the moving frame which makes the vortex soliton steady in space, particle motions are confined in a torus near the loop for a wide range of three parameters that characterize the shape and strength of the vortex soliton. The transported volume is obtained numerically as a function of these parameters. The product of the volume and the translational velocity of the soliton provides the rate of transport. By calculating this quantity, the optimized shape of the soliton for the maximum rate of transport is considered. The torus is composed of groups of invariant surfaces around periodic trajectories. Similar phenomena are observed with the KAM tori for non-integrable Hamiltonian systems. To extract the essential mechanism of the transport properties, an ODE model is proposed, which is named the chopsticks model. This model explains the qualitative features of the transport.

Streamline Topology of the Nearwake of a Circular Cylinder at Low Reynolds Numbers

FM23S_10247
Thu • 15:15 • 307

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(2) *IMFUFA, Roskilde University, Roskilde, Denmark*
(3) *HV Turbo, Helsingor, Denmark*

We consider the topology of instantaneous streamlines in the wake behind a circular cylinder. Using bifurcation theory, we describe the possible streamline patterns that may occur as the symmetric pair of vortices in the steady flow is perturbed. The result of the analysis is a two-parameter bifurcation diagram. We show that two different sequences of patterns in the periodic regime are to be expected. From numerical simulations we verify the existence of these sequences. At Re = 42, the flow becomes periodic, and the first sequence of patterns exists until Re = 45. For Re > 45 the second sequence exists, and no further qualitative changes occur for Re < 200 where 3D effects will become important. The present results differ from the scenario proposed by Perry et al. (J. Fluid Mech. 116, 1982) on the basis of experiments.

Gauge Principle for Ideal Fluids and Variational Principle

Tsutomu Kambe
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FM23S_11166
Thu • 15:20 • 307

Gauge-covariant variational formulation is given for flows of a compressible ideal fluid. Symmetry groups, i.e. the gauge groups, of fluid flows are a translation group and a rotation group. We propose a Galilei-invariant Lagrangian, and require its variation to be gauge-invariant (both global and local) with respect to the symmetry groups, and try to deduce the Euler's equation of motion for fluid flows from the gauge principle. The velocity field consistent with the first translation group is found to be irrotational, and corresponding equation of motion is that for potential flows. In complying with local gauge invariance with respect to the second gauge group, i.e. SO(3), a gauge-covariant derivative is defined by introducing a new gauge field. Galilei invariance of the covariant derivative requires that the gauge field coincides with the vorticity. As a result, the covariant derivative of velocity is found to be the material derivative of velocity. Thus, the Euler's equation of motion for an ideal fluid is derived from the Hamilton's principle. According to the Noether's theorem, the gauge symmetry with respect to the translation group results in the conservation law of total momentum, while the symmetry with respect to the rotation group results in the conservation of total angular momentum.

Topological Aspects of the Tornado Problem

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FM23S_12868
Thu • 15:25 • 307

We examine the topological aspects of a concentrated vortex structure, a tornado, in inviscid fluid. A laboratory study is complemented by numerical simulations of vortex dynamics taking into account the topological structures of vortex knots. Natural observation performed in Kazakhstan (June 2002) agree reasonably well with laboratory experiments. We explored the Lagrangian method for study of vortex surface evolution based upon the vorton model. The Lyapunov stability conditions is essential while studying the Euler characteristic of the vorticity field. The possibility of effective stirring mixing by steady motion in the vortex core is pointed out. These problems might be benchmark ones for various numerical schemes in the vortex dynamics.

FM24

Turbulence

Chairpersons: O. Metais (France), R. Moser (USA)

Large Eddy Simulations of Decaying Rotating Turbulence

FM24L_10149

Wed • 08:30 • 309

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Large eddy simulations of homogenous isotropic turbulence subjected to system rotation were performed using the Truncated Navier–Stokes method. We observe that the nonlinear energy transfer from large to small scales is reduced by rotation, the energy decay is inhibited, the energy spectrum at high Reynolds numbers departs from the classical Kolmogoroff form, and initially isotropic turbulence becomes anisotropic, with the anisotropy reflected in longitudinal integral length scales and directional stress tensors. Contrary to conclusions reached for low Reynolds number flows, at high Reynolds numbers and sufficiently long times the Reynolds stress tensors and their invariants become anisotropic as well. The anisotropy is responsible for the spectral slope of -3 rather than the classical slope of -2 found under the assumption of isotropy.

Large-Eddy Simulation of Shock-Wave / Turbulent-Boundary-Layer Interaction

FM24L_10455

Wed • 08:50 • 309

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A Large-Eddy Simulation (LES) is conducted to investigate the characteristics of the mean flow and the turbulence structure of the boundary layer along a compression corner. The compression corner has a deflection angle $\beta = 25\,^0$, and the mean free-stream Mach number is $M_\infty = 2.95$. The Reynolds number based on the incoming boundary layer thickness is $Re_{\delta 0} = 63560$ in accordance with reference experiments. An analysis of the flow computation shows a good agreement with the experiment in terms of mean quantities (shock position, separation zone length, skin friction and surface pressure distributions) and turbulence characteristics. A mechanism of turbulence amplification in the external flow by travelling compression waves is proposed. The existence of three-dimensional large-scale structures (Görtler-type vortices) is shown.

Inertial Similarity of Velocity Distributions in Homogeneous Isotropic Turbulence

FM24L_12151

Wed • 09:10 • 309

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The Lundgren-Monin (1967) equations for the velocity distributions in homogeneous turbulence are made closed by using the cross-independence hypothesis, which is equivalent to Kolmogorov's premise. The one- and two-point velocity distributions are obtained as the solutions of these equations. The one-point velocity distribution is found to be inertial normal distribution and the velocity-sum distribution and the lateral velocity difference distribution are shown to be another inertial-normal distribution for all non-zero distances between the two points. The longitudinal velocity–difference distribution also takes the inertial-normal distribution at large distances but assumes an asymmetric algebraic distribution at small distances corresponding to Kolmogorov's inertial range. Apart from these inertial similarity, these velocity distribution are shown to obey the viscous similarity at very small distances, which are taken to be zero under the inertial similarity.

Nonlinear Scale-Free Cascades and Their Stationary Spectra

FM24L_12436
Wed • 09:30 • 309

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A wide variety of complex multi-scale mechanical phenomena produce power-law distributions: the turbulence spectra of Kolmogorov, Kraichnan, and Batchelor, and turbulence intermittency spectra; size distributions of coagulating particles in multiphase flows, coalescing drops in clouds, and cracks in solids; the asteroid size distributions due to collisional fragmentation – to mention just a few examples. We propose that all such processes can be viewed from the vantage point of nonlinear scale-free conservative cascades, which we define in a novel rigorous framework and classify by the values of three indices. Next, we show how stationary power-law spectra arise in our framework, and derive an expression for the power-law exponent, τ. For many cascades τ is found to depend only on the indices values by a simple algebraic formula. This formula unifies complex multi-scale phenomena, and various turbulence spectra in particular, that had been seen as different before.

PDF Computation of Turbulent Flows with a New Near-Wall Model

FM24L_10564
Wed • 09:50 • 309

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The modeling and computation of near-wall turbulent flows is addressed with the probability density function (PDF) method for velocity and the turbulent frequency. Near-wall extensions are considered in detail and a new model for viscous transport is proposed. A method of elliptic relaxation for a blending function is applied in the PDF approach to model the pressure-strain term. A numerical integration scheme is developed to deal with the near-wall singularity of coefficients that appears in the discrete formulation. The PDF equation is solved by a Monte Carlo method and the whole approach appears as a self-contained Lagrangian simulation using stochastic particles. For the sake of numerical example, the fully developed channel flow case at $Re_\tau = 395$ and $Re_\tau = 590$ is computed; results are compared with the available DNS data.

The Cellular Structure and Its Tracks of a H2/O2/Ar Detonation Waves

FM24L_11802
Wed • 10:10 • 309

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In this paper, the cellular structure and its tracks of a two-dimensional ordinary detonation wave in low pressure H_2/O_2/Armixture simulated with detailed chemical reaction model, high order scheme and high resolution grids are investigated. The regular cellular structure is produced by introducing perturbations in the reaction zone of a steady one-dimensional de tonation wave. The calculated structure shows a double-Mach like strong type configuration, in which strong ignition is observed behind the transverse wave. It is also observed that there are three different structure tracks associated with different triple points or the kink on the transverse wave. The comparisons with previous experiments indicates the presence of strong structure for an ordinary detonation.

Interaction Between a Columnar Vortex and External Turbulence

FM24L_10937
Fri • 11:00 • 306

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The interaction between a columnar vortex and external turbulence is investigated numerically. As the columnar vortex, the Lamb-Oseen vortex and the q-vortex are used. The columnar vortex is immersed in an initially isotropic homogeneous turbulence field, which itself is produced by a direct numerical simulation of decaying turbulence. Using visualization techniques, we investigate the formation of inhomogeneous fine turbulent eddies around the columnar vortex, the vortex-core deformations and the dynamical evolution in the passive scalar field.

3D-Measurements in an Adverse-Pressure-Gradient Turbulent Boundary Layer over Smooth and Ribbed Surfaces

FM24L_12564

Fri • 11:20 • 306

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3D-PIV and 2D-LDA measurements in a fully turbulent boundary with adverse pressure gradient have been performed. Two types of surfaces were investigated: a smooth surface and a surface with riblets aligned in main flow direction. Particle image velocimetry was used to determine the influence of the surface structure on large-scale structures in the near wall region whereas profiles of mean and fluctuating velocity inside the boundary layer were acquired by laser Doppler anemometry. Significant changes of size and location of near-wall vortex structures were found ongoing with a deformation of the mean velocity profile due to the riblet surface.

On the Structure of Turbulence and Reynolds Stress Distribution in the Bottom Boundary Layer of the Coastal Ocean

FM24L_12757

Fri • 11:40 • 306

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Turbulent flow measurements were performed in the bottom boundary layer on the U.S. Southeastern continental shelf using particle image velocimetry (PIV). The experiments were performed within 2 m above the bottom, during half of a tidal cycle. At each elevation and mean flow, 3600 vector maps were collected. The data demonstrate the existence of a log layer within a mixed oscillatory motion and a mean current flow. A major challenge is to separate between waves induced motion and turbulence. To estimate the Reynolds stresses, free of wave contamination, we calculates the 2nd order structure function of the velocity vectors. In addition, turbulence in the bottom boundary layer consists of powerful vortical structures (gusts), separated by periods of quiescent flow. The shear stresses are high during periods of gusts, and essentially zero during the quiescent periods.

Study of the Turbulent Energy Spectrum Build Up in an Experimental Vortex Burst

FM24L_12876

Fri • 12:00 • 306

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We present an experiment where a stretched vortex is experiencing quasi-periodical turbulent bursts inside a laminar environment. It is shown that the velocity fluctuations resulting from the bursts are responsible for the build up of a turbulent $k^{-5/3}$ spectrum. Benefiting from the quasi periodicity of the bursts, we have developed a data post processing that allow to characterize the build up of the turbulent spectrum with time. This analysis is particulary motivated by an existing theoretical framework for the energy transfer in that type of structure, notably the Lundgren mechanism.

Impact of Pressure–Gradient Conditions on High Reynolds Number Turbulent Boundary Layers

FM24L_12965

Fri • 12:20 • 306

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Mean velocity distributions in the overlap region, over the range 10,000 < ReTheta < 70,000, under five different pressure-gradient conditions are accurately described by a log law. The pressure-gradient conditions include adverse, zero, favorable and strongly favorable. The wall-shear stress was measured using oil-film interferometry, and hot-wire sensors were used to measure velocity profiles. Parameters of the logarithmic overlap region developed from these higher Reynolds number boundary layers continue to be consistent with our recent findings and to remain independent of Reynolds number. The best estimate of the log-law parameters from the zero-pressure gradient boundary layers is Kappa = 0.38, B = 4.1. However,

the Karman coefficient (Kappa) is found to vary considerably for the non-equilibrium boundary layers under the various pressure gradients. Variations with pressure gradient are not only in the outer region of the boundary layer but also within the inner region.

Resonant Interactions of 3D Instability Waves in an Airfoil Boundary Layer for Harmonic and Broadband Perturbations

FM24L_12675
Fri • 12:40 • 306

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This paper is devoted to a systematic experimental investigation of resonant interactions of Tollmien-Schlichting (TS) waves occurred at weakly-nonlinear stages of the laminar-turbulent transition in a non-self-similar boundary layer on an airfoil with a long laminar run. The paper is aimed to analyze the importance of the TS-wave interactions in dependence on the base-flow and disturbance parameters in order to clarify two main questions: (i) how does the base flow non-uniformity influence the efficiency of the resonant interaction and (ii) when are these interactions important for the transition prediction. The experiments were carried out at controlled disturbance conditions. The TS-waves were excited in the boundary layer by a specially designed disturbance source. Several dozens of initial disturbance spectra were examined, including cases of simple tuned subharmonic triplets, regimes with frequency and spanwise-wavenumber detunings, multi-wave regimes, and regimes with excitation of broadband perturbations simulating some "natural" transition conditions. The base flow non-self-similarity is found to influence significantly the nonlinear disturbance interactions. Several unusual properties of such interactions have been detected and investigated.

Stochastic Model of the Conditional Lagrangian Acceleration of a Fluid Particle in Developed Turbulence

FM24S_10474
Thu • 14:30 • 327

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Various types of models have been recently suggested to fit the Lagrangian high-Re turbulence data by the groups at Cornell and ENS-Lyon, and DNS by Mordant et al., Yeung, and Gotoh and Fukayama. The random intensity of noise approach to the 1D Laval-Dubrulle-Nazarenko model, based on the Navier–Stokes equation, is used to describe Lagrangian acceleration of a fluid particle in developed turbulence. This leads to consideration of a nonlinear Langevin equation for the acceleration a with coupled additive and multiplicative noises. The stationary PDF associated to this equation is calculated exactly for model white-in-time Gaussian noises. The additive noise intensity and the cross correlation are assumed to depend on velocity fluctuations u in an exponential way. The resulting conditional acceleration PDF $P(a|u)$, variance, and mean are found to be in a good agreement with the recent high-precision Lagrangian data by Mordant, Crawford, and Bodenschatz (2003).

Experimental Study of Rotor-Stator Flows with Centripetal Fluxes

FM24S_10506
Thu • 14:35 • 327

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The evolution of the entrainment coefficient K of the rotating fluid in a rotor-stator cavity, is studied with an imposed centripetal flux and according to the flow control parameters. Measurements are realised by a two component laser Doppler anemometry (L.D.A.). It is shown that the coefficient K depends on a local flow rate coefficient Cqr of the fluid according to a 5/7 power law whose coefficients depend on the value of the velocity at the entry of the cavity. A theoretical analysis confirms the asymptotic behavior.

Turbulence Scalings in Supersonic Channel Flow

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FM24S_11116
Thu • 14:40 • 327

Direct numerical simulations of compressible channel flow have been performed at subsonic and supersonic Mach numbers with the aim to better understand effects of compressibility in wall-bounded turbulence. The ability of outer and inner scalings to collapse profiles of turbulence stresses on to their incompressible counterparts is investigated. It turns out that such collapse is possible with outer scaling when sufficiently far from the wall, but not with inner scaling. Compressibility effects on the turbulent stresses, their anisotropy, and their balance equations are identified. A reduction in the near-wall pressure–strain, which is found to be responsible for the changed Reynolds stress profiles, is explained using a Green's function-based analysis of the pressure field. In the case of isothermal walls which are considered here, the density variation is primarily responsible for the decrease of the pressure-strain correlations, a result that should inspire turbulence modellers.

On the Scale Similarity in Large Eddy Simulation

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FM24S_11151
Thu • 14:45 • 327

Scale similarity models in LES were created to overcome the drawbacks of eddy viscosity-type models. This similarity allows to effectively relate the unresolved scales, represented by the Modified Cross tensor and the Modified Reynolds tensor, to smallest resolved scales represented by the modified Leonard tensor (Bardina et al.) or by a term obtained through multiple filtering operations at different scales (Liu et al.). The models of Bardina et al. and Liu et al. are affected, however, by a fundamental drawback: they are not dissipative enough, i.e they are not able to assure a sufficient energy drain from resolved scales of the motion to unresolved ones. The goal of this paper is to investigate on the reason of such drawback. A scale similarity LES model that is able to grant an adequate drain of energy from resolved scales to unresolved ones.

Two Scale Approach to Anisotropic Turbulence in Hel II

Tomasz Lipniacki
IPPT PAN, Warszawa, Poland

FM24S_11161
Thu • 14:50 • 327

The superfluid Helium is described by system of equations: Navier–Stokes and Euler equations for the macroscopic normal and superfluid velocity fields. These equations are coupled by mutual friction force, exerted on superfluid vortices by normal component. The force is proportional to the counterflow and the density of vortices. The latter being determined by the modified Vinen equation, adequate for flows with net macroscopic vorticity. The derived system is applied to the numerical analysis of formation of the shear flow between two infinite parallel material surfaces. Before the shear flow is formed, we observe the rise of anisotropic quantum turbulence. The Magnus force makes the anizotropic tangle drifts out of the region where the counterflow exists. There are three characteristic regions in the flow; of high tangle polarization in which the components are locked together, of intensive vortex generation, and of relatively dilute tangle, where the superfluid velocity is almost constant.

Optimization of an Implicit Subgrid-Scale Model for LES

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FM24S_11256
Thu • 14:55 • 327

The presentation gives a summary of the derivation of an implicit subgrid-scale model for LES which is obtained from a new approach for the approximation of hyperbolic conservation laws. Adaptive local deconvolution is performed using a quasi-linear solution-adaptive combination of local interpolation polynomials. The physical flux function is substituted by a suitable numerical flux function. The truncation error has physical significance and effectively acts as subgrid-scale model. It can be determined by a modified-differential-equation analysis and is adjustable through free parameters.Computational results for Burgers equation show that the model with parameters identified by evolutionary optimization give significantly better results than other models.

Empirical Galerkin Models for Incompressible Flow–Pressure-Term and ‘Subgrid’ Turbulence Representations

FM24S_11454
Thu • 15:00 • 327

Bernd R. Noack[1], Paul Papas[2], Peter A. Monkewitz[2], Marek Morzyński[3], Gilead Tadmor[4]

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(3) *Poznań University of Technology, Poznań, Poland*
(4) *Dept. of Electrical and Computer Engineering, Northeastern University, USA*

Necessary ingredients of *accurate* empirical Galerkin models for incompressible free and wall-bounded shear flows are discussed. These models are based on the Karhunen-Loève (K-L) decomposition of a Navier–Stokes simulation and a Galerkin projection on the Navier–Stokes equation. Specifically, a novel analytical pressure-term representation is first developed and shown to be necessary for accurate Galerkin systems of near-field wakes and of mixing layers. Secondly, a hierarchy of ‘subgrid’ turbulence models based on Rempfer’s (1991) modal eddy viscosities is presented and shown to be helpful if a low-dimensional K-L ansatz does not resolve a significant portion of the fluctuation energy. Finally, the role of ‘missing’ phase space directions in the K-L ansatz is revisited and additional modes are proposed. The proposed generalizations and improvements have been integrated in a modular Galerkin ‘tool-box’ with a hierarchy of procedures to determine model coefficients.

Orthonormal Wavelet Analysis of CGT in Fully Developed Asymmetric Turbulent Channel Flow

FM24S_11488
Thu • 15:05 • 327

Yu-Lu Liu, Jian-Bo Jiang, Xiang Qiu
Shanghai Institute of Applied Mathematics and Mechanics, Shanghai, China

Orthonormal wavelet analyses are applied to the counter gradient transport (abbr. CGT) phenomena in the asymmetric fully developed turbulent channel flow. The main emphases are on the statistical characteristics of fluctuating velocity in the CGT region. The major results are the local counter-gradient transport phenomena happen on the various scales, thus it may be concluded that they are universal phenomena in turbulent flow; the global CGT phenomena are in close relation with the principal coherent scale.

Experimental Observation of a Two-Regime Spectrum in Rotating Turbulence

FM24S_11814
Thu • 15:10 • 327

Frederic Moisy, Cyprien Morize, Marc Rabaud
FAST, Campus Universitaire, France

Transition from three-dimensional to quasi-two-dimensional turbulence in a rotating frame is experimentally investigated. A decaying turbulent field is generated from oscillating a grid in a rotating water tank, and velocity measurements are performed using particle image velocimetry. The power spectrum, $E(k)$, measured in the plane normal to the rotation axis, shows a transition from the classical Kolmogorov $k^{-5/3}$ spectrum towards a k^{-2} spectrum as the Rossby number is decreased. For intermediate values of Ro, a two-regime spectrum can be observed, showing a crossover between the 3D and quasi-2D regimes, in good agreement with the phenomenology proposed by Zhou [Phys. Fluids **7**:2092 (1995)]. This mixed regime takes place in a narrow band of Rossby numbers, from $\mathrm{Ro}_{3D} \simeq 0.15 \pm 0.10$ down to $\mathrm{Ro}_{Q2D} \simeq (0.10 \pm 0.03) Re^{-1/2}$.

Three-Dimensional Turbulent Structures of Different Scales

FM24S_12004
Thu • 15:20 • 327

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An orthogonal vector wavelet multi-resolution technique has been developed and applied to decomposing the three-dimensional velocity data, which were simultaneously obtained by sixteen X-wires in two orthogonal planes in the turbulent near-wake of a circular cylinder, into a number of wavelet components based on their central frequencies or scales. The three-dimensional turbulent structure of each wavelet component is examined in terms of sectional streamlines and vorticity contours. The spanwise vorticity contours of the wavelet component at f0 (the vortex shedding frequency) display a secondary spanwise structure near the saddle point, whose vorticity is opposite-signed to that of the Kármán vortices. The

wavelet components of f0 or 2f0 make a predominant contribution to the Reynolds normal stresses and account for most of the shear stress. On the other hand, the components of frequencies higher than f0 and 2f0 or the relatively small-scale turbulent structures contribute most to vorticity variance.

A New Mixed Nonlinear LES Models for Boundary Layers

FM24S_12430
Thu • 15:25 • 327

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It is shown for plane channel flow that a new mixed nonlinear/eddy viscosity model reproduces the mean profile of a benchmark dynamic LES and DNS. Profiles of the components of kinetic energy have the same shape as in the DNS, but the magnitudes differ by between 25% and 50%. There are three components to the model. URANS for k_T with a damping function in the viscous sublayer, an eddy viscosity based upon k_T, and filtered nonlinear terms imposed on the grid scale that are based upon the Leray regularization. Coefficients were determined by theoretical considerations of the energy cascade and discretization on the grid-scale, then checked by comparing to isotropic decaying turbulence,

POD Analysis of Coherent Structures in Turbulent Flows

FM24S_12652
Thu • 15:30 • 327

Song Fu, Min Tang, Jiang He
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POD (proper orthogonal decompositions) is an efficient method to extract turbulent coherent structures. In this paper, POD technique is applied to the study of turbulent natural thermal convection between two vertical plates and the study of planar compressible mixing layer flow, based on DNS database. Both the direct POD method and the snapshots method are applied in the former case; only snapshots method is applied to the analyzing of the mixing layer flow by reason of the data size. The distribution of energy among POD modes has been closely examined. The most energetic structures are extracted, respectively spiral structures and streamwise vortexes in natural convection and span-wise vortices, turbulent structure etc. in mixing layer. It has been observed that the flow structures in the experiment match well with the ones in POD, and these structures are the essential characteristic of these flows. The direct method and the snapshots method have also been compared in this paper.

Compressibility Effects and Sound Propagation in Turbulent Channel Flow

FM24S_12740
Thu • 15:35 • 327

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(3) *LAUM, France*

Large-Eddy Simulations of supersonic channel flow and the advection of a passive scalar oscillating at the walls are presented. A new and non-local scaling of the wall co-ordinate is proposed, which yields significant improvement of the scaling of the mean velocity and temperature profiles with respect to the van Driest transformation. With this scaling, the spanwise correlations of the velocity fluctuations collapse at least up to Mach 2, with indication of a preferential streak spacing of about 120 of the proposed wall units. In the quasi-incompressible regime, the oscillating passive scalar obeys the laminar Stokes law at high driving frequencies and exhibits increasing wall shear at decreasing frequency in agreement with experimental and numerical results in pulsating shear flows. However, the established albeit controversial subrange of reduced shear is not recovered with this linearized scalar approach.

Numerical Simulations of Flows in Dimpled Channels

FM24S_12794
Thu • 15:40 • 327

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Laminar and turbulent channel flows over dimples are studied using our parallel multiblock multigrid incompressible flow solver. “Horse-shoe” vortex has been found in laminar regime. Due to the separation structures inside dimples large reduction of shear drag can be achieved. However, net reduction of total drag in laminar regime is rather minor because the inevitable increases of form drag. DNS of turbulent flow over dimpled channel has also been carried out. Flow visualization shows turbulent flow structures are more complex on dimpled channel than those on a flat wall channel. These results may help to explain the heat transfer augmentation effects of dimpled surfaces.

Numerical Modelling of Small-Scale Turbulence in Clouds

FM24S_12922
Thu • 15:45 • 327

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This paper discusses results from a series of idealized numerical simulations of decaying moist turbulence accompanying the microscale cloud/clear-air mixing. In the moist case, kinetic energy of microscale motions comes not only from the classical downscale energy cascade, but it can also be generated internally due to the evaporation of cloud droplets. Three sets of numerical simulations are performed for three intensities of initial large-scale eddies. In each set, a control dry simulation is performed, as well as two moist simulations applying either bulk or detailed representation of cloud microphysics.Model results suggest that, as far as the evolutions of enstrophy and turbulent kinetic energy are concerned, significant impact of moist processes occurs at low intensities of initial large-scale eddies. In such a case, mixing and homogenization are dominated by the kinetic energy generated as a result of evaporation of cloud water and its impact on the microscale buoyancy. Detailed microphysics, which explicitly treat the size-dependence of cloud droplet sedimentation and evaporation, appear to have a comparatively small effect, although this result might be an artifact of a coarse grid-resolution used in the simulations. High anisotropy, also observed in laboratory experiments with mixing between cloudy and cloud-free air, prevails even at high intensities of initial large-scale eddies, despite the fact that mixing and homogenization proceed in a similar manner in moist and dry simulations.

FM25

Vortex dynamics

Chairpersons: E. Krause (Germany), G. van Heijst (Netherlands)

On Local Vortex Identification

FM25L_12161

Thu • 11:00 • 309

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It is widely accepted that coherent vortical structures play a key role in determining the dynamics of complex turbulent flows. Identification of vortical structures from three-dimensional velocity fields is a crucial problem and various vortex identification schemes are proposed to achieve this purpose. We investigate popular vortex identification criteria based on point-wise analysis of the velocity gradient tensor. A new measure of spatial coherence in vortices is introduced. A new local vortex identification criterion and requirements for a vortex core are proposed. The inter-relationships between the different criteria are explored analytically using both zero and non-zero thresholds. Canonical flow examples are studied and it is observed that all the criteria, given the proposed usage of threshold, result in remarkably similar looking vortical structures. An explanation based on local flow kinematics is offered for the flows where the differences in the different criteria result in conflicting identification of vortices.

New Means of Vortex Breakdown Control

FM25L_10683

Thu • 11:20 • 309

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It is shown that an additional near-axis swirl, temperature gradients, and their combination can help to efficiently control vortex breakdown (VB). The numerical analysis of a flow in a cylindrical container driven by a rotating bottom disk reveals the underlying mechanisms, explains the experimental observations of control co- and counter-rotation with no temperature gradient (Husain et.al. 2003, Phys. Fluids, 15, 271), and reveals some flaws of dye visualization. Co- (counter-) rotation diminishes (enhances) the unfavorable axial gradients of pressure and thus suppresses (stimulates) VB. A moderate negative (positive) axial gradient of temperature enforces the effects of the additional swirl, e.g., significantly stimulates (suppresses) VB. A strong positive temperature gradient induces the centrifugal instability and time oscillations in the flow with counter-rotation. These results indicate that an additional co-rotating cold (counter-rotating hot) swirling jet can help to suppress (enhance) VB in practical flows, e.g. over delta-wing aircraft and vortex burners.

Instabilities of a Vortex Pair in a Stratified and Rotating Fluid

FM25L_11391

Thu • 11:40 • 309

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We present laboratory experiments on the instabilities developing on a counter-rotating vertical vortex pair in a stratified and rotating fluid. Four distinct types of three-dimensional instability have been identified. For large Rossby number, both vortices are subjected to the zigzag instability at low Froude number and to the elliptic instability at large Froude number. For moderate Rossby number, the elliptic instability is observed only on the cyclone while the anticyclone is subjected to a centrifugal instability which produces toroidal Taylor-like vortices and to an oscillatory instability with an azimuthal wavenumber $m = 1$. To understand the physical mechanism of this new instability, the stability of the Lamb-Oseen vortex in a stratified rotating fluid has been investigated both numerically and theoretically. These analyses demonstrate that this oscillatory instability is a non-axisymmetric centrifugal instability. The numerical and experimental results are in good agreement.

Stability of Oceanic Vortices: a Solution to the Problem

FM25L_11467

Thu • 12:00 • 309

Eugene Benilov
University of Limerick, Ireland

It is well-known that oceanic vortices exist for years, whereas almost all theoretical studies indicate that they must be unstable. A rare exception is the work by Dewar & Killworth (1995), who demonstrated that a Gaussian vortex in the upper layer of a two-layer ocean becomes stable if accompanied by a weak co-rotating circulation in the lower layer. Note that this paper assumed the lower-layer circulation to have the same profile as the main (upper-layer) vortex. The present paper considers the case, where the profile of the circulation in the lower layer is determined by the condition that potential vorticity (PV) there is constant – which models a vortex surrounded by water of a different origin. Given that most oceanic vortices are shed by frontal currents, such model appears to be more realistic than any ad hoc choice. The stability of vortices with uniform lower-layer PV is examined for both quasigeostrophic and ageostrophic cases, numerically and asymptotically, assuming that the upper layer of the ocean is thin. It is shown that such vortices are stable in a wide range of parameters. The effect of vortex stabilization is interpreted through representation of the unstable disturbance by two phase-locked Rossby waves, rotating around the vortex in the upper and lower layers. Then, if the lower-layer PV gradient is zero, it cannot support the corresponding wave, which inhibits the instability.

The Modelling of The Dynamics of Hairpin Vortex Packets in Wall Turbulence

FM25L_12196

Thu • 12:20 • 309

Vyacheslav V. Meleshko(1), Eugene I. Nikiforovich(2), Alexandre A. Gourjii(2), Ronald J. Adrian(3)
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(3) *Department of Theoretical and Applied Mechanics, University of Illinois at Urbana-Champaign Urbana, USA*

The talk addresses the experimental, analytical and numerical modelling of the dynamics of concentrated vortex packets over a rigid smooth plane. To answer the principal question why and how does fluid in outer region of the turbulent boundary layer organize itself into hairpin streamwise vortex packets with low-speed convective velocity we developed the vortex filament model of hierarchy of hairpin packets. The idea is to explore the flow of effectively inviscid fluid with embedded vorticity, with topology change allowed upon close encounters of vortical fluid regions. We addressed the global vorticity dynamics by representing each hairpin vortex as a filament with a 'core parameter', interacting via the Biot-Savart law. The contour kinematic spline method for tracing the vortex filaments in a shear flow over a rigid wall was developed. Special attention is paid to the soliton-like behaviour of the vortex filaments over the rigid plane. Comparisons with experimental results and DNS data show a good correspondence. Although an extreme idealization, the analytical model of vortex filaments appears to shed considerable light on what to expect in the laboratory experiments. This work was supported by the CRDF CGP grant UP-2429-KV-02

Strong Cyclonic Vortices over Topography on a Beta-Plane

FM25L_11741

Thu • 12:40 • 309

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Strong cyclonic vortices over topography on a beta-plane were investigated by a joint analytical, experimental and numerical approach. Experimental parameters in the rotating tank with a gently sloping bottom were carefully determined according to the conservation of potential vorticity. A shallow water model was numerically integrated incorporating with a gradient-wind-balanced vortex model. The motion of the vortices showed complicated track deflections associated with meandering Rossby wave wakes. The track behaviours can be further explored by a dynamic model which predicts similar results to those observed from the experiments, numerical calculations and some historical typhoon trajectories encountering the Island of Taiwan.

The Development of an Axisymmetric Gravity Current

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FM25L_12051
Fri • 11:00 • 309

Three-dimensional releases of fixed volumes of saline fluids into fresh water and their radial spread have been examined experimentally. At high Reynolds numbers three distinct regimes have been identified. A short initial phase, a secondary phase where the frontal speed is constant and a final stage where the front speed is reduced. In the secondary stage the gravity current's head is dominated by the presence of a ring vortex above the front. This stage of the flow propagation comes to an abrupt end with the breakdown of the ring vortex at a clearly defined point. The experimental results have been compared to 2D and 3D numerical simulations. The simulations compare well with the experimental data for the early stages of the flow. The results show the development of a complex flow field and highlight the unsuitability of shallow water modelling for axisymmetric lock releases.

Curvature Instability of a Vortex Ring

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FM25L_11615
Fri • 11:20 • 309

A new instability mechanism is found for Kelvin's vortex ring, which may surpass the Widnall instability for thin cores. The basic state is a steady asymptotic solution of the Euler equations, in powers of the ratio ε of core radius to ring radius, for an axisymmetric vortex ring with vorticity proportional to the distance from the symmetric axis. In this, the effect of ring curvature of $O(\varepsilon)$ precedes the $O(\varepsilon^2)$ straining field. We show that the $O(\varepsilon)$ field causes a parametric resonance instability between a pair of Kelvin waves whose azimuthal wavenumbers are separated by one. The eigenvalue problem of the Euler equations is solved explicitly, in terms of the Bessel and the modified Bessel functions, and the maximum growth rate is found to be $165/256\varepsilon$. This result is reinforced by invoking the geometric optics approach for local stability. The closed-form solution facilitates nonlinear stability analysis.

Coherent Structure of Point Vortices Influenced by Uniform Straining Flow

Marcin Kurowski, Konrad Bajer
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FM25L_12275
Fri • 11:40 • 309

Numerical simulations of motion of an elliptic vortex patch modelled by a group of identical point vortices in an inviscid uniform straining flow is given. The strength of the external flow modifies the angular velocity and amplitude of oscillations of the axes. The density of vortices becomes non-uniform, and disturbances created at the edge of the structure penetrate inside. Fluctuations can be the reason of loosing a little groups of vortices. The decay of the cloud can go slowly (single vortices are being 'scraped' by the flow) or rapidly (vortices leave the structure and the flow can penetrate the cloud deeper to pull out more vortices). The elliptic shape of the cloud can evolve. At a critical strain the axes are rotated by $\pi/4$ and two little streaks of vortices flow out from the cloud (quasi-steady state). As a consequence of the Kelvin-Helmholtz instability the cloud comes apart and the big structure becomes a vortex street.

Strong Shock–Vortex Interaction – a Numerical Study

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FM25L_12690
Fri • 12:00 • 309

The intersection of a longitudinal vortex by a normal shock is studied with a numerical solution of the Euler and Navier–Stokes equations for time-dependent, three-dimensional, laminar flow. Earlier investigations of the shock–vortex interaction problem were mainly focussed on the generation of vortices by moving shocks. The present study is concerned with the destruction of the vortex core, usually referred to as vortex breakdown or bursting, by letting the shock intersect the vortex normal to its axis. The pressure rise across the shock decelerates the oncoming supersonic axial flow to subsonic flow and enforces a redistribution of vorticity. A stagnation point is formed downstream from the shock and the swirling motion is locally stopped. The flow exhibits periodic fluctuations, resulting from vortex shedding from the burst part of the vortex. Results are presented for a free-stream Mach number $Ma_\infty = 1.6$, with a longitudinal Burgers vortex as inflow condition. The calculations were performed on a Cartesian mesh with approximately 2 millions grid points. The computations show

noticeable differences between the two solutions, and viscous forces become important in the burst part of the vortex. Visualization studies clearly reveal the time-dependent, three-dimensional nature of the flow after breakdown.

Isolated Vortices over Seamounts: Laboratory Experiments and Numerical Simulations

FM25L_12748
Fri • 12:20 • 309

O.U. Velasco Fuentes
CICESE, Ensenada, Mexico

We study the competition between the instability of isolated vortices and the nearly geostrophic balance in a rotating fluid of varying depth. The laboratory experiments were performed in a water tank placed on top of a rotating table and the numerical simulations were done with a vortex-in-cell method. The intrinsic vortex instability produces horizontally elongated vortex structures while the nearly geostrophic balance forces the vortices to remain on top of the seamount where they are generated. It was found that the condition for the topographic confinement of the laboratory vortices (which have a Rossby number of order one) is that the semount height be at least one half of the total fluid depth. This condition was confirmed by the numerical simulations.

Spontaneous Sign Reversals in Self-Organized States of Forced Two-Dimensional Turbulence on a Bounded Square Domain

FM25L_11964
Fri • 12:40 • 309

David Molenaar, Herman J.H. Clercx, **GertJan F. van Heijst**
Eindhoven University of Technology, Eindhoven, The Netherlands

The inverse energy cascade present in two-dimensional (2D) turbulence leads to the formation of large-scale flow structures. In the case of decaying 2D turbulence on a square domain with no-slip walls the flow usually shows self-organization into a single domain-filling circulation cell with an associated increase in the total angular momentum of the flow – a process referred to as “spontaneous spin-up”. Subsequently, this organized state may persist until all energy is depleted by viscous dissipation and the fluid eventually comes to rest. In contrast, if the energy of the flow is maintained by some external forcing mechanism, a spectacularly different behaviour may be observed. Boundary layers present at the domain walls can destabilize the organized state, such that the dominating circulation cell collapses, and the self-organization process may start anew. Most strikingly, the circulation may even show sign reversal. This flow behaviour has been investigated by high-resolution numerical simulations based on spectral techniques.

Numerical Experiments on Vortex Shedding From an Oscillating Cylinder

FM25S_11676
Thu • 14:30 • 305A

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(2) *Virginia Polytechnic Institute & State University, Virginia, USA*

Vortex street wakes behind oscillating cylinders have been studied experimentally and numerically by several authors. Williamson and Roshko attempted a classification of the various wake patterns observed as a function of two dimensionless parameters, the wavelength and amplitude of the undulatory motion of the cylinder scaled by the cylinder diameter. Several qualitatively distinct wake regimes were observed experimentally. These were classified in terms of the vortex patterns, e.g., two singlets, two pairs, pair and singlet, and so on. We have performed a number of numerical experiments for Re=140 and established several points of correspondence with the experiments. Our simulation results also shed light on the classification scheme of Williamson and Roshko and suggest how this classification may change with Reynolds number. We find remarkable sensitivity to details of the oscillation of the cylinder, in particular whether the oscillation takes place at fixed streamwise velocity or at fixed cylinder speed along its trajectory.

Bifurcation of Motions of Three Vortices and Applications

FM25S_11683
Thu • 14:35 • 305A

Lu Ting[(1)], **Denis Blackmore**[(2)]
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We study pertured planar motion of three point vortices for special combinations of strengths and distances between them such that the triangle they form will remain similar. Depending on the orientation of the vortices, the similar triangles will be either contracting or expanding. The contracting (expanding) solution was shown to be unstable (stable). We show that when the ratios of the sides of a contracting triangle are perturbed, the triangle bifurcates from the similar solution and finally approaches the corresponding expanding similar solution, i.e. the one with the opposite orientation. We then study a related perturbation problem with the planar motion of three vortices serving as the leading order approximation to that of three slender coaxial vortex rings in a meridian plane having radii much larger than the distances between the rings.

A Model for the Formation of 'Optimal' Vortex Rings with Taking into Account Viscosity

FM25S_12032
Thu • 14:40 • 305A

Felix B. Kaplanski, Ylo A. Rudi
Tallinn University of Technology, Laboratory of Multiphase Media Physics, Tallinn, Estonia

The evolution of a viscous vortex ring from thin to thick-cored form is considered using the improved asymptotic, which is obtained after impressing a spatially uniform drift on the first-order solution of the Navier–Stokes equations. The obtained class of rings can be considered as the viscous analogy to the Norbury vortices and classified in terms of the ratio of their initial outer radius to the core radius. The model agrees with the reported theoretical and experimental results referring to the post-formation and the formation stages. By using the matching procedure suggested earlier and the obtained properties of the viscous vortex ring, it is found that when the length-to-diameter aspect ratio L/D reaches the limiting value 4.0 ('formation number'), the appropriate values of the normalized energy and circulation become around 0.3 and 2.0, respectively. An approach that enables to predict the 'formation number' is proposed.

Numerical Simulation of Vortical Flows Using a Highly Accurate Finite Difference Scheme

FM25S_12041
Thu • 14:45 • 305A

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A combined compact finite difference (CCD) scheme with high accuracy and high resolution is proposed for numerical simulation of incompressible vortical flow fields. The CCD scheme has eighth-order accuracy and spectral-like resolution for the first derivative except for the boundary. The Poisson equation is also solved accurately by using the CCD scheme and the ADI method. The vortical flows in the three-dimensional lid-driven square cavities with different spanwise aspect ratios are studied using this new scheme. The numerical results clearly show the bifurcation of flow structures in a lid-driven cavity with different spanwise aspect ratios.

Numerical Investigation of the Laminar–Turbulent Transition of the Flow in a Rotor–Stator Cavity

FM25S_12080
Thu • 14:50 • 305A

Ewa Tuliszka-Sznitko(1), Eric Serre(2), Patrick Bontoux(2)
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Flow in rotting disks systems is not only a subject of fundamental interest but is also a topic of practical importance. Typical configurations are cavities between compressors and turbines disks. Numerous works have been recently devoted to the investigation of the instabilities associated to a single disk flow and to a differentially rotating disks flow. Identification and characterization of mechanisms related to this process should improve the prediction methods and lead to new more efficient control strategies. In the present work the incompressible fluid flow in a stator/rotor cavity (cylindrical and annular) is numerically investigated using direct numerical simulation (DNS) and theoretical method (LSA). The numerical computations (DNS) are based on a pseudo spectral Chebyshev-Fourier method for solving 3D Navier–Stokes equations. The nature of the transition to unsteadiness as well as the influence of the end-walls boundary conditions (the influence of the attachment of the shroud and shaft to the rotor or to the stator and the influence of the approximation of the end-walls azimuthal profiles) on the stability of the flow have been investigated. Moreover, the absolute instability regions are theoretically identified using LSA method.

Viscous Vertical Length Scale Selection in Stratified Fluids

Ramiro Godoy-Diana, Jean-Marc Chomaz, Paul Billant
LadHyX, CNRS-École Polytechnique, France

FM25S_12108
Thu • 14:55 • 305A

The evolution of pancake dipoles of different aspect ratios is studied in a stratified tank experiment. When the vertical Reynolds number is large enough, the vertical size of the dipole is shown to decrease whereas its horizontal circulation is conserved. This decrease of the dipole thickness is due to the peeling off of two boundary layers, on top and bottom of the dipole, where the fluid is slowed down by viscosity. The thickness of the dipole diminishes until a viscous length scale δ, defined by the vertical size of these boundary layers, is reached. Viscosity is therefore responsible for a fast vertical decorrelation of the flow. The mechanism that we evidence may play a significant role in the determination of the vertical length scale in strongly stratified flows.

Vortex Dynamics in the Sphere Wake at Moderate RE

Paul V. Matyushin, Valentin A. Gushchin
ICAD RAS, Moscow, Russia

FM25S_12544
Thu • 15:00 • 305A

For the investigation of the formation mechanisms of vortices in the sphere wake for different fluid flow regimes (for $270 < Re < 3000$) the direct numerical simulation and the Hussain's $-\lambda_2$ vortex-eduction technique have been used. Two different types of the formation mechanisms of vortices for $270 < Re < 400$ and for $Re > 400$ are demonstrated. For $270 < Re < 400$ a periodical separation of the hairpin-shaped vortices is observed only from one edge of the cylindrical shear layer (surrounding the recirculating zone of the sphere wake) and the time-average lift/side and torque moment coefficients are not equal to zero. For $Re > 400$ the periodical separation of the hairpin-shaped vortices is observed from opposite edges of the shear layer alternatively and the time-average lift/side and torque moment coefficients are equal to zero. In addition the regular and irregular rotation of the cylindrical shear layer are observed for $360 < Re < 400$ and for $Re > 600$ correspondingly. All stages of the extraction of the hairpin-shaped vortices from the recirculating zone of the wake are shown in detail.

Three Dimensional Velocity Field of Vortices Impinging on a Wall Obtained by Scanning Particle Tracking Velocimetry

Klaus W. Hoyer
IHW, ETHZ, Zurich, Switzerland

FM25S_12821
Thu • 15:05 • 305A

The interaction of a concentrated vorticity filament (e.g. a vortex ring) impinging on a solid boundary exhibits a complex dynamical behaviour rooted in the interplay of the vortex filament with the induced strain field together with the shear layer of opposite vorticity generated close to the wall. Two distinct scenarios develop depending on the angle of impingement with the wall normal direction. For wall normal impingement, the original vortex exhibits multiple localized breakdowns along the toroid axis, which are triggered by the localized engulfment of the primary vortex of weaker and opposite vorticity, which rolled up from the shear layer. For inclined impingement, a similar mechanism causes a single symmetric pair of vortex breakdowns to originate at the point of closest contact and propagate to the less perturbed part of the vortex further away from the wall. We apply classical 3D PTV, however, a scanning technique used for the data acquisition together with a high-speed camera allows increasing the particle density and therefore the spatial resolution.

Study of the Vortex Rings Interaction by 3d Vorticity Particle-In-Cell Method

Henryk Kudela, **Pawel Regucki**
Wroclaw University of Technology, Department of Numerical Modelling of Flows, Wroclaw, Poland

FM25S_12836
Thu • 15:10 • 305A

In paper it was presented numerical investigation of the vortex rings interaction. It was studied the leap-frogging phenomenon for inviscid flow. It was shown that dynamics of the vortex rings is very sensitive to the initial parameters like diameters of the rings, their mutual positions and circulations. It was studied also the reconnection of the vortex rings in viscous flow. The vorticity particle-in-cell method for three-dimensional, viscous flow was used. Equations of motion were formulated in the terms of vector potential and vorticity. A viscous splitting algorithm was applied. The viscous effect was taken into account by the particle strength exchange method. While solving of the Euler equation the invariants of the motion like kinetic energy, enstrophy and helicity were controlled. It was also controlled the divergence of the vorticity, velocity and vector potential fields. Agreement of numerical results with the experimental data was very good.

FM26

Waves

Chairpersons: W. Melville (USA), V. Shrira (UK)

Unidirectional Steep Waves in Wave Tanks

FM26L_10245

Tue • 17:00 • 306

L. Shemer, K. Goulitski, E. Kit
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A nonlinear focusing process in which a single unidirectional steep wave emerges from an initially wide amplitude- and frequency-modulated wave group at a predicted position in the laboratory wave tank is studied both theoretically and experimentally. The spatial version of the Zakharov equation was applied in the numerical simulations. Experiments were carried out in two facilities which have substantially different scales: in the Tel-Aviv University wave tank, which is 18 m long, and in the Large Wave Channel in Hanover, which is 330 m long. Comparison between the experimental studies in both facilities and the corresponding numerical results is carried out. Good agreement was obtained between experiments and calculations. The effect of dissipation and bound waves is discussed.

Propagation and Interactions of Nonlinear Internal Gravity Wave Beams

FM26L_10762

Tue • 17:20 • 306

T.R. Akylas[(1)], Ali Tabaei[(2)]
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(2) *Department of Civil and Environmental Engineering, Cambridge, USA*

Recent numerical simulations and field observations reveal that thunderstorms often give rise to gravity-wave disturbances that propagate in the atmosphere along specific directions. Similar beam-like wave structures are generated in the ocean by tidal flow over bottom topography. These wave beams are akin to the arms of the classical St Andrews-Cross wave pattern (see, for example, the front cover of the paperback version of the text Waves in Fluids by M.J. Lighthill) due to a localized source oscillating at a frequency below the buoyancy frequency in a uniformly stratified, inviscid Boussinesq fluid. An asymptotic theory for the propagation of modulated two-dimensional and axisymmetric nonlinear wave beams will be presented, that takes into account viscous effects as well as refraction effects due to the presence of a mean flow and nonuniform buoyancy frequency. The theory explains why a linear approach has been useful in interpreting certain observations of isolated beams in the atmosphere. On the other hand, nonlinear effects play an important part in the reflection of wave beams from a sloping wall and in collisions of obliquely propagating beams. Nonlinear interactions are confined solely in the vicinity of the sloping wall where the incident and reflected beams meet, and this interaction region gives rise to additional reflected beams with higher-harmonic frequencies. Similarly, nonlinear interactions in the overlap region of two colliding beams induce secondary beams with frequencies equal to the sum and difference of those of the colliding beams. The theoretical predictions are consistent with numerical simulations and experiments.

Weak-Turbulent Theory of Wind-Driven Sea

FM26L_10861

Tue • 17:40 • 306

Vladimir E. Zakharov
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A bulk of experimental data on the wind-driven sea collected in physical oceanography for several decades can be explained in a framework of a simple analytical theory based on the Hasselmann kinetic equation for squared amplitudes of the wave with stochastic phases. The theory is based on the assumption that the main physical process in the wind-driven sea is four-wave nonlinear resonant interaction. As a result, in the leading order, the surface wave turbulence is described by conservative kinetic equation that does not include forcing and dissipation terms. This equation has a rich family of self-similar solutions, which can be found from the next approximation; this approximation is the balance equation for wave action. The theory, supported by massive numerical experiments makes possible to explain a lot of experimental data in the major fetch-limited and duration-limited experiments; these data include fetch and duration dependance of integral

characteristics of the sea, such as energy and mean frequency, as well as shapes of spectra both in the equilibrium range and in the energy-containing spectral area.

Contact-Line Effects on Capillary-Gravitywaves

Jose A. Nicolas, Javier Hilario
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FM26L_11081
Tue • 18:00 • 306

Experiments show that the natural frequency and damping rate of capillary-gravity waves in containers greatly depend on the contact-line conditions. In particular, there are important differences between the cases when the contact-line is fixed and when the contact-angle is fixed, and between the cases when the static contact-angle is acute (hydrophillic surface) or obtuse (hydrophobic surface). Two problems are considered: a) the effects of the static contact-angle on the natural frequency in the inviscid case and, b) the effects of a phenomenological condition (which assumes a linear variation of the contact-angle with the speed of the contact-line) on the frequency and damping rate in the case of orthogonal intersection at the contact-line and nearly-inviscid liquid. The results are compared with experimental results showing a significant improvement.

The Theory of Travelling Deformation Waves and Its Applications in Biomechanics, Engineering, and Geophysics

Anatoli I. Dobrolyubov
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FM26L_11144
Tue • 18:20 • 306

The theory of travelling deformation waves and its applications in biomechanics, engineering, and geophysics A.I. Dobrolyubov United Institute of Information Problem, Surganov st. 6, Minsk, 220012, Belarus, dobr@newman.bas-net.by Our theoretical and experimental researches of the travelling waves of deformation in solid, liquid, and gaseous bodies have resulted in an establishment of some unknown before wave phenomena and effects. It was established, that running waves of deformation play an important role both in living organisms and in inanimate nature and act in various physical matter in micro- and macrocosm. The created theory of travelling waves of deformation and wave masstransfer has allowed to receive new scientific results and to make inventions in such areas as theoretical mechanics, the theory of mechanisms and machines, biomechanics and medicine, the Earth sciences. These results were recognized as fundamental by various experts in our republic and abroad. Our results on a competitive basis were awarded with grants of Fund of basic researches of Belarus, the American Physical Society, the International Soros scientific fund.

The Spacing of Langmuir Circulation in Strong Wavy Shear

William R.C. Phillips
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FM26L_11179
Tue • 18:40 • 306

The inviscid instability of $O(\varepsilon)$ two-dimensional free surface gravity waves propagating along an $O(1)$ parallel shear flow is considered. The modes of instability involve spanwise-periodic longitudinal vortices resembling oceanic Langmuir circulation. Here, not only are wave-induced mean effects important but also wave modulation, caused by developing mean streamwise-velocity anomalies. The former is described by a generalized Lagrangian-mean formulation and the latter by a modified Rayleigh equation. Since both effects are essential, the instability is called "generalized Craik-Leibovich (CLg).Of specific interest is whether spanwise distortion of the wave field acts to enhance or inhibit instability to longitudinal vortices. Also of interest is whether the instability gives rise to a preferred spacing for the vortices and whether that spacing concurs well or poorly with experiment. The layer depth is varied from much less than the e-folding depth of the $O(\varepsilon)$ wave motion, to infinity. Relative to an identical shear flow with rigid though wavy top boundary, it is found that wave modulation acts to increase the maximum growth rate of the instability. Finally, the preferred spacings calculated herein concur well with those observed in laboratory experiments, with the implication that the instability acting in the experiments very likely is CLg.

Experiments on Rotating and Reflecting Internal Wave Beams

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FM26L_11199
Wed • 08:30 • 306

We present the results of two sets of experiments on internal wave beams; one concerns conical beams in a rotating fluid and the other concerns the reflection of planar beams from inclined surfaces. The theory of linear disturbances is well known for the rotating system, as it is relavent to phenomena in the ocean and atmosphere (Le Blond and Mysak), but direct experimental verifi cation of the cut-off frequencies and inclination angles seems not to have been previously performed. The reflection of planar beams from inclined surfaces is the subject of a more recent theoretical study (Tabaei and Akylas), which predicts the generation of second harmonic beams via a nonlinear mechanism. The orientation of the reflected beams is dictated by the slope of the inclined surface, and we present the fi rst set of experimental results on this matter. For both sets of experiments visualization is performed using the synthetic schlieren technique.

Spatio-Temporal Measurements of Capillary-Gravity Waves

Paul A. Hwang[1], David W. Wang[1], Guillemette Caulliez[2], Vladimir K. Makin[3]
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(3) *KNMI, The Netherlands*

FM26L_11230
Wed • 08:50 • 306

Small scale surface waves in the capillary-gravity region can be easily advected by surface currents from all sources. Temporal measurements using fi xed-point wave probes, therefore, cannot resolve reliably the spatial or wavenumber structure of short waves unless the surface currents are also monitored, which is an even more diffi cult task than surface wave measurement. A two-dimensional scanning slope sensor system is developed to perform 4D measurements [z(x,y,t)] of small scale surface waves. The data yield 3D spectrum [B(kx,ky,omega)] covering the capillary-gravity wave scales. Reflection of short waves as described by Shyu and Phillips can be clearly seen. The directional properties of small scale waves would be influenced by this mechanism greatly. These data can be used to investigate the balance of source functions in the wave action conservation equation following the approach suggested by Phillips.

Generalized Internal Solitary Waves and Fronts

Frederic Dias, Christophe Fochesato
CMLA, École Normale Supérieure de Cachan, France

FM26L_12089
Wed • 09:10 • 306

It has been shown by several authors that waves in a two-layer system with free-surface boundary conditions (or in a three-layer system) can be modelled by a system of two coupled long wave equations. The study of the resonance between a solitary wave of one of the two equations and a copropagating periodic wave of the other equation is carried out numerically. The resulting wave is a generalized solitary wave. It is shown that in the case of a thick solitary wave (solution of a modifi ed Korteweg–de Vries equation with a cubic nonlinearity), the generalized solitary waves do not behave like common sech square generalized solitary waves. Simplifi ed models are introduced, which allow a better understanding of these stationary and time-dependent long wave solutions.

Three Dimensional Gravity Water Waves

Walter Craig
McMaster University, Hamilton, Canada

FM26L_11548
Wed • 09:30 • 306

Three dimensional gravity water waves are ubiquitous, and of importance to physical oceanography and marine engineering. Yet being a complex nonlinear process the study of water waves remains a rich source of mathematical problems, whose answers can be of relevance to ocean scientists. My presentation concerns the form of three dimensional traveling water waves, contrasting the geometry of waves over deep water with the shallow water regime. In particular, solutions typically occur in two-parameter bifurcation families, which can have complex secondary bifurcations in resonant situations. The rigorous mathematical theory will be compared with numerical computations and controlled laboratory experiments. I will also discuss the existing stability theory, especially of the deep water case.

Transverse Instability of Surface Solitary Waves

FM26L_11746
Wed • 09:50 • 306

Takeshi Kataoka, Michihisa Tsutahara
Graduate School of Science and Technology, Kobe University, Kobe, Japan

The linear stability of finite-amplitude surface solitary waves with respect to long-wavelength transverse perturbations is examined by the asymptotic analysis for small wavenumbers of perturbations. The instability criterion is explicitly derived, and it is newly found that there exist transversely unstable surface solitary waves for the amplitude-to-depth ratio of over 0.713. This critical ratio is well below that for the one-dimensional instability (=0.781).

A Lagrangian Approach to Wave-Induced Oceanic Mass Transport

FM26L_11803
Wed • 10:10 • 306

Jan Erik Weber
Department of Geosciences, University of Oslo, Oslo, Norway

The mean mass transport induced by surface gravity waves is investigated theoretically for a deep, rotating ocean with a constant eddy viscosity. The waves are periodic in space, and have amplitudes that grow or decay slowly in time. The analysis is based on a Lagrangian description of motion, and the results are valid to second order in the wave steepness. An equation for the wind- and wave-induced mean Lagrangian mass transport in the oceanic surface layer is derived. The mean wave-induced mass transport is driven by the form drag associated with the fluctuating wind stress normal to the wave slope. In the present formulation this consists of two terms. One of these terms is the time-derivative of the total mean horizontal wave momentum. The analysis is based on an idealized ocean with monochromatic waves. The generalization to a realistic sea, and the application to general ocean circulation models are discussed.

Effect of Horizontal Component of the Coriolis Force on Propagation of Near-Inertial Waves in the Ocean

FM26L_12087
Fri • 09:30 • 306

Theo Gerkema(1), **Victor I. Shrira**(2)
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Oceanic motions of scales small compared to the Earth's radius are commonly described as if the rotating Earth were locally flat with the horizontal component of the Coriolis force being neglected (the so-called traditional approximation). We show that taking into account the horizontal component of the Coriolis force changes dramatically dynamics of near-inertial waves. A new family of sub-inertial waves, which are absent under the traditional approximation, is found to play a crucial role: on the non-traditonal beta-plane inertial waves propagating poleward and reaching their inertial latitude are not reflected at this latitude, as is the case under the traditional approximation, but turn into subinertial waves which propagate further poleward trapped within near bottom and near surface wave-guides around the minima of the buoyancy frequency. Their horizontal and vertical scales rapidly decrease and tend to zero at a critical latitude. There is no reflection and, thus, inertial waves are absorbed contributing to deep ocean mixing.

Standing Gravity Waves in Deep Water

FM26L_11290
Fri • 09:50 • 306

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We consider the two-dimensional potential flow of *standing gravity waves on an infinitely deep water*, with *no surface tension at the free surface*. Linear theory gives *infinitely many eigenmodes for any rational value of the dimensionless parameter* $\mu = gT^2/2\pi\, lambda$ (T and λ being time and space periods). We use a formulation of Dyachenko *et al* leading to a nonlocal second order partial differential equation, for which the existence of infinitely many emphapproximate solutions at any order is known. For proving the existence of solutions with a given asymptotic expansion, we use an appropriate version of the Nash-Moser implicit function theorem, where the major difficulty is to invert the linearized operator near a non zero point. We can show the *existence of standing waves for an infinite sequence of values of μ tending to any rational number*).

Interaction of an Inertia-Gravity Wave Packet with a Baroclinic Shear Flow

FM26L_12424
Fri • 10:10 • 306

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We investigate the interaction of an internal gravity wave packet in a rotating fluid with a baroclinic shear flow, using ray equations and three-dimensional direct numerical simulations of the Boussinesq equations. In this problem, the intrinsic frequency of the wave packet increases as it propagates, due to the horizontal shear of the background flow. The packet is trapped where the intrinsic frequency reaches its upper bound and is amplified there. When the horizontal shear of the background flow is low enough, ray equations predict that the packet may further penetrate into that flow through reflection within a wave guide. The numerical simulations show that the packet is actually dissipated before reflecting because its group velocity and horizontal scale strongly decrease during the interaction. Consequently, the wave packet does not induce any significant transport across the shear flow.

Nonlinear Long Waves on the Interface of a Two-Layered Horizontal Flow of Viscous Liquids

FM26S_10123
Thu • 14:30 • 309

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This paper deals with the theoretical study of plane waves with small but finite amplitude in the two-layer system bounded by the horizontal lid and bottom. It is supposed that characteristic lengths of perturbations are sufficiently larger, its amplitudes are much smaller, and non-stationary boundary layers are much less than depths of liquids. It is shown that dissipation affects distinctly on a vertical motion at relatively high velocities of the steady unperturbed flow. The evolution equation for the interface disturbances, which takes into account long-wave contributions of the layers inertia, weakly non-linearity of waves and non-stationary shear stresses at all boundaries of the system is obtained. On neglect of dissipation for the perturbation current steady-state solutions of conidal and solitary waves type are determined. It is found that amount and direction of a flow may change not only lengths of disturbances but its polarity too.

Wave Breaking and Equilibrium Surfacewave Spectra

FM26S_10746
Thu • 14:35 • 309

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Knowledge of the equilibrium range of surface wave spectra is of practical importance since existing numerical wave prediction models cannot solve right down to the smallest gravity waves. Recently, the authors proposed an analytical theory of the equilibrium spectra with an assumption that the wave induced stress is entirely due to nonbreaking waves. However, at high winds a significant portion of waves breaks and causes airflow separation and enhancement of the wave drag. In this paper the effect of enhanced wind input by breaking waves on the form of the equilibrium surface wave spectra is investigated. The theory is based on the conservation of momentum and energy in the wave boundary layer together with the conservation of the wave action spectrum. The results show that the breaking wave effect is not very strong for fully-developed wave spectra but may be significant for the spectra of growing seas.

Shallow-Water Theory for Wave–Current–Bottom Interactions

FM26S_11126
Thu • 14:40 • 309

Hu Huang
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A new shallow-water theory valid for wave-current-bottom interactions with arbitrary depth and unsteady horizontal currents is derived by Hamilton's canonical equations for surface waves, which constitutes a systematic hierarchy of partial differential equations for linear gravity waves in the near shore region. The first and second members of this hierarchy, the Helmholtz equation and the mild-slope equations of Berkhoff (1972) for pure waves and of Kirby (1984) with current, are second order. The third member is fourth order but may be approximated by Miles & Chamberlain's (1998) fourth-order partial differential equation for pure waves which contains as a special case Chamberlain & Porter's (1995) modified mild-slope equation.

Unsteady Undular Bore Transition in Fully Nonlinear Dispersive Wave Dynamics

FM26S_11134
Thu • 14:45 • 309

Gennady El
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A complete set of conditions describing the expanding undular bore transition in nonlinear conservative wave dynamics is derived. The transition conditions are obtained in a general form by employing the asymptotic formulation of the problem based on the Whitham modulation equations and allow, in particular, determination of the lead solitary wave amplitude as a function of the initial jump in (generally) non-integrable systems. Several examples pertaining to the shallow water dynamics and collisionless plasma physics are considered.

Mass Transport Due to Partially Reflected Waves in a Two-Layer Viscous System

FM26S_11235
Thu • 14:50 • 309

Chiu-On Ng
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Based on Lagrangian coordinates, a perturbation analysis is conducted to find the mean drifts due to partially reflected surface waves in a two-layer system, where the lower fluid is assumed to be much more viscous than the upper one. A single analytical expression is obtained for the mass transport velocity in each layer, incorporating the cases where the wave can be progressive, standing or partially standing, and the domain can be closed or open at its far field. It is shown that the patterns of mean flow in the two layers are materially affected by the lower-fluid viscosity. It is possible that the mass transport in the core region of the upper layer is completely quiescent despite the existence of some strong drifts in the lower layer. The wave reflection may also have different effects on the mean flow structures when the system is closed or open.

Nonlinear Three-Dimensional Free Surface Flows in Finite and Infinite Depth

FM26S_11345
Thu • 14:55 • 309

Emilian Parau, Jean-Marc Vanden-Broeck, Mark J. Cooker
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Steady three-dimensional free surface flows generated by disturbances (distributions of pressure, ships or submerged objects) moving at a constant velocity in a fluid of finite or infinite depth are considered. The fluid is assumed to be inviscid, incompressible and the flow is supposed to be irrotational. On the free surface the fully nonlinear kinematic and dynamic boundary conditions are used. The three dimensional problem is formulated as a nonlinear integro-differential equation by using Green's functions. This equation is then discretised and the resulting algebraic equations are solved by Newton's method. Numerical results are presented for subcritical and supercritical three-dimensional free surface flows. The importance of nonlinearity is demonstrated by comparing the numerical results with the classical linear theory.

Dynamics of Crescentwave Patterns in a Channel

FM26S_11417
Thu • 15:00 • 309

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Solving the full set of water wave equations, we perform numerical simulations of evolution of class II instabilities. We reproduce the well known steady horse-shoe patterns and the newly discovered oscillating horse-shoe. For small initial steepness of the basic Stokes wave, we identify the existence of a recurrence cycle similar to the Fermi-Pasta-Ulam recurrence for modulational instability. We further study the feasibility of experimental observation of such patterns and give an explanation for the selection mechanism responsible of trigging non-dominant instability leading to the formation of the oscillating patterns.

Evolution of Packets of Surface Gravitywaves over Smooth Topography

FM26S_11468
Thu • 15:05 • 309

Eugene S. Benilov, Jason D. Flanagan, **Colm P. Howlin**
University of Limerick, Ireland

Weakly nonlinear packets of surface gravity waves over topography are governed by a nonlinear Schroedinger equation with variable coefficients (Djordjevic & Redecopp 1978). Using this equation and assuming that the horizontal scale of

topography is much larger than the width of the packet, we show that, counter-intuitively, the amplitude of a shoaling packet decays, while its width grows. Such behaviour is a result of the fact that the coefficient of the nonlinear term in the topography-modified Schroedinger equation decreases with depth. Furthermore, there exists a critical depth, where this coefficient changes sign: if the packet reaches this depth, it disintegrates.

Integration of the Equations of Long Waves in the Channels and Jets

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FM26S_11531
Thu • 15:10 • 309

The equations for long waves on the water surface are represented in the form of the shallow water equations in the Boussinesq approximation. The Boussinesq approximation takes into account the transverse acceleration of liquid particles. The total pressure at the cross section area of the flow is expressed in the form of Lagrange equations (Drozdova, Kulikovskii 1996). Lagrange function depend on cross-section area and its derivative. For the steady-state motion in the general case we have formed three integrals, where are arbitrary constants of integration. As a result we obtained the analytical solutions of many problems for cnoidal-type and solitude waves in channels of different forms taking into account surface tension or an elastic film. http://ictam04.ippt.gov.pl

Sharpening and Breaking of Subharmonic Gravity Waves on Deep Water

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FM26S_11591
Thu • 15:15 • 309

The process of sharpening and formation of singular flows in symmetric and non-symmetric subharmonic gravity waves, whose period is multiple to the period of Stokes waves, is investigated in the framework of the canonical model of hydrodynamics. Subharmonic waves, which are excited due to subharmonic instabilities of Stokes waves and have the crests of different height, are traced up to limiting waves. Non-symmetric subharmonic waves appear via symmetry-breaking instabilities of symmetric subharmonic waves. The effect of non-symmetry of subharmonic waves was found to be more essential with wave sharpening. Irregular flows with stagnation point inside the flow domain and discontinuous streamlines near the wave crests beyond limiting subharmonic waves were found to originate in the following way. Streamlines become discontinuous only in the highest sharp crests while the flow in all other crests (that are still rounded and have much lesser amplitude) remains regular.

Short Wind Waves and Surface Wind Drift

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FM26S_11680
Thu • 15:20 • 309

Short wind waves and wind drift shears have been subjects of profound studies among oceanographers. Under the assumption of small monochromatic surface waves on a steady horizontally uniform surface shear of an inviscid fluid, the governing equation becomes the well-known Rayleigh equation. The exact analytical solutions are found for a very limited number of current profiles. For arbitrary current profiles, approximate solutions are used (Stewart and Joy 1974, Shrira 1993). The conditions for the approximations are often violated in the case of short wind waves and wind drift shear. As an alternative approach, the piecewise linear approximation is explored. We provide a proof of the convergence of the piecewise linear approximation under certain conditions. The first application is finding the neutral modes which determine the boundaries of linear instability regions. The second aim is to invert surface shear current from measured short surface wave propagation speeds.

Intermittent Mixing by Multiscale Breaking of Wind Waves: Implications for Oil Dispersion

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FM26S_12268
Thu • 15:25 • 309

We simulated the intermittent mixing by breaking waves with the use of non-stationary 1D two-equation turbulence model. The wave-breaking layer with thickness of half significant wave height was included into consideration. An injection of turbulence by penetrating breakers in this layer was parameterized by source term in the turbulent kinetic energy and dissipation equations. The Monte-Carlo simulations of intermittent mixing were carried out. They support assumption that observed log normal distribution of dissipation rate is associated with breaking of waves in many scales. An intermittent mixing effects on the scales of breakup and dispersion in water of oil droplets in the wave breaking layer. The detailed results of simulations of turbulence and droplet spectre and concentration in the wave enhanced layer for stormy conditions by linked model of surface turbulent layer and 3D Lagrangian model of oil spill are presented.

Equatorial Wave Attractors and Inertial Oscillations

FM26S_12318
Thu • 15:30 • 309

Leo R.M. Maas, Uwe Harlander
Netherlands Institute for Sea Research, The Netherlands

Stratification and rotation, both essential elements of geophysical fluids like ocean and atmosphere, impose a strong constraint on the internal waves supported by them. This constraint pertains to the fixed angle of propagation with which they propagate obliquely through the fluid domain. The consequence of this constraint is that such wave systems do not possess discrete eigenmodes, but rather lead to the wave approaching certain spatially confined limit cycles, called wave attractors. It is argued that in the equatorial zone meridionally propagating waves are always steered towards such wave attractors. A subclass of these is presented by the trapping of the waves at the bottom near the latitude where these waves are perceived as 'inertial oscillations', a well-known feature in any ocean observation record.

Steep Capillary Waves in Electrified Fluid Sheets

FM26S_12715
Thu • 15:35 • 309

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(2) *Department of Mathematical Sciences and Center for Applied Mathematics and Statics, New Jersey Institute of Technology, USA*

Capillary waves on fluid sheets are computed in the presence of uniform electric fields. The fields are acting vertically or horizontally with respect to the undisturbed configuration. Both conducting and nonconducting fluids are considered. The effects of viscosity and compressibility are neglected. Traveling waves of arbitrary amplitudes are calculated and the effects of the electric fields are studied. Numerical solutions are obtained by boundary integral equation methods. Analytic solutions based on long wave asymptotics are also presented. Two dimensional and axisymmetric configurations are studied.

Breaking Internal Waves in a Sheared Fluid with Critical Layers

FM26S_12797
Thu • 15:40 • 309

Oleg G. Derzho
Institute of Thermophysics, RAS, Novosibirsk, Russia

A new model for long internal waves in a sheared flow with a critical layer near either lower or upper rigid boundary has been developed. In such system even small disturbances give rise to a formation of a zone filled with the mixed fluid. One nonlinear differential equation for the wave amplitude is derived in the steady case, in which the nonlinearity arises essentially due to the presence of the mixed zone. Solutions of the obtained equation include periodic waves on the induced mixed layer, a stationary bore and a combinational solution consisting of series of recirculation zones located alternatively near both boundaries.

Bi-Directional Water Waves and Integrable High Order KDV Equations

FM26S_12813
Thu • 15:45 • 309

Georgy I. Burde
J. Blaustein Institute for Desert Research, Ben-Gurion University, Israel

The Boussinesq system, arising as a result of the asymptotic expansion procedure applied to the Euler equations for the shallow water wave motion, is decomposed to a set of coupled equations for the right- and left-moving waves. It is shown that a non-uniqueness of such a decomposition can be used to derive a system, in which, to any order, one of the equations is dependent only on the main right-moving wave and has the form of the KdV equation with higher order corrections but, as distinct from the unidirectional case, with arbitrary coefficients. Some classes of solutions of the right-moving wave equation, which include impacts of all orders of the asymptotic perturbation expansion, are constructed via a new approach to the use of the LIe-Baecklund groups of transformations for the PDEs with perturbations.

SOLID MECHANICS

SM1

Computational solid mechanics

Chairpersons: T. Belytschko (USA), P. Wriggers (Germany)

Model Updating a Multicriteria Optimization Process in Mechanics

SM1L_10423
Tue • 17:00 • 134

Hans H. Muller-Slany
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Model updating is a widely used area of research in the field of dynamics of elasto-mechanical structures. The ill-conditioned inverse mathematical problem is primarily solved in a sensitivity based numerical process, considering regularization methods. Usually, only modal properties (selected natural frequencies and selected natural mode shapes) and selected data of the frequency response functions are considered in model updating procedure. This contribution shows how additional dynamical properties of the structure can be introduced in the updating process. The elasto-mechanical structure will be modelled by using FE-macro-elements and the model updating will be formulated as a constrained multiobjective optimization problem. In this procedure the parameters of the macro-elements are collected in the unknown design vector. The optimization problem will be solved by a special hierarchical scalarization method in which the errors of each different dynamical property between the mathematical model and measurements will be minimized. Applications will be shown.

Experiment and Quasicontinuum Simulation of Nanoindentation in Copper

SM1L_10559
Tue • 17:20 • 134

Yuan Lin, Shan Debin, Guo Bin
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Experiment and quasicontinuum simulation of nanoindentation in fcc copper are performed. The indented material is a single crystal. Indentation is accommodated by elastic deformation of the surface, up to an indenter displacement of about 6 Åand by nucleation of crystalline defects for deeper indents. The critical load for the event is computed and the nucleation is observed. The result is compared with experimental data. The comparison conveys the conclusion that incipient plasticity is induced at much earlier times and much smaller loads than observed in nanoindentation experiment, and the measured instabilities are collective events involving a large number of pre-existing dislocations.

A BEM Solution to Transverse Shear Loading of Beams

SM1L_10665
Tue • 17:40 • 134

Evangelos J. Sapountzakis, **Vasilios G. Mokos**
School of Civil Engineering, National Technical University, Athens, Greece

In this paper a boundary element method is developed for the evaluation of the transverse shear stresses in beams of arbitrary simply or multiply connected constant cross section subjected in transverse shear loading. The shear loading is applied at the shear center of the cross section, avoiding in this way the induction of a twisting moment. Two boundary value problems that take into account the effect of Poisson's ratio are formulated with respect to harmonic functions and solved employing a pure BEM approach. The evaluation of the transverse shear stresses is accomplished by direct differentiation of these harmonic functions, while both the coordinates of the shear center and the shear deformation coefficients are obtained from these functions using only boundary integration. Numerical examples with great practical interest are worked out to illustrate the efficiency, the accuracy and the range of applications of the developed method.

Mechanical Features of Piano Hammer Felt

SM1L_10728
Tue • 18:00 • 134

Anatoli Stulov
Centre for Nonlinear Studies, Institute of Cybernetics, Tallinn, Estonia

Experimental testing of piano hammers, which consist of a wood core covered with several layers of compressed wool felt demonstrates, that all hammers have the hysteretic type of the force-compression characteristics. It is shown, that different mathematical hysteretic models can describe the dynamic behavior of the hammer felt. In addition to the four-parameter nonlinear hysteretic felt model, another new three-parameter hysteretic model was developed. The both models are based on the assumption that the hammer felt made of wool is a microstructured material possessing history-dependent properties. Both of the models are equivalent for the slow loading of the felt.

Mesh Optimization for the Quasicontinuum Method: A Generalization of VALE

SM1L_11154
Tue • 18:20 • 134

J. Knap, J. Marian, M. Ortiz
Division of Engineering and Applied Science, California Institute of Technology, USA

The current formulation of the Quasicontinuum (QC) method relies on a static triangulation of the reference crystal configuration. This computational mesh needs to encompass a wide range of spatial resolutions, from fully atomistic at defect cores, to continuum-like in defect-free regions. Moreover, it must continously adapt to the structure of the deformation field, so as to return the least possible potential energy for a fixed number of nodes. To this end, the mesh adaption process has been usually governed by empirical indicators. We present an extension of the Variational Adaptive Lagrangian-Eulerian (VALE) method into the QC context. In the spirit of VALE, the computational mesh is factored directly into the description of the energetics of the crystal. Therefore, the potential energy minimizer determines not only the equilibrium configuration of the crystal, but also the optimal configuration of the computational mesh. We apply the VALE-QC method to the investigation of early stages of plastic deformation during nano-indentation.

Multiscale Buckling Analyses of Corrugated Fiberboard

SM1L_12177
Tue • 18:40 • 134

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In this paper, multiscale micro-macro interaction analyses of corrugated fiberboard are conducted by the finite element method in conjunction with the homogenization theory. It is assumed that corrugated fiberboard is piled periodically in quasi three-dimensional state. The updated Lagrangian method is adopted for the geometrically nonlinear analyses of microstructure and the scaled corrector method for detecting the buckling mode. The conclusions obtained in this study are summarized as follows. 1) The large deformation and buckling analysis based on the homogenization theory is conducted and the mechanical properties of corrugated fiberboard are investigated. 2) The micro–macro interaction analysis procedure for the buckling of the corrugated fiberboard based on the homogenization theory is newly proposed. The validity of the proposed procedure is clarified qualitatively by comparing with the experimental results.

Lingopti Project: Semi-Continuous Casting Process of Copper–Nickel Alloys

SM1L_11298
Wed • 08:30 • 134

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Lingopti Project is a First Europe project. The research, performed in University of Liège, consists in the optimisation of the mould and the whole casting process of the enterprise LBP (Chènèe-Liège) to obtain better cast products. In fact, cast products sometimes present long oscillation marks ($\lambda \simeq 500$ mm) and some ingots have many internal cracks. The semi-continuous process consists in the vertical casting of 7 m height ingots and the section is 960×310 mm. The research is focused on two points: laboratory and bibliography researches and development of numerical modelizations. Laboratory tests provide thermal and mechanical properties of the ingot and the mould but also heat transfer coefficients between the ingot and the environment (mould, air and water coolings). These parameters are required in the numerical simulations. Currently, numerical calculations by the finite element method are focused on an horizontal slice. This one, by progression in the casting process give a 3D view of the ingot in stationary situation by a 2D modelization.

Bridging Scale Methods for Nano Mechanics and Materials

Wing Kam Liu
Northwestern University

SM1L_11629
Wed • 08:50 • 134

We demonstrate that the atomistic simulation tools are not sufficient for many of the interesting and fundamental problems that arise in computational materials design. These deficiencies lead to the thrust of multiple-scale methods. Hierarchical and concurrent multiple scale modeling of heterogeneous systems through the development of a set of coupled multiscale governing equations are then derived followed by the development of hierarchical and concurrent multiscale simulation methods for the solution of these equations. These are fundamentally necessary to account for the multiple scale behavior observed in heterogeneous materials. As an added benefit, we aim to use our models and methods to assist in the design and analysis of nano-materials and nanostructures, such as the Cybersteel, nano-composites, granular materials, fracture and shear bands, and bio-fluids.

Some Investigations on FM Bem in Solid Mechanics

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SM1L_11720
Wed • 09:10 • 134

As well known, the boundary element methods (BEM) has remarkable advantages of dimension reduction and higher accuracy, but the conventional BEM is not efficient for large scale problems. For the conventional BEM O(N*N*N) operations and O(N*N) memory are required, where N is the number of DOF. Fast multipole (FM) methods presented by mathematicians have reduced the operations and memory requirement to O(N). The FM BEM becomes an attractive way to solve complex practical engineering problems with BEM. In this presentation, a new version algorithm of O(N) FM BEM for 2D elastostatics is presented and applied to the simulation of 2D elastic solid with large number of randomly distributed inclusions. Furthermore, FM BEM is applied to the simulation of 2D elastic solid containing large number of randomly distributed cracks.

Radial-Type Approximation Technique for a Space-Time Multiscale Computational Strategy

Anthony Nouy, Pierre Ladeveze
LMT-Cachan, France

SM1L_11769
Wed • 09:30 • 134

A new multiscale computational strategy for the analysis of small disturbances of structures (such as composite structures) described in detail both in space and in time was introduced recently. This strategy is iterative and involves an automatic homogenization procedure in space as well as in time. At each iteration, this procedure requires the resolution of a large number of linear evolution equations, called the micro problems, on the micro scale. Here, we present a robust approximate resolution technique for these micro problems based on the concept of radial approximation. It consists in approximating the solution defined over the space-time domain by a sum of radial functions, each of which is the product of a scalar function of the time variable by a function of the space variable. This very general technique, which leads to the construction of a relevant reduced basis of space functions, is particularly suitable for the analysis of composite structures.

An Energy Conserving Scheme for Time Dependent Problems Using the Extended Finite Element Method

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LaMCoS, INSA Lyon, Villeurbanne, France

SM1L_11797
Wed • 09:50 • 134

Lots of techniques have been developed to take into account discontinuities such as cracks, holes or material interfaces. The eXtended Finite Element Method (X-FEM) for example has first been presented for crack modeling but is also used for arbitrary discontinuities. This paper proposes, with a proof of stability for the numerical scheme in the linear case, a generalization of X-FEM for time dependent problems with an application to dynamic crack propagation. An enrichment strategy is developed to satisfy conditions obtained from a theoretical study. This strategy is energy preserving and satisfies the same stability conditions as Newmark type schemes. Numerical results reveal the advantage of X-FEM which avoids numerical problems due to remeshing and projections. This framework is still valid for other time dependent problems and this general enrichment strategy should be applicated to arbitrary moving discontinuities.

Development of a Novel 'Crack' Finite Element for Propagation Simulation

SM1L_11817
Wed • 10:10 • 134

Young-Sam Cho, Sukky Jun, **Seyoung Im**
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In this paper, we propose a 2D 'crack' element for the simulation of propagating crack with minimal remeshing. A regular finite element containing the crack tip is replaced with this novel crack element, while the elements which the crack has passed are split into two transition elements. Singular elements can easily be implemented into this crack element to represent the crack-tip singularity without enrichment. Both crack element and transition element proposed in our formulation are mapped from corresponding master elements which are commonly built using the moving least-square (MLS) approximation only in the natural coordinate. In numerical examples, the accuracy of stress intensity factor K_I is demonstrated and the crack propagation in a plate is simulated.

Modelling of Static and Dynamic Processes of Nanoparticles Interaction

SM1L_12054
Wed • 11:00 • 134

Alexander V. Vakhrouchev
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The problem of dynamic and static of the nanoparticles interaction is considered. Object of research are singl nanoparticles and nanoparticles systems, making composites. The methods of molecular dynamics are used. The numerical investigation allowed to cover the fundamental mechanisms of NP interaction and to ascertain the basic parameters, defining the conditions of stability NP. In particular, at NP-surface interaction processes nanoparticles can be shattered or dive inside of a material, depending on its drop energy of move, temperature and proportion between ultimate strengths of a material and particle. Depending on thickness of a material nanoparticle can as remain inside a material or pass it through. At low-level energy of move the particle is simple adheres to a surface of a material. At shock of particle at bevel way to a surface it can pull out a slice of a material of a surface, which one can fly away. At interaction nanoparticles among themselves the processes of agglomerate formation, formation of larger particles at merge of particles of the smaller size, absorption by large particles of the smaller ones, dispersion of particles on separate atoms are observed.

Singularities of the Four-Sided Antiprism Ring

SM1L_12101
Wed • 11:20 • 134

Andras Lengyel
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An antiprism ring is a simple type of spatial truss structures, which is able to produce finite motions and bifurcation points on their compatibility paths. The structure may, under certain topological and geometric conditions, become both statically and kinematically indeterminate, i.e. an overconstrained mechanism. At singular positions the number of instantaneous degrees-of-freedom can change. The structure is quite sensitive to geometric errors. Depending on the initial geometry and different imperfection parameters, various singularities can occur referring to different cases of mobility of the structure. It may form a rigid structure or produce finite or infinitesimal mechanisms as well.

Analysis of Evolving Deformation Microstructures in Instable Inelastic Solids Based on Energy Relaxation Methods

SM1L_12115
Wed • 11:40 • 134

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An incremental variational formulation for the constitutive response of dissipative materials is applied to the stability analysis of inelastic solids. The material stability is governed by weak convexity properties of an incremental potential obtained from a local minimization problem. As a result of instability deformation microstructures develop and are resolved by energy relaxation methods. We develop relaxation analyses in terms of rank–one–convexifications and investigate the effect of different orders of lamination on the response of the material and the microstructures. The talk also points out the physical relevance of the pattern and the evolution of the microstructures obtained from abstract mathematical relaxation analysis. Furthermore a comperative study on specific laminate type microstructures with fixed orientation, which have a physical relevance for specific problems, is investigated.

Microstructural Behaviour of Solder Joints

SM1L_12131
Wed • 12:00 • 134

Rene L.J.M. Ubachs, Piet J.G. Schreurs, Marc G.D. Geers
Eindhoven University of Technology, Eindhoven, The Netherlands

Mechanical properties of soldered connections, as well as damage initiation and propagation, are strongly influenced by the continuously changing microstructure of the solder. Therefore, in this contribution the microstructure evolution is included in the model by a diffuse interface model that is dependent on a strongly nonlocal parameter. The material behaviour is described by the hyperelasto-viscoplastic Perzyna model. The material parameters are taken to be dependent on the mass fraction. The model has been implemented within a finite element context. A quantitative comparison has been made between two-dimensional simulations and experiments of the static ageing of a eutectic tin-lead solder. A good agreement was found. The mechanical response is shown to be sensitive to the coarseness of the microstructure. Furthermore, stress concentrations develop near interfaces, which are known to be crack initiation sites during fatigue failure.

Molecular Mechanics Simulations of Carbon Nanostructures Using Multi-Scale Boundary Conditions

SM1L_12167
Wed • 12:20 • 134

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A new method of Multi-Scale Boundary Conditions (MSBCs) is applied to Molecular Mechanics simulations of carbon nanostructures such as graphite sheets and diamond. The method allows simulation of a deformable boundary, thus reducing the size of computational domain and, consequently, cost of computations. The approach is particularly effective in cases when deformation is localized in a relatively small region. The idea of the method is based on Fourier analysis of regular atomic structures and assumption of small (linear) deformations. However, this assumption has to hold in a small vicinity of the deformable boundary, where MSBCs are applied, whereas large deformations (including plasticity) are allowed inside the reduced domain and far enough from the deformable boundaries. The method is tested on model problems and the results are in good agreement with the full domain solutions. Currently, effort is being made to apply this method to simulate real-life experiments on nanoindentation of diamond and layered graphite.

A New Approach for the FE Modelling of Cohesive Cracks

SM1L_11211
Wed • 12:40 • 134

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The present contribution is concerned with the computational modelling of cohesive cracks in quasi-brittle materials, whereby the discontinuity is not limited to interelement boundaries, but is allowed to propagate freely through the elements. In the elements, which are intersected by the discontinuity, additional displacement degrees of freedom are introduced at the existing nodes. Therefore two independent copies of the standard basis functions are used. One set is put to zero on one side of the discontinuity, while it takes its usual values on the opposite side, and vice versa for the other set. To model inelastic material behaviour, a discrete damage-type constitutive model is applied, formulated in terms of displacements and tractions at the surface. Some details on the numerical implementation are given, concerning the failure criterion, the determination of the direction of the discontinuity and the integration scheme. Finally numerical examples show the performance of the method.

Modified Error in Constitutive Relation and Its Application to Dynamic Tests with Corrupted Boundary Conditions

SM1L_12237
Thu • 11:00 • 134

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The aim of this work is to develop an identification strategy suitable for the identification of models dedicated to crash simulation. Due to the experimental difficulties, the method has to take into account the uncertainties of the measurements. Therefore, a method is proposed, based on the modified error in constitutive relation. Its principle is to split the quantities of the identification problem into two groups, one of the reliable quantities, that will be verified exactly, and one of the unreliable quantities, that will be only verified at best. First developed in the case of homogeneous elasticity, the strategy has been study in order to point out its two main points: taking the whole experimental information in one calculation and

introducing a distance between the measurements and the simulation. this method appears to be very robust. Its extension to the case of heterogeneous elasticity gives various interesting examples.

Geometry Based Rational Enrichment Functions for Triangular Plane Elasticity Element

SM1L_12310
Thu • 11:20 • 134

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In the p-version of the finite element method elements are often large and their shape can be very complicated. In this paper the sides of the plane elasticity triangular element are allowed to be rational Beziér curves, and the element geometry is mapped by the blending function method. If only the typical hierarchic polynomial shape functions are used for the displacement field approximation, the element with rational sides is able to reproduce neither rigid body rotation nor constant strain state, so it is not complete. In this paper we present how the element can be made complete by enriching the shape function space with rational functions, which are simply a part of the geometry mapping functions. A numerical example shows that the element enriched with these rational shape functions works better than the one without enrichments.

Adaptive Discontinuous Galerkin Method for Elastodynamics on Unstructured Spacetime Grids

SM1L_12441
Thu • 11:40 • 134

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We present an adaptive implementation of a spacetime discontinuous Galerkin (SDG) method for linearized elastodynamics. The SDG formulation features a simple Bubnov-Galerkin projection that is stable and free of spurious oscillations for arbitrary polynomial order, $O(N)$ computational complexity on causal grids, and exact momentum balance on every spacetime element. We use unstructured spacetime meshes that support simultaneous grading in space and time. The SDG basis functions, which naturally accommodate nonconforming grids, facilitate refinement and coarsening. The mesh generation and finite element solution processes are interleaved on a patch-by-patch basis, so decisions to vary the polynomial order or to refine the grid can be made locally. An extended version of the Tent Pitcher algorithm provides a robust method for generating adaptive causal grids. We present results in 1D and 2D x time, emphasizing problems with shocks. This work was supported by NSF grant DMR 01-21695 and DOE subcontract B341494.

Continuum Mechanics and Carbon Nanotubes

SM1L_12455
Thu • 12:00 • 134

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The understanding of the mechanics of atomistic systems has greatly benefited from continuum mechanics. One appealing approach aims at deductively constructing continuum theories starting from models of the interatomic interactions. This viewpoint has become extremely popular with the quasicontinuum method. The application of these ideas to carbon nanotubes presents a peculiarity with respect to usual crystalline materials: their structure relies on a two-dimensional curved lattice. This renders the cornerstone of crystal elasticity, the Cauchy-Born rule, insufficient to describe the effect of curvature. We discuss the application of a theory which corrects this deficiency to the mechanics of carbon nanotubes. We review recent large scale simulations based on this theory, which have unveiled the complex nonlinear elastic response of thick multiwalled carbon nanotubes. We also discuss simplifications of the continuum theory, useful for fast engineering computations, and its application to the prediction of nanotube failure, refining other recent analysis.

Toward Convergence in Initially Rigid Cohesive Fracture Models

SM1L_12458
Thu • 12:20 • 134

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We analyze the convergence of finite element methods for cohesive fracture. The focus is on generalized fracture in which finding the crack path or paths is part of the solution process. Initially rigid cohesive models, in which interface elements are inactive until a critical traction is attained, are usually preferred in this context. We show that convergence as the time-step tends to zero is erratic or nonexistent unless the model satisfies a property called time continuity. We also argue that convergence as the spatial mesh size tends to zero is unlikely unless the mesh is able to represent all possible crack paths without preferred directions. We propose a method to achieve this kind of mesh isotropy in two dimensions based on Radin's pinwheel tiling. The pinwheel tiling in the limit can approximate any plane curve with the correct length.

Computational Homogenisation of Microheterogeneous Materials Including Decohesion at Finite Strains

SM1L_12534
Thu • 12:40 • 134

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In this paper we present some aspects of computational homogenisation procedures of microheterogeneous materials which can show decohesion in a cohesive zone around the particles. Applications to this are e.g. polymer coatings stiffened with sand. Due to the decohesion we get finite deformations and finite strains within the RVE. The geometrical and material nonlinearities cause the main difficulties. The homogenisation procedure leads to an effective stress strain curve for the RVE. Here we set a special focus on the adaptive numerical model, the statistical testing procedure and the different boundary conditions (pure traction, pure displacement and natural boundary conditions) applied on the RVE.

The Load Cases in Numerical Model of Pelvic Bone with Artificial Acetabulum

SM1L_12562
Fri • 11:00 • 134

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Bioengineering concerns many important problems apply to human body. The pelvic joint and its correct working is one of them. In the paper the numerical model is prepared on the ground of the geometrical data from 3D scanning or CT. The accuracy of geometrical model depends on number of scanning levels. A numerical routine (numerical code) was built to translate the geometrical data (the set of coordinate points) to the Patran/Nastran code. The layer structure of bone tissues is taking into account. Using an in-house numerical code the inner surface in numerical model is implemented (between cortical bone tissue and trabecular bone tissue). Separate solid elements layers are modeled by cortical and trabecular bone. In the aim to creating an artificial acetabulum a few procedures were done. All procedures were written in the C++ language. The procedures create the flange (width), the spherical cap (radius), and the bolts of artificial acetabulum (2 angles in spherical coordinates, width, height). There is possible to model cemented and cementless acetabulum, with contact element and without. At present MSC.Patran/Nastran and MSC.Patran/Marc systems are applied. Here, boundary conditions are given in two area: in contact area with sacral bone and in pubic symphysis. Stress and strain distribution of human pelvic bone is a result of external load coming from upper body part's weight and muscles forces. For checking the influence of the forces acting in acetabulum on the stress and strain distribution in the surroundings of the artificial acetabulum a simple bench-mark was proposed, with force acting in acetabulum by ceramic ball. There is planning to take into account adhesion, diffusion and friction in contact area bone-implant. The work was done as a part of research project 4T11F00325 sponsored by Polish Ministry of Science and Information Technology.

Modelling of Non-Uniform Deformation of Metals with Dislocation Cell Structure

SM1L_12723
Fri • 11:20 • 134

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The hardening behaviour of metals physically originates from a complex microstructure evolution. To describe non-uniform deformation of metals a model of the dislocation cell structure is proposed in this contribution. The material containing cells

is modelled to behave like a composite consisting of a periodic array of two types of elements: hard cell walls and soft cell interiors. To ensure compatibility of plastic deformation across the interface between the hard and soft phases, polarised layers of geometrically necessary dislocations are introduced at the interface. The internal stresses created in the material by the geometrically necessary dislocations are taken into account. The model is capable of describing the material behaviour for monotonic deformation and for deformation with a strain path change. The model predicts the strain path change effect, its dependency on the amount of prestrain and on the amplitude of the strain path change.

Discrete Dislocation Calculations of the Stored Energy of Cold Work

SM1L_12737

Fri • 11:40 • 134

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The stored energy of cold work is calculated for crystalline material samples where plastic deformation occurs through dislocation glide. Superposition is used to represent the solution of boundary value problems in terms of the infinite fields for discrete dislocations and image fields that enforce boundary conditions. Constitutive rules are used which account for the effects of 3D dislocation dynamics such as dynamic junction formation. At each deformation step, the stored energy, defined as the change in free energy with a change in dislocation positions at constant stress, can be explicitly calculated both under load and after load removal with the line energy contribution accounted for. The extent to which the energy stored in the sample depends on the deformation state is analyzed by considering plane strain tension and bending of a single crystal. The effects of crystal orientation and of the amount of supplied mechanical energy are also investigated.

Dynamic Analysis of Gradient Elastic Solids by BEM

SM1L_12845

Fri • 12:00 • 134

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A boundary element methodology is presented for the frequency domain elastodynanic analysis of three-dimensional solids characterized by a linear elastic material behavior coupled with microstructural effects taken into account with the aid of a simple gradient elastic theory. Both time harmonic and transient problems are considered. A variational statement is used to determine the equation of motion as well as all the possible classical and non-classical boundary conditions. The gradient frequency domain elastodynanic fundamental solution is explicitly derived. In addition to a boundary integral representation for the displacement, a boundary integral representation for its normal derivative is also necessary for the formulation of the problem. For the transient case the problem is solved with the aid of the fast Fourier transform algorithm. Two numerical examples serve to illustrate the method, demonstrate its accuracy and assess the gradient effect on the response.

Variable-Order Singular Boundary Element for Calculation of Three-Dimensional Stress Intensity Factors

SM1L_12901

Fri • 12:20 • 134

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A new variable-order singular boundary element has been developed for stress analysis of three-dimensional cracks and multi-material junctions. The singular element shape functions include the variable orders of singularity and the angular profiles of the field variables. The stress intensity factors are formulated as nodal unknowns and are obtained directly from the final system of equations without the need of post processing, such as three-dimensional J-integral. Two numerical examples are presented to demonstrate the accuracy and versatility of the singular element: a penny-shaped crack in homogeneous medium and a corner in a bi-material system. The stress intensity factors which are normally difficult to determine using conventional numerical techniques are hereby easily computed with good accuracy using relatively coarse elements.

Application of the Material Force Method to Structural Optimization

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SM1L_12924
Fri • 12:40 • 134

The present contribution aims at deriving a variationally consistent strategy to generate truss structures which are optimal in the sense of energy minimization. Accordingly, not only the spatial node point positions of the individual truss members, but also their material node point positions, i.e. the truss geometry itself, are introduced as primary unknowns. The governing equations follow straightforwardly from the Dirichlet principle for conservative mechanical systems. Thereby, the central idea is the reformulation of the total variation of the potential energy at fixed referential coordinates in terms of its variation at fixed material and at fixed spatial coordinates. The corresponding Euler–Lagrange equations define the spatial and the material motion version of the balance of linear momentum, i.e. the balance of spatial and material forces, in a consistent dual format. The suggested algorithm is then essentially characterized through the discretization and simultaneous solution of both, the spatial and the material motion problem. In this sense, the proposed strategy can be interpreted as a variational ALE formulation which renders not only the deformed truss structure but also an improvement of the node point positions themselves. The suggested algorithm will be discussed by means of illustrative examples.

Elastic-Plastic Large Deformation Analysis of 2D Frame Structure

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SM1S_10270
Tue • 14:30 • 144

This paper presents a numerical simulation method, so called vector form intrinsic finite element (VFIFE) method that can conduct the analysis of 2D frame structure under elastic-plastic large deformation. This new method can simultaneously calculate large rigid body motions and large geometrical changes of a structural system consisting of multiple continuous bodies. The essence of the method includes a set of equations of motion for the modeling nodes of the system, an explicit time integration scheme, the use of a deformation coordinate system to dissect rigid body and deformation displacements, and the use of a convected material reference frame to handle the deformation. Numerical examples of frame structure having large elastic-plastic deformation states under static and dynamic excitations are demonstrated to verify the accuracy and effectiveness of this newly proposed method.

Multiscale Analysis of Scattered Elastic Waves Based on the Lippmann–Schwinger Equation

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SM1S_10274
Tue • 14:35 • 144

There has already been vast literature concerning scattering of elastic waves. It is still questionable, however, that how a small scale fluctuation of a wave field influences scattering of waves. In this paper, a method for the multiscale analysis is developed for scattered elastic waves by means of the Lippmann–Schwinger equation. The multiscale decomposition of the solution of the equation is carried out by using a scaling function and wavelet of compact support. Numerical calculations are performed to examine the scale effects of fluctuation of a wave field on sacttering of waves. The numerical results show that the small scale solution has also a significant role as the large scale solution has.

Flutter Analysis of Subsonic Wing

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SM1S_10396
Tue • 14:40 • 144

In this paper, a procedure is developed based on Galerkin method to predict the speed and frequency in which flutter occurs. The finite element structural model used for the wing is a three-DOF cantilever beam, in which one coordinate is related to the vertical displacement and the other two are corresponding to bending and rotation. This beam element has Hermit-cubic-type in bending and linear in rotation characteristics. Consequently, an eigenvalue problem with non-symmetric matrix coefficients was derived. It was found that as free stream velocity increases from zero up to 0.554 Mach (for incompressible flow) and 0.526 Mach (for compressible flow), the real parts of the eigenvalues have negative signs and

the system become stable. Further increasing of free-stream velocity causes the amplitude of the frequencies approach zero and become positive, which indicates dynamic instability, or flutter of the system.

A Dual Particle Computational Method for Continua

SM1S_10829
Tue • 14:45 • 144

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A brief history of particle methods will be presented towards assessing the promise offered by these techniques for computational continuum dynamics. We will then discuss recent progress in Dual Particle Dynamics (DPD), a spatially staggered particle discretization of the strong form. Particular attention will be given to stability, boundary conditions, and neighbor searching. We demonstrate stability for Eulerian kernels resulting from the coupling of linear completeness in spatial derivative estimates and two-step Predictor–Corrector time derivative approximations. Boundary conditions are formulated in a unified and consistent way using constrained MLS fits. Several test problems are shown and conclusions drawn.

Derivation of the Higher-Order Stiffness Matrix of a Space Frame Element for Geometric Nonlinear Analysis of Structrues

SM1S_11193
Tue • 14:50 • 144

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A physical concept, the rigid body rule, is applied for the derivation of the higher-order stiffness matrix of a space frame element. The derivation has a physical meaning that is the higher-order stiffness matrix can be derived by regarding there is a set of incremental nodal forces existing on the element, then the element undergoes a small rigid body rotation. The incremental forces should keep their magnitude and follow the rigid body motions. Then taking advantage of the existing geometric stiffness matrix derived by researchers, the higher-order stiffness matrix can be analogy derived without any difficulty. The derived higher-order stiffness matrix has explicit expressions. It can be used at the forces recovery stage in the geometric nonlinear analysis of frame structures. Meanwhile an effective numerical method, the Generalized Displacement Control (GDC) method, was adopted to trace the load-defection curves of the structures. Some numerical examples were tested by taking the proposed higher-order stiffness matrix into consideration in the nonlinear analysis of the structures.

The Method of Solving of Non-Stationary Coupled Problems of the Theory Thermal-Plasticity for the Rotation Shells

SM1S_11202
Tue • 14:55 • 144

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The new effective method for numerical solving of two-dimensional non-stationary coupled problems of the theory of thermoplasticity for the case of nonsteady loading of the rotation shells is proposed. The numerical solving of these problems is reduced to the solution of the systems of differential equation in partial derivatives of the second order, consisting of five equations of motion (equilibrium), nine geometrical correlations, six equations of physic state and equation of thermal conduction. This system is solved by means of new version of the oncomponent splitting method of higher accuracy. Unknown values (the components of the vector of velocity displacements, specific efforts and specific moments, deformations, shifts, angles of rotations and temperature) for each step by time are found in the spline-function form (cubic B-splines, strained splines). The offered method has allowed to receive the fourth order of approximating of the method on coordinates. To increase the accuracy of calculations on time the iterative procedure has been developed. The convergence theorem has been proved. The numerical examples of implementation of the method are presented.

Effective Solution for Finite Element Problems with Nonlinear Constraints

SM1S_11291
Tue • 15:00 • 144

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Solutions of problems of Mechanics are nowadays obtained most often be using Finite Element Method. This method provides the solution usually in the form of linear algebraic equations. In cases when the equations become nonlinear due to imposed constraints, effects of material or geometrical nonlinearity, optimization, identification, etc, all equations are

considered nonlinear and are solved using iterative techniques, for example: Newton-Raphson method. However, there are difficulties with convergence and effectiveness of this approach. This paper presents a new, very effective solution for the above problems by reducing the number of nonlinear variables. A new algorithm has been developed and applied to various identification and adaptive modeling problems with excellent results. The new algorithm allows for the solution of cases that were not solved previously due to the lack of convergence and large number of nonlinear variables.

Two Scale Finite Element Method

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SM1S_11334
Tue • 15:05 • 144

A two scale computational method based on the finite element method is presented. A method is suited for problems with two length scales, macro and micro, where a direct numerical resolution of the micro scale by the standard finite element method is too expensive. At the micro scale a standard finite element method is used, while at the macro scale the Petrov-Galerkin method is used. The coordinate functions of the Petrov-Galerkin method are chosen to be the coordinate solutions of the associated micro scale problems while the weight function are the standard finite element basis functions of the macro scale finite element discretization. The method is illustrated by the computation of the torsion of the prismatic bar that at the micro mechanical level consists of the square cells with the elliptical fibres which are randomly oriented. Problems with several thousand cells and tens of the fibre orientations are readily computed.

Problems of Application of Hierarchical Modelling, Displacement FEM and a Posteriori Residual Error Estimation to Static and Dynamic Adaptive Analysis of Complex Structures

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SM1S_11389
Tue • 15:10 • 144

The paper addresses the main problems of implementation of the idea of hierarchical modelling in the scope of displacement finite element methods and of application of the a posteriori residual error estimation to adaptive analysis of complex structures. These structures consist of solid, thin- and thick-walled parts and transition zones as well. Our presentation is limited to linear static and linear dynamic (modal) analyses. The main source of the problems under consideration is incompatibility of the various mechanical models forming hierarchy of models for complex structures, locking, improper solution limit and boundary effect sensitivity of the displacement finite element formulation, and similar sensitivity of the a posteriori error estimation by the Element Residual Methods. The elaborated methods of overcoming the mentioned problems are elucidated, if available. For those of the problems which have not been resolved yet, the suggested methods are indicated and their potential for overcoming the problems are thoroughly discussed.

Statics And Kinematics of Symmetric Swelling Viruses

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SM1S_11482
Tue • 15:15 • 144

Some viruses in biology are able to expand due to the change in pH. These biological systems consist of pentagonal and hexagonal units (hexamers and pentamers) connected by protein links, and show icosahedral symmetry that is preserved also during the expansion. Swelling motion is characterised by simultaneous radial translation and rotation of polygonal units. Using symmetry-adapted first order analysis of a perfectly rigid structural model called “expandohedron”, a discussion on possible self-stresses and finite mobility is made. Finite character of swelling is proven by symmetry but other finite paths may theoretically appear. Following the fully symmetric kinematical path of expansion, some bifurcation points are found. It is shown by analytical description that translation-rotation relationship is generally not unique for pentamers even in the physically admissible domain. Data obtained from electron microscopy will be used to refine parameters of initial geometry for better approximation of virus swelling.

Comparison of Stress Recovery and Displacement Recovery Techniques in Adaptive Finite Element Simulation of Sheet Forming Operations

SM1S_11550
Tue • 15:20 • 144

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In the present work, a comparative evaluation of the performance of stress and displacement recovery techniques during adaptive finite element analysis of sheet forming operations is presented. The simulation results are assessed on the basis of computational efficiency and accuracy. Whereas in the case of the stress recovery procedure, an element patch surrounding and including a particular node is considered for the smoothing process, an element patch consisting of all the elements surrounding and including the particular element is taken into account in the case of displacement recovery procedure. The solution error is estimated on the basis of an energy norm. It is shown with the help of an illustrative example of axisymmetric stretching of a metal blank by a hemispherical punch that the velocity recovery approach captures the deformation behaviour more accurately and at lower expense of CPU time.

A Numerical Approach for Large-Scale Computation CEM

SM1S_11580
Tue • 15:25 • 144

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A new numerical method for large-scale computation-cellular element method is introduced. In this method the integer analysis of structure is changed into a series of part analysis. It may have a good future in the aspect of large structure because it hardly has any special request on the capability of computer. Simultaneity, It can be developed into a high parallel arithmetic to suit for the request of parallel compute. Its computing steps are presented. The similarities and differences among the moment distributed method, finite element method and cellular element method are discussed. Though the discrete technique of finite element method is used in it, cellular element method is different from finite element method. Several numerical computing examples are given. Based on the numerical results, the feasibility, advantages and disadvantages of cellular element method are discussed.

Solving of Indirect Problems Using Trefftz Method

SM1S_12340
Thu • 14:35 • 144

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In indirect problems we can observe distribution of certain quantities inside the considered region of a given structure and, after that, knowing this distribution, we can approximately define the whole boundary-value problem. Usually this is done by virtue of minimization of a special form of a functional that is dependent on the searched, unknown boundary values. Thus this leads to a kind of optimization procedure. Some improvements of such a procedure are proposed. These improvements are based on using the generalized Trefftz method (in which the trial functions identically fulfill the given partial differential equations) and the fact that the shape of considered structure remains unchanged. Also a method of direct solving of such kind of indirect problems is proposed. The methods are illustrated in the series of numerical examples.

Tensor Invariants and Mechanisms of Transition to Chaos in Nonholonomic Dynamical Systems

SM1S_12351
Thu • 14:40 • 144

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Nonholonomic dynamical systems, i.e. systems with nonintegrable constraints, are different both from Hamiltonian systems and from typical dissipative systems. They do not have the Poisson structure and the measure (unlike the former) and, as a rule, conserve the energy (unlike the latter). We study the problem of existence for nonholonomic systems of various tensor invariants, such as integrals of motion, fields of symmetries, the invariant measure, and the Poisson structure. We also consider the relation that exists between various types of dynamical behavior of these systems and the existence of tensor invariants. We show that the classical problems of nonholonomic mechanics, such as the problem of a body rolling on a plane and on a sphere, and that of ball rolling on an arbitrary surface, involve various cases when tensor invariants

exist, which determine the entire hierarchy of possible types of dynamical behavior. The extreme cases of this hierarchy are, on one hand, completely integrable systems (according to the Euler–Jacobi theorem), which can have the full set of first integrals and the invariant measure that behave quite regularly, and on the other hand, systems that have neither integrals of motion, nor invariant measure. The latter can display chaotic behavior, which can be either Hamiltonian or dissipative. Besides, we show the existence of a strange attractor in such systems, at certain energy levels in the system's phase space. We also find a number of new integrable cases in these problems of nonholonomic mechanics and a new example of a system, which displays not only typical features of the well-known rattleback model, but some new interesting properties as well.

Analysis of a Structural Detail Using a Two-Scale Approach

SM1S_12359
Thu • 14:45 • 144

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The aim of this work is to solve mechanical problems on a large structure containing a detail. Contrary to classical methods of resolution which need significant refinement of the mesh of the structure to able to define precisely the detail, our approach suggest another way to solve this kind of problem. Our method is based on a seperation of scales. Therefore, there are two distinct problems: a detail problem and a modified structural problem. We start by solving the detail problem. We consider the detail embedded in an infinite media with zero displacement at infinity considering the detail has no impact at an infinite distance. The purpose of this resolution is to obtain local elementary solutions. Afterwards, the modified structural problem is treated. Two approaches are studied: an "extended" homogenization and an enrichment strategy. In the first one, the regular element stiffness are replaced by the homogenized element stiffness for those elements close to the detail. The stiffness matrix is deduced to the previous elementary solutions. In the second approach, the approximation of the elements close to the detail is enriched using addition of degrees of freedom and a partition of unity enrichment strategy. After all, the localisation is executed. Thanks to the previous enriched solution, we can define the deformation field close to the detail.

Residual Stresses in Nonlinear Strain Hardening Annular Disks of Variable Thickness Subject to External Pressure

SM1S_12505
Thu • 14:50 • 144

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A computational model is developed to estimate the residual stresses in nonlinearly hardening variable thickness annular disks under external pressure. The model is based on von Mises' yield criterion, deformation theory of plasticity and a Swift-type hardening law. A thickness profile in the form of a general parabolic function is considered. The residual stresses occurring in annular disks upon complete unloading of external pressure are determined and the possibility of occurrence of secondary plastic flow is investigated. It is shown that, depending on both the aspect ratio and the thickness variability, different plastic flow regimes may occur in such disks and secondary plastic flow does not occur during elastic-plastic stress states.

Shakedown Safety Criterion in Reliability Analysis

SM1S_12579
Thu • 14:55 • 144

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This paper discusses the problems of integration of the shakedown analysis with the reliability analysis. Failure functions with respect to inadaptation (non-shakedown) and limit state are defined in the space of random material/geometrical parameters, load multipliers, and directional cosines. Then, a general problem of time-invariant shakedown reliability analysis is formulated. For special cases with low variance of stochastic parameters, simplified formulations are derived and discussed. Separation of load and resistance terms in the failure functions is suggested. The computation can be further simplified since the shakedown response surface may be computed in advance. The problems may be efficiently solved by reliability simulation methods or FORM/SORM combined with a general shakedown analysis algorithm integrated with the Response Surface Method. A practical industrial example of shakedown reliability evaluations is presented.

A New Finite Element Formulation Based on the Theory of a Cosserat Point

SM1S_12584

Thu • 15:00 • 144

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The theory of Cosserat points is the basis of a finite element formulation, that recently was presented by NADLER & RUBIN (2003). First attempts have revealed, that this formulation is free of showing undesired locking or hourglassing-phenomena. It additionally shows excellent behaviour for any type of incompressible material, for large deformations and sensitive structures such as plates or shells. Within the theory of Cosserat points, the position vectors are described through director vectors. The special choice of the director vectors enables to split the deformation into homogeneous and inhomogeneous parts, which allows the use of stiffnesses that correspond to different deformation modes. Currently, analytical solutions for the calculation of stiffnesses for different modes are used. They are based on a parallelepiped shaped reference element, which is at present the major drawback to this formulation. This work gives insight to the possibilities of the Cosserat point element as well as first approaches on overcoming the difficulty of initial element geometries, that differ strongly from the shape of a parallelepiped.

Arc-Length Method for Explicit Dynamic Relaxation

SM1S_12607

Thu • 15:05 • 144

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The work comprises the procedure adopted to combine the arc-length method and the iterative dynamic relaxation technique. The resulting method has been successfully applied to simulate the quasi-static propagation of buckles in cylindrical shells under external pressure. The method developed is an explicit solver that can be used to trace convolute load-deflections paths for unstable structures, handling “snap-through” or “snap-back” problems. The solver is also capable to overcome limit points, when complex roots may occur, and a valid solution can not be obtained. The dynamic relaxation technique is very attractive for problems with highly nonlinear geometric and material behavior. The method described can also be adapted to others explicit vector iteration solvers.

The Numerical Homogenization of the Concrete Behavior

SM1S_12727

Thu • 15:10 • 144

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This article presents a numerical method of homogenization for the thermal-hydro-mechanical behavior of heterogeneous materials. We choose a representative volume in which heterogeneities are generated in random process. The numerical model is used to predict elastic behavior as well as thermal damage behavior and the permeability of cement-based materials. This numerical model, named Digital Concrete, is developed and implemented in the general finite element code ’SYMPHONIE’. It is used then to the calculation of the High Strength Concrete homogenized behavior. Obtained results appear in good agreement with experimental measures. They show the capacity of the model to take in account the effect of the size distribution of aggregates and pores of concrete. Furthermore, this method allows through the process of localization to estimate the local fields and to predict possible damages of the material under thermal loads.

Deformation Analysis of Inflated Cylindrical Membrane of Composite Material with Rubber Matrix Reinforced by Cords

SM1S_12844

Thu • 15:15 • 144

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In the paper an orthotropic hyperelastic constitutive model is proposed which can be applied to numerical simulation for the response of the nonlinear anisotropic hyperelastic material of the air-spring sheet used in inhibitive vibration of driver’s seat and of the biological soft tissue. The strain energy function defining the constitutive behavior of orthotropic hyperelastic material is expressed with regard to the assumed material symmetry. The parameters of strain energy function are fitted to the experimental results by the nonlinear least squares method. The deformed shape of the air-spring surface is measured from the photographic records of the grid points drawn on the cylindrical surface of the air-spring used in experimental measures. The stress tensor is calculated from the non-linear membrane theory. The deformation field of inflated cylindrical

membrane of air-spring sheet is calculated by solving the system of five first-order ordinary differential equations with the material constitutive law and proper boundary conditions. The finite element method (FEM) was used to simulate deformed process of inflated cylindrical membrane of air-spring sheet. Stability analysis is carried out in finite element analysis (FEA) to detect limit points by arc-length method.

New Family of Finite Element Models for Composite and Non-Uniform Polarization Piezoelectric Structures

SM1S_12905

Thu • 15:20 • 144

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The mathematical modeling by FEM of the piezoelectric devices is considered. By applying semi-discrete FEM approximations of the solution to the governing equations in weak form the variational FEM equations with symmetrical saddle matrices are derived. On the base of symmetrical algorithms the computer program ACELAN were developed. For one- and two-dimensional piezoelectric structures new quasielastic finite elements are obtained. New models for describing process of polarization or repolarization of piezoceramic are suggested. The 3D mathematical models of porous and polycrystalline piezocomposites with 3-0 and 3-3 connectivity are built. The finite element programs for the effective constants and effective properties calculations are developed.

SM2

Contact and friction mechanics

Chairpersons: I. Goryacheva (Russia), A. Klarbring (Sweden), G. Szefer (Poland)

Fundamental Relations for Frictional and Adhesive Nanoindentation Tests

SM2L_11215
Wed • 08:30 • 219

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We discuss the connections between Hertz type contact problems and depth-sensing nanoindentation, when the displacement of the indenter is continuously monitored. For both loading and unloading branches, fundamental relations are derived for indenters of various shapes and for various boundary conditions within the contact region. For the loading branch, relations are derived among depth of indentation, size of the contact region, load, hardness, and contact area, using authors' re-scaling formulae. Further, a relation is derived for the slope of the unloading branch of the adhesive (no-slip) indentation. The relation is analogous to the frictionless BASh relation, that is commonly used for evaluation of elastic modulus of materials, and is independent of the geometry of the indenter. Finally, exact formulae are obtained for adhesive contact between axisymmetric monomial indenters and isotropic, linear elastic materials. These formulae coincide with the frictionless Galin solutions when the material is incompressible.

Hertz Contact at Finite Friction and Arbitrary Profiles

SM2L_11365
Wed • 08:50 • 219

Bertil Storakers, **Denis Elaguine**
Royal Institute of Technology (KTH), Stockholm, Sweden

Axisymmetric contact at finite Coulomb friction and arbitrary profiles is examined analytically and numerically for dissimilar elastic solids. An incremental procedure is developed resulting in a reduced problem corresponding to rigid flat indentation of an elastic half-space being independent of loading, contact region and shape. This issue was solved by a finite element method based on a stationary contact contour and subsequently a tailored cumulative superposition procedure was developed to resolve the original problem. It is shown that at partial slip the evolving relative stick-slip contour is independent of any convex contact profile at monotonic loading. For flat and conical profiles with rounded edges and apes, relations between force, depth and contact contours are given together with surface stress distributions. For dissimilar solids, full field values were computed individually. The location and magnitude of critical stress measures are determined for a range of geometrical and material parameters.

Adhesive Component of the Rolling Friction Force

SM2L_11196
Wed • 09:10 • 219

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Adhesive component of the rolling friction force is calculated by using the model of a cylinder rolling on the boundary of the elastic base. When the cylinder rolls, each asperity approaches the base and then moves away from it. In each approach-separation cycle, the energy dissipation takes place. It is assumed that the total energy dissipation produced by all asperities is equal to the work of the friction force. To calculate the energy dissipation in an elementary approach-separation cycle for a separate asperity, contact problems are considered and solved taking into account two types of adhesion: capillary adhesion of surfaces covered by fluid films and adhesion of dry surfaces. The friction force is calculated depending on the surface energy of the bodies, surface tension and volume of fluid, mechanical properties of the base, normal load applied to the cylinder, shape of aspeirties and their height distribution.

Molecular Adhesive Contact for Indenters of Non-Ideal Shapes

SM2L_11135

Wed • 09:30 • 219

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The JKR and the DMT theories of contact in the presence of forces of molecular adhesion are developed to describe contact between an indenter and an elastic sample, when the distance between the solids is described as a monomial function of an arbitrary degree d. Exact formulae are obtained in the framework of the former theory, while an integral equation is derived for the latter theory. In the case of integer degrees d, the obtained analytical formulae coincide with the known solutions. The integral equation is solved numerically. The results are applied to depth-sensing nanoindentation of soft and hard materials by indenters of non-ideal shapes, when the shape function is a monomial function of degree d, $1<d<2$. It is shown that both the adhesive molecular interaction and non-ideality of the shape may affect the results obtained using the standard Hertzian approach.

Second-Order Cone Complementarity Formulation for Quasi-Static Incremental Frictional Contact Problem in Three-Dimensional Space

SM2L_12646

Wed • 09:50 • 219

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The numerical solution of quasi-static incremental frictional contact problems involving discrete versions of two- and three-dimensional elastic solids or structures is sought with a formulation as a Second Order Cone Linear Complementarity Problem (SOCLCP). In this formulation the three-dimensional Coulomb friction cone is considered without any pyramidal approximation, and the friction conditions are written as linear complementarity conditions over two second-order cones. The SOCLCP's are solved by a method developed by Hayashi, Yamashita and Fukushima (2003) that combines smoothing and regularization procedures, and is based on the Euclidean Jordan algebra on second-order cones. Two illustrative numerical examples are presented, which involve the frictional contact with flat obstacles of a three-dimensional double layer truss and a two-dimensional finite element model of a block in plane strain.

Existence and Uniquness of Steady State Solutions in Thermoelastic Contact With Frictional Heating

SM2L_10686

Wed • 10:10 • 219

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It is well known that contact and friction problems in thermoelasticity may lack solutions or have multiple solutions. Previously, issues related to thermal contact and to frictional heating have been discussed separately. Here they are coupled. Theorems of existence and uniqueness in two or three space dimensions are obtained, essentially extending, to frictional heating, results due to Duvaut, which were built on Barber's heat exchange conditions. Two different existence results are given. The first one requires that the contact thermal resistance goes to zero at least as fast as the inverse of the contact pressure. The second theorem has no such growth condition, but requires instead that the frictional heating, i.e., the sliding velocity times the friction coeffcient, is small enough. Finally, uniqueness is shown, if the inverse of the contact thermal resistance is Lipschitz continuous, and if the Lipschitz constant and the frictional heating are small enough.

FE Analysis of Bond for Smooth FRP Rods Embedded in Concrete

SM2L_10718

Wed • 11:00 • 219

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Application of FRP reinforcement in modern concrete structures is increasing in comparison with common techniques to inhibit corrosion. The main objective; in this paper, is to propose a reliable method for numerical analysis of the bond between FRP composites and concrete. Note that the proposed model is based on a FE simulation of a tentative test carried out by other researchers. The composite material has been assumed transversely isotropic. Major causes of bond between the smooth rod and concrete are assumed to be friction and chemical adhesion in modelling, as well as reality. The procedure of evaluation, calibration, and validation of contact parameters is summarized. Some obtained numerical graphs are compared

with the corresponding tentative ones as a validation. Curves indicating changes in tangential and normal statue of the interface between two materials are shown and justifi ed. Finally, it has been concluded that the suggested method can be effectively used for simulation of bond behaviour of smooth FRP rods with concrete.

Contact Optimization Problems Associated with the Wear Process

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SM2L_11074
Wed • 11:20 • 219

The optimal shape design of contact surfaces has usually been aimed at controlling the contact pressure distribution. However, a much wider class of contact optimization problems can be formulated by maximizing contact force or displacement, torsional moment, or minimizing the rate of dissipation. A special class of optimization problems is considered, namely, the minimization of wear rate depending on both normal pressure and slip velocity. The specifi c modifi ed Archard wear rule is assumed. The illustrative examples demonstrate the evolution of wear process toward their steady states. It is demonstrated that the wear dissipation power at the contact surface is minimal in the steady state of the wear process and in many cases corresponds to the uniform wear rate. The discretization of the contacting bodies was performed by the displacement based on p-version of fi nite elements assuring fast convergence of the numerical process and accurate specifi cation of geometry for shape optimization, or by half space Boussinesq solution. It is assumed that the displacements and deformations are small, the material of the contacting bodies are elastic.

Experimental and Analytical Investigation of Rubber Friction

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SM2L_12086
Wed • 11:40 • 219

The physical phenomenon of friction appears in many technical applications. One of the most interesting fi elds is friction of rubber that depends on different parameters e.g. velocity, roughness, normal pressure and temperature. The hysteresis friction of rubber is caused by the energy dissipation due to internal material damping during the process of deformation. The adhesion increases with the true contact area which depends on the roughness, on the viscoelasticity and on the sliding velocity. In this presentation, some effects of rubber friction will be analyzed. A mechanical model of hysteresis and adhesion friction will explain the physical background. The dependence of the friction coeffi cient on the relative velocity will be shown by measurements and compared to predictions. The dependence on the normal force will be explained and demonstrated by measurements on different surfaces.

Numerical Modeling of Contact Fracture of Elasto-Plastic Cracked Bodies

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SM2L_11933
Wed • 12:00 • 219

One of actual problems of a fracture mechanics is a research of crack extension in elasto-plastic bodies under a local contact loading. In the present work the algorithm of numerical modeling of such processes is developed on the basis of a variational method of contact problems solution for elasto-plastic cracked fi nite bodies. Boundary conditions of unilateral contact were set on contact surfaces of bodies and crack faces at the presence of a Coulomb friction. Quasivariational inequalities for defi nition of velocities or increments of displacements were built. The fi nite element method is used for their discretization. Modifi cations of the successive overrelaxation method and the conjugate gradient method are developed for solution of the obtained fi nite-dimensional nonlinear programming problems. The numerical modeling and the analysis of crack extension in elasto-plastic fi nite bodies under contact compression are fulfi lled. Calculations were carried out based on various theories of plasticity: the theory of small elasto-plastic deformations, the theory of plastic fbw with isotropic, transmit and combined hardening. It is clarifi ed, that both sliding mode crack and a opening mode crack can develop at contact compression in a body.

Boundary Layers Induced by Contact of Rough Bodies

SM2L_12553
Wed • 12:20 • 219

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A micromechanical framework is developed for the analysis of deformation inhomogeneities in the boundary layers that are induced by contact of rough bodies. The aim of such analysis is to develop improved constitutive laws of contact phenomena that would account for the interaction of the deformation inhomogeneities in the contact boundary layer with the macroscopic stress/strain states. The equations of the boundary layer are derived using the method of asymptotic expansions. The averaging operation is then introduced so that the inhomogeneous fields are averaged along the contact surface but the dependence of the averages on the distance from the surface is preserved. Some properties of such averages are provided. As an example a boundary layer associated with ploughing by an array of periodic sine-shaped asperities is analyzed by the finite element method.

The Accounting of Surface Roughness in Contact of Arbitrary Shaped Bodies Using FEM

SM2L_12559
Wed • 12:40 • 219

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A universal method of accounting the surface roughness in contact of arbitrary shaped bodies using finite element method is developed. “Load – approach of bodies” and “load – real contact area” diagrams for several pairs of rough surfaces are obtained. The accounting elastic-plastic character of deforming is based on theory of yield. Results of contact problem solution for real bodies with rough surfaces are given. Finite element models of rough surfaces are based on real profilometric data. A contact of two small parts of bodies with nominally flat rough surfaces is considered in order to obtain dependence of bodies approach due to rough layer presence on a load value. The “load value – approach of bodies” diagram is approximated with simple analytic functions and then applied to compute contact parameters of the arbitrary shaped bodies taking into account the compliance of their rough surfaces.

Chaotic Response of Non-Reversible Dry Friction Oscillator

SM2L_12246
Thu • 11:00 • 219

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In this paper we show, that the relative acceleration of sliding bodies used in the description of the dry friction model leads to the similarity between system attractor and friction characteristic. In other words, friction characteristics is a certain representation of the system dynamics. On the basis of this property we propose a novel way of dry friction modelling. This approach has more general, universal nature, i.e. it develops a description of friction phenomenon on non-linear systems having irregular attractor but also it reduces to the known models of dry friction in case of regular motion. The proposed model is based on a certain mathematical description of the experimentally determined non-reversible dry friction characteristics, which causes chaotic and irregular motion of the studied system.

Frictional Sliding of a Multislip System

SM2L_12563
Thu • 11:20 • 219

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The brittle/ductile transition in rocks has an essential influence in determining the strain rate in lithospheric plates. With this motivation we attempt to study the micromechanics of an elastic medium with interfaces whose slip is governed by rate and state friction. As a preliminary analysis we study the linear stability of the steady-state slip of a finite number N of parallel interfaces caused by a constant velocity applied at one edge of the medium. We show that interfacial slip can occur with one or two different slip rates if the steady-state friction law displays a minimum as for dry friction. Our results suggest that, when active slip on all N interfaces is unstable, the medium will select a smaller number of interfaces which continue to slide, the others stopping.

Crack-Like and Pulse-Like Modes of Frictional Sliding along an Interface Under Dynamic Shear Loading

SM2L_11987
Thu • 11:40 • 219

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Frictional sliding along an interface between elastic solids under impact shear loading conditions is analyzed numerically. The configuration analyzed consists of two plates of the same material connected along a planar interface. The plates are characterized as isotropic elastic materials and the interface is characterized by a rate- and state-dependent frictional law that also accounts for dependence on normal stress variations. Calculations are carried out for various characterizations of the frictional response and for various impact velocities. Two modes of sliding are observed: a pulse-like mode where the slipping at a point on the interface is of short duration and a crack-like mode where the duration of slipping is much longer. The dependence of these sliding modes on the initial compressive stress, the impact velocity and the friction parameters is explored. The convergence of the numerical results is also considered.

A Dynamic Unilateral Contact Problem for a Cracked Body

SM2L_12382
Thu • 12:00 • 219

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In this work we investigate a class of dynamic contact problems for cracked viscoelastic and elastic bodies, when Signorini's conditions between the two faces of the crack are considered. Firstly, using a penalty method we study a variational formulation of a unilateral contact problem with nonlocal friction for a cracked viscoelastic body. Several estimates on the penalized solutions are obtained which enable us to analyze the time and spatial discretizations of the problem. Then we consider the corresponding elastic problem, for which a fictitious domain formulation is proposed with Lagrange multipliers representing the normal jump of the displacements. Numerical examples, based on the fictitious domain method for solving the diffraction of elastic waves by cracks, are presented.

Electric-Mechanical Beam-To-Beam Contact

SM2L_10415
Thu • 12:20 • 219

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In this paper the formulation of an electric-mechanical beam-to-beam contact element is presented. Beams with circular cross-sections are assumed to get in contact in a point-wise manner and with clean metallic surfaces. The voltage distribution is influenced by the contact mechanics, since the current flow is constricted through small contacting spots. Therefore the solution is governed by the contacting areas and hence by the contact forces. As a consequence the problem is semi-coupled with the mechanical field influencing the electric one. The electric-mechanical contact constraints are enforced with the penalty method within the Finite Element technique. The virtual work equations for the mechanical and electric fields are written and consistently linearized to achieve a good level of computational efficiency with the FE method. The equations set is solved with a monolithic approach.

Thermomechanics Modeling of Two Solids in Contact: Application to Total Hip Arthroplasty

SM2L_12227
Thu • 12:40 • 219

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Friction is one of the most classical dissipative phenomenon. The mechanical power dissipated by friction is transformed into heat. Yet the thermomechanics of contact between two deformable solids is underdeveloped in comparison to continuum mechanics. In this study, a two-body thermomechanical contact theory is proposed together with approximate numerical methods for solving the resulting problems. The study consists in four parts. First, the governing equations of thermomechanical contact problrms are derived from the thermodynamics principles. Second, the tribological laws of uni-

lateral contact, friction and heat transfer across the interface are developed. Third, numerical methods are proposed: the finite element one for spatial discretization, an augmented Lagrangian method for treating the contact and friction constraints and a generalized Newton method for solving the non-linearities. Fourth, for illustration, the model is applied to thermomechanical problem of heat propagation subsequent to cement polymerization during a Total Hip Arthroplasty in orthopedics.

Non Liner Phenomena For Stick–Slip Motion Which Take Shape Latent Period of Fretting-Wear Into Nominal-Fixed Joints

SM2S_10100
Tue • 14:30 • 206

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Behaviour of nominal-fixed joint is describe by specific laws for frictional reciprocated interaction. It is defined as micro-slip and stick-slip between contacting surfaces. Micro-slip, as initial condition, consist in an elastic and the plastic deformation and it is important for evolution of fretting-process.The real contact conditions at oscillatory motion undergo changes in the result of fretting cycles: modification stick-slip regime, increasing or decreasing field of sliding and normal pressure of interface. All this and also cycles of preliminary displacement regime and contact fatigue into stick zone is determine a latent period of fretting. Mathematical model of nominal fixed frictional contact (NFFC) at this loading by shear force in plane of contact was propose. This model on the basis of principal thesis of theory microplastic deformation for frictional contact. Put into operation new basis criterion for description plastic property of contact-parameter of plasticity. Transformation of this parameter in boundary preliminary displacement at cyclic loading give information about evolution of fretting damage in mechanical joints,flanges, wires, steel ropes, medical implants and the like.

Thermocontact Interaction of Bodies of Revolution During Induction Heating

SM2S_10211
Tue • 14:35 • 206

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Transient stress and strain fields in bodies of revolution joined with interference by induction heating are analysed numerically. Axisymmetric quasi-coupled electromagnetic, thermal and thermo-elastic problems are solved taking into account contact interaction of the bodies. Solution is performed by the time-stepping method. Parameters of linearised equations describing all three fields and contact zones are determined by iterative processes. The boundary problems are solved using the finite element method. External actions and boundary conditions are generally time-dependent, material properties depend on temperature. Analysis of fixing and liberation of a drill in a chuck of a drilling machine by induction heating is presented. For the real structure the rational selection of radial interference between the drill and chuck, material properties, duration of heating and cooling, power of inductor, operating time, etc. is performed. It is shown that a conic shape of mounting surfaces is more preferable than the cylindrical one. For example, the arrangement does not lose its serviceability even at small plastic strains in the chuck that it is impermissible for cylindrical mounting surfaces.

Dynamic Characteristics and Monitoring of Rubbing Surfaces Quality

SM2S_10342
Tue • 14:40 • 206

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The work is devoted to identifications of dynamics of cicling wear process.The experimental realization of the problem has been carried out wirh use of tribometrical system Tribal-2.The circuit of contact interaction coupling has been analyzed.The offered method given us an opportunity to consider a process of wearing as process with one input and one output. The usage of aimular approaches allows to receive a transfer function of wearing process.The details of theoretical substantiation of the method and a new approach in modeling have been given.The results of experimental-analitycal researches have shown,that the use of system dynamic characteristics allows to establish top and bottom borders of treated surfaces' quality in real time.There is a correlation of dynamic estimations of surfaces' quality with measured profilogrammes.

Contact Mechanical Analysis of Elastic Multibody Structures

SM2S_10459
Tue • 14:45 • 206

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The theory of elastic multibody structures with dry joints is based on the mechanics of elastic voussoirs in mutual contact with Coulomb's friction. The state of deformation of the structure is split up into that of the corresponding monolithic elastic structure, and, that of a rigid body assemblage with linearly distributed longitudinal gap with partial interpenetration in the compressed contact area and constant slip between the rigid blocks. The gap and slip can be expressed by the mutual translations, axial and transverse, and rotation between the adjacents blocks. Provided that the joint can be considered as a plane of symmetry, axial translation and rotation are proportional to normal force N and depend on the eccentricity of N, whereas transverse translation depends also on shear force Q. With this assumption and some generalizations, deformation parameters for different forms of blocks are worked out and an elastic theory of voussoir arches and segmental beams is developed.

Contact Force Distribution Among Pins of Trochoid Transmissions

SM2S_10540
Tue • 14:50 • 206

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Trochoid transmissions are widely used in industry. There are three types defined by field of application: cycloid speed reducers, trochoid pumps, and linear motion trochoid drive. Cycloid speed reducer is a statically indeterminable system. Therefore it is required using a deformation equation while analyzing force distribution. Besides significant influence on contact force is caused by machining tolerances. In the paper the clear mathematical models of cycloidal speed reducer with account machining tolerances, methods for gap and contact force distribution determination and computer-aided modeling results on these approach basis are presented. The simple practical design equation for backlash calculation, expressing relationship between drive parameters (eccentricity, gear ratio, transmission angle), machining tolerance and backlash has been developed. The three-dimensional model of the new linear motion trochoid drive has been presented.

Modelling of Contact of Structured Materials Based on Data from Scanning Probe Microscopy

SM2S_10999
Tue • 14:55 • 206

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The micromechanical aspects of the formation of the contrast images in scanning probe microscopy and their relationships with the local mechanical properties of nanohomogeneous materials are discussed. The solutions of the contact problems with the consideration of the influence of surface forces and the layer composition of the material in the discussion of the experimental functions of interactions between the tip and the tested material: force or gradient of force -distance curves are ptoposed. The algorithms of the formation of the calibrated maps of the distribution of physico-mechanical properties on the surface are presented. We tried also to elaborate the spatial model of the real area of contact for the nonhomogeneity materials with the application of the results of experimental studies: 3D images of the topography, maps of the elasticity modulus and surface free energy and also the variable thickness of the surface layer on the tested area.

A Universal Property of Geometrical Hardening

SM2S_11008
Tue • 15:00 • 206

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Geometrical hardening relates to the effective hardening of elasto-plastic materials resulting from repeated, identical impacts which flatten the impacting surfaces. This increases Newton's coefficient of restitution, making the material appear as if its yield strength has increased, and hence apparently hardened. A remarkable aspect of geometrical hardening is that while Newton's coefficient of restitution for the first impact is dependent on the the relative speed of impact, and the physical and geometrical properties of the impacting particles, the subsequent increase in Newton's coefficient of restitution from the repeated quasi-static impacts is effectively a universal property, characterised essentially only by the initial coefficient of restitution and the number of subsequent impacts.

Influence of Acoustic Waves on Stability of Sliding Between Two Elastic Solids

SM2S_11028
Tue • 15:05 • 206

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Steadily sliding between two contacting elastic half-spaces with Coulomb friction under the action of incident harmonic body waves is studied. Partial stick and separation of the interface is considered. Fourier analysis technique and an iterative method are used to solve the mixed non-linear boundary value problem. Influences of the incident wave on the steady sliding between two solids are discussed in details, Some questions, which may be of interest to scientists working in the fields of friction, earthquake, etc., are answered: What is the condition for the appearance of the stick zones? Can the two solids slide with the original sliding speed under the action of the incident acoustic waves, especially when the partial stick appears? If not, how can the solids be kept sliding with the original speed? Under what condition does the local separation of the interface take place? And how does the separation affect the sliding?

Frictional Contact with Wear Diffusion

SM2S_11452
Tue • 15:10 • 206

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A quasistatic problem of frictional contact, with wear, between a deformable body and a moving foundation is considered. The material is assumed to be viscoelastic and nonlinear. The contact is modeled with normal compliance condition and the associated law of dry friction. The wear takes place on a part of the contact surface, and its rate is described by the Archard differential condition. The main novelty in the model is the diffusion of the wear particles over the potential contact surface. Such phenomena arise in many applications and, in particular, in orthopaedic biomechanics where the wear debris spread out and cause the degradation in the effectiveness of joint prosthesis and implants. A weak formulation of the model, which is a coupled system with an evolutionary variational inequality, a wear rate production ordinary equation and a nonlinear evolutionary variational equation. it is proved that, under a smallness assumption on some of the problem data, there exists a unique weak solution for the model.

On the Contact Thermoelastic Problem with Frictional Heating, Wear and Auto-Vibrations

SM2S_11481
Tue • 15:15 • 206

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Friction, wear, heat generation, relative velocity and temperature deformation are complex processes which influence each other making up a sole diverse process of a friction unit work. In this work the results devoted to a novel problem of the mechanical system exhibiting frictional thermoelastic contact of a moving body subject to both non-constant friction coefficients and wear are presented and discussed. It is worth noticing that in the case of non-constant friction coefficient and heating, the self-excited vibration can appear in our system without an elastic part (stiffness). Consider contact and wear of one-dimensional model of the thermo-elastic contact of a body with a surrounding medium. Assume, that this body is represented by a rectangular plate. The vector components related to displacements as the plate temperature depend only on the co-ordinate vertical to the contact surface and time. The plate has the mass subject to the force and moves vertically along walls in direction along the contact surface. It causes a parallelepiped heat extension, and the body starts to contact with walls. In the result of this process a frictional contact and wear on the parallelepiped sides occurs. We assume Archard's law of wear. Stability of the stationary solutions is estimated, and contact parameters are computed numerically.

Three-Dimensional Problem of the Contact by Doubly Connected Domain Taking into Account Roughness and Friction

SM2S_11611
Tue • 15:20 • 206

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Modern engineering level is characterized by diversity of machine parts contact interaction. Contact problem of doubly-connected punch is researched taking into account friction, roughness. Main equation of the problem contains integrals with weak singularity:

$$\varphi_0(p(\rho_0,\theta_0))+\iint_\Omega \lambda\, p(\rho,\theta)/r\,\mathrm{d}\Omega+\iint_\Omega \cos\widehat{rx}/r\,\psi(p(\rho,\theta))\,\mathrm{d}\Omega=f(\rho_0,\theta_0).$$

The technique is developed for doubly-connected punch reduction to the sequence of problems for annular punch. In every approximation, with use of found expansion of potential with nonsymmetrical density, integral operators are transformed to Frechet differentiable operators. The problems are reduced to linear in every approximation besides zero approximation in case of nonlinear laws of roughness. Accounting friction with nonlinear laws the method is also developed for approximate and exact solutions. The method is acceptable for engineering practice. Specifi c examples of doubly-connected punches are presented in the paper in case of linear and nonlinear laws of roughness, friction.

Evolutions of Friction Anisotropy and Heterogeneity

SM2S_11613
Thu • 14:30 • 206

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Besides surface roughness changes during friction, material sliding surfaces may be subjected to evolution and reorientation of their microstructures. For instance, complex kinematics of sliding initiate microstructural and frictional changes in some polymers and in layer-lattice materials as graphite and molybdenum disulphide. Advanced friction models can describe evolutions of frictional anisotropy and heterogeneity induced by the sliding kinematics. Due to this, fi rst-, second- and higher-order descriptions of friction are developed with respect to powers of the sliding path curvature. The proposed friction equations are in conformity with the objectivity axiom and the Second Law of Thermodynamics. The sliding path curvature generates: (a) additional resistance to sliding (dissipative type forces), (b) constraint forces normal to the sliding path (gyroscopic type forces). It can induce positive and negative additional friction, and it can change essentially the sliding trajectory. Friction cones depend on the sliding path curvature in this case.

Inverse Problems of Thermoelasticity for Frictionally Interacting Layers

SM2S_11697
Thu • 14:35 • 206

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For friction contact of two different layers, the following new inverse problems have been formulated and analyzed. Problem 1 consists in determining unknown thermal loading on one of the outer boundary surfaces of the friction couple using additionally given vertical displacements of the other surface. In problem 2, under prescribed boundary and initial conditions using additionally given vertical displacements of the outer boundary surface, intensity of frictional heat flux (friction coeffi cient) is determined. The solving of these problems is reduced to the Volterra integral equations of the fi rst kind. The stable solution of the integral equation corresponding to problem 1 is constructed using the Laplace transformation, while that corresponding to problem 2 is solved by the method of averaged functional corrections. Based on the solution of the direct contact thermoelasticity problem for the friction couple bronze-steel, numerical verifi cation of the method of solving the formulated problems has been performed.

Multidimensional Model of Combined Dry Friction

SM2S_11778
Thu • 14:40 • 206

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A new multidimensional model of combined dry friction is presented. This model is generalization of primary one-dimensional Coulomb model to the case when relative motion of rubbing solids is combination of sliding and spinning for arbitrary form of area of contact. It is proved that expressions for the both components of friction force and for momentum as function of velocity of sliding and rotations are invariant with respect to similarity group. The method of straight constricting of quadratic Pade approximation of components of friction force and momentum is developed for using of the proposed model in the task of solids dynamics. The case of axially symmetric areas of contact such as ellipse, rectangular is investigated in details.

Experimental and Numerical Study of the Brick-Mortar Interface

SM2S_12082
Thu • 14:45 • 206

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Laboratoire de Mécanique (LaM), France

Masonry is a composite material made of brick and mortar. The mortar constitutes the bed and head joints that act as planes of weakness. The shear slip at the bed joint is one of the failure modes of masonry structures. In order to investigate the shear behaviour of the bed joint, some experiments were carried out. The specimens were built with two half bricks jointed with 10 mm mortar. First, loading/unloading tests have been performed to define the type of shear bond behaviour up to the softening regime. Then, tests with several normal compressive stresses were carried out to identify the bond characteristics when a confinement is concomitant with shearing. The brick holes influence was also studied by performing tests on both solid and hollow bricks made of the same basic material. The brick holes do not affect the friction angle, but increase the stiffness and the residual cohesion. The obtained results, leads us to develop an interface model defined by two yields functions. This model was implemented in a finite element code, which will permit to carry out some numerical simulations.

Penalty Approximation of Impact with Coulomb Friction

SM2S_12097
Thu • 14:50 • 206

Michelle Schatzman
MAPLY, CNRS et Université Claude Bernard Lyon 1, Villeurbanne Cedex, France

Impact problems with Coulomb friction in a finite number of degrees of freedom are not yet completely understood from the mathematical point of view, and it is useful to possess a range of methods for the constuction of solutions. Moreau, Monteiro-Marques, Stewart used a time-stepping method in order to construct a solution. Here a penalty approximation is proposed; it is simpler than time-stepping, and it allows for more general friction cones and for more transparent mathematical proofs. The non interpenetration constraint is replaced by normal compliance approximation; it is not difficult to obtain estimates on the penalized equation. The passage to the limit on Coulomb's relation as the compliance tends to 0 seems to require the multiplication of Dirac masses by functions which are discontinuous at the coordinate of the Dirac masses. However, precise asymptotics of the approximating problem make it possible to find a relation in the limit between the tangential and normal components of the reaction.

A Simple Model to Account for the Locking Effect Between Two Rough Surfaces under Cyclic Loading

SM2S_12412
Thu • 14:55 • 206

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A contact between two rough surfaces subjected to normal and shear loads is an unavoidable source of energy dissipation. The latter is associated with frictional losses caused by shear micro-displacements along the interface. It has been observed in experimental studies at Sandia National Laboratories that the loss of energy undergoes certain evolution when contact is subjected to cyclic loading. It manifests itself in the form of a gradual decrease approaching a steady state as cycling progresses. This behavior has a repeatable character after the contact is re-established and subjected to cycling again. In the present work a simple model is developed that suggests a hypothesis that two rough surfaces brought into contact tend to lock up with a number of cycles resulting in a reduction of a total energy loss. A multiple asperity contact model is introduced to capture this phenomenon. Asperities are assumed to change their contact type under cyclic loading from being normal to being inclined.

On Optimal Control of a Quasivariational Inequality Arising From a Viscoelastic Contact Problem

SM2S_12678
Thu • 15:00 • 206

O.P. Layeni, A.P. Akinola
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We consider the problem of dynamic unilateral contact of a viscoelastic material of the Kelvin-Voigt type with a rigid foundation under the assumption of isotropy and small deformation. The mathematical formulation is a hyperbolic variational

inequality which under a transformation yields a quasivariational inequality. We minimize a pertinent cost functional subject to this quasivariational inequality. The case of an elastic composite foundation is also considered using an appropriate energy function under large deformation.

A Novel Contact Model Based on Volumetric Information

SM2S_12773
Thu • 15:05 • 206

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In this paper, a novel contact model is presented which includes normal contact force and damping, rolling and tangential resistance force. A modified Winkler elastic foundation model is introduced to obtain the pressure distribution across the contact area. The contact force is derived analytically by integrating the pressure distribution over the contact area. The resulting model features a contact stiffness proportional to the contact area and leads automatically to the correct selection of the point of action of the force, which is shown to be proportional to the interpenetration volume. The proposed model is not restricted to contact situations where the bodies have non-conforming geometries, but can be used for any geometry with reasonably flat contact area. A numerical simulation of a sphere impacting on the inside surface of a cylinder is presented and demonstrates ball motion is eventually stopped by the frictional effects.

SM3

Control of structures

Chairpersons: F. Chernousko (Russia), S. Pellegrino (UK)

Optimal Vibration Control of Guyed Masts

SM3L_10457
Mon • 16:00 • 213

Bartlomiej D. Blachowski, Witold Gutkowski
IPPT PAN, Warsaw, Poland

Ice, together with wind pressure, are the most common reasons of mast failures. With this in view a robust, optimal control is proposed. The feedback control is designed to measure the structural motions of a guyed mast and to generate corrective control forces, to improve the structure response characteristics. The control forces cause tension changes in guy cables, using mechanical actuators at anchor points. The optimization is performed by minimizing a performance index, accounting for the closed-loop output error and the control effort required to regulate the system. The study starts with a discussion of dynamic properties of the mast and nonlinearities present in the problem. Then, based on the assumption of small amplitudes of vibrations, equations of motion are derived using motion linearization. Conditions of stability, controllability and observability are also investigated. Finally, the paper is illustrated with a numerical simulation of a vibration control process.

Exact Tracking Control for Nonlinear Structural and Mechanical Systems

SM3L_11163
Mon • 16:20 • 213

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Based on recent results from analytical dynamics, this paper develops a class of tracking controllers for controlling general, non-linear, structural and mechanical systems. Unlike most control methods that perform some kind of linearization and/or nonlinear cancellation, the methodology developed herein views the nonlinear control problem from a very different perspective. It utilizes recent, fundamental developments in an allied field – analytical dynamics – to obtain closed-form expressions for the tracking controller. This leads to a simple and new control methodology that is capable of 'exactly' maintaining the nonlinear system along a certain trajectory, which, in general, may be described by a set of differential equations in the observations/measurements. The approach requires very little computation compared to standard approaches. It is therefore useful for on-line, real-time control of nonlinear systems. The methodology is illustrated with examples.

Control of Multibody Systems Moving along a Plane

SM3L_11243
Mon • 16:40 • 213

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Plane multibody systems are considered that consist of several rigid bodies connected by prismatic and/or revolute joints. Control forces and/or torques are created by actuators installed at the joints. The dynamics of possible motions of the systems along the horizontal plane is investigated in the presence of dry friction acting between the system and the plane. The respective control algorithms are proposed. Two-link and three-link systems can perform various periodic motions by alternating slow and fast phases. For multilink systems, wavelike locomotion is possible. Displacements, the average speed, and the magnitude of required controls are estimated. Optimal values of geometrical and mechanical parameters are determined that correspond to the maximum speed of motion. The obtained results are confirmed by computer simulation and experimental data. These results are related to the biomechanics of snake-like locomotion and are of interest for transportation systems and mobile robots.

Control of Random Dynamics of a Rigid Rocking Block

SM3L_11265
Mon • 17:00 • 213

Agnessa Kovaleva
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The paper focuses on the controlled dynamics of a rigid block. The rocking oscillations are excited due to random horizontal ground motion. The response analysis of random rocking motion of a rigid block has been pursued for last decades; this paper considers the problem of the toppling prevention as a control problem. Assuming rigid foundation, large friction to prevent sliding, and the Newton restitution law during the impact, the only possible response mechanism under ground excitation is the rocking about the corners of the block. Control is interpreted as torque acting against the block inclination. The control task is to minimize the toppling probability with due regard to control constraints. The control problem is considered by the dynamic programming method. The equation of rocking motion corresponds to the equation of a non-linear discontinuous oscillator. The dynamic programming equation for the stochastic discontinuous oscillatory systems is resolved asymptotically, by making use of the averaging and stochastic averaging procedures.

Optimization of Active Control of Structural Vibration by the Beam Analogy

SM3L_12756
Mon • 17:20 • 213

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A numerical approach based on the finite element method to determine the optimal action of a set of discrete actuators controlling vibration of elastic structures is presented. The approach uses an analogy between the optimality equations for the problem in the time domain and the governing equations for a certain set of static beams in the spatial domain. Consequently, the finite element model for the optimality equations can be built of fictitious 2-D beams. Applying standard hermitian beam elements easily solves static displacements and forces in these beams. The results are then transferred to the time domain to describe the optimal dynamic response of the structure. The analogy (referred to as the beam analogy) allows for an efficient application of the finite element method to solve optimal active vibrations attenuation problems for open- and closed-loop control schemes. Simple numerical examples will illustrate the approach.

A Model for the Hysteresis of Shape Memory Wires

SM3L_12729
Mon • 17:40 • 213

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We study the hysteretic behavior of shape memory wires under repetitive loading cycles. Our model is constituted by a chain of bi-stable elements whose elastic energy varies with the loading history to take into account the modifications of the material properties associated to the phase transition processes. The hysteretic behavior of this simple, predictive model reproduces important phenomena observed in the cyclic experiments of shape memory wires.

Coupled Optimal Design of Building with TMD

SM3S_10098
Thu • 14:30 • 227A

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An integrated approach to optimize the total cost of building and the associated control device has been proposed. Design parameters that constitute the costs of the structure and the control system have been considered simultaneously in the optimization process. Constraints for performance of the design include peak inter-story drift and peak absolute acceleration of the floors. Genetic algorithm has been implemented to solve the coupled optimization problem. A three- and a nine-story building subjected to design seismic excitations were studied as examples to assess suitability of this integrated optimization strategy. The control device considered for example problem is a tuned mass damper (TMD) installed at the roof of the building. Results indicate that the proposed approach leads to superior solutions not previously envisaged. The study concludes that for 3-story example problem, building alone without any TMD is an optimal solution while for 9-story, a building with a TMD is the best design.

Time-Optimal Control of Hydraulic Manipulators

SM3S_10458
Thu • 14:35 • 237A

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Polish Academy of Sciences, IPPT, Warsaw, Poland

Many hydraulic manipulators work in unstructured surroundings, and perform non-repetitive tasks. These may involve transporting unknown loads along paths in space, which are decided online by the operator. This paper addresses the prob-

lem of optimizing such motions for speed, under given actuator capacities and bounds on payload uncertainty. An arbitrary reference trajectory is input, as an untimed sequence of desired manipulator's configurations. The timing of the actual trajectory is then chosen such, that it fully utilizes the capacity of actuators, under the most disadvantageous loading conditions. This is done by extending in time sections of the trajectory, where actuator capacities are exceeded, and shrinking those sections, where actuator capacities are not yet met. The resultant control law tracks the reference trajectory, to within a certain threshold of accuracy, with almost highest possible speed. The paper is illustrated by simulation results of a three-link hydraulic arm, tracking several reference paths.

Surface Accuracy of Inflatable Reflector Covered with Stretched Cable

SM3S_10879
Thu • 14:40 • 237A

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We present here an idea of the inflatable reflector and the surface error evaluation of this reflector, which is segmented into N-regular polygonal facets by the uniformly stretched cable net to improve the reliability on surface accuracy. As for the surface error evaluation, we treat the problem by using power series expansion of the complex variables, in which we take into account of the self-consistent boundary condition of the membrane on the supporting cable. From this study, we made it clear the effects of design parameters on the surface accuracy, such as the internal pressure, the cable tension, the membrane tension, the facet size, and etc. We also derived simple approximate formulas to give the RMS surface accuracy within 5% error in the realistic design region, where the surface error was almost proportional to the ratio of the cable force to the membrane tension.

H-inf Control for Smart Multistory Building Structures

SM3S_11036
Thu • 14:45 • 237A

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One of the important problems in achieving reliable active control structures that could ensure the safety for strong earthquake is its robustness. A dynamic finite element model for multistory buildings under external excitations is presented in this paper. Structured uncertainties associated with the design model are considered to reflect the errors between the model and the reality. H-inf optimal control for the active control structure is implemented. The cost functional is the H-inf norm of the transfer function from the exogenous disturbances to the errors that is to be inimized. The goal is to design the control forces vector satisfying the dynamic equations of the structure and subjected to this optimal performance criterion. Relevant numerical techniques, which have been done with the help of MATLAB routines, are applied to solve the arising structural control problem. Numerical results show high robust performance of the proposed method.

Pre-Acting Impact Isolation Systems

SM3S_11219
Thu • 14:50 • 237A

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The pre-action control concept is considered as applied to impact isolation systems. Pre-acting systems start responding to an impact before this impact has occurred. The limiting performance analysis of the pre-acting isolator is performed for a SDOF system subject to an instantaneous impact. The isolation performance index is defined as the peak displacement of the object to be isolated relative to the base, provided that the magnitude of the control force does not exceed a prescribed value. A substantial advantage of pre-acting isolators over isolators without pre-action is established. A pre-acting isolator based on a passive elastic element (a spring)is suggested. To provide the pre-action operation mode, one should cock the spring and release it at an appropriate instant before the impact. The optimal stiffness of the spring and the optimal time of release are identified. The application of pre-acting impact isolation systems for injury prevention is discussed.

Suppression of Train-Induced Vibrations of Continuous Truss Bridge by Hybrid TMDs

SM3S_11287
Thu • 14:55 • 237A

Jong-Dar Yau
Tamkang University, Taipei, Taiwan

Steel truss bridges possess the advantages of light weight, high strength, and ease in construction, they therefore are often utilized in railways for crossing streams or chasms. However, because of the existence of clustered frequencies of vibration, there may occur multi resonant peaks in the impact response of continuous truss bridges subjected to high speed trains. To overcome this problem, a hybrid tuned mass damper (TMD) system will be employed to mitigate the train-induced vibrations of the continuous truss bridges. By modeling a continuous truss bridge as a combination of beam and truss elements and the train over it as a sequence of moving loads. The numerical results indicate that the proposed hybrid TMD system can effectively suppress the main resonant peaks of the continuous truss bridge due to the train loads moving at high speeds.

Slow Snake-Like Motions of Linkages

SM3S_12622
Thu • 15:00 • 237A

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We investigate slow (quasi-static) snake-like motions of linkages along a rough horizontal plane owing to changing their confi gurations. We consider two-member linkages with variable lengths of the links, controlled by forces acting along the links. The angle between the links can be constant or variable. We consider also three-member linkages with rigid links connected in star or in series, controlled by two torques acting between pairs of the links. Quasi-static controllability of all the linkages, with some constraints on their parameters, is proved. The slow gaits that enable the linkages to be driven to any prescribed position are constructed. Finally, we consider a homogeneous snake which can bend at each point of its body. The snake can be modeled by a linkage with large enough number of identical rigid links. We constructed an effi cient slow gait enabling the snake to move along a given direction.

Control of a Nonlinear Slewing Flexible Beam

SM3S_13004
Thu • 15:05 • 237A

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Nowadays, a great number of space missions involve large space structures, where a high degree of pointing accuracy is need. In such systems, the coupling between the energy source and flexible structure must be taken into account in the control system design. In this paper, a control law is designed for the ideal (no influence of the structure over the energy source) and the non-ideal (the structure behavior changes the energy source behaviour) linear model using a dc motor to drive a flexible slewing beam-like structure. Although, the gain of the control law is obtained for the linear model, its performance is tested also for the non-linear system. The non-linear term is proportional to the square of the angular velocity of the motor. Low and high velocities are investigated in order to verify the robustness of the proposed control law when dealing with the not modeled terms.

SM4

Damage mechanics

Chairpersons: M. Chrzanowski (Poland), P. Steinmann (Germany)

Modeling of the Damage Evolution at the Granular Scale in Polycrystals under Complex Cyclic Loadings

SM4L_10456
Mon • 16:00 • 231

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A multi-scale model of damaged elasto-inelastic behavior is proposed to predict the plastic fatigue life for FCC metallic polycrystals under multiaxial loading paths. This model is expressed in the time dependent plasticity for a small strain theory. It is assumed that the damage variables initiate and then evolve at the grain level in the polycrystal where the phenomenon of the localized plastic deformation occurs. The totally damaged polycrystal is defined by a probabilistic approach. In this work, the model is tested under different multiaxial cyclic loading situations (tension-compression and tension-torsion with different out-of-phase angles) to show the effect of the loading paths on the fatigue life of polycrystals. As a conclusion, the model can appropriately describe the overall and local damaged behavior of polycrystals.

A CDM Approach of Ductile Damage with Plastic Volume Changes

SM4L_11885
Mon • 16:20 • 231

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Continuum Damage Mechanics approaches for ductile damage are revisited in order to incorporate plastic volume changes in conformation with micromechanics based approaches. The theory is still consistent with a general thermodynamic framework and allows the possibility for damage anisotropy as well as damage deactivation effects. Systematic comparisons are made for various multiaxial loading conditions and some applications are shown in the context of metal forming simulation.

Micromechanical Modelling of the Deformation and Damage of Inelastic Brittle Three-Phase Composites: Application to Fiber-Reinforced Concrete

SM4L_11959
Mon • 16:40 • 231

A. Ouaar[1], **I. Doghri**[1], J. F. Thimus[2], F. Huge[1]
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A micromechanical model based on the Mori-Tanaka homogenization scheme is presented to investigate the effective non-linear behaviour of a three-phase brittle composite materials. The matrix phase is assumed to be linearly elastic coupled with damage, the inclusion phase is elastoplastic and the third phase represents cavities. We use the Ju's energy-based damage model to describe the anisotropic damage of brittle material behavior and the classical J2P theory for the elastoplastic one. To handle our micromechanical modeling we have developed a robust numerical algorithms for an incremental tangent formulation which enables us to simulate and predict, within reasonable CPU time and memory, the response of such composite materials. As an application, we have simulated the mechanical response of Fiber-Reinforced-Concrete. Our predictions are compared with experimental data obtained by experimental tests performed on several specimens of Fiber-Reinforced-Concrete. We have also validated our micro-macro predictions against 3D and 2D Finite Element simulations.

A Nonlocal Plasticity-Damage Formulation Based on the Micromechanics of Defect Growth

SM4L_11415
Mon • 17:00 • 231

R.H.J. Peerlings, R.A.B. Engelen, M.G.D. Geers
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A large-strain plasticity formulation is coupled with a damage influence in order to model damage development in ductile materials. Two damage variables are used: one which characterises the defect volume fraction and which is predominantly governed by hydrostatic stress and plastic dilatation, and one which describes the average defect shape and is particularly sensitive to shearing. Growth relations for these variables as well as the yield surface are determined from unit cell analyses of defect growth and defect extension by fitting relations whose structure is based on relatively simple mechanical assumptions. The resulting evolution laws are formulated in terms of nonlocal effective plastic strain measures, which are obtained as the solution of two additional boundary value problems. As a result, no pathological localisation and mesh-sensitivity effects are observed in applications.

Continuumthermodynamic and Variationalmodeling and Simulation of Ductile Failure at Large Deformation with Application to Engineering Structures

SM4L_10865
Mon • 17:20 • 231

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The purpose of this work is the extension of local Gurson-based ductile damage and failure modeling in engineering materials and structures to account for the non-local nature of void coalescence. In particular, the extension pursued here is based on the introduction of an non-local effective damage parameter ν analogous to that f^* of Needleman and Tvergaard which is modeled thermodynamically as a scalar-valued continuum microstructural field or generalized phase field via a recent thermodynamic approach. In the simplest case, the resulting field relation for ν is formally analogous to the inhomogeneous temperature equation. As such, analogous to temperature, ν represents an additional continuum degree-of-freedom here. And in the complete model, damage and deformation are coupled. Further, the field relation for ν contains a characteristic length determining the effective dimension of the process zone for void coelescence.

An Elasto-Viscoplastic Model Coupled to Damage and Grain Growth to Take Account of Material Variability

SM4L_10974
Mon • 17:40 • 231

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The final objective of this study is the prediction of the failure of nuclear structures at very high temperatures in accidental conditions taking account of the material variability. The material used to build French reactor pressure vessel 16MND5 steel, shows at high temperature different damage mechanisms according to its origin: transgranular by growth and coalescence of cavities or intergranular. This phenomenon can dramatically modify the failure time for creep tests. A metallurgical study has shown that intergranular damage is activated by the smallest size of austenitic grains for temperature around 1000°C. To describe these phenomena, we have developped an elasto-viscoplastic constitutive law with isotropic hardening coupled to two damage evolution laws. The first damage variable is isotropic and is related to transgranular mechanism whereas the second damage variable is anisotropic dependent on grain size and related to intergranular mechanism. We have implemented this constitutive equation in finite element code CAST3M.

Propagation of Cracks in Terms of Continuum Damage Mechanics

SM4L_11665
Tue • 17:00 • 231

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The paper deals with crack nucleation and propagation caused by time-dependent process of deterioration in creep conditions. Three distinctive stages of the damage growth in a rectangular plate subjected to uniform pressure load are considered: nucleation in a point, propagation through the plate thickness, and development of critical network of the cracks bringing a structure to the final collapse. With corresponding times denoted by t1, t2, and t3, their relationships had been evaluated to indicate the safety margins throughout the whole process. Spatial configuration of crack networks, including their profiles

and branching, is shown as time-dependent process, which leads to the structure collapse caused by the loss of kinematical stability.

Damage and Failure of Brittle Solids

SM4L_11228

Tue • 17:20 • 231

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The aim of this paper is to study the process of the damage growth that results in material failure for rock-like cementitious brittle materials subjected to multi-axial state of stress. To this end the stress-strain curves and stress at failure were determined experimentally for cylindrical specimens of mortar under tri-axial state of stress. The programme of loading consisted of uni-axial compression that supplied the data necessary to calibrate the material and two cases of tri-axial loading. The first case was superposition of hydrostatic pressure and axial compression and the second case consisted in simultaneous action of hydrostatic pressure and bi-axial uniform compression. The experimental results were compared with the theoretical predictions obtained from the own theoretical model based on the methods of the damage mechanics.

Damage Quantification and Simulation of Flyer Plate Spallation and Round Notched Tensile Experiments

SM4L_11379

Tue • 17:40 • 231

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Dynamic and quasi-static failure and dynamic incipient failure tensile experiments were performed on a half-hard 10100 Cu material using several different specimen geometries, including uniaxial stress and several notches, as well as uniaxial strain flyer plate experiments designed to achieve incipient failure. The dynamic tensile tests were performed on a momentum trapped tensile split Hopkinson pressure bar. Damage quantification of the incipient failure specimens was performed and statistically reduced for comparison with continuum damage model predictions from explicit simulations of the experiments. The damage model contains both a nucleation and void growth components. The experimental data provides a wide parameter space of stress triaxiality, ranging from near 1/3 to about 5, with equivalent plasticity ranging from a couple of percent up to near 100 percent. This information is used to develop and calibrate a nucleation damage model component that results in simulation predictions that closely match a wide variety of diagnostic and post-mortem measurements of these experiments.

Lifetime Prediction with a Damage Model Based on Mixed-Mode Microcrack Propagation

SM4L_12088

Tue • 18:00 • 231

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The derivation of a damage model for brittle damage by growth of micro-cracks is shown. First a finite deformation framework is presented. This framework is based on the multiplicative decomposition of the deformation gradient in an elastically recoverable part and a damage part whose energy is dissipated. No plastic part is present, since in brittle damage no macroscopic plastic strains occur. The micro-plasticity at the crack tip leads only to very small macroscopic plastic strains, so that it is assumed, that for vanishing stresses, no deformation remains. This approach introduces, similar to finite plasticity, three different configurations, but with different physical meaning. The reference configuration is the undamaged configuration, which is connected to the damaged intermediate configuration by the damage mapping. The actual configuration is then reached with the help of the elastic mapping. So the undamaged intermediate configuration works for the macroscopic observable process as a reference with changing properties. With the help of this framework, the damaged tensor of elastic moduli can be obtained with the help of push and pull operation, as the elasticity tensor of the damaged intermediate configuration. The evolution equation for the damage deformation follows from a micro-mechanical approach of growing mixed-mode microcracks in a unit cell, which show kinking of the crack path. The crack growth is based on the variational principle of a body containing a crack, resulting in the maximum energy release rate principle for growing 2D or 3D cracks.

As the simulation of a growing mixed mode crack per integration point would lead to a numerical expensive Method, a replacement crack approach is developed. With the help of this, the infinitesimal kinked crack is replaced by a straight crack with different orientation, resulting in the same energy dissipation. Finally the transition from the microscopic to the macroscopic framework is performed by a thermodynamical consistent homogenization procedure, which is based on the equivalence of the energy dissipated in crack growth and damage evolution. A finite element implementation of this model is used to predict the lifetime of model problems under cyclic loading conditions.

Damage Acquired Anisotropy in Elastic-Plastic Materials

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SM4L_11796
Tue • 18:20 • 231

A thermodynamically consistent framework for elasto-plasticity coupled with damage is discussed based on existing state and dissipation coupling models. Weak dissipation coupling, based on the concept of existence of multiple dissipation potentials, expressed in the space of thermodynamic forces associated with plasticity and damage variables, is focused. Unilateral damage response to reverse loading cycles is addressed by the use of generalised projection operators that extend the Hansen and Schreyer concept. The elastic-plastic-damage constitutive equations derived in a total form and calibrated for spheroidized graphite cast iron by Hayakawa and Murakami are adopted. They are based on the assumption of existence of the Gibbs state potential and two dissipation potentials, plasticity and damage. Only isotropic plasticity and damage hardening are included to thermodynamic forces conjugated to the fluxes. In what follows the incremental elastic-damage and plastic-damage equations are developed in a matrix form derived in Bielski, Kuna-Ciskał and Skrzypek to finally yield the local elastic-plastic compliance (or stiffness) matrix. Crack opening/closing effect is controlled by the modified stress tensor, in an analogous way as in Kuna-Ciskał and Skrzypek. The effective plane stress equations are implemented to ABAQUS finite element code via the user-supplied procedure. The predictor-corrector approach is applied with doubly-passive predictor used at each iteration step.

Nonlocal Constitutive Model for Impact Damage in Metals

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SM4L_10828
Tue • 18:40 • 231

Classical continuum mechanics models of inelastic deformation processes are size scale independent. There is considerable experimental evidence that plastic flow and damage in materials is size-dependent. As soon as material failure dominates a deformation process, the material increasingly displays strain softening (localization) and the finite element computation is considerably affected by the mesh resolution and alignment and gives non-physical descriptions of the localized regions. Gradient-enhanced constitutive viscoplastic-viscodamage equations that include explicit and implicit micro-structural length scale measures are presented in this work. The governing equations are derived using a thermodynamically consistent formulation. Numerical simulations are performed to study the effect of including these material lengths on the dynamic localization of plastic flow in shear bands for impact-damage related problems. It is shown that the inherent material length scale predictions agree well with the width of the shear bands in ductile metals as compared to the experimental results.

Anisotropic Damage Model for Concrete Including Unilateral Effects

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SM4L_12913
Wed • 08:30 • 231

A thermodynamically consistent damage model for concrete is proposed, which accounts for the anisotropy induced by damage, and for the unilateral effects upon transition from tension to compression. The main features of the model are: (i) limited number of parameters: 5 material parameters in addition to elastic constants; (ii) two damage variables: a second order symmetric tensor pertaining to damage created in tension and a scalar pertaining to damage created in compression; (iii) an activation criterion that couples the evolution of both damage variables; (iv) a strain-dependent threshold that accounts for the asymmetry between tension and compression and for the confinement effect. The model fits within the framework of standard generalised materials, as defined by Halphen and Nguyen (1975). Numerical simulations exhibit satisfactory model predictions when compared to experimental tests.

A Micromechanically Based Network Model for Rubbery Polymers Incorporating Mullins-Type Stress Softening

SM4L_12116

Wed • 08:50 • 231

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We present a new micromechanically based constitutive model that embodies the Mullins-type stress softening in rubberlike materials. The overall rubber network is decomposed into two parts: crosslink-to-crosslink (CC) and particle-to-particle (PP) network. The Mullins-type damage phenomenon is embedded in the PP network. The key idea of the constitutive approach is a two-step procedure: (i) The set up micromechanically based constitutive models for a single chain orientation and (ii) the defi nition of the macroscopic stress response of the polymer network by a directly evaluated micro-to-macro transition for a discrete orientation space on a micro sphere structure. Due to intrinsic discrete orientation distribution of micro-variables, the model allows to formulate inelasticity in terms of one dimensional scalar variables in lieu of tensorial ones. To this end, the model inherently includes a deformation-induced anisotropic behavior since the different loading histories are experienced by different orientations.

Coupled Meso-Macro Simulation of Masonry Cracking

SM4L_12341

Wed • 09:10 • 231

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A computational multi-scale framework is proposed for the representation of the complex non-linear behaviour of planar masonry structures. The average response of the masonry material is deduced from a unit cell through scale transitions with specifi c periodicity requirements. A standard continuum approach is used at the macroscale. Finite width damage localization bands with a mesostructurally motivated width are introduced in the macroscopic description. Localization detection is based on the homogenized acoustic tensor analysis. Macroscopic localization along preferential orientations is detected in a consistent way with the underlying mesostructural failure patterns and with the applied loading. As a result of the use of homogenization techniques on fi nite volumes, mesostructural snap-backs may occur in the homogenized material response. A methodology to introduce this type of response in the originally strain driven scale transition is proposed. The framework is applied to examples showing the numerical robustness of the method.

Coupling Between Progressive Damage and Permeability of Concrete

SM4L_12749

Wed • 09:30 • 231

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In damage models, damage D and the reduction of elastic stiffness of a quasi-brittle material are strictly connected. Experimentally a good correlation between the evolution of damage and permeability K of concrete is also observed. Supposing that concrete is a disordered material, which can be simulated with the help of a discrete lattice model, the correlation between K and D can be analyzed theoretically. The relationship between the mechanical parameters of a fully disordered material and microcracking has been investigated. It has been shown that microcracking in lattices must be described by a degradation of stiffness if a scale independent representation is sought. In this paper we extend such a model to the analysis of a coupled hydro-mechanical problem. We observe that permeability is the size independent variable and is strongly correlated with the degradation of stiffness. Additionally, the evolution of permeability with mechanical damage and with stress ratio at pre-peak phase are studied and compared with experimental results.

Discrete Models and Their Application in Damagemechanics

SM4L_11414

Wed • 09:50 • 231

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Different discrete element models (DEM) for the simulation of problems in the context of damage mechanics will be presented. The target materials to be simulated are cohesive and non-cohesive geomaterials like concrete- or sand-type materials.Starting from a basic polygonal two-dimensional DEM model for non-cohesive granular materials, more complex models for cohesive materials are obtained by inclusion of beam or interface elements between corresponding particles. The last step in the series of increasing complexity is the realization of a microstructure-based simulation environment which utilizes the enhanced DEM models. With growing model complexity a wide variety of failure features of geomaterials can be represented. Furthermore, adequate homogenization approaches are derived which supplement the definition of the discrete models. These homogenization approaches allow us to relate microscopic quantities, like contact forces or displacements, to corresponding macroscopic quantities, like stresses or strains. Representative numerical examples are used to validate the proposed DEM models along with the homogenization.

A New Energy-Based Elastoplastic Damage Model for Concrete

SM4L_12036

Wed • 10:10 • 231

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In this paper, a new elastoplastic damage model is proposed, in which tensile damage variable and shear damage variable are adopted to describe the degradation of macro-mechanical properties of concrete. Within the framework of continuum damage mechanics, an elegant constitutive law which is the same as the effective stress concept is obtained. The plastic Helmholtz free energy is accounted for the damage growth, and the damage criteria are based on the elastoplastic damage energy release rates, which is consistent with thermodynamics theory. The evolutions of damage variables and plastic strains are established based on the normal rule and the effective stress space plasticity, respectively. Some pertinent computational aspects concerning the numerical algorithm are discussed. The model has been coded into a general finite element program which is capable of predicting the nonlinear behaviours of concrete under different stress states, whose predictive results demonstrate its adequate accuracy for the intended applications.

Localized Necking Criterion Based on Acoustic Tensor for Materials with Anisotropic Damage

SM4L_10961

Thu • 09:30 • 231

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Localized Necking Criterion Based on Acoustic Tensor for Materials with Anisotropic Damage C.L.Chow and M.Jie Department of Mechanical Engineering, The University of Michigan – Dearborn, Dearborn, MI 48128, USA Abstract The paper presents the development of a criterion of localized necking for strain-softening materials. The criterion takes into account of the material behavior of anisotropic damage and anisotropic plasticity. The critical condition of damage evolution is of primary interest in this study. For localized necking as a consequence of plastic instability, the singularity of acoustic tensor is taken as the critical condition for localized necking in strain-softening materials. Effective tangent modulus tensor for materials with anisotropic damage is established. The damage-coupled localized necking criterion, along with inclination angle of localization band, for strain-softening materials is derived. The closed-form expression of localized necking criterion offers potential applications in the analysis of failure in strain-softening materials such as hot metals, rocks, soil, solder, etc. It is observed that the critical damage value at localized necking is not a constant but depends on stress and strain states.

Numerical Analysis of Nonlocal Anisotropic Continuum Damage

SM4L_11406

Thu • 09:50 • 231

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The presentation deals with nonlocal anisotropic continuum damage in ductile metals. The model relies on the introduction of metric transformation tensors. The kinematic description employs the consideration of damaged as well as fictitious undamaged con-figurations related via metric transformation tensors which allow for the interpretation of damage tensors. A nonlocal yield condition and a nonlocal damage criterion are in-troduced which lead to a system of partial differential equations which are solved using the finite difference method. Since this requires no additional boundary conditions, the displacement-based finite element procedure is governed by the standard principle of virtual work. Numerical simulations of the elastic-plastic deformation behavior of dam-aged solids demonstrate the efficiency of the formulation. Large strain damage-elastic-plastic problems including severe localization are presented and the influence of various model parameters on the prediction of the deformation and localization of ductile metals is discussed.

Damage Field Identification using Full-Field Displacement Measurements

SM4L_12021
Thu • 10:10 • 231

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An identification procedure is developed to identify damage fields by using kinematic fields. A non-standard finite element formulation is derived in which the nodal displacements are known and the elastic properties (or the damage field) are unknown. The latter are assumed to remain uniform over each element, but vary from element to element. A linear (over-determined) system is obtained. When artificial measurements are used, a comparison can be performed with an a priori prescribed damage field. Less than a few percents relative error is obtained for all the many tested configurations. When some additional noise is considered, the error does not change significantly. Different local error indicators are proposed, and of those, a family can be used when the exact solution is unknown. The example of a cross-shaped specimen loaded along two perpendicular directions allows one to analyze the multiple point inception of macrocracks.

Time-Frequency Characterization of a Cracked Rotor by Wigner–Ville Distribution and Wavelet Transform

SM4S_10216
Thu • 14:30 • 208

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In the current paper, a cracked de Laval rotor has been represented by a simple hinge crack model and the system transient response numerically evaluated leading to solutions of the cracked and uncracked rotor's dynamic equation. Two strategies, namely Wigner-Ville distribution and Wavelet transform are then employed to obtain the time frequency features of the cracked and uncracked rotor system and the difference is presented and discussed. By simulation, the sensitivity of the Wigner-Ville distribution and the wavelet transform to the stiffness variation is investigated and the influence of the unbalance and the unbalance angle on the Wigner-Ville distribution and the wavelet transform is given. The time-frequency features are unique and could well serve as identification criteria of cracked rotor.

Stability and Creep Damage of Quasi-Brittle Materials

SM4S_10011
Thu • 14:35 • 208

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Design of reliable concrete structures subjected to high level and long time loading has to integrate the coupling between softening and time-dependence of microcracking. A time-dependent damage model is developed for quasi-brittle materials like rock or concrete, in the framework of Continuum Damage Mechanics. The three-dimensional model is based on strong thermodynamical arguments. Phenomena like relaxation, creep and rate-dependent loading are covered using a unified framework. As for endochronic models, no initial threshhold is assumed. Nevertheless, an apparent elastic domain is identified for constant strain rate tests, which reveals the competition between the internal kinetics of damage and the strain rate imposed on the material. Creep failure under high-sustained load is explained quite simply within stability theory. Kachanov's equation is commented within the new approach. Creep failure appears as the manifestation of a bifurcation phenomenon.

Low Cycle Fatigue Based on Unilateral Damage Evolution

SM4S_12335
Thu • 14:40 • 208

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The present paper deals with a modelling of low cycle fatigue of AISI 316L stainless steel with aid of kinetic law of unilateral damage evolution. The classical theory by Lemaitre and Chaboche is extended in order to take into account two separate damage mechanisms, unilateral damage effect, continuous crack closure/opening effect and simplified description of the neck mechanism. Results of numerical simulation are compared and verified in order to achieve the best agreement with the experimental data. Detail quantitative and qualitative analysis of obtained solutions confirms necessity and correctness of an application of continuous microcrack closure/opening effect.

Discrete Probabilistic Modelling of Damage and Adhesion

SM4S_11118
Thu • 14:45 • 208

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The continuous and deterministic view inherent to continuum mechanics can be substituted by a probabilistic approach, which is generally achieved for brittle materials by the weakest link model, and its generalizations. Discrete probabilistic modelling of interfaces are elaborated, considering the impact of heterogeneities on the macroscopic behaviour. In the present contribution, we enlarge the so-called Daniels model, which consists of a bundle of parallel fibbers, first considering various probability laws for the distribution of the rupture thresholds. The rheology of the bundle is further considered, whereby a viscous behaviour of the fibber bundle interface is introduced. We exhibit a bifurcation behaviour in different configurations, such as adhesively bonded joints, considering different histories of the applied load. The progressive degradation of the fibber bundle is further modeled assigning a Scott Blair type behaviour to the interface; the response of the recursive block is evaluated by an electrical analogy.

Computational Micro–Meso Modeling for Laminates Under Thermomechanical Fatigue and an Oxidizing Atmosphere

SM4S_12277
Thu • 14:50 • 208

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One computational approach for studying damage in laminated composites is the damage mesomodel for laminates, which has been developed for more than fifteen years, particularly at LMT-Cachan. Recently, we introduced micro-meso relations which prove that this mesomodel is compatible with classical micromechanical analysis and, therefore, can be viewed as a homogenization of classical theories on the microscale. Consequently, basic material quantities on the microscale can be easily interpreted on the mesoscale. Here, we propose to use these micro-meso relations as a tool for studying the degradation of laminates under fatigue in an oxidizing atmosphere. The reason why we are interested in this specific topic is that carbon-epoxy laminated composites are candidate materials for the construction of the future European civil supersonic aircraft. Our approach is rather simple: first, the influence of fatigue or oxidation on basic material characteristics is studied on the microscale; then, the equivalent damage evolution law on the mesoscale is obtained thanks to the micro-meso relations.

A Non-Associative Anisotropic Damage Model for Brittle Materials

SM4S_12298
Thu • 14:55 • 208

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A micromechanically based anisotropic damage model for brittle materials having different tensile-compressive response is proposed. The material is modelled as an elastic isotropic matrix containing a statistically uniform distribution of growing microcracks. Under the simplifying assumption of non-interacting and self-similar propagating flat cracks, a friction-damage coupled model based on two tensor-valued internal variables, representing damage and frictional contact tractions, is derived. The use of a tensor-valued variable for damage, in particular, makes the model to be capable of describing the load-induced anisotropic response of brittle and quasi-brittle materials. In the framework of thermodynamics with internal variables, overall frictional sliding and crack growth criteria with associated flow rules are used to complement the model. The constitutive equations are then applied to analyze the material response to meaningful loading paths. In order to validate the model, limit strength domains for biaxial and triaxial stress states are derived as well.

Modeling of Thermo-Damage Coupling in Anisotropically Damaged Materials

SM4S_11234
Thu • 15:00 • 208

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A current damaged configuration B_t and the corresponding fictitious undamaged configuration B_f of a Representative Volume Element (RVE) characterized by a second rank anisotropic damage tensor D_{ij} are first postulated. Then, by taking account of the effective undamaged surface element of B_f, the heat flux vector q_i^C due to heat conduction in B_t is formulated. The heat flux q_i^R through cavities is also formulated by calculating the gray-body radiation through a row of cavities in RVE of B_t. The heat conduction law for overall heat flux $q_i = q_i^C + q_i^R$ and the equation of heat conduction in anisotropically

damaged materials are expressed by defining the equivalent thermal conductivity tensor L_{ij}^{EQ} in the damaged material. The tensorial nature of the resulting equations and the variation of L_{ij}^{EQ} due to the development of anisotropic damage D_{ij} are discussed. Finally, the resulting equations are applied to the analysis of anisotropic creep damage problems under thermo-mechanical loading.

Material Models for Hookean Materials with Voids or Cracks

SM4S_10960
Thu • 15:05 • 208

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Stress-strain relations for Hookean materials with spherical voids or penny-shaped microcracks are derived. The constitutive relation for voided material is based on the analytical expression by Eshelby whereas the theoretical work by Kachanov provided the foundation for the material model of microcracked material. The postulate of strain equivalence was shown to be incompatible with the analytical expression by Eshelby for porous material. Although the present formulation assumed that the microcracks are parallel, the extension for a multidirectional non-interactive microcrack field is evident. These two stress-strain relations play an important role in damage mechanics, since they are analytical solutions. They can be used in the verification of the assumptions of damage mechanics, such as the postulate of strain equivalence

On the Modeling of the Pre-Fracture Zones for an Interface Crack in Anisotropic and Piezoelectric Bimaterials

SM4S_12327
Thu • 15:10 • 208

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An interface crack in anisotropic and piezoelectric bimaterials under the action of mixed mode mechanical loading is studied. It is assumed that the pre-fracture zones at the crack tips arise and certain relations between the stresses in these zones are valid. Due to the last assumption the pre-fracture zones can be considered as the crack continuations and the problem of linear fracture mechanics with the unknown pre-fracture zone lengths and the stresses in these zones is formulated. Mathematically this problem is described by Hilbert problem of linear relationship which is solved exactly. From the condition of the stresses finiteness at the crack continuations the system of transcendental equations for the determination of pre-fracture zones lengths is derived. The solution of this system is defined numerically and afterwards the crack opening displacements at the initial crack tips are found. As a special case of this model the pre-fracture zones of the craze type are considered. For an arbitrary number of crazes and voids between them the exact analytical solution of the associated Hilbert problem is found and from the same conditions as above the equations for the pre-fracture zone lengths and the crack opening displacements are formulated. It is shown that for a particular case of the void lengths tending to zero the obtained results are in a good agreement with the associated results obtained for continues pre-fracture zones.

Robust Identification of an Augmented Gurson Model for Elasto-Plastic Porous Media

SM4S_12333
Thu • 15:15 • 208

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In the paper we investigate robust identification approach to identify the material parameters in the augmented Gurson model for the elasto-plastic porous media. The model describes processes of nucleation and growth of voids in the porous body subjected to inelastic deformation. Robust identification, in contrary to the least squares approach, assumes minimization of the sum of the selected weighted differences between the measured and calculated from the model output values. The advantage of using a robust method which automatically rejects extreme observations is that it does not require a subjective decision on the part of the experimenter. The identification problem is solved by means of the global optimization method of Boender at al. In our solver we permit the use of the Hooke–Jeeves direct search method as the local minimizer that does not involve any derivatives. Identification is carried out on the basis of Fisher's data measured on the steel cylindrical specimens subjected to the uniaxial tension.

An Asymptotic Analysis of Mode I Crack in Creepnig Damaged Solids

SM4S_11779

Thu • 15:20 • 208

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To evaluate the mechanical behaviour around a Mode I crack tip the governing equations are formulated by light of Continuum Damage Mechanics. The asymptotic stress and continuity fields near the tip of a stationary crack are derived for non-linear viscous damaged materials, which deform according to the creep power constitutive law. The conventional Kachanov–Rabotnov creep-damage theory is utilized and the scalar continuity parameter is incorporated into the constitutive relations. Thus, the coupled system of damage mechanics – creep theory equations is considered. Based on the similarity variable a stress analysis is carried out for Mode I crack under plane stress and plane strain conditions assuming the existence of a totally damaged zone near the crack tip. It is found that the Hutchinson-Rice-Rosengren solution can't be used as the remote boundary condition and the actual far field stress is obtained. The shape of the totally damaged zone is given and analysed.

SM5

Dynamic plasticity of structures

Chairpersons: N. Jones (UK), T. Wierzbicki (USA)

Blast Resistance of Clamped Sandwich Beams

SM5L_11022

Wed • 11:00 • 206

Vikram S. Deshpande, Norman A. Fleck
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A systematic design procedure has been developed for analysing the blast resistance of clamped sandwich beams. The structural response of the sandwich beam is split into 3 sequential steps: stage I is the 1D fluid-structure interaction problem during the blast loading event, and results in a uniform velocity of the outer face sheet; during stage II the core crushes and the velocities of the faces and core become equalised by momentum sharing; stage III is the retardation phase over which the beam is brought to rest by plastic bending and stretching. The 3-stage analytical procedure is used to obtain the dynamic response of a clamped sandwich beam to an imposed impulse.Performance charts for a wide range of sandwich core topologies are constructed for both air and water blast, with the monolithic beam taken as the reference case. These performance charts are used to determine the optimal geometry to maximise blast resistance for a given mass of sandwich beam. For the case of water blast, an order of magnitude improvement in blast resistance is achieved by employing sandwich construction, with the diamond-celled core providing the best blast performance. However, in air blast, sandwich construction gives only a moderate gain in blast resistance compared to monolithic construction.

Collision Between Two Deformable Structures

SM5L_11051

Wed • 11:20 • 206

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The studies on dynamic plasticity of structures in the past 50 years mainly concerned a single structure's response to a prescribed impulsive/pulse loading or to impact of a rigid projectile. However, a real collision always involves two deformable structures. Hence, aiming to extend our knowledge to these realistic problems and to reveal some common features of the collision between two deformable structures, we systemically explored this new area with a focus on the energy partitioning between two colliding structures. The complete and modal solutions on beam-on-beam collisions were first constructed and their validity was illustrated. Various local contact models was then proposed and implemented in the solution of structures' global deformation. The study of a mass-spring colliding system reveals some fundamental features of the collision phenomena. These fundamental features were further examined in a more complex ring-on-beam collision, analyzed by using a mass-spring finite difference (MS-FD) model.

Counterintuitive Response of Long Circular Tubes to Axial Impact

SM5L_11107

Wed • 11:40 • 206

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The dynamic transition from progressive buckling to a global bending collapse of a long circular tube subjected to an axial impact is studied in relation to its energy absorbing capacity. A tendency to increase the critical length, which marks the transition, is observed when raising the impact velocity but this increase depends also on the striking mass. The analysis reveals a specific impact velocity associated with the geometric and material properties of a tube, which causes a counterintuitive response. It is shown that a predictable initiation of buckling can be obtained for impact velocities away from this critical value, which is only a necessary condition since sufficiently large impact energy can cause a switch from progressive buckling to a global collapse. An empirical criterion for the lower and upper bounds to the critical lengths for buckling transition is proposed based on the theoretical analysis of the buckling phenomenon.

Self Similar Dynamic Expansion of a Spherical Cavity in Elastoplastic Media

SM5L_12043

Wed • 12:00 • 206

Rami Masri, David Urban

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SELF SIMILAR DYNAMIC EXPANSION OF A SPHERICAL CAVITY IN ELASTOPLASTIC MEDIA Rami Masri and David Durban Faculty of Aerospace Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel Brief Abstract The self-similar field induced by dynamic expansion of a pressurized spherical cavity is investigated for elastoplastic solids. Material behavior is described by the hypoelastic model of the non associated Drucker-Prager material with arbitrary strain-hardening. We examine in detail the external elastic field, which is expected to develop at a distance from the cavity prior to plastic yielding. A new observation that emerges from the elastic solution is the possible existence of a compressive elastic zone where yielding is prevented since the effective stress remains negative. Simple analytical solutions are given for fully incompressible elastic/perfectly-plastic material with a non-associated flow rule. In particular, we study the influence of plastic pressure sensitivity on the dynamic cavitation pressure. A few useful relations are derived for the cavitation pressure, which reveal the coupled effect of plastic pressure sensitivity and material inertia. Several numerical illustrations are presented for the solid with an associated flow rule along with a plastic boundary layer analysis for the thin singular zone near the cavity wall. An elegant expansion, in powers of Mach number, is derived for the cavitation pressure in a Mises medium

Numerical Investigation of Dynamic Shear Bands in Inelastic Solids as a Problem of Mesomechanics

SM5L_12949

Wed • 12:20 • 206

Adam Glema[(1)], Tomasz Łodygowski[(1)], **Piotr Perzyna**[(2)]

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The main objective of the present paper is the numerical investigation of dynamic shear bands in inelastic solids during impact–loaded adiabatic processes. An idea of this investigation has been inspired by recent experimental observations performed by Guduru, Rosakis and Ravichandran, *Mechanics of Materials* **33** (2001), 371–402. Their experimental work has brought deep understanding of the initiation and propagation characteristics as well as temperature field evolution of dynamic shear bands in C 300 maraging steel. A photograph of an arrested shear band in the specimen showed that the thickness of the band is about 40 μm (so it is mesoscale size range). Utilizing the finite element method and ABAQUS system for regularized thermo–elasto–viscoplastic constitutive model the numerical investigation of dynamic shear band propagation in an asymmetrically impact–loaded prenotched plate is presented. We idealize the initial boundary value problem investigated experimentally by assuming the velocity boundary condition and different material of the specimen (HY–100 steel). Shear band advance, shear band velocity and the development of the temperature field as a function of time have been determined. Qualitative comparison of numerical results with experimental observation data has been presented.

On Non-Axisymmetric Collapse of Thin Tubes

SM5L_12982

Wed • 12:40 • 206

N.K. Gupta

Indian Institute of Technology, Delhi, India

Thin walled tubes of different diameter to thickness ratios and made of aluminium and mild steel were subjected to axial compression tests in both annealed and as received conditions. The occurrence of non-axi-symmetric deformation mode shapes have been studied as a function of tube diameter to thickness ratio, annealing process, variation in tube wall thickness over the circumference, eccentricity in the shape, and boundary conditions. Cut outs in the form of circular holes were laterally drilled in some of the tubes and their influence on the mode of collapse is discussed. Influence of imperfections in tube thickness, shape, and boundary conditions on the occurrence of diamond mode of collapse is studied with the help of FE simulation. The results thus obtained compare well with the experiments. It is seen that the combined effect of thickness eccentricity and unsymmetrical in plane tube end conditions contributes significantly to the tube collapse in diamond mode.

SM6

Elasticity

Chairpersons: R. Kienzler (Germany), L. Wheeler (USA)

Stability of Compressible Elastic Blocks

D M Haughton
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SM6L_11220
Mon • 16:00 • 206

Recently a new method of obtaining a full nonlinear stability analysis of inhomogeneous deformations of arbitrary hyperelastic has been found. This method replaces the second variation condition expressed as an integral involving arbitrary perturbations, with an equivalent system of (quadratically nonlinear) ordinary differential equations. The aim of this work is twofold. Firstly, we look at the bifurcation and stability of equi-biaxial plane strain loading of a cube (one version of Rivlin's cube) for compressible materials. This has some interesting features that are not apparent for incompressible materials. Secondly, we use this simple homogeneous problem, whereby stability can be obtained directly from the second variation condition, to compare with some analytical results and numerical results obtained from the system of differential equations.

Analysis of Trabecular Bone as a Hierarchical Material

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SM6L_12189
Mon • 16:20 • 206

We study trabecular bone as a hierarchical material with a highly complex and random structure. First, we characterize the trabecular bone's structure at several structural levels: nanoscale (apatite crystal and collagen fibril level), sub-microscale (single lamella level), microscale (single trabecula level), and mesoscale (porous trabecular network level) using atomic, scanning and transmission electron microscopy and x-ray microtomography. Then, we model the trabecular bone at each structural level as a linear elastic solid employing either classical elasticity or higher order elastic theory (Cosserat theory). Modeling techniques include analytical micromechanics theories and numerical simulations involving finite element, spring network, and beam network approaches. We compare our theoretical results at each scale of observation with our experimental measurements. This study sets a framework for the analysis of other biological materials with hierarchical structures.

Investigation of Couple-Stress Effects in Elastic Bodies Under Deformation

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SM6L_12289
Mon • 16:40 • 206

One of the criteria for estimation of the applicability of the asymmetric elasticity theory is the availability of problems solved in the framework of this theory, which makes possible the corresponding experimental realization. In this work new analytical solutions to the following problems of asymmetric elasticity theory are presented. To extend the scope of problems to be solved the finite element method algorithm has been developed for solving two-dimensional problems of asymmetric elasticity theory. Numerical solutions are found for several problems in which couple effects are more pronounced than in the problems with realized analytical solutions. In this work, a series of experiments have been performed. The experimental schemes of material deformation are constructed based on the Kirsh problem of the infinite plate extension weakened by a circular hole. The experiments performed for different hole diameters have provided much evidence in support of couple-stress behavior of materials under deformation.

Modelling of Complex Elastic Crystals by Means of Micromorphic Gyrocontinua

SM6L_12434
Mon • 17:00 • 206

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We model elastic crystals with a complex deformable unit cell containing many gyroscopic subparticles. To obtain the equations of this medium we use two approaches, phenomenological and microstructural. The phenomenological approach is based on the fundamental laws of balance of mechanics. We introduce analogues for the stress and the couple tensor for this micromorphic gyroscopic continuum. For the microstructural consideration we model the interaction between subparticles as a potential interaction of general kind between rigid bodies both of force and torque nature. We sum the laws of the balance of linear and angular momentum over all subparticles of a cell. To pass from the discrete model to the continuum we expand these laws in two space co-ordinates of different scale; one scale is concerned with the distance between subparticles, and another with the cell size. This theory may have applications for the description of magnetic crystals.

Nonlocal Eshelby Entities: a One-Dimensional Example

SM6L_12122
Mon • 17:20 • 206

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An important feature for the representation of global constitutive laws for a material body is obtained by adopting the point of view that although the material may exhibit a completely general global behavior, there is still a physical meaning to be attached to the contribution of each material point to the total energy of the body. In other words, the state of the body, at a material point, is influenced by the state of all points in the body – the so-called nonlocal effect. In this paper, a nonlocal formulation has been devised to express the energy functional in two phases: the first phase indicates what the contribution of each material point (including the boundary) is, and the second phase describes how all these contributions are to be added up to obtain the total energy of the body. We then apply this model to a number of examples emphasizing that the existence of point-wise contributions in no way contradicts the global behavior of the material.

Generalized Stress Concentration Factors

SM6L_11523
Mon • 17:40 • 206

Reuven Segev
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While the traditional stress concentration factor for a given loading is the ratio between the maximal stress in a body and the stress evaluated using simplified geometry, we regard the stress concentration factor as the ratio between the maximum of a stress component over the body, and the maximum value of the applied force fields. Then, for the given loading, we consider an optimal stress distribution which is a stress field together with additional volume force density that will equilibrate the external loading and will result in the smallest stress concentration factor. Finally, the generalized stress concentration factor K is defined as the maximum of all optimal stress concentration factors for all external loading fields. The generalized stress concentration factor is clearly a geometric property of the body. It is shown that K is equal to the norm of the mapping that extends Sobolev functions to the boundary of the body.

On Invariants of the Elasticity Tensor for Orthotropic Materials

SM6S_10442
Tue • 14:30 • 215

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The vast number of composites and textured metals exhibit orthotropic symmetry. Also for biological tissues as well as in damage analysis orthotropic approximation of elastic properties is considered to be admissible. The form of stiffness tensor for linear elastic orthotropic material described by Hooke's law and its spectral analysis is widely known. As it was shown, such tensor is specified by nine independent parameters: six Kelvin moduli and three stiffness distributors specifying three coaxial eigen-states. However, definitions of three stiffness distributors with use of invariants of eigen-states was not yet proposed. Such definitions that allow to specify uniquely elasticity tensor for any orthotropic material is proposed. In order to derive the presented results spectral theorem for elasticity tensor as well as harmonic decomposition for orthogonal projectors of the orthotropic stiffness tensor are used. The proposed approach can be also applied for the stiffness tensors of lower symmetry.

Motion and Stability of an Elastic Heavy Top

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SM6S_10972
Tue • 14:35 • 215

Motion and stability of an elastic top with stress-free surface and a fixed point moving in a gravitational field is considered. The investigation is based on a direct approach in the energy momentum method split into two steps. The deformation of the top due to the gravitation and an arbitrary rotation is considered first and after that – the motion of the deformed top as a rigid one. This separation is possible since the elastic deformation is assumed static during the motion which leads to a relative equilibrium state of the top. It is stable if the top is in a stable state with respect to both of them – the deformation and the motion. The Koiter's definition for nonlinear stability with respect to the deformation and the usual Lagrange definition for stability of the motion of the deformed top as a rigid one are adopted. Relative equilibrium states are determined and criteria for stability are proved.The obtained results are applied for the case of a sleeping heavy top when the top is an elastic circular cylinder.

On Asymptotic Method of Static and Dynamic Boundary Problems Solution

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SM6S_11526
Tue • 14:40 • 215

The equations of elasticity theory for thin bodies (bars, beams, plates, shells) are singularly perturbed by small geometric parameter. For the solution of such systems an asymptotic method is suggested to be used. The solution of the corresponding boundary problem of elasticity theory consists of two qualitatively different types of solutions – inner problem and boundary layer. The ways of constructing these solutions and their conjunctions are described. We consider as classic boundary problems as well as nonclassic boundary problems from the point of view of the plates and shells theory on the facial surfaces the displacement vector components or mixed conditions are given. Asymptotics of the inner problem solution is established, it is proved that it sensitively reacts on the type of the boundary problems conditions of elasticity theory laid on the facial surfaces. Solutions of the boundary layers are constructed. The relation of the boundary layer with Saint-Venant principle is displaced. In case of the first boundary problem for a rectangle it is proved that Saint-Venant principle is mathematically exact. Iteration processes for the determination of the inner problem solution are built, the connection with the solutions on classical Bernoulli-Coulomb theory of beams, Kirchhoff-Love theory of plates and shells with precise theories on the base of softened hypothesis is established. The formula of calculation of the bed coefficient for a layered foundation is reduced. The asymptotic method is especially effective for the solution of nonclassical dynamic boundary problems. Free and forced vibrations of thin bodies are considered. The connections between the frequencies values of free vibrations and the velocities of propagation of elastic shear and longitudinal waves are established.

Exact Nonlinear Theory of Bending and Torsion of Elastic Rods

Leonid M. Zubov
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SM6S_11598
Tue • 14:45 • 215

The Saint–Venant's problems for prismatic rod, rod as sector of a circular ring and rod in the shape of a helical spring are considered on the basis of exact three-dimensional equations of nonlinear elasticity. By the Saint-Venant's problems we mean here problems of large tension, bending and torsion deformations of prismatic and curved beams loaded with end forces and moments. The central point of the investigation is the semi-inverse solution of three-dimensional equations of a non-linearly elastic body statics. The solutions found represent two-parameteric sets of finite deformations defined by Cartesian, cylindrical or special curvilinear coordinates. At these deformations the initial three-dimensional system of nonlinear equilibrium equations is reduced to a system of equations with two independent variables. By means of semi–inverse solutions, spatial problems of nonlinear elastostatics are reduced to two–dimensional boundary value problems for flat domain in the shape of cross-section of a prismatic or curved rod. The numerical solutions of two-dimensional boundary value problems on a cross-section of a beam are found with the use of variational methods of nonlinear elasticity. The results listed above are also extended to nonlinearly elastic bodies with microstructure possessing couple stress.

Axisymmetric Force Solution for a Semi-Infinite Cubic Solid

SM6S_11901
Tue • 14:50 • 215

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(2) *Laboratory of Applied Mechanics, Besancon, France*

An exact three-dimensionnal analysis is developped for an axisymmetric loading on the surface of a half-space composed by an anisotropic cubic medium. The loading is assumed to be parallel to the elastic symmetry axis of the material. The general solution of the axisymmetric problem for a homogeneous medium is given for a surface concentrated loading by exact integral expressions, and from it a closed form solution for a point force is deduced. The numerical results are performed to show the anisotropic effect with isovalue curves of stress.

Generalization of the Eshelby Method for Solving Elasticity Problems with Phase Transformations and for Piecewise Homogeneous Bodies

SM6S_11948
Tue • 14:55 • 215

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The elastic problems with phase transformations and for piecewise homogeneous bodies are considered. Generalization of Eshelby's method is developed. This generalization enables to consider both frontal and distributed phase transformations in inclusions of arbitrary shape. The stress state is investigated for the following problems: 1. Phase transformation of an inclusion accompanied by a change of the shape and the sizes of the inclusion; 2. A problem for an inhomogeneity of an arbitrary shape; 3. Phase transformation of an inclusion accompanied by a change of its shape, sizes and also elastic constants. A system of integral equations relatively the components of the stress tensor inside the inclusion is derived for the problems 2 and 3. When the inclusion is an elliptical cylinder the system of equations is solved analytically and explicit analytical expressions for the stress tensor both inside and outside the inclusion are obtained.

On Calculating Effective Elastic Properties of Media with Inclusions: Asymptotic Representations and Areas of Their Applicability

SM6S_11949
Tue • 15:00 • 215

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A rather general solution for calculating effective elastic moduli of media with isolated inhomogeneities (disperse composites) based on Eshelby's method of equivalent inclusion is written in the explicit form. A number of particular cases are obtained by limit transitions. For arbitrary flat ellipsoidal inclusions three particular cases have been distinguished: extremely rigid inclusions, extremely soft inclusions, inclusions of moderate rigidity. Similar formulas were obtained for needle-like inclusions. Some of the solutions coincide with the known ones, while the others appear to be new. The theoretical estimations and numerical calculations were made to assess the areas of applicability of the asymptotics, which is determined by two parameters: ratio of moduli of inclusions and matrix, and aspect ratio of inclusions.

An Exactly Solvable Microgeometry in Torsion

SM6S_11960
Tue • 15:05 • 215

Tungyang Chen
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Finding a geometric configuration that is amenable to an exact characterization of the torsional rigidity is a relatively new territory that has only recently begun to be explored. Here we present our latest finding of an exactly solvable microgeometry in torsion for a cylindrical shaft with arbitrary cross section. The idea is to introduce a successive construction of neutral multicoated inclusions under torsion. We show, for a given cross-sectional shape of the host shaft, how to design permissible multicoated inclusions, with phase shear rigidities and area fractions appropriately balanced, so that after its introduction into a homogeneous host shaft the warping field in the host shaft will not be disturbed. We prove, without solving any field equations, that the torsional rigidity of a given cross section filled with an assemblage of multicoated inclusion can be exactly determined in a simple, explicit form.

A New Nonlinear Constitutive Relation for Magnetostrictive Materials

SM6S_11998
Tue • 15:10 • 215

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To overcome some deficiencies in previous constitutive relations of magnetostrictive materials, a new constitutive relation for a Terfenol-D rod is proposed in this paper to describe the non-linear and coupling constitutive features of the rod based on its magnetoelastic coupling mechanism. In comparison with the previous constitutive relations, the new constitutive equations can effectively not only predict the magnetostrictive strain values of Terfenol-D rods under various compressive pre-stresses in various region of the magnetic fields, but also describe the effect of the pre-stress on the maximum magnetostrictive strain and the magnetization of a Terfenol-D rod as well as the effect of the pre-stress and the magnetization on the Young's modulus. Moreover, it is convenience for the new relation to be used in engineering application since the constitutive constants adopted in the new model are easily measured in experiments.

Nonlinear Radial Oscillations of Anisotropic Thin-Walled Cylindrical Tubes

SM6S_12039
Thu • 14:30 • 215

G. H.-S. Maluleke, D.P. Mason
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Nonlinear radial oscillations of a thin-walled cylindrical hyperelastic tube with either radial, tangential or longitudinal transverse isotropy are investigated. For isotropic materials and longitudinal transverse isotropy, the Ermakov-Pinney equation is obtained. It is well known that it has three Lie point symmetries from which a nonlinear superposition principle can be derived. The differential equations for radial and tangential transverse isotropy each have one Lie point symmetry which exist only for special values of the parameters and for special time dependent net applied pressures. The differential equations are transformed to autonomous equations using the Lie point symmetries. The results are compared with radial oscillations of an isotropic cylindrical tube.

New Analytical Approach for Investigation of Non-Stationary Dynamics of Media with Moving Inhomogeneities

SM6S_12324
Thu • 14:35 • 215

Serge N. Gavrilov
IPME RAS, St. Petersburg, Russia

Non-stationary processes in various elastic media with moving inclusions like material point bodies, phase boundaries, defects, are under investigation in this paper. The law of motion for an inclusion is considered to be unknown. Small strain approximation is used. The interaction of inhomogeneities with the continuum is described by configurational forces (internal and external). This statement leads to necessity to consider nonlinear (because configurational force is a quadratic quantity) non-stationary problems. A new asymptotical approach for problems of such kind is suggested. The solution of simplest model problem (a point mass moving along a string on an elastic foundation) is given and discussed.

Agmon's Condition for Incompressible Elasticity: a Variational Formulation

SM6S_12354
Thu • 14:40 • 215

Gearoid Mac Sithigh
Univ. of Mo-Rolla, Rolla, USA

In a previous paper, I developed the analogues for incompressible, finite, elasticity to results obtained by Ball and Marsden, and by Simpson and Spector for the compressible case. Specifically, a condition of quasiconvexity at the boundary, its weak version-the localized second variation condition, and conditions necessary and sufficient for the truth of the latter were found. Here, in emulation of results of Mielke and Sprenger for compressible elasticity, I recast the aforementioned necessary and sufficient conditions in an equivalent, variational form. In nonsingular cases, Agmon's condition is shown to be equivalent to the condition that a certain algebraic Riccati equation should possess a positive-semidefinite solution. The implications of this condition are explored for various special situations.

Axisymmetric Problem for an Elastic Medium with a Spherical Inclusion When There Is a Crack at the Interface

SM6S_12520
Thu • 14:45 • 215

Iryna V. Lebedyeva[(1)], Myhaylo A. Martynenko[(2)]
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(2) *Ukraine National University of Food Technology, Kyiv, Ukraine*

A problem on the stressed state of an elastic medium with a spherical inclusion when there is a crack at the interface is solved by exact methods of the linear theory of elasticity. At first the problem is reduced to an interrelated system of paired equations with respect to the Legendre functions, and then – to a system of singular integral equations relative to two unknown functions. The behaviour of the equation solutions is studied near the interface circle of a spherical section. The case is examined when the cross-section surfaces are under normal internal pressure of constant intensity. This problem is linked to the study of stressed state of high-strength composit materials with low-percentage content of the spherical dispersed particles.

Truncated Elastic Wedge under Torsional Load

SM6S_12575
Thu • 14:50 • 215

Vyacheslav V. Lyakh
Dept Theoretical & Applied Mechanics, Kiev National Taras Shevchenko Univ., Kyiv, Ukraine

This talk deals with an analytical solution of the boundary-value problem of plane elasticity for a truncated infinite wedge of an arbitrary opening angle. The flanks of the wedge are free of traction. Its circular boundary is subjected to torsional load due to the given tangential displacements or the moment-replacement loading prescribed. The main goal of the paper is to verify whether the Carothers paradox is actual when the statement of the Carothers problem is modified and more rigorous. Two powerful methods, viz. the method of superposition and the method of homogeneous solutions, are introduced and compared. By means of them the boundary-value problem amounts to solving an infinite integro-algebraic system of equations and an infinite system of algebraic equations, respectively. Our numerical simulations with these systems provide graphical results. The distributions of stresses in some principal cases are presented. Numerical results turn out to be in a complete agreement with results by Neuber.

Homogenization of Triply Periodic Elastic Media with Random Imperfections

SM6S_12685
Thu • 14:55 • 215

Valeriy Buryachenko
University of Dayton Research Institute, Dayton, USA

Triply periodic particulate matrix composites with random imperfect unit cells are analyzed by three new different versions of the multiparticle effective field method (MEFM, see Buryachenko, Appl. Mech. Review 2001, 54(1), 1-47). The first one is a generalization of the version of the MEFM proposed for the analysis of the perfect periodic particulate composites and based on the choice of a comparison medium coinciding with the matrix. The second one is a Monte Carlo simulation. The third method uses a decomposition of the desired solution on the solution for the perfect periodic structure and on the perturbation produced by the imperfections in the perfect periodic structure. The fundamentally new last method is based on the choice of a comparison medium coinciding with the perfect periodic structure.

On the Impact Law in Elastic Plate-Like Bodies

SM6S_12987
Thu • 15:00 • 215

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ipartimento di Ingegneria Strutturale e Geotecnica, Universita di Genova, Genova, Italy

We study the problem of normal impact of a rigid sphere on a circular elastic plate whose thickness is not so small with respect to its diameter, so the Kirchhoff's theory cannot be applied. For plate-like bodies of this kind it is convenient to apply a theory proposed by Levinson (1985). To describe mathematically the pressure distribution and the extent of the contact area we adopt the Hertz's theory. The solution of the equations of the three dimensional theory of the elastodynamic is obtained by using a semi-inverse method and a solving technique based on the method of the separation of variables By combining these theories we derive an impact law in elastic plate-like bodies.

SM7

Experimental methods in solid mechanics

Chairpersons: I. Emri (Slovenia), J. Freire (Brasil)

An Optical Strain Rosette/Ring-Core Method Applied on Laser Weld

SM7L_10492
Wed • 11:00 • 123

Wei Ren, **Keyu Li**
Oakland University, Rochester, USA

Residual stresses are induced in manufacturing processes and exist in many industrial parts. For the measurement on small areas with high stress gradients,the resistance strain rosette/hole-drilling method is no longer suitable to be used. As an ideal alternative, an optical rosette-interferometric strain/slope rosette (ISSR) has short gage length (on the order of 100 micrometers) and noncontacting nature. It can measure displacements, strains and slopes by tracing the shifts of interferometric patterns. The miniature ISSR is suitable to be used in the measurement on very small areas with high stress gradients. Ring-core cutting more fully relieves the residual stresses and has higher sensitivity than hole-drilling. The newly developed ISSR/ring-core cutting method is discussed in this paper. Basic principles are introduced and an application performed on a laser weld demonstrates its advantages over the conventional methods.

Phase Transitions and Mechanical Properties of Ternary Chalcogenides

SM7L_12272
Wed • 11:20 • 123

Vladimir V. Shchennikov(1), Sergey V. Ovsyannikov(1), Natalya Yu. Frolova(1), **Vsevolod V. Shchennikov**(2)
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(2) *Institute of Mathematics and Mechanics of RAS, Yekaterinburg, Russia*

In the present work the mechanical properties of mercury semiconductors in the vicinity of the phase transitions were studied. Under the high hydrostatic pressure treatment the macroscopic bending of samples was observed, that gave the evidence of high plasticity of these materials near the phase transition point. The influences of chemical substitutions in cation and anion sublattices on the properties of ternary chalcogenides were analysed.The results obtained are: observation of macroscopic bending and plastic deformation of the samples undergone a high hydrostatic pressure treatment above the phase transition point Pt, microhardness dependencies on content of substitution atoms x, irreversible arising of H(x) after reversible phase transition sphalerite (B3) – cinnabar (B9) controlled by resistivity measurements. The dependencies of Pt (x) and H(x) obtained were explained quantitatively by modern theoretical approaches taking into account the recent neutron and synchrotron data of lattice transformation under variation of x and P. A correlation between electronic and mechanical properties of ternary chalcogenides near the phase transition point has been revealed. High plasticity has been established of materials in the vicinity of phase transition under pressure. The mechanism of phase transitions from tetrahedral bonded to octahedral bonded lattice at Hg, Cd and Zn chalcogenides seems to be similar, so the behaviour of mechanical properties at phase transition may be the same for this family of ternary semiconductors.

SHPB Technique for Identification of Complex Modulus Under Condition of Non-Uniform Stress

SM7L_12551
Wed • 11:40 • 123

S. Mousavi, U. Valdek, K. Welch, B. Lundberg
The Angstrom Laboratory, Uppsala, Sweden

In classical SHPB (Split Hopkinson Pressure Bar) testing, the specimen is assumed to be in equilibrium and have axially uniform stress. An SHPB procedure was developed for non-parametric identifi cation of complex modulus under conditions of non-equilibrium and axially non-uniform stress. A simplifi ed procedure was also established. Tests were carried out with polymethyl methacrylate and aluminium bars, and polypropylene specimens having diameter 20 mm and lengths 10, 20, 50 and 100 mm. The complex moduli identifi ed with the full pro-cedure are in good or fair agreement with each other and with published results in the fre-quency range 1–10 kHz for all specimens with polymethyl methacrylate bars and for the

10–50 mm specimens with aluminium bars. With the simplified procedure, identical with classical SHPB 1-wave procedure, the magnitude of the complex modulus was overestimated. The overestimation increases with frequency, specimen length and the magnitude of the specimen-to-bar characteristic impedance ratio.

Estimation of Principal Axes of Inertia

SM7L_10691
Wed • 12:00 • 123

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In the previous studies concerning the inertia characteristics of a rigid body, the components of the inertia tensor, that is, the moments and the products of inertia were mainly estimated. However, it is advantageous to obtain the principal axes and the principal moments of inertia of a rigid body. This paper presents a new experimental method to measure the principal axes of a rigid body without the principal axis transformation. A rigid body is suspended from a vertical axle by a slender rod. Each end of the rod has a universal joint. And the axle rotates with a constant angular velocity. The experimental results for a cylinder and a rectangular prism agreed well with the theoretical results. And the principal axes of a golf club head were estimated experimentally.

Investigation into Variable Contact Load Effects on Fretting Fatigue Behaviour of Ti-6Al-4V

SM7L_11622
Wed • 12:20 • 123

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Fretting fatigue behavior in titanium alloy Ti-6Al-4V, a common material used in commercial & military aero-engines, under realistic loading conditions was investigated which involve bulk load on substrate, tangential and contact loads on fretting pads, all cyclic. Therefore, a test set-up was developed which provided capability to apply these three loads as cyclic. Several tests were conducted using cylinder-on-flat configuration. These tests showed that fretting fatigue lives are reduced under variable contact load relative to their counterparts under constant contact load. Finite element analysis was used to compute a critical plane based fatigue parameter which was then evaluated based on their ability to predict crack initiation location/orientation angle, and number of cycles to fretting fatigue crack initiation. These predictions were compared with their experimental counterparts. These comparisons showed that fretting fatigue crack initiation mechanism in the titanium alloy is governed by both shear stress and normal stress on critical plane.

Electromagnetic-Resonance-Ultrasound Microscopy with Isolated Langasite Oscillator for Measuring Local Elastic Constants of Multi-Phase Solids

SM7L_10873
Wed • 12:40 • 123

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We developed a new acoustic-resonance microscopy, electromagnetic-resonance-ultrasound microscopy (ERUM), to map a material's elastic constant in a local surface region. It is based on the resonance-frequency shift of a langasite ($La_3Ga_5SiO_{14}$) crystal excited by an electric field from a surrounding solenoid coil: no electrodes were used. The acoustic coupling is made only at the tip of the crystal touching the specimen surface. Analysis on the dynamic contact stiffness with the Rayleigh–Ritz method deduced the local elastic constant from the resonance frequency. As an illustrating example, Young's modulus distribution of a duplex stainless steel is presented, which shows good agreement with the existing study.

The Whole Field Non-Destructive Optical Slicing Method in Three-Dimensional Photoelasticity

SM7S_11556
Thu • 14:30 • 244A

Michael N. Osipov, Vychislav K. Emelin
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The whole field non-destructive optical slicing method in three-dimensional photoelasticity is based on the analysis of the scattered light field is presented. This method is based on the modification of the scattered light photoelasticity method. The thin optical slice of the photoelastic model is formed by two plane sheets of light emitted from the same laser beam. The two-dimensional scattered light field from the two plane sheets is analyzed by analyzer in the direction orthogonal to these plane sheets. For the determination of the stressed state in the thin optical slice is suggested analyse of the two-dimensional

scattered light field from each plane sheets and theirs interference. The theoretical bases of this method and the boundary application are presented. Experimental optical arrangement with a C.C.D. camera is suggested to put this method in to practice.

Porous Ceramics – Experimental Research and Modelling

SM7S_11617
Thu • 14:35 • 244A

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The paper presents the results of experimental research and modelling of porous ceramics under uniaxial compression. Alumina specimens with the porosity up to 30% were loaded axially, then unloaded and loaded again with a certain increase of the load. The loading-unloading process was stopped at the failure of the sample. The testing allowed to estimate approximately the influence of porosity on the initial elastic constants and further on change of elastic properties of ceramic material due to damage development. A scalar damage parameter evolution was also analysed.

Critical Sensitivity in Rock Experiments

SM7S_11764
Thu • 14:40 • 244A

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Rupture in heterogeneous brittle media displays catastrophe and sample-specificity. Hence, the prediction of rupture is still questionable due to its complexity. Previous analytical works and numerical simulations suggested that critical sensitivity might be a possible common feature prior to catastrophe in these media. To validate the concept of critical sensitivity, a series of experiments has been conducted. 167 gabbro samples were compressed uniaxially and the damage process was observed with acoustic emission. The experimental results do support the concept of critical sensitivity reasonably. In addition, we found that the experimental results of sensitivity display fluctuations, while the sensitivity obtained from a previous theoretical model is a smooth curve. It is found that the discreteness of the distribution function of the mesoscopic unit's threshold might be a reason for the fluctuations shown in the critical sensitivity.

Non-Gap Design Method and Test for Post-Tensioned Prestressed R.C. Structure

SM7S_12287
Thu • 14:45 • 244A

Li Lijuan, Liu Feng, Fu Ganqing, Lu Weiwen
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A non-gap design method is introduced, which includes using post-poured concrete strips, cold-rolled ribbed welded steel grids and post-tensioned pre-stressed concrete beams. The purpose of the method is to resist cracking of the slabs.The method was used despite the general requirement for setting gaps in slabs exceeding 40 m long in the Chinese code of practice. The purposes of the test are to confirm that the concrete strain is within the desired limits and the stress can be transferred to slabs evenly from beams as expected. The test was carried out before the pre-stress was applied and lasted for one year after pre-stress construction finished. The stresses and their variations on different slabs and at different locations were measured. Test results showed that the strains met the requirements of the code of practice and the new design technique used in this new building is effective and can be extended to the design of similar structures.

IN-SITU Observation of Fatigue Crack Growth in Carbon Steel

SM7S_12666
Thu • 14:50 • 244A

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One of the main features associated with small fatigue crack growth is that they frequently exhibit deceleration when they approach microstructural barriers such as grain boundaries. In-situ observation of crack propagation can give interesting information about crack development in multi-phases materials. In this paper authors present their results of crack propagation behaviors in steel samples under cycling loading, obtained using optical microscope with in-situ recording device. For measurements was chosen, common used carbon steel (0.45% weight C). Because mechanical and morphological properties of pearlite and ferrite are different so crack propagation behavior should be different, what is very interesting from material design point of view, where even grain boundary properties could play significant role. Local behavior is not well described

by classical fracture theory, which assuming material as continuum solid body, so authors focused on this problem closer in the paper.

New Solutions in Experimental Modal Analysis of Mechanical Structures

SM7S_12799

Thu • 14:55 • 244A

Tadeusz Uhl, Krzysztof Mendrok, Wojciech Lisowski, Piotr Kurowski
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One of the most intensive investigates problem in modal analysis is automation of identifi cation procedure. In the area two main problems can be distinguish: – identifi cation of modal properties of the mechanical systems if structure of model is not known (model order, location of excitation, predicted mode shapes, etc.) – tracking of modal parameters during structure operation (real time modal analysis). Both problems are under investigation at the University of Science and Technology – AGH from many years. Proposed methods and software tools helping to solve above problems are presented in the paper. The methods formulation, simulation and experimental validation are discussed. Case studies on application of methods for modal analysis and diagnostics for complex mechanical structures (airplane and civil structure) are shown.

SM8

Fatigue

Chairpersons: J. Dominguez (Spain), K. Reifsnider (USA)

A Microscopic Mechanics Model

SM8L_11686

Fri • 11:00 • 219

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In the present work, an analytical micromechanics model is proposed to describe the influence and interaction of fatigue and creep. Here, a recently proposed fatigue crack growth model by the present authors is adopted which views the fatigue crack growth process as the intermissive elastic cleavage fracture of the dislocation free zone (DFZ). The effects of cyclic loading make the plastic zone hardening (or softening), thus raise the stress level in DFZ and bring it to fracture. The calculated curves exhibit three different stages of fatigue crack growth which is in general agreement with the experimental observation. The fatigue-creep interaction model is such that the fatigue damage is represented by the climbing dislocations and the creep damage is represented by the micro void ahead of the dislocation pile-up. The dislocation distribution function is determined by the integral equation of the equilibrium condition of dislocations. For the tensile stress distribution in DFZ, we adopt the cohesive zone model. The bridging relation is taken of the form as nonlinear atomic action. When the bridging stress within DFZ increases up to the tensile strength, fracture takes place. The growth of the void enhances the stress concentration ahead of crack-tip, thus promote the growth rate of fatigue crack.

Stress Concentrations Caused by Dislocations at the Free Surface

SM8L_11927

Fri • 11:20 • 219

Steffen Brinckmann, Erik Van der Giessen
University of Groningen

The key to understand fatigue lies in the understanding of fatigue crack initiation at the free surface. In turn, stress concentrations are essential to predict and comprehend the nucleation of the crack. Stress concentrations can arise from surface roughness, but also from dislocations in the bulk material. Persistent Slip Bands (PSBs) are found to be the primary structure of dislocations in fcc crystals. Brown and Ogin (1984) proposed a model which leads to logarithmic stress concentrations at the free surface. In this contribution edge dislocations are modeled as parallel line singularities which can move on multiple slip systems. We study a two-dimensional region next to the free surface in which plasticity is seen by dislocation movement. We compare the continuum solution of Brown with static and dynamic discrete dislocation simulations to show that his prediction of stress concentrations caused by PSBs at the free surface assumes a rather unphysical limiting situation.

Influence of Contact Conditions on Fretting Fatigue Under Spherical Contact

SM8L_10698

Fri • 11:40 • 219

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This work analyzes the effect in fretting fatigue (stresses, stress intensity factor, eccentricity of the stick zone and estimated life) with spherical contact of several assumptions needed to calculate the stresses beneath the contact. These assumptions are: i) supposing plane stress or plane strain when introducing the bulk stress on the element; ii) taking or not taking into account the eccentricity of the stick zone due to the bulk stress. The stresses in the different conditions are compared using analytical solutions for this problem and using the Finite Element Method (FEM). The stress intensity factor is compared analytically using a weight function. The eccentricity of the stick zone is compared for plane stress and plane strain also analytically and with FEM. The influence on the estimated fretting fatigue life is studied using a model developed by the authors. It can be concluded that more realistic results and lower estimated lives are obtained using plane stress and taking into account the eccentricity

Characteristics of Very-High-Cycle Fatigue for a High Carbon Low Alloy Steel

SM8L_12391
Fri • 12:00 • 219

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This paper described an experimental investigation on the behavior of very- high-cycle fatigue (VHCF) for a high carbon low alloy steel (main composition: C 1% and Cr 1.5%). Fatigue testing was carried out in a rotating loading machine with a cyclic frequency of 52.5 Hz. The specimen is of hour-glass cylindrical type with the minimum section diameter of 3 mm. The results showed that, for the number of cycles to failure between 10^6 and $4 \cdot 10^8$ cycles, fatigue cracks almost initiated in the interior region of specimen and originated at non-metallic inclusions. The fatigue life of specimens with crack origin at the interior of specimen is longer than that with crack origin at specimen surface. Fractography observations of scanning electron microscopy indicated that fi sh-eye patterns were the main characteristics of VHCF, which was responsible for the predominant part of fatigue life. The mechanism of VHCF was discussed in terms of fracture mechanics.

Stimulated Simulation Methods for Accelerated Fatigue Characterizations

SM8L_12433
Fri • 12:20 • 219

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Reifsnider and Case (2002) have recently discussed a methodology for combining the effects of multiple physical phenomena (like fatigue and creep) to estimate long-term performance metrics (like remaining strength and life) in the presence of changes in material states and stress states. This methodology was originally conceived to enable the application of composites to high-performance aircraft, including the F-16 in the 1980's, with the help of several industrial partners. The most common operative form of that methodology is a simulation code (called MRLife) which combines data from physical measurables with rate equations and kinetic models of material state changes to simulate, in real time, the performance of composite materials and systems. Halverson has taken the methodology one step further and has shown that one can improve the predictions of performance for a specifi c component by using at least one of the physical measurables to "stimulate" the simulation in real time, to make a greatly improved prediction of future performance for that specifi c component. That "stimulated simulation" is the subject of the present paper. In particular, the authors will discuss the use of stimulated simulation to accelerate the characterization of the fatigue response of heterogeneous materials such as specialized composites (including functional composites used in fuel cells). Examples of the accelerating effects of stimulation will be presented. The integration of statistical considerations in the method will also be discussed.

Erergy Release Rate Approach for Delamination in a Fatigue Crack Configuration in Glare

SM8L_12217
Fri • 12:40 • 219

Rene Alderliesten
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Glare is a Fibre Metal Laminate developed at Delft University of Technology, consisting of thin aluminium and S2-glass fi bre layers, and it will be applied in the upper fuselage of the Airbus A380. Due to the brigding fi bres, the fatigue crack propagation behaviour is excellent, showing very small and approximately constant crack growth rates. From previous investigations it was found that the bridging stress varies along the crack length and depends on the delamination shape. The bridging stress needs to be determined, to describe the stress intensity at the crack tip in the aluminium layers. To incorporate the delamination, the delamination growth was investigated using the 2D delamination specimen confi guration. For this confi guration the Energy Release Rate can be derived, which can be related to the delamination growth using a Paris type relation. This relation is determined for different Glare grades (unidirectional and cross-ply) and corrected for the effect of the stress ratio.

Analysis on Crack Growth and Fatigue Life of Welded Bridge Components with Initial Crack

SM8S_10184
Thu • 14:30 • 134B

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This work aims to investigate the behavior of crack growth and assess fatigue life of welded components with initial crack in bridges under traffi c loadings. It is assumed that fatigue crack in welded bridge components remains semi-elliptical shape

during crack propagation. Considering the damage evolution on the tip of cracks and its influence on crack propagation, the equation of crack propagation is deduced on the basis of the theory of continuum damage mechanics and fracture mechanics for welded bridge components under traffi c loading. The method on calculation of stress concentration factor for welded components is then improved by using the geometric shape factors from the BS7910. The proposed method is adopted to calculate crack growth and fatigue life of two types of welded specimens with experimental results. The calculated result shows that the proposed method is reasonable and some of useful results on behavior of fatigue crack growth are obtained.

Fatigue Investigations into a Composite Glider Structure

SM8S_11371
Thu • 14:35 • 134B

Miroslaw Rodzewicz, Krystyna Majorkowska-Knap
Warsaw University of Technology, Institute of Aeronautics and Applied Mechanics, Warsaw, Poland

The increasing demand for high strength-to-weight ratio structures in the construction of advanced aeronautical and aerospace vehicles, led to continuously growing interest on composite materials, and to development of new smart materials. The design for modern gliders structure will rely on FRPs to meet weight criteria. Due to the economic and safety criteria, the structure of them must be durable over an expected life time at environmental conditions. The authors present results of fatigue investigations into the primary structure of composite glider undertaken at the WUT: Institute of Aeronautics and Applied Mechanics. The specimens representing the main joints of wings and fuselage, as well as the wing spar root were tested, since they form a most representative part of the glider structure. The integral fatigue tests of the wings-fuselage system were fi nally performed. This vehicle construction requirement has lead to extensive research work on increasing application of new composite materials.

Fatigue Life Prediction Considering Residual Stress Relaxation

SM8S_11737
Thu • 14:40 • 134B

Byeongchoon Goo, Sungyong Yang
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Residual stress relaxation during fatigue tests and the metallurgical difference between weld metals and parent materials play an important role in fatigue behavior. We studied the effect of welding residual stress relaxation on the fatigue behavior of a material, JIS SM 490 A, with yielding strength of about 350 MPa and tensile strength of about 520 MPa. Fatigue tests of X-grooved butt weld plates under tensile loading and unloading at loading ratio, R=0.1, were carried out to failure. The dimension of the specimens is 200 25 10 mm. We developed a fatigue life prediction model based on a nominal stress approach considering residual stress relaxation. The stress relaxation is assumed to be a function of applied load and loading cycles. Finite element analysis of residual stress relaxation was carried out on an X-grooved butt weld specimen. The estimated fatigue lifetime was compared to experimental results.

Effects of Frequency Temperature and Loading Waveform on Fatigue Crack Growth Rate in Steel 15Kh13MF

SM8S_11920
Thu • 14:45 • 134B

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Department of Material Science, Ternopil Ivan Puluj State Technical University, Ukraine

The tests were carried out on bimaterial single edge notch tension specimens made of steels 15Kh13MF/25Kh1M1F. The test temperature was 293, 668, 873 K, stress ratio $R = 0$, loading frequencies 0.1 and 0.01 Hz. The load waveform was triangular and trapezoidal with hold time 10 sec. Decrease of the loading frequency from 0.1 to 0.01 Hz leads to the decrease of the fatigue crack growth (FCG) rate for the SIF range $K < 26$ MPa·m$^{0.5}$ In coordinates $da/dN - K$ fatigue crack growth rate in 15Kh13MF steel is not sensitive to the testing temperature. But FCG rate increases in 5–7 times, when the temperature raises from 293 to 873 K depending on the CTOD and of J-integral ranges. Tempering causes the increase of creep-fatigue crack growth rate at 668 K, tempering at 873 K causes the decrease of it in 5–6 times as compared with the triangle form of loading cycle.

A Study on the Effect of Residual Stress on a Fatigue Bahavior

SM8S_12001
Thu • 14:50 • 134B

Seung-Yong Yang, Byeongchoon Goo
National Research Lab., Korea Railroad Research Institute, Uiwang-City, Korea

The effect of residual stress on fatigue crack growth was investigated in terms of fi nite element analysis. Simulations were performed on a CT specimen in plane strain. An interface-cohesive element that accounts for damage accumulation due to

fatigue along the notch direction has been used. Numerical results show that fatigue crack growth rate slows down when compressive residual stress field exists in front of the crack tip.

Probabilistic Analysis of Fatigue Crack Growth using Moment Method

SM8S_12034
Thu • 14:55 • 134B

Ki-Seok Kim, Hyun Moo Koh, Hae Sung Lee
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This paper presents a new incremental approach to estimate the path and the probabilistic distribution of the fatigue crack growth using the dual boundary element method. Paris-Erdogan law and maximum circumferential stress criterion are adopted to simulate the incremental growth. A new iterative scheme using a secant method is proposed to model curved crack growth. To predict the distribution and failure probability of fatigue crack, the second-order moment method using lognormal distribution is incorporated with the proposed incremental formulation. For each loading step, the distribution of crack length is approximated by those of the previous step. The failure probability is directly predicted from the distribution derived at each loading step. Proposed moment method produces a good approximation of the crack distribution compared with the results of the Monte Carlo simulation. For the calculation of the failure probability, moment method needs much less computational cost than the first-order reliability method.

Modelling Fatigue Crack Growth with Time-Derivative Equations

SM8S_12228
Thu • 15:00 • 134B

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Predicting fatigue crack growth in metals remains a difficult task since available models are based on cycle-derivative equations, while service loads are often far from being cyclic. A set of time-derivative equations for fatigue crack growth is proposed here. For this purpose, three global variables and their thermodynamics counterparts are introduced in order to characterize the state of the crack: the crack length, the plastic blunting at crack tip and the elastic opening of the crack. The model is based on the thermodynamics of dissipative processes with a special attention paid to the elastic energy stored inside the crack tip plastic zone. Two laws were finally used: a crack propagation law, and an elasto-plastic constitutive behaviour for the cracked structure. The model was also implemented and tested. It reproduces successfully typical effect under monotonic and non-monotonic fatigue.

Modelling of Short Fatigue Crack Growth in a Metal in HCF Range

SM8S_12914
Thu • 15:05 • 134B

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Military University of Technology, Depart. of Mechanical Engineering, Warsaw, Poland

Modelling of short fatigue crack growth in a polycrystalline metal in high cycle fatigue range (HCF) is the subject of the paper. Special attention is paid on the short crack behaviour under reversed cyclic torsion. Short fatigue crack growth is analysed in three stages: as a small crack of a size comparable to the grain size (stage I), a microstructurally short crack (stage I-like) and a physically short crack (stage II). Stages I and I-like crack growth are strongly microstructurally depended and the crack advances under mode II. To predict stage-I and stage I-like crack growth a fracture mechanics approach is adopted here. On the contrary, stage II crack growth is modelled using a probabilistic approach. Main equations of dynamics of stage II crack growth are both the Fokker-Planck partial differential equation and the propagation equation by means of crack tip opening displacement defined on the base of the Dugdale-Barenblatt model.

SM9

Fracture and crack mechanics

Chairpersons: D. Gross (Germany), A. Needleman (USA)

Branching Instability of Brittle Fracture

SM9L_10338

Tue • 11:00 • 231

M. Adda-Bedia
LPS, ENS Paris, Paris, France

A new method for determining the elastodynamic stress fi elds associated with the propagation of antiplane branched cracks is presented. The exact dependence of the stress intensity factor just after branching is given as a function of the stress intensity factor just before branching, the branching angle and the instantaneous velocity of the crack tip. The jump in the dynamic energy release rate due to the branching process is also computed. Applying a growth criterion for a branched crack, it is shown that the minimum speed of the initial single crack which allows branching is equal to $0.39c$, where c is the shear wave speed. At the branching threshold, the corresponding bifurcated cracks start their propagation at a vanishing speed with a branching angle of approximately 40 degrees. Using these exact results, the branching of a single propagating crack under mode I loading is also considered and the critical velocity for branching is computed.

Interaction of Propagting Cracks and Shear Waves

SM9L_12378

Tue • 11:20 • 231

Daniel Bonamy[(2)], **Krishnaswamy Ravi-Chandar**[(1)]
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(2) *Commissariat A l'Energie Atomique DSM/DRECAM/SPCSI, Gif sur Yvette Cedex, France*

Shear waves generated from an ultrasonic transducer are used to twist dynamically growing crack fronts; the response of crack front to such external perturbations is examined in order to investigate the primary cause of surface roughening in brittle materials. The response of the crack front is found to be linear in amplitude and frequency of the perturbing wave and without persistence. The response to random perturbations, introduced by localized material inhomogeneities at the free surface, is also discussed. The implications of these results to the existence of the theoretically predicted crack front waves are also discussed.

Massively Parallel Simulations of Dynamic Fracture and Fragmentation of Brittle Solids

SM9L_12171

Tue • 11:40 • 231

Irene Arias[(1)], Jaroslaw Knap[(1)], Anna Pandolfi[(2)], Michael Ortiz[(1)]
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(2) *Politecnico Milano, Milano, Italy*

We present the results of massively parallel numerical simulations of dynamic fracture and fragmentation in brittle solids. Our approach is based on the use of cohesive models to describe processes of separation leading to the formation of new free surface. Within the framework of the conventional fi nite element analysis, the cohesive fracture models are introduced through cohesive elements embedded in the bulk discretizations. These cohesive elements bridge nascent surfaces and govern their separation in accordance with a cohesive law. In this work we assess the validity of the cohesive models and the computational algorithms. We present careful quantitative validation against experiments designed specifi cally for this purpose by A.J. Rosakis *et al. Moreover, the branching instability is investigated numerically. Finally, in relation to the mesh dependency observed for under-resolved meshes, we explore the concept of renormalization of cohesive laws.*

Disorder of the Front of a Tensile Tunnel – Crack Propagating in Some Inhomogeneous Medium

SM9L_12393
Tue • 12:00 • 231

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We study the time evolution of the shape of the front of a tunnel-crack loaded in mode I and propagating quasistically according to some Paris-type law in some inhomogeneous material. The two parts of the front are assumed to remain symmetrical for simplicity, and differ only slightly from straight lines at each instant, and a first-order perturbation approach is used. The degree of geometrical disorder of the front is evaluated via the autocorrelation function of the perturbation. It is found that this autocorrelation function increases without bound for large times. Its rate of growth is much larger than for the problem, envisaged by Rice and coworkers, of a semi-infinite crack propagating dynamically in a brittle medium with random toughness. This difference essentially arises from presence of some characteristic length in the problem envisaged here, namely the mean half-width of the crack. This induces an effect of instability of crack front perturbations with large wavelengths which is typical of finite crack geometries.

3D Microstructural Effects on Plane Strain Ductile Crack Growth

SM9L_10910
Tue • 12:20 • 231

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Ductile crack growth in structural metals occurs by the nucleation, growth and coalescence of microvoids. Quite typically, this mechanism involves two populations of void nucleating particles; larger inclusions that nucleate voids rather early in the deformation history and smaller particles that nucleate voids at larger strains. Even when the overall mode of crack growth is plane strain, the distribution of the larger inclusions plays a major role in setting the crack path which affects the material's crack growth resistance. In this study, ductile crack growth under mode I, plane strain, small scale yielding conditions is analyzed. An elastic-viscoplastic constitutive relation for a porous plastic solid is used to model the material. Two populations of second phase particles are represented, large inclusions with low strength, which result in large voids near the crack tip at an early stage, and small second phase particles, which require large strains before cavities nucleate. The larger inclusions are represented discretely and it is their spatial distribution that gives rise to the 3D effects in our analyses. Adiabatic heating due to plastic dissipation and the resulting thermal softening are accounted for in the analyses. The effect of the 3D distribution of the larger inclusions on the initiation of crack growth, on the evolution of the crack path and on the material's crack growth resistance are investigated.

Incremental Minimization Principles in Fracture and Damage Mechanics

SM9L_12921
Tue • 12:40 • 231

G.A. Francfort, J.J. Marigo
Université Paris, Paris, France

The formulation of cracks or damage evolution in a body from a principle of minimization of the total energy of the body is an alternative to usual appoaches. To introduce into the model the irreversibility condition of growing of the defects with time a discretization of the problem is first needed. That leads to the notion of incremental evolution problems. This discrete formulation is sometimes sufficient to obtain accurate information on the damaging process. However this bypass is not satisfactory from a conceptual point of view and it is better to pass to the limit when the discretization step goes to zero to obtain the so-called "time-continuous evolution problem. The goal of the conference is to illustrated these different points from several examples chosen in Damage Mechanics, in Griffith Fracture Mechanics and in Barenblatt Fracture Mechanics.

Finite Element Analysis of Fracture and Polarization Switching Behavior in Modified Small Punch Testing of Piezoelectric Ceramics

SM9L_11425
Wed • 11:00 • 231

Yasuhide Shindo, Fumio Narita, Yasuyo Magara, Masaru Karaiwa
Tohoku University, Japan

FINITE ELEMENT ANALYSIS AND MODIFIED SMALL PUNCH TESTING FOR DETERMINING THE ELECTRIC FRACTURE AND POLARIZATION SWITCHING BEHAVIOR OF PIEZOELECTRIC CERAMICS Yasuhide Shindo*, Fumio Narita, Yasuyo Magara and Masaru Karaiwa *Department of Materials Processing, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan This paper discusses the fracture behavior of a piezoelectric ceramic under

applied electric fields. The modified small punch (MSP) tests were made on a commercial piezoelectric ceramic plate. The fracture initiation loads under different electric fields were obtained from the experiment. Nonlinear three-dimensional finite element analysis was also used to study experiments with the MSP technique and to calculate the MSP energy and maximum strain energy density. The effects of applied electric field and 180, 90 degree polarization switching on the MSP energy and maximum strain energy density are discussed, and the model predictions are compared with the results of the experiments. The results show that measured fracture initiation load, calculated MSP energy and maximum strain energy density are sensitive to the change in the applied electric field and polarization switching. The polarization switching zones corresponding to combined mechanical and electrical loads are obtained and discussed in detail.

Numerical Approach for Dynamic Fracture in Piezoelectric Solids

SM9L_11321
Wed • 11:20 • 231

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A mixed boundary element approach for two-dimensional dynamic piezoelectric fracture mechanics problems is presented. The numerical approach is based on displacement and traction integral equations for external and crack boundaries, respectively. Integral equations for time harmonic problems are considered. Integrals with strongly singular and hypersingular kernels are analytically transformed into weakly and regular integrals by using an integration variable consistent with the material characteristic parameters. Transient problems are analyzed by means of the FFT.Curved and quarter-point elements are used.Stress and electric displacement intensity factors are evaluated from nodal values next to the crack tip. The present BE approach has allows for solution of a variety of crack problems including curved cracks. Several piezoelectric crack problems are studied in the paper. Some of these problems had never been studied before.

Automatic 3D Crack Growth Simulation Based on Boundary Elements

SM9L_12044
Wed • 11:40 • 231

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An automatic 3D crack growth algorithm for fatigue crack propagation of arbitrary three dimensional problems with linear-elastic material behavior is presented. The stress analysis is based on a special BEM formulation – the 3D Dual Discontinuity Method (DDM) – which is advantageous for modelling propagating cracks. An optimized evaluation of very accurate SIF's and T-stresses along the whole crack front and the knowledge of 3D corner singularities are the basis of the proposed 3D crack growth criterion. The criterion is a predictor-corrector procedure taking into account the T-stresses and the often missing K_{III} in addition to K_{I} and K_{II} for the calculation of the kink angle. Moreover, a 3D singularity analysis is performed ensuring a valid square-root singularity along the crack front, especially in the vicinity of the intersection with the free surface. This guarantees a bounded energy release rate. Finally, the high level of automatization is accomplished by a sophisticated re-meshing algorithm for the update of the numerical model.

Failure Model of Protective Coatings

SM9L_11626
Wed • 12:00 • 231

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The integrity of protective coatings is a continuous subject of concern for a variety of industrial applications. The determination of active failure development parameters during a series of thermal cycles is the key step for life prediction of thermal barrier coatings. Selective results of a rigorous analytical-computational model are presented. The emphasis is on relating thermal cyclic loading and mechanical loading to the developing system of periodically distributed cracks through the protective coating and the branching cracks along the interface. The developed model gives insight into the processes taking place during failure development and the effect of the details of the applied thermal loading. The model will serve as a guiding tool for service life estimation of components subjected to the described conditions. The analysis separates the coatings into two groups: thin and final thickness coatings. Both cases were analyzed and are presented.

On the Simulation of the Coating Flaking Off

SM9L_10644
Wed • 12:20 • 231

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Most varnishes, paints and coatings have the drawback of flaking and peeling off, by propagating of a crack at the interface, from an initial micro- or macroscopic defect, when the substrate is deformed, for instance, by thermal expansion. We propose a simple theoretical and experimental model to explain this phenomenon. The experimental model is made of two superimposed rubber strips, in adhesive contact under the alone action of van der Waals forces, neither additional adhesive nor pre-stresses, one of them being submitted to an instantaneous elongation or to a constant speed of strain. The detachment of the other strip, that represents the spontaneous peeling and flaking off of a varnish layer, is measured and analysed using concepts of the fracture mechanics, such as the strain energy release rate, in order to determine the conditions of stability and of propagation of a crack at the interface. The main aim of this study is to draw the master curve representing the variation of the dissipation function versus the crack propagation speed at the interface. Knowledge of this dissipation function, which varies as the power 0.55 of the crack speed for the rubber-like material used, makes it possible to predict the kinetics of propagation in all particular cases, provided that elongations are purely elastic (with viscoelastic losses being left localized at the crack tip) and that the peeling results from the rupture of an adhesive joint, i.e. with propagation at the interface.

On Crack Assessment at Bimaterial Interfaces

SM9L_11484
Wed • 12:40 • 231

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Wedge type situations create stress concentrations which may lead to crack initiation. Based on the knowledge of the singular fields, the direction of crack nucleation can be detected using the novel Boundary Finite Element Method which requires significantly less discretization effort compared to the well established Finite Element Method. The investigations presented here concentrate on a plane model of a bimaterial wedge which is set under arbitrary loading, simulating various mixed mode situations. An essential question is to find a criterion for the assessment of crack nucleation. For that aim, the hypothesis of Leguillon is adapted for thin layers on a substrate and calculated for sealing joints of high temperature fuel cells. The crack is assumed to be critical when and only when both the released energy and the local stress reach critical values along a hypothetical crack of finite length.

Experimental and Numerical Crack Growth in a Special Geometry

SM9L_10864
Fri • 09:30 • 208

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From experimental tests on a motor grain model it appears that both SIF values and crack geometry during growth are quite variable due to shear modes for the off-axis inclined cracks. The numerical study was to find the SIFs versus crack length for three different configurations: symmetric crack, off axis straight-in crack and off-axis inclined crack. The experimental off-axis straight-in crack remains straight in growth after some minor rearrangements, and Mode I is present. For the off-axis inclined crack, which turns on a curved path, after some limited amount of growth Mode II as well as Mode I remained. The numerical simulation shows a rapid change of direction and presence of Mode I. At maximum depth all the experimental 3-D SIFs were smaller than the numerical 2-D corresponding values. For complete three-dimensional numerical simulations mode III has to be considered.

Initial Energy Dissipation Mechanism at Crack Tip and the Ductile to Brittle Transition

SM9L_12390

Fri • 09:50 • 208

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It is commonly assumed that the trigger for the brittle to ductile transition of a material is a change in the initial energy dissipation mechanism that is activated near or at a crack tip. In this talk, the criteria which determine the initial energy dissipation mechanism that is activated at or near a crack tip are derived. The possible mechanisms considered are cleavage, crack tip dislocation nucleation and also Frank-Read dislocation source activation near the tip. The applied energy release rates at which cleavage and crack tip dislocation nucleation occur are well-known. An elementary derivation of the applied energy release rate required for Frank-Read dislocation sources to be activated will be presented. Competitions between the three mechanisms are then established in terms of ratios of the respective energy release rates. The criteria can be succinctly expressed in graphical form and compare favorably to experiments in the literature.

Experimental Investigation on Concrete Shear Crack Extension

SM9L_10676

Fri • 10:10 • 208

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The special properties of concrete lead to difficulties of measuring shear strength of this material. Especially the characteristic of its tension resistance lower than shear resistance results in concrete mode-? fracture always occurs prior to the mode-? fracture. It is still a difficult job to achieve mode-? initiation propagation of concrete specimens. The studies presented about the mode-? fracture of concrete are very few. At present, most interests about this field primarily focus on four-point specimens and Brazilian disk specimens, but there are many debates about their results. This paper tries to present a detail investigation on these two specimens. The whole evolution process of crack initiation and propagation trajectory of two specimens are presented and discussed, and the values of of the specimens are calculated.

A Fractal Cohesive Crack Model

SM9S_10250

Tue • 14:30 • 226

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When the fractal dimension of the crack D is allowed to vary from 1 to 2, a fractal crack changes from a smooth crack to a plane filling entity, which is more like a void than a crack. Significant variations from the classic solution are demonstrated as the singularity exponent α, entering in the near-tip stress field, $r^{-\alpha}$, sweeps the range (0,0.5). The fractal cohesive crack model described here is based on a simplifying assumption, according to which the original problem is approximated by considerations of a smooth crack embedded in the stress field generated by a fractal crack. The well-known concepts of the stress intensity factor and the Barenblatt cohesive modulus, which is a measure of material toughness, have been redefined to accommodate the fractal view of fracture. Specifically, the cohesion modulus, in addition to its dependence on the distribution of the cohesion forces, is shown now to be a function of the 'degree of fractality', reflected by the fractal dimension D, or by the fractal roughness parameter, H. Two measures of the characteristic material length parameter have been suggested for solids weakened by presence of a fractal crack. For most fractal cracks, when D is not too close to 2, the characteristic length is chosen as the length of the cohesive zone, R. Above a certain threshold value of D, the root radius of the equivalent blunted crack (r) is suggested as the characteristic length parameter. The equivalent blunted crack is chosen by use of the Neuber stress magnification concept and the classic fracture mechanics equations for a crack with a finite root radius. The threshold for D is chosen as 1.846, which is 7.7% below the value of D corresponding to a 2D entity, a plane filling fractal crack, for which D = 2. In the limit case r turns out to be a fraction of the crack length. As the degree of fractality increases, the characteristic material length constant is shown to rapidly grow to the levels around three orders of magnitude higher than those predicted for the classic case. Such phenomenon may be helpful in explaining a distinct size-sensitivity of fracture processes in materials with cementitious bonding such as concrete and certain types of ceramics, where fractal cracks are commonly observed. It is an experimentally confirmed fact that in these materials the size of the process zone, which frequently is identified with the characteristic length, and the size of the end zone as modeled by the cohesive crack representation, frequently approach the size of the entire specimen used in a typical laboratory test.

Influence of Stress State on Crack-Tip Driving Force

SM9S_10334
Tue • 14:35 • 226

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In this paper, a two-parameter crack-tip driving force in terms of Kmax and DeltaK has been developed to account for load interaction effects on fatigue crack growth behaviour. The development is based on the premise that the load interaction effects depend upon the applied and residual stress state at the crack tip. Examples from the literature on crack growth behavior due to an overload application in air and vacuum are analysed. It is shown that a maximum retardation corresponds to the minimum value of Kmax at the crack-tip calculated due to the applied load and due to post-overload residual stresses. The results indicate that the post-overload behavior in air and vacuum is essentially the same. The observed quantitative variations are associated with the inherent differences in the fatigue crack growth in these environments. This approach shows explicitly how residual stresses induced by overload lead to delayed crack growth retardation.

Size Effect in Tensile Fracture of Concrete – A Study Based on Lattice Model Applied to CT-Specimen

SM9S_10419
Tue • 14:40 • 226

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In this paper, a study on size effect in tensile fracture of concrete and simulation of strain softening of plain concrete using 2D lattice model is presented. A compact tension specimen (CT) is adopted and triangular lattice network is used to simulate the heterogeneous structure of concrete. A computer program is developed to generate random variation of Young's modlulus values foe each element presentin the lattice, which can represent a heterogeneous concrete medium. Load Vs. CMOD plots thus obtained shows softening behaviour of concrete. Size effect curve in tensile strength of concrete has been plotted.

Numerical and Experimental Study of the Plastic Zone in the Vicinity of the Crack Tip by the Optical Caustics Method

SM9S_10429
Tue • 14:45 • 226

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In industrial applications, knowing the morphology of the plastic region allows the prevention of crack propagation that may lead to serious crack extensions. In the case of fragile materials, the development of the plastic zone is ignored, but the same hypothesis does not apply to ductile materials. For these materials, when dealing with a stationary problem, we notice an important development of the plastic zone in the proximity of the crack tip, before reaching the rupture stress limit and before the crack begins to extend. We have to add that the plastic region keeps developping alongside with the crack extension. In this paper we aim at demonstrating by numerical simulations, followed by experimental tests that for a ductile specimen SEN loaded in the mode I, the topological changes of the crack tip, due to plasticity, can be revealed by the optical caustics phenomenon.

Thermoelastic Problems for a Bimaterial with Defects/singularities

SM9S_10579
Tue • 14:50 • 226

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The paper presents a method for solution of 2D thermoelastic problems for a bimaterial with internal singularities/defects, like cracks, dislocations. A heat source can also be considered as the singularity. A bimaterial interface is either virgin or contains an interface crack. The method is based on the well-developed theory complex potentials, analytical continuation theorem and superposition technique and leads to singular integral equations for the problems in hand. As examples of the effectiveness of this technique the solution of some problems are presented and discussed. In particular, for the thermoelastic problem of the system of internal microcracks and an interface crack closed form expressions for the stress intensity factors at the interface crack tips are derived.

Dynamic Crack Analysis Under Thermal Shock

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SM9S_10646
Tue • 14:55 • 226

A boundary element method using Laplace transform in time domain is developed for the analysis of fracture mechanic considering transient coupled thermoelasticity problems with relaxation times in two dimensional finite domain. The dynamic thermoelastic model of Lord and Shulman are selected for showing finite thermal propagation speed. Thermal dynamic stress intensity factor for mode I is evaluated. The accuracy of the method is investigated through comparison of the results with the available data in literature. Condition where the inertia term plays important role is discussed and variations of dynamic stress intensity factor is investigated. Different relaxation times are chosen for briefly showing the effects on stress intensity factor considering Lord and Shulman (LS) theory. REFRENCES Hosseini-Tehrani, P., Eslami, M.R., (2001) “Dynamic Crack Analysis Under Coupled Thermoelastic Assumption”, Trans. ASME J. of Applied mech., 68, 585–588.

Crack Arrest Model for Cracked Piezoelectric Plate – a Modified Dugdale Approach

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SM9S_10740
Tue • 15:00 • 226

A modified Dugdale model is proposed for a piezoelectric plate weakened by a hairline straight crack. Two cases investigated are: when the crack lies perpendicular and parallel to poling direction of the plate. Uniform constant unidirectional tension and electric field applied remotely opens the faces of the crack in Mode I type deformation. Consequently the plate is yielded mechanically and also electrically. The piezoelectric plate being electrically ductile and mechanically brittle, first encounters mechanical singularity. Thus plastic zone formed ahead of the crack tip is encountered first. To arrest the crack from further opening the rims of plastic zones developed are subjected to normal cohesive linearly varying yield point stress of the plate. Each of the problems is solved using complex variable technique and the condition that the stress remains finite at every point of the plate. The local energy release rate and stress intensity factors are calculated.

Effect of Inter- and Intralaminar Damage on the Compressive Fracture of Hyperelastic Materials

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SM9S_10824
Tue • 15:05 • 226

The present analysis investigates a mechanism of compressive fracture for heterogeneous non-linear materials undergoing large deformations under uniaxial or equi-biaxial loading. Special attention is given to accounting for the presence of both, inter- and intralaminar defects. The upper and the lower bounds for the critical load are examined. In order to calculate the bounds, the 3-D problem of the internal instability is considered within the model of a piecewise-homogeneous medium. The analytical solution is found for different types of interlaminar boundary conditions. The characteristic determinants are derived for the first four modes, which are more commonly observed. The results obtained for composites consisting of hyperelastic layers described by the simplified version of Mooney’s potential (namely, by the neo-Hookean potential) show that the bounds present a good estimation for the particular modes and material properties.

Elastodynamics Problems in Domains with Edges

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SM9S_10897
Tue • 15:10 • 226

Basic initial-boundary value problems of elastodynamics are considered in a domain of general type with edges on the boundary, in particular, with cracks and conical points. The asymptotics of solutions near the singularities is obtained and justified. The coefficients in asymptotics (stress intensity factors) are expressed in terms of special solutions to the homogeneous problem. Properties of the coefficients are discussed; among others, some phenomena related to the property of finite propagation speed.

Weight Functions for Cracks in Piezoelectrics

SM9S_11045

Tue • 15:15 • 226

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The weight function in fracture mechanics relates the stress intensity factor at the tip of a crack in an elastic body to a point load at an arbitrary location. For a piezoelectric material, this definition is extended to include the effect of point charges and the presence of an electric displacement intensity factor at the crack tip. The weight functions for the different crack opening Modes are derived from any known mixed-mode solution in terms of displacements and electric potentials of the cracked body under specific electromechanical loads. A second type of piezoelectric crack weight function is derived from a mixed-mode solution in terms of stresses and electric charge densities yielding field intensity factors due to mechanical displacements and electric potentials. Furthermore, the piezoelectric weight function is applied to calculate displacement and electric potential fields in a cracked body under arbitrary electromechanical loads. More applications include the investigation of effects like bridging or small scale switching on the field intensiy factors.

Three-Dimensional Correction of Two-Dimensional Fracture Criteria Using a Constraint Factor

SM9S_11087

Tue • 15:20 • 226

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Correction of the originally two-dimensional (2D) fracture criteria used in linear fracture mechanics is considered. The three-dimensional (3D) stress state at the crack tip is transformed into quasi-two-dimensional one by introducing effective elasticity constants governed by the stress and/or strain constraint factors (SCF). It is shown, that the variation of the stresses and, as a consequence, of the fracture criteria along the crack front is predicted by the variation of the SCF, while 3D correction may be defined by integrating of SCF along the crack front. The proposed approach is illustrated by the examination of the stress intensity factor and energy release rate in a single edge notch bending SENB specimen and proved by the results obtained using a direct 3D finite element simulation.

Elastodynamic Contact Problem for Two Penny-Shaped Cracks

SM9S_11195

Tue • 15:25 • 226

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The three-dimensional fracture dynamic problem for two penny-shaped cracks located in the plane under a normally incident harmonic tension-compression wave is considered. The problem is solved by the method of boundary integral equations with allowance for the cracks' edges contact interaction (Signorini constraints). The contact forces and the displacement discontinuity of the cracks' edges are examined. The dependence of the mode I stress intensity factor on the reduced wave number and mutual arrangement of cracks is studied. The computational solution is compared with the results obtained without allowance for the cracks' edges contact interaction.

Modeling of Environment Assisted Delamination I. Quasistatic Case

SM9S_11856

Tue • 15:35 • 226

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In a present paper, a theoretical model of quasistatic growth of delaminations of a protection covering of metal due to diffusion of dissolved in metal atomic hydrogen into the formed cavity is considered. For the case of a penny-shaped delamination the main equation describing its growth is derived. The expression for incubation time and the closed-form solution of the equation are obtained. It is shown that after incubation time the contour of a delamination begins to spread with the finite velocity which doesn't change in process of growth, as well as in the case of a crack in infinite medium.

Analysis of Tensile Testing of a Soft Ferromagnetic Elastic Strip Containing a Central Crack under a Magnetci Field

SM9S_11502

Thu • 14:30 • 226

Daisuke Sekiya, Yasuhide Shindo, Fumio Narita, Katsumi Horiguchi
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This paper discusses the fracture behavior of a ferromagnetic plate under uniaxial tension. The effect of magnetic fields on the fracture mechanics parameters such as the stress intensity factor, energy release rate, energy density, etc. is discussed by

analyzing the plane problems of a soft ferromagnetic strip with a central crack under a uniform magnetic field. The problem of an infinitely long soft ferromagnetic elastic strip with a central crack is formulated by means of integral transforms and reduced to the solution of a Fredholm integral equation of the second kind. Numerical values on the fracture mechanics parameters are obtained. Tensile tests are also conducted on center-cracked soft magnetic plate with strain gage technique, and the numerical predictions are compared with the test results. Agreement between theory and experiment is fair.

A Quasi-Spherical Coordinate System and Its Application to the Determination of Vertex-Type Singularities

SM9S_11568
Thu • 14:35 • 226

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To avoid the inherent singularity of the spherical coordinates at their poles, a new quasi-spherical coordinate system is developed. In this coordinate system, a finite element procedure is proposed to determining the eigensolutions at three-dimensional vertices in which the field variables are proportional to the (lambda+1)-th power of the distance from the vertices. The resulting global equation is a second order characteristic matrix equation. Several demonstrating problems are investigated. It can be seen that the formulation yield satisfactory results.

The Influence of Remote Stresses on the Near Crack Tip Stress Field

SM9S_11910
Thu • 14:40 • 226

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The near crack tip stress field serves as one of the main guidelines in fracture mechanics. Two methods of finding this field can be specified. While one consists of retaining only terms valid in the infinitesimal vicinity of the crack tip, the other is obtained by infinitely extending the whole crack. For one unloaded crack these approaches give the same results. For interacting cracks or cracks with loads acting on their planes, we get an improper statement of the boundary value problem (loss of uniqueness). This occurs for elastic and elastic-plastic materials. In the paper we present examples and a discussion which enables to distinguish the differences. Also the kinked crack tip is analyzed in the case of a small kink or small angle, explaining the differences of solutions in literature.

The Elasto-Plastic Thin Film/Substrate Via Buckle-Driven Delamination and Crack Growth

SM9S_11934
Thu • 14:45 • 226

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Indentation test is becoming increasingly used to quantitatively assess the thin film interfacial adhesion for its simplicity and ability to mechanically probe the smallest of solids. The conventional technique is based on the analysis of Marshall and Evans (1984) which is a combination of Linear Elastic Fracture Mechanics (LEFM) and simplified post-buckling theory. In this paper a full post-buckling response of elasto-plastic thin film is investigated by FEM calculation; the contributions of double-buckling and plastic buckling to the indentation test is discussed. The results show that double-buckling needs more energy than single-buckling case thus lead to a greater value of strain energy release rate; and plasticity is a significant factor for those films with low yield stress and must be taken in account in adhesion measurement.

On 3-D Thermoelastic Problems of Interfacial Cracks in a Periodic Stratified Space

SM9S_11980
Thu • 14:50 • 226

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This paper provides the methods of solutions to three-dimensional stationary thermoelastic problems involving a two-layered microperiodic space weakened by an interface crack of arbitrary smooth profile. An approximate analysis is performed within the framework of linear stationary thermoelasticity with microlocal parameters. By constructing the appro-

priate potential functions, the resulting boundary-value problems are reduced to the corresponding ordinary mechanical crack problems in homogeneous isothermal elasticity. The governing singular integral and integro-differential equations are also derived. The thermal stress field exhibits the classical inverse square root singularity without the normal interface oscillatory feature, which allows us to apply the classical concepts of fracture mechanics in terms of stress intensity factors.

the Shield Effect of Phase Transformation Stress Field at Crack Tip

SM9S_12174
Thu • 14:55 • 226

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Abstract: It is shown in this paper that the phase transformation happened and a white-bright layer is formed at crack tip. Thus, a compressive stress field is formed because of the volume growing up of phase transformation at crack tip. The compressive stress field is the shield of the crack propagation after using electromagnetic heat effect to stop crack propagation. Mechanical property tests under nanometer scale of these materials have been finished. The experimental survey of the volume expansion caused by phase transformation is also presented too. Key words: electromagnetic heat effect, crack propagation, compressive stress field of phase transformation, white-bright layer, volume expansion

Contact Zone Approach to the Analysis of Interface Cracks in Thermomechanically Loaded Piezoelectric Bimaterials

SM9S_12249
Thu • 15:00 • 226

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A piezoelectric bimaterial composed of two bounded semi-infinite spaces having a tunnel interface crack with a mechanically frictionless contact zone under the action of a remote mixed mode mechanical loading as well as of thermal and electrical fluxes is considered. Assuming that all electromechanical fields are independent on the coordinate co-directed with the crack front the matrix-vector representations of thermal, mechanical and electrical characteristics via a sectionally-holomorphic vector-function are formulated. Due to these representations the combined Dirichlet-Riemann and Riemann problems of linear relationship are formulated both for electrically permeable and electrically insulated models of the open part of the crack. These problems are solved exactly and close analytical expressions for all electromechanical components at the interface as well as the transcendental equations and analytical formulas for the determination of the contact zone length and the associated fracture mechanical parameters are derived. The influence of the mechanical loading as well as of the thermal and electrical fluxes upon the mentioned values is studied and a comparison of the results obtained in the framework of the electrically permeable and electrically insulated crack models has been performed. It is particularly demonstrated that the contact zone length is rather small in comparison to the crack length for a pure tensile load, however it can substantially increase in the presence of a shear load as well as of thermal or electrical fluxes. Moreover, the increase of the electrical flux can lead to an essential difference of the results obtained by means of the electrically permeable and electrically insulated models of the crack, respectively.

Creep Deformation in Thermal Barrier Coatings due to the Effect of Thermal Growth Oxidation and Temperature Gradient

SM9S_12492
Thu • 15:05 • 226

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Thermal barrier coatings (TBCs) have been utilized in order to increase the turbine inlet temperature and hence increase the efficiency of turbine engines. Due to the fact that the TBCs system was working at high temperature, a thermal growth oxidation(TGO) would form at the interface of top ceramic coating and bond coat and the deformation of the TBCs system would be creep. The creep deformation and TGO, especially their nonlinear effect would induce the failure of the TBCs. In the paper, the creep deformation in thermal barrier coatings due to the effect of thermal growth oxidation and temperature gradient were theoretically and experimentally studied. In the theoretical investigation, the residual stress in the thermal barrier coating due to the effect of creep deformation and thermal growth oxidation at the condition of temperature gradient along the thickness direction of TBCs were analytically obtained for a plane rectangle sample. It was found that the temperature gradient and TGO have great effect on the residual stress. In some cases, the residual stresses in ceramic

coating are compressive, but in other cases the residual stress are tensile. As we know, the failure mode is very different for different residual stresses. For compressive residual stresses, the ceramic coating would fail due to the buckling of the ceramic coating, however, for tensile residual stresses, the ceramic coating would fail due to the surface crack in the ceramic coating. In the paper, we obtained the failure map in the general space of ceramic surface temperature, the substrate surface temperature and heating time. In the experiment, the samples were heated in high temperature furnace at different temperature and with different time. In this case, the uniform high temperature in TBCs reduced the formation of thermal growth oxidation at the interface of top ceramic coating and bond coat and the thickness was measured by three methods. The oxidized and non-oxidized samples were again heated by a laser beam and in this case there was a high temperature gradient along the thickness direction of TBCs. It was found that the failure modes would be surface crack or interface crack for different thickness TGO and different temperature gradient. The experimental results were good agreement with the theoretical results. Key Words thermal barrier ceramic coating, thermal growth oxidation, creep deformation, residual thermal stress, temperature gradient.

Phase Dependent Fracture and Damage Evolution of Polytetrafluoroethylene (PTFE)

SM9S_12782
Thu • 15:10 • 226

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Compared with other polymers, polytetrafluoroethylene (PTFE) presents several advantages for load-bearing structural components including higher strength at elevated temperatures and higher toughness at lowered temperatures. Failure sensitive applications of PTFE include surgical implants, aerospace components, and chemical barriers. Polytetrafluoroethylene is semi-crystalline in nature with their linear chains forming complicated phases near room temperature and ambient pressure. The presence of three unique phases near room temperature implies that failure during standard operating conditions may be strongly dependent on the phase. This paper presents a comprehensive and systematic study of fracture and damage evolution in PTFE to elicit the effects of temperature-induced phase on fracture mechanisms. The fracture behavior of PTFE is observed to undergo transitions from brittle-fracture below 19°C to ductile-fracture with crazing and some stable crack growth to plastic fbw aver 30 °C. The bulk failure properties are correlated to failure mechanisms through fractography and analysis of the crystalline structure.

Numerical Analysis of Strain Hardening and Pressure Sensitivity Effects on J-Integral

SM9S_12798
Thu • 15:15 • 226

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Compact tension (CT) specimen testing is used to compute the fracture toughness parameter J-integral for different materials using load-displacement curves. In this work, J is investigated for compact tension specimen for a strain-hardening pressure-sensitive material. For the theoretical work, a lower-bound plastic limit-load analysis is used with linear hardening assumed for the material. Pressure sensitivity, is accounted for by using the Drucker-Prager yield criterion. Analytic expressions for fracture parameters are derived from basic formulation. For numerical work, ABAQUS was used for the fi nite element analysis of the specimen. Strain hardening is modelled for typical hardening materials in addition to linear hardening used in theoretical work. Numerical results are compared with the theoretical investigations and results obtained for different cases of pressure sensitivity and strain hardening show that as the material strain hardening increases, J increases especially at low values of crack length. The effect of pressure sensitivity, on the other hand, tends to reduce J value.

SM10

Functionally graded materials

Chairpersons: R. Batra (USA), G. Paulino (USA)

Adiabatic Shear Bands in Functionally Graded Materials

SM10L_12594
Tue • 11:00 • 123

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The initiation and propagation of adiabatic shear bands (ASBs) in functionally graded materials (FGMs) with continuously varying material properties and deformed in plane strain tension are studied. An ASB is a narrow region, a few microns wide, of intense plastic deformation that forms after softening of the material due to heating and damage evolution has overcome its hardening due to strain- and strain-rate effects. Each constituent and the composite are modeled as isotropic microporous strain- and strain-rate hardening and thermally softening materials with effective properties of the composite derived by the rule of mixtures. Gurson's fbw potential, a hyperbolic heat equation, and degradation of material properties with porosity are employed. It is found that ASBs, always aligned along the direction of the maximum shear stress, form sooner in an FGM than in either of the two constituent materials with their location, orientation, pattern and speed depending upon the compositional profi le.

Wave Propagation in Functionally Graded Materials

SM10L_11592
Tue • 11:20 • 123

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The propagation of two-dimensional stress waves in functionally graded materials (FGMs) is studied numerically. Two distinct models of FGMs are considered: i) a multilayered metal-ceramic composite with averaged properties within layers; ii) randomly embedded ceramic particles in a metal matrix with prescribed volume fraction. The numerical simulation demonstrates the applicability of the composite wave-propagation algorithm to the modelling of FGMs without any averaging procedure. The analysis based on simulation shows signifi cant differences in the stress wave characteristics for the distinct models that can be used for optimizing the response of such structures to impact loading.

Strength Evaluation of Functionally Graded Materials Under Severe Thermal Environments

SM10L_11207
Tue • 11:40 • 123

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Thermal shock strengths of a plate of a functionally graded material are analyzed when the plate is suddenly exposed to an environmental medium of different temperature. A Finite Element/Mode Superposition (FE/MS) method is proposed to solve the time dependent temperature fi eld. The admissible temperature jump that the material can sustain is studied using the stress-based and fracture mechanics-based criteria. The critical parameters governing the level of the transient thermal stress in the medium are identifi ed. Thermal shock resistances of the functionally graded materials under transient thermal stresses are analyzed using both the maximum local tensile stress criterion and the maximum stress intensity factor criterion.

Micromechanics-Based Elastic Model for Functionally Graded Materials with Particle Interactions

SM10L_10135
Tue • 12:00 • 123

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The present paper aims to develop a micromechanics-based effective elastic model of functionally graded materials (FGMs). The effective properties of FGMs are uniform in the same graded layer while changing along the grading direction. Microstructurally, infinite particles are randomly dispersed in the matrix with gradual transitions. Spherical particles are perfectly bonded with the matrix. A micromechanical framework is proposed to investigate effective mechanical properties along the grading direction. Within the context of the representative volume element, the effect of pair-wise interactions between particles is taken into account for the local stress and strain fields by using the modified Green's function method. Homogenization of the local field renders relations between the averaged strain, strain gradient and external loading. The effective elastic modulus tensor of the functionally graded composites is further constructed by numerical integration. The model prediction is compared with available experimental data.

Transient Dynamic Crack Analysis in FGMs Under Impact Loading

SM10L_10836
Tue • 12:20 • 123

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Transient elastodynamic analysis of a two-dimensional (2-D) in-plane crack in functionally graded materials (FGMs) is performed by a time-domain boundary integral equation method (BIEM). An exponential law is applied to describe the material gradients of the FGMs. A finite crack in an unbounded solid of FGMs subjected to an impact crack-face loading is considered. The initial-boundary value problem is formulated as a set of hypersingualr time-domain traction boundary integral equations (BIEs) with the crack-opening-displacements (CODs) as unknown quantities. A time-stepping scheme is developed for solving the hypersingular time-domain BIEs. Both unidirectional and bidirectional FGMs with cracks are investigated. Numerical results are presented to show the effects of the material gradients and the crack orientation on the dynamic stress intensity factors (DSIFs) and their dynamic overshoot over the corresponding static values.

Thermoelastic Analysis of Functionally Graded Materials Submitted to Shocks

SM10L_13018
Tue • 12:40 • 123

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Thermal protection systems using advanced materials are used to attenuate damage on the basic structure due the stress waves propagation as a consequence of thermal shocks. This is typically find on re-entry motion of space vehicles. Ceramic materials have been used due to their capacity of thermal isolation and to their low specific weight. The utilization of Functionally Graded Materials (FGM) enhances the quality of the thermal protection as they tend to avoid stress concentration on the interfaces if they combine ceramics and the basic material that constitutes the structure to be protected. The present work presents a numerical formulation to solve the strongly coupled thermomechanical problem submitted to thermal shock like solicitations. An staggered algorithm without upsetting the unconditional stability property characteristic of fully implicit schemes is used. Numerical simulations are presented for an FGM bar submitted to an abrupt variation of external temperature representing thermal shocks.

Design of FGM Bimorph Piezo-Actuators

SM10L_12978
Wed • 08:30 • 123

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Despite large bending displacement, the bimorph piezo-actuator is known to suffer from large induced stress at the interface region. To overcome this, we designed two types of piezo-actuators, one-sided (Rainbow type) actuator with functionally graded microstructure (FGM), where the electroelastic properties are graded smoothly along the thickness direction and

FGM bimorph actuator where the top and bottom piezoelectric plates are composed of multilayers where the electroelastic properties are graded smoothly across the plate thickness. In this talk, I will introduce two types of FGM piezo-actuator designs.

Asymptotic Ananlysis of a Stationary Crack in a Ductile Functionally Graded Material

SM10L_11177
Wed • 08:50 • 123

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The dominant and higher-order asymptotic stress and displacement fields surrounding a stationary crack embedded in a ductile functionally graded material subjected to anti-plane shear loading are derived. It is shown that the leading (most singular) term in the asymptotic expansion is the same in the graded material as in the homogeneous one with the properties evaluated at the crack tip location. Assuming a power law for the plastic strains and another power law for the material spatial gradient, we derive the next term in the asymptotic expansion for the near-tip fields. The second term in the series may or may not differ from that of the homogeneous case depending on the particular material property variation. This result is a consequence of the interaction between the plasticity effects associated with a loading dependent length scale (the plastic zone size) and the inhomogeniety effects, which are also characterized by a separate length scale (the property gradient variation).

Topology Optimization Applied to the Design of Functionally Graded Material (FGM) Structures

SM10L_12665
Wed • 09:10 • 123

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Functionally Graded Materials (FGMs) possess continuously graded properties with gradual change in microstructure. The concept of FGM is closely related to the topology optimization concept which essentially consists in a design method that seeks a continuum optimum material distribution in a design domain. This suggests that FGM structures can be designed by using topology optimization method. Thus, in this work topology optimization method is applied to design FGM structures considering a minimum compliance design problem. The topology optimization formulation considers the so-called continuous topology optimization formulation where a continuous change of the material properties is considered inside the design. As example, a new design was obtained where the design is considered in a FGM domain, that is, a domain where the properties change in a certain direction in according to a specified law, allowing us to obtain a structure with asymmetric stiffness properties. In addition, the design of FGM layered structures is also considered.

Complex-Variable Methods Applied to Functionally-Graded Elastic Plate Problems

SM10L_12273
Wed • 09:30 • 123

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Exact solutions have been found to the equations of elasticity in a thick plate of inhomogeneous linearly elastic material in which the elastic moduli are known functions of the coordinate normal to the plane of the plate.The upper and lower surfaces of the plate are assumed to be traction free.These solutions may be expressed in terms of four complex potentials which are analytic functions of a complex coordinate in the mid-plane of the plate. Whilst the solutions do not contain enough generality to satisfy the boundary conditions pointwise around the edge of the plate, resultant force and moment conditions or averaged displacement conditions may be specified over the edge of the plate. In general the bending and in-plane extensional behaviour of the plate is coupled. The solutions are illustrated by considering an infinite plate containing a cylindrical hole or a through-thickness line crack.

Dynamic Stability of Functionally Graded Plate Under In-Plane Compression

SM10L_10045

Wed • 09:50 • 123

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Functionally graded materials have gained considerable attention in the high temperature applications. With the increased usage of these materials it is also important to understand the dynamics of FGM structures. A study of parametric vibrations of functionally graded plates is presented. Nonlinear moderately large deflection equations taking into account a coupling of in-plane and transverse motions are used. Material properties are graded in the thickness direction of the plate according to volume fraction power law distribution. An oscillating temperature causes generation of in-plane time-dependent forces destabilizing the plane state of the plate equilibrium. The asymptotic stability and almost-sure asymptotic stability criteria involving a damping coefficient and loading parameters are derived using Liapunov's direct method. The energy-like Liapunov functional is constructed as a sum of modified kinetic energy and potential energy of the plate and is written in the form similar to the functional involved in stability analysis of laminated plates. The plates made up of steel and zirkonia as well as made of titanium alloy with SiC fibers are analyzed in details. Effects of power law exponent on the stability domains are studied.

Actuator and Sensor Modelling for Laminated Piezoelectric Plates

SM10L_12093

Wed • 10:10 • 123

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We propose an accurate and efficient approach to laminated piezoelectric plate based on a refinement of elastic displacements and electric potential through the thickness co-ordinate of the plate. The model accounts for shearing function and a layerwise approximation for the electric potential. The equations of motion for the piezoelectric plate are deduced from a variational formulation taking into account the continuity conditions at the layer interfaces by using Lagrange multipliers. Different situations are investigated among them (i) bimorph and (ii) sandwich structures for two kinds of electromechanical loads (i) density of applied forces and (ii) applied electric potential and are compared to the finite element computations. A good agreement is observed for the local (field distributions) and global (deflection, induced electric potential) responses of the composite. The extension of the present approach to vibration of piezoelectric plates is studied. The prediction of the modal frequencies of vibration is obtained.

A State Space Formalism for Piezothermoelasticity of Functionally Graded Materials

SM10S_10364

Tue • 14:30 • 134A

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A state space formalism and solution approach for electromechanical analysis of functionally graded materials (FGM) is presented. The materials considered possess rectilinear anisotropy or cylindrical anisotropy of the most general kind. The novelty of the formalism lies in that the 3D equations of piezothermoelasticity are represented in full by a state equation and an output equation in which only a displacement vector, a stress vector, and six sub-matrices that characterize the material properties appear. On the basis of the formalism, the piezothermoelastic solution to a problem may be determined through its elastic counterpart by analogy and correspondence. The formalism embraces the Stroh formalism for plane problems and brings in matrix algebra in the solution process. When dealing with FGM, the material inhomogeneity renders the state equation non-uniform. Viable schemes for treating the non-uniform system are considered. The schemes are useful for problems both in Cartesian coordinates and in cylindrical coordinates.

Conservation Laws of Functionally Graded Materials in Elastodynamics

SM10S_10501

Tue • 14:35 • 134A

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Keywords: elastodynamics; functionally graded material; Lie's invariance criterion; energy-momentum tensor; conservation law. A special version of Noether's theorem for the sake of absolute invariance on invariant variational principles is applied to the Lagrangian density function for obtaining conservation laws of functionally graded materials. It is found that the mass density and Lame's coefficients have to satisfy a set of first-order linear partial differential equations. Satisfaction of

these equations evolves the infinitesimal symmetry-transformations and the conservation laws in material space. Under the consideration of varying the volume fraction of the constituent materials, the effective mass density and Lame's coefficients, satisfying those partial differential equations, are obtained. They are numerically well and would not be unrealistic for various FGMs. Four conservation laws in material space are presented. A path-independent integral, which is directly related to the dynamic energy release rate, in the moving coordinate reference attached at the tip of crack is given.

The Plane Crack Problem in a Functionally Graded Orthotropic Strip

SM10S_11551

Tue • 14:40 • 134A

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In this paper, the plane crack problem in a functionally graded orthotropic strip with an edge crack or an internal crack perpendicular to the boundaries is investigated. The strip with the principal axes x (1-direction) and y (2-direction) is infinite along the y-axis and has the thickness h along the x-axis. Since the present model can be used as an approximation to a number of structural components and laboratory specimens, it is very significant to investigate this kind of crack problems. The elastic property of materials is assumed to vary continuously along the thickness. Four independent material parameters, namely, (stiffness parameter), (Poisson's ratio), (stiffness ratio) and (shear parameter) are used to denote the elastic properties. According to the integral transform technique, the elastic displacement field can be expressed in the integral form. By introducing auxiliary functions, the present problem can be turned into solving a group of singular integral equations. The corresponding asymptotic expressions of the singular kernels for the internal crack and the edge crack are obtained, respectively. In numerical examples, the effects of the gradient index of materials, the geometric parameter of structure and loading conditions (crack surface pressure, fixed-grip loading and bending) on stress intensity factors are analyzed in details. According to author's knowledge, the results on the edge crack problem of an orthotropic functionally graded strip are not reported up to now.

Frictional Slip Between a Gradient Non-Homogeneous Layer and a Half-Space in Anti-Plane Elastic Wawe Field

SM10S_11572

Tue • 14:45 • 134A

Gai Bing-Zheng
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Frictional slip between a layer and a half space caused by SH pulse is examined. Both layer and half-space are composed of the gradient non-homogeneous medium, and the interface between them is the unilateral interface with Coulombs friction. When the shear elastic modulus and the density of medium vary by the second power in the gradient direction of medium, the analytical solution of the problem is found. Through the numerical calculations for the cases of the incidence of a parabolic pulse, some characteristics of the interaction of the frictional interface between a gradient non-homogeneous layer and a half-space are revealed.

Adaptive Modelling of Microscopic Heterogeneous Medium Undergoing Large Deformation

SM10S_11671

Tue • 14:50 • 134A

Eduard Rohan, Vladimír Lukeš
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The problem of computing large deformation in microscopic heterogeneous media is characterized by non-uniform change of microstructure; starting with perfect periodic distribution of inhomogeneities in the reference state, the material becomes functionally graded due to nonuniform macroscopic deformation. We consider two-scale method of homogenization. The proposed algorithm for the numerical modelling allows for significant reduction in number of the cell problems to be solved on the microscopic scale. The homogenized stiffness coefficients and the averaged stresses associated with the updated Lagrangian formulation are approximated over the macroscopic domain according to the local deformation. A concept of the so-called macroelements is introduced, each of which spans the deformation gradients in particular macroscopic subdomain. Various approximation schemes can be defined over the macroelements using simplexes, sensitivity analysis of homogenized coefficients is employed. An adaptive refinement of the approximation is suggested, which is controlled by the "modelling error" indicator computed using two different approximation schemes. Numerical examples for materials with incompressible, or rigid inclusions are introduced to demonstrate performance of the method.

Study of Two-Dimensional Elasticity on FGM

SM10S_12461

Tue • 14:55 • 134A

Takemasa Seto, Tetsu Nishimura

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Functionally Graded Materials (FGMs) have been developing as future materials. These materials have a required property of strength or flexibility and the chemical resistance according to actual applications. However, the classical elastic theory is unavailable for FGMs, because the elastic modulus of FGM is not uniform over the body. In the case of uniaxial tension of a rectangular FGM plate, the elastic property of which varies along the tensile direction, the compatibility equation becomes very complicated so that the stress distribution over the plate is hard to resolve analytically. The numerical calculation of the stress distribution is mentioned in the study. By employing the step function for the distribution of elastic modulus, the stress distribution of edge bonded dissimilar materials can be solved. It is mentioned in this paper that reasonable stress distribution is obtained by the suggested method.

Three-Dimensional Transient Thermoelastic Analysis of Orthotropic Functionally Graded Rectangular Plate

SM10S_12465

Tue • 15:00 • 134A

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This paper is concerned with the transient thermoelastic analysis of an orthotropic functionally graded rectangular plate due to nonuniform heat supply. The thermal and thermoelastic constants of the orthotropic rectangular plate are assumed to vary exponentially in the thickness direction. The transient three-dimensional temperature is analyzed by the methods of Laplace and finite cosine transformations. We obtain the exact solution for the three-dimensional transient thermoelasticity of a simple supported orthotropic functionally graded rectangular plate. Some numerical results for the temperature change, the displacement and thermal stress distributions in a transient state are shown in figures. Furthermore, the effects of the nonhomogeneity and orthotropy of the material on the temperature change, the displacement and the stress distributions are investigated.

Nonlocal Effects in Micromechanics of Functionally Graded Composites of Random Structure

SM10S_12664

Tue • 15:05 • 134A

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A general non-local integral equation involving the statistical averages of stresses in the composite and inclusions of random structure functionally graded composite is obtained in the framework of multiparticle effective field method (see Buryachenko, Appl. Mech. Review 2001, 54(1), 1-47). The particular cases of the nonlocal integral equation were solved by three different methods: the quadrature method, the iteration method, and the Fourier transform method with subsequent comparative analysis. The different nonlocal effects are detected; some of them are fundamentally new. The method also allows one to estimate the second moment of stresses in the constituents as well as at each point on the interface between the matrix and fibers, which is used for the prediction of the effective envelope for failure initiation.

First Principles-Based Equations of State for Functionally Graded Materials

SM10S_12968

Tue • 15:10 • 134A

S. Hanagud, Xia Lu

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Thermodynamically complete equations of state (EOS), which characterize the material thermo-mechanical behavior under hydrostatic pressure and are expressed as the dependence of pressure on the specific volume and temperature, are predicted by using quantum mechanical methods. EOS for mixtures is needed in the shock-induced impact analysis of kinetic energy projectiles with functionally graded mixture of materials. Traditionally, EOS has to be obtained by experimental measurement. The complete EOS requires a large amount of measurements at different state points. However, the extreme difficulty of the temperature measurement in shocked systems unavoidably leads to an incomplete EOS. The most important contribution from, the use of abinitio technique, is that it can provide the thermodynamically complete EOS. There exist some literature on the use of the first principles to calculate EOS of solids including semiconductor material silicon and

some metals but not for mixtures. For the mixture of materials, first, the EOS is obtained for each individual component from first-principle calculations. Abinitio methods are based on the psuedopotential plane-wave methods. The generalized gradient approximations and the ultrasoft psuedopotential are utilized. The prediction of the EOS consists of two parts: the static-lattice EOS and thermal effects. The range of the pressure and the temperature varied for the specific mixture that is considered. In this work, the possible polymorphic phase transitions are not considered. The single-phase EOS agrees well with the experimental data. The EOS for the mixture is then obtained from the homobaric mixture theory.

SM11

Impact and wave propagation

Chairpersons: A. Norris (USA), K. Wilmanski (Germany)

Surface Waves on an Impermeable Boundary of a Poroelastic Medium

SM11L_10072
Tue • 17:00 • 219

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The dispersion relation for surface waves on an impermeable boundary of a fully saturated poroelastic medium is investigated numerically in the whole range of frequencies. To this aim a linear simplified model of a two-component poroelastic medium is used. Similarly to the classical Biot's model, it is a continuum mechanical model but it is much simpler due to the lack of coupling of stresses. In the whole range of frequencies there exist two modes of surface waves corresponding to the classical Rayleigh and Stoneley waves. The numerical results for velocities and attenuations of these waves are shown for different values of the bulk permeability coefficient in different ranges of frequencies. In particular, we expose the low and high frequency limits, demonstrate the existence of the Stoneley wave in the whole range of frequencies as well as the leaky character of the Rayleigh wave.

Shock-Induced Surface Waves in Porous Reservoirs

SM11L_11271
Tue • 17:20 • 219

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A detailed knowledge of the relation between the material properties and the propagation of surface waves in liquid-saturated porous media is important in order to obtain an accurate characterization of water and hydrocarbon reservoirs. The fundamental surface mode the tube wave and its relation with permeability has been subject of study in the past. In this work, the frequency-dependent properties of the different surface modes that propagate in a cylindrical interface between a fluid and a fully saturated porous medium are studied theoretically and experimentally. Numerical calculations based on Biot's theory are presented for the dispersion relation, pore pressure and displacements of the different waves. Experimentally, we use shock waves to generate surface waves in a borehole. Synthetic and natural samples with permeability values ranging from 360 mD to 10.8 mD were used to study the permeability effects in the broad band of frequencies (1–60 kHz) involved in the experiments.

Analysis and Design of Dispersive Materials and Structures

SM11L_12772
Tue • 17:40 • 219

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Within periodically heterogeneous structures, wave scattering and dispersion take place across constituent material interfaces in such a way that an overall wave attenuation effect arises at certain frequency ranges known as stop bands. This phenomenon can be utilized in developing composite materials and structures with tailored frequency-dependent dynamic characteristics. The objectives of this work are twofold. First, a multiscale assumed strain variational formulation is developed for the prediction of frequency spectra of periodic materials. This approach facilitates the generation of reduced order models using mode projections. Second, computed frequency band structures are tailored to yield synthesized composite materials with desired dynamic characteristics. The designed materials are then used to form structures, at a larger length scale, for a variety of purposes. Applications include high-frequency vibration isolators and structural waveguides. For large systems, the multiscale projection methodology provides up to an order of magnitude reduction in size of computational

problem compared to direct analysis. As for the multiscale design technique, this generates composite structures that are significantly more amenable to manufacturing compared to those generated via traditional topology optimization.

Critical Time for Acoustic Waves in Weakly Nonlinear Poroelastic Materials

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SM11L_10612
Tue • 18:00 • 219

The final time of existence (critical time) of acoustic waves is a characteristic feature of nonlinear hyperbolic models. We consider such a problem for poroelastic saturated materials whose material properties are described by Signorini-type constitutive relations for stresses in the skeleton and whose material parameters depend on the current porosity. In the one-dimensional case under considerations the governing set of equations describes changes of an extension of the skeleton, a mass density of the fluid, partial velocities of the skeleton and of the fluid, and a porosity. We rely on a second order approximation. Relations of the critical time to an initial porosity and to an initial amplitude are discussed.

Non-Destructive Testing of Wood by Wave Propagation

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SM11L_11085
Tue • 18:20 • 219

In this paper the determination of the material properties of a rectangular wooden bar will be presented and the detection of defects in the bar will be discussed. Wood is modeled as an orthotropic material. The material properties of the bar are evaluated using dispersion curves. The dispersion curves of the bar are determined theoretically by the semi-analytical finite element method and experimentally from measurements. The material properties of the bar are determined using parametric model fitting. A numerical finite difference model with second- and fourth-order approache is developed. To detect a defect in the wooden bar a numerical time-reversal experiment using the finite difference model is discussed. By this method, structural waves in the bar are excited in an experiment and the displacements are recorded in several points. The determined material properties of the wooden bar are applied to the numerical model and the recorded signals are played back. The waves interfere just at the position of the defect.

Elastoplasticity of Gravel Protecting Rockfall-Endangered Steel Pipelines

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SM11L_12313
Tue • 18:40 • 219

This contribution deals with the development of a numerical model providing reliable estimates of the loading of a gravel-buried steel pipe subjected to rockfall. Gravel is modeled by Hooke's law and a Cap Model. Based on wave propagation tests and triaxial strength tests, the material parameters are identified. They correspond to the elastic properties, shear failure, and compaction of gravel. Moreover, loading assumptions, i.e., estimates of the penetration depth and the maximum impact-force arising from rockfall onto gravel, are deduced from impact tests. Finally, a real-scale rockfall test onto a gravel-buried steel pipe is re-analyzed by means of a three-dimensional Finite Element model considering the impact loads in a reasonably simplified manner. The simulated stress distributions referring to the pipe compare well to the experimental results. Therefore, the developed model is well suited to provide prognoses of the loading of a gravel-buried steel pipe for rockfall scenarios that were not investigated experimentally.

Trapping of Plastic Waves by Adiabatic Deformation

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SM11L_11360
Wed • 11:00 • 213

Abstract: Adiabatic heating due to conversion of plastic work into thermal energy substantially changes the boubdary value problem of plasic wave propagation. The thermal coupling in plastic wave propagation causing the wave trapping is the main subject of this contribution. Two cases have been analyzed, that is the adiabatic wave trapping of plastic waves in tension and also in shear. The case of shear is relatively new and recently studied by this author.Theory, experiments and numerical analyses of the Critical Impact Velocity (CIV)in shear due to adiabatic wave trapping is discussed in details. A review of recent studies on CIV in tension and shear is given. The CIV in tension and shear can be viewed as new material constants characterizing the impact resistance for metals and alloys.

Impact Fracture of Rock Materials Due to Percussive Drilling Action

SM11L_12481
Wed • 11:20 • 213

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A theoretical model describing impact fracture of rocks caused by percussive drilling is presented. The process is modelled using particle dynamics (molecular dynamics) approach where a special interaction law for brittle materials is formulated. Relations between the microscopic quantities of the model and the macroscopic mechanical properties have been established. The material fracture and cracks formation under the periodic set of inserts are investigated showing that the impact fracture is concentrated in the areas directly under inserts, and also between them which is due to the shock wave interactions. The cracks distribution and their orientation differ signifi cantly from the quasistatic computations and correlate well with the known experimental impact tests, and this confi rms the dynamic nature of the considered process.

Bulk Solitons do not Decay in Elastic Wave Guides

SM11L_10114
Wed • 11:40 • 213

Alexander M. Samsonov, Galina V. Dreiden, Irina V. Semenova

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Theoretical and experimental research has been performed to prove the existence of long bulk strain solitary waves produced by a laser-induced impact in nonlinearly elastic isotropic wave guides. In experiments with short wave guides (up to 30 length scale), we were not able to prove a lossless propagation of observed bulk solitons. New experiments on bulk soliton propagation in much longer wave guides (up to 150 length scale) allow to confi rm that the solitons do not reveal any amplitude decay and shape transformation, while any linear or shock wave completely disappear at much shorter distance. We propose a new NDT approach and a method to determine the 3d order elastic moduli of non-crystalline materials based on bulk elastic solitary waves propagation theory. The approaches are builded upon the generation and recording of elastic strain solitons (reversible compression deformation waves) in various wave guides.

On the Propagation of Solitary Waves in Microstructured Solids

SM11L_12568
Wed • 12:00 • 213

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Wave propagation in microstructured media is essentially influenced by nonlinear and dispersive effects. The simplest model governing these effects results in the Korteweg-de Vries (KdV) equation. In the present paper a KdV type evolution equation, including the third- and fi fth order dispersive and the fourth order nonlinear terms, is used for modelling the wave propagation in microstructured solids like martensitic-austenitic alloys. The model equation is solved numerically under localised initial conditions. Possible solution types are introduced and discussed. It is shown that if the relatively small solitary waves decay in time. However, if the amplitude exceeds a certain critical value then such a solitary wave can propagate with nearly a constant speed, an amplitude and consequently the energy. Unlike the KdV solitons, interaction of such solitary waves is not elastic – after the interaction their speed and amplitude are altered.

Simultaneous Simulation of Dispersion Curves and H/V Spectra

SM11L_10422
Wed • 12:20 • 213

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Subsurface modelling beneath an earthquake observation station is necessary to study incident waves from observed earthquake records. Unless we have a vertical array, we have to rely on either observed records on the ground or micro-tremor observation. We can deduce surface wave dispersion curves by micro-tremor array observation and simulate them for subsurface models and we can use H/V spectra to obtain rough image of subsurface model such as base rock depth; however, simultaneous use of them has been scarcely reported. In this paper, we will demonstrate an advantage of simultaneous simulation where array size is only valid for higher frequencies; shallower part of the subsurface model is evaluated by stable surface wave dispersion curves and deeper part of the model is constrained by less informative peak and trough frequencies of H/V spectra.

Modeling of Oblique Impact of Yawed Projectiles on Ceramic Targets

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SM11L_12281
Wed • 12:40 • 213

The investigation of three-dimensional problem of oblique interaction of yawed projectiles with ceramic plates in a velocity range up to 4000 m/s was carried out by the finite element method. The paper presents an advanced constitutive model of AD995 Alumina. The model of damaged medium is used; it is characterized with possibility of crack initiation and propagation under impact loading. A kinetic fracture model of the active type developed earlier for the simulation of fracture in various materials is used for numerical modeling of ceramic failure at high velocity impact. Temperature effects are taken into account in the constitutive model.

Level-Sets and Mixed Approaches for Dynamic Contact Problems

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SM11L_12763
Thu • 09:30 • 226

Impact problems are nonlinear in essence, but also irregular and multiscales in space and time. Theses evidences are shown by analytical investigations giving explicit solutions of simple model impact problems (see e.g. Gloldsmith, . . .). General industrial impact problems have however to be approximated by means of numerical tools. Hughes et al. have designed special numerical schemes since the late seventies and increasing efforts have been since furnished by the computational contact community to address this numerical issue (see e.g. (Laursen and Love 2002 and the sampling references therein). The present work is a contribution to this wide and complex theme. Using the "viability lemma" of J.J. Moreau, the unilateral contact laws are written as equations by using two unknown Level-Set type fields standing for i) a location of the position of contact surfaces with respect to each other and ii) the Sign of the normal velocity jump on the interface. A weak-strong formulation of dynamic unilateral contact conditions is then derived in a straightforward manner. An original continuous weak-strong mixed formulation of a dynamic 3-D contact problem is carried out. The associated discrete nonlinear systems are then derived by using a Theta_scheme time discretization, a Galerkin method and a collocation one. The numerical solution strategy used to solve this problem is briefly commented and numerical tests are carried out. The numerical solutions do not exhibit pathologies (due to shocks) such as spurious oscillations. The paper is ended with a prospective use of the local multiscale Arlequin method. First promising numerical results exemplifying this approach are given.

Flaw Identification by Angle Beam Electromagnetic Acoustic Transducers

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SM11L_12418
Thu • 09:50 • 226

Electromagnetic acoustic transducers (EMATs) can transmit and detect ultrasonic waves in a conductive specimen without any contact. This process can be given theoretical modeling and formulation based on elastodynamics and electromagnetics. It suggests some possibility of quantitative nondestructive evaluation using EMATs. This research deals with angle beam EMATs which can transmit ultrasonic waves in oblique directions as plane waves. FEM-BEM simulations show us some relation between the receiver signal's peaks and wave propagation, and also explain effects of a flaw. Numerical results of receiver signals agree well with experimental ones, which verifies our mathematical modeling. Flaw identification is formulated as a problem of parameter optimization. The initial guesses of the parameter were successfully evaluated from the computed relationship between flaw size and the peak's area of the receiver signal. Through optimization, the flaw size was well identified from measured receiver signals, which verified our present method of flaw identification.

Stress-Focusing Effect in a Spherical Zirconia Inclusion with Dynamically Transforming Strains

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SM11L_10344
Thu • 10:10 • 226

Some composite materials, such as Zirconia toughened ceramics, are remarkable material, which has a high strength, a high elastic modulus, and an improved toughness, etc. These good qualities are made possible through the stress-induced phase transformation of composite particles, which is accompanied by a volumetric expansion. When a spherical inclusion in infinite elastic domain is suddenly subjected to an instantaneous phase transformation, stress waves occur at the surface of spherical inclusion the moment instantaneous transformation strains are applied. The wave may accumulate at the center

and show the stress-focusing effects, even though the initial stress should be relatively small. This paper analyzes the stress-focusing effect caused by the instantaneous phase transformation in the spherical Zirconia inclusion. By using the ray theory, the numerical results give a clear indication of the mechanism of stress-focusing effect in an inclusion embedded in the infi nite elastic medium.

Nonlinear Waves in Shock-Loaded Solids

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SM11S_10426
Tue • 14:30 • 231

We consider evolution of nonlinear waves generated by a shock loading of elastoplastic solid. In many cases of interest the stress amplitude is small in comparison with the bulk modulus but exceeds considerably the elastic limit for most metals. Therefore, a set of small parameters can be defi ned and the asymptotic methods known may be extended to these problems. As a result a system of the approximate independent nonlinear equations belonging to different directions of longitudinal characteristics is obtained. On the basis of the equations proposed we consider the following problems: self-action of a shock wave when it reaches a free-surface of an elastoplastic plate; propagation of two-dimensional shock wave, generated by detonation of explosive located on the metal half-space; simulation of two-dimensional damage of a plane plate loaded by normal impact of a cylindrical impactor with the velocity of 200 m/s. A comparison with experimental data is conducted.

Nonlinear Wawe Processes in a Bi-Layer

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SM11S_11242
Tue • 14:35 • 231

Combinations of two materials are commonly used to obtain a structure with the properties better than those of the parent constituents. Coupled nonlinear Klein-Gordon equations can be used to study the properties of wave processes in a bi-layer, where the parameters depend on the materials forming the bi-layer, and the coupling depends on the properties of the glue bond. It is shown that heterogeneity can result in the apperance of a gap in the velocity spectrum of solitary waves (kinks). The influence of a delamination zone on the propagation of these solitary waves is studied numerically. Next, it is shown that heterogeneity makes possible energy exchange between the layers. We consider the structure and stability of solutions involving two waves or two pairs of counter-propagating waves describing periodic energy exchange between the layers. Using both asymptotic analysis and numerical simulations, we show that these solutions may be modulationally unstable. These instabilities may lead to the formation of localized structures, and to a modifi cation of the energy exchange between the components.

Cubically Nonlinear Waves in Structured Materials of Macro-, Micro- and Nanoscale

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SM11S_11403
Tue • 14:40 • 231

Last two years authors are actively analyzing the cubically nonlinear waves in elastic materials with internal structure. This analysis can be divided into a few steps. 1. We started with the statement of the problem, for this type of waves was ignored up to now by mechanicians despite of well study of the cubically nonlinear waves in physics. 2. Then some reasons for these waves studying were produced, including simplicity of transition from conventional in mechanics of materials quadratically nonlinear waves to cubically ones and the new possibilities of wave analysis – quadruples (four waves interaction), for instance. 3. Within the framework of cubic nonlinearity, many new wave effects can be predict-ted and described. These predictions were formulated and commented. 4. Some of new effects were theoretically and numerically analyzed for plane waves. For example, new schemes of wave profi le evolution were detected. These steps will be explained in the paper.

Modeling of Solitary Impulses in a Composite Material Using Wavelet Analysis

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SM11S_11377
Tue • 14:45 • 231

An original method for description of the solitary wave evolution in a material with the microstructure (a composite) is presented. A peculiarity of the proposed technique consists in using wavelet-analysis on the base of Mexican hat wavelets.

These wavelets are the elastic wavelets, so they are solutions of the wave equations for elastic materials. In contrast to the prior studies when initial pulses had to satisfy rather strict conditions, it is shown that initial impulse shape can be an arbitrary form (it should only admits wavelet representation and be solitary one). The last can be meant as the main result of carried out study. Elastic wavelets based solution permits to reveal the microstructure effects, namely the essential dependence of the distance, on which evolution is visible, on the characteristic size of microstructure, and to extend the class of investigated pulses.

Hidden and Driven solitons in Microstructured Media

SM11S_11813
Tue • 14:50 • 231

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Wave propagation in microstructured materials is studied by making use of the Korteweg–de Vries type model equations. The first case concerns the alloy-type materials for which the nonlinearity is of the quadratic and quartic character and dispersion includes so-called cubic and quintic terms. The second case corresponds to a nonlinear microstructured layer where the driving force is of importance. It has been shown that in both cases the soliton trains may emerge. In the conservative case, the soliton train includes both visible and hidden solitons. The latters play a role in causing additional phase shifts in interaction processes, but do not play any significant role in energy sharing within the soliton train. In the nonconservative case (external driving force) hidden solitons can be amplified under certain resonance conditions. Such a phenomenon may open new possibilities for generating wave fields with designed properties that may be used in nondestructive testing.

Waves of Deformation Propagation in Nonlinear Viscously Elastic Porous Material

SM11S_12203
Tue • 14:55 • 231

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A mathematical model of a firm porous material is studied. Material is supposed isotropic, viscidly elastic. Cavities are assumed spherical; distance between cavities is much greater than radius of cavities and much smaller, than length of a wave. Pressure in cavities is neglected. The analysis of the equations of longitudinal wave propagation has shown, that the consequences of the existence of cavities are dispersion of a wave, the frequency-dependent damping and an additional non-linear component (so-called cavitary non-linearity). These factors are not equivalent, and in different situations one of them prevails. Influence of dispersion, dissipation and non-linearity on behavior of waves in the medium was evaluated. The propagating wave is influenced by both dispersion and non-linearity. The combined effect of these two factors can be a reason for forming a non-linear stationary wave of deformation. Dependencies between the parameters of the soliton and porosity of the material have been established.

Self-Consistent Methods in the Problem of Elastic Wave Propagation Through Matrix Composite Matrials

SM11S_11989
Tue • 15:00 • 231

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The problem of monochromatic elastic wave propagation through composite materials reinforced with isolated inclusions is considered. The hypotheses of two main self-consistent schemes (effective field and effective medium methods) that allow to construct the mean wave fields in such composites are analyzed and compared. The effective medium method is in fact a group of methods based on the hypotheses that for the evaluation of the wave field inside a typical inclusion in the composite the medium outside some vicinity of such an inclusion may be changed for the effective medium with overall properties of all the composite. The effective field method is based on the other hypothesis that every inclusion in the composite behaves as an isolated one in the original matrix, and the presence of the surrounding inclusions is taken into account via the effective external wave field that acts on every inclusion. The main hypotheses of the method concern the structure of the effective field. In the work the dispersion equations for the wave numbers of the mean wave field in the composites are developed in the framework of both methods. The long wave and short wave asymptotic solutions of these equations are obtained in closed analytical forms. Numerical solutions of these equations are constructed in a wide region of frequencies of the incident field that covers long, middle and short regions. The predictions of both methods are compared for matrix composites reinforced with isolated spherical inclusions and unidirected cylindrical fibers.

Dispersion and Stability Analysis of Waves in Pre-Stressed Imperfectly Bonded Layered Composites

SM11S_12514
Tue • 15:05 • 231

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The dispersive behaviour and stability issues of time-harmonic waves propagating in an imperfectly bonded pre-stressed symmetric layered composite is considered. The bimaterial composite consists of incompressible isotropic elastic materials. The shear spring type resistance model employed to simulate the imperfect interface can accommodate the extreme cases of perfect bonding and a fully slipping interface. The dispersion relations for both extensional and flexural waves are obtained by formulating the corresponding incremental boundary value problems. The asymptotic behaviour at low and high wavenumber limits are discussed. The stability criteria are studied and neutral curves are plotted. Numerical results are given for Mooney-Rivlin and Varga materials. The effect of the imperfect interface is clearly evident in the numerical results.

Mathematical and Numerical Modeling of Elastic-Plastic Waves in Granular Materials

SM11S_11527
Tue • 15:10 • 231

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To describe a deformation of materials with different resistance to tension and compression the rheological method is supplemented by a new element-rigid contact. It is used to construct a model of granular medium possessing elastic and plastic properties. Loosened state is determined by Mises-Schleiher strength condition, plastic state – by Mises yield condition. The propagation of plane longitudinal compression shock waves is analyzed analytically in one-dimensional case. It is shown that velocities of such waves decrease with loosening of material ahead of front, and that one- or two-wave configuration occurs depending on the intensity of compression and the degree of initial loosening. Effective numerical algorithm is developed on the basis of the space-variable decomposition for multidimensional analysis. By means of computational experiments the next effect is found: plane fronts of two shock waves, bending due to inhomogeneous loosening, can be reflected from each other with formation of transverse cumulative splash.

Thermo-Mechanical Wave Propagation in Materials with Internal State Variables

SM11S_11853
Tue • 15:15 • 231

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Conditions imposed on the initial data by the assumption that an acceleration wave may propagate in a termo-visco-plastic material and its amplitude blow-up to infinity in finite time are discussed. Full termomechanical coupling in 3D case is considered. Constitutive model is derived from a free energy function taking into account the non-negativity of entropy production. Thermal properties are characterized by the dependence of the heat flux on the gradient of a new thermal variable called the semi-empirical temperature scale. The theory leads to a modified model of thermo-elasto-viscoplasticity with an extra thermal stress effect and wave-type heat conduction. In the case of plane waves the solution is constructed numerically even beyond the point where Lipschitz continuity is lost and a shock with finite amplitude arises. Conditions under which a pure mechanical disturbance generates thermal one and the both may lead to blow up are established. Such a situation can model the ultimate state of a viscoplastic material in the vicinity of the dynamically propagating crac tip.

Acceleration Wavefronts in Random Media

SM11S_11682

Thu • 14:30 • 231

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In contradsitinction to deterministic continuum mechanics, we consider wavefronts whose thickness is smaller than the Representative Volume Element (RVE) size. As a result, the wavefront is an object more appropriately analyzed as a Statistical Volume Element rather than an RVE., and therefore to be treated via a stochastic, rather than a deterministic, dynamical system. There are two entirely new aspects considered in the present study. One is the coupling of fields of material spatial randomness to the wavefront amplitude: as the amplitude grows, the wavefront gets thinner tending to a shock, and thus the material heterogeneity shows up as an ever 'stronger' random field. The second new facet is the explicit consideration of randomness and various cross-correlations of the instantaneous modulus, the dissipation coefficient, the instantaneous second-order tangent modulus, and the reference state mass density.

Strongly Coupled Inversion of Rayleigh Dispersion and Attenuation Curves

SM11S_12728

Thu • 14:35 • 231

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Some of the most common procedures used by seismologists and geophysicists to solve problems associated with the propagation of surface waves in inelastic media are based on the assumption of weak dissipation. One important consequence of this assumption is that surface waves attenuation coefficients can be easily computed from the solution of the corresponding elastic eigenproblem using variational principles. Although the assumption of weak dissipation is often reasonable for the strain levels mobilized in geomaterials during the propagation of seismic waves, there are situations where this is not true. In such cases the rigorous solution of both Love and Rayleigh forward and inverse problems become more involved because the governing differential equations are complex-valued. This short memoir illustrates an elegant technique for the solution of the Rayleigh inverse problem in arbitrarily dissipative, linear viscoelastic media. The technique is based on using the holomorphic properties of Rayleigh phase velocity, and upon a previous result on the solution of the corresponding forward problem.

A Two-Dimensional Analysis of Surface Acoustic Waves in Finite Anisotropic Solids with Electrodes

SM11S_11099

Thu • 14:40 • 231

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Analytical solutions of surface acoustic waves in finite solids with electrodes are of great interests in both theoretical study and practical applications, and the two-dimensional theory based on the expansion of the exact solutions from semi-infinite solids offers an excellent two-dimensional theory with complete equations and boundary conditions similar to well-known plate theories for high frequency vibration applications. By considering the electrode layer on a piezoelectric substrate, the effects are evaluated through the integration of displacement fields along the thickness direction, effectively including both mass and stiffness. Extending these solutions to substrates with periodic electrodes, we can study the surface acoustic waves for accurate prediction of the phase velocity and displacement fields, thus enabling detailed analysis for actual resonator devices. We conclude this study with straight-crested wave solutions of surface acoustic waves in a finite solid with electrode to demonstrate the theory, solution technique, and the applications.

Uniqueness Results for the Reflection-Transmission Problem

SM11S_11596

Thu • 14:45 • 231

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Reflection and transmission of mechanical waves are investigated for a uniaxially inhomogeneous viscoelastic layer which is sandwiched between two homogeneous elastic half-spaces. As a result, uniqueness is established for the reflection-transmission process regarded as a initial boundary value problem. The approach is entirely developed in the time domain subject to the restriction of the normal incidence. Two main ideas prove crucial. First, the boundary conditions for the layer are written in a form which accounts directly for the outgoing character of unknown waves. Second, motivated by

thermodynamics, an energy functional is considered for the viscoelastic layer which is a potential for the traction. The total energy of the layer is shown to decay in time because of the boundary conditions. Owing to the boundedness of the speed of propagation and to the initial value problem, the reflected and transmitted waves are taken to have compact support. Uniqueness is then established for C^2 solutions in the space-time domain.

Inhomogeneous Circularly Polarized Waves in Orthorhombic Crystals

SM11S_11812
Thu • 14:50 • 231

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For time-harmonic homogeneous plane waves, in the context of the linearized elasticity theory, Fedorov & Fedorov introduced a decomposition of the acoustical tensor, valid (apart from a “pathological case”) for all orthorhombic, tetragonal, hexagonal and cubic crystals. In considering this decomposition, they also introduced linearly polarized pseudo-transverse and “pseudo-longitudinals”" waves. Here, we consider the propagation of time-harmonic inhomogeneous plane waves in orthorhombic crystals. Using the directional ellipse method introduced by Hayes, we generalize the concept of pseudo-transverse and “pseudo-longitudinal” waves to elliptically polarized inhomogeneous plane waves. We then determine, for orthorhombic crystals, the corresponding possibilities for circularly polarized inhomogeneous waves.

Wave Interaction Resonances in Inhomogeneous Elastic Materials

SM11S_11620
Thu • 14:55 • 231

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An inhomogeneous nonlinear elastic material is considered. The inhomogeneity in density and elastic coeffi cients is assumed to be weak with polynomial functionality. Nonlinear interaction of two counter-propagating longitudinal waves is studied theoretically. An analytical solution is derived for the initial stage of wave interaction process in the material with fi nite thickness. Oscillations on the material boundaries are investigated and wave interaction resonances are clarifi ed. Value of the resonance is sensitive to the properties of the material and to the excitation frequency. Resonance data may be used for qualitative and quantitative nondestructive characterization of inhomogeneous nonlinear elastic material. The last conclusion is supported by the results of numerical simulations.

Some Degenerated and Extended Wave Models of Elasto- and Hydrodynamics with Finite Velocity Disturbance Propagation

SM11S_11401
Thu • 15:00 • 231

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A number of real models are presented when parabolic models singularly egenerate into hyperbolic ones and, controversly, when hyperbolic models can be obtained by the extention of parabolic operator up to hyperbolic ones. Degeneration of problems for wave guide type systems in transverse coordinate is considered in detail. Degeneration of the original IBV problem in R^n for the hyperbolic system of equations with respect to a transverse coordinate of a hyperlayer whose thickness is assumed to be much lesser than the others is investigated.Our aim is to derive hyperbolic approximations degenerated with respect to coordinate s,i.e. to construct a mapping $R^n \to R^{n-1}$ satisfying the condition of limiting correctness to be of hyperbolic type. Necessary and suffi cient conditions are established to such a hyperbolic degeneration. This is proved for the case R^3 considering the elastodynamic problem for the layer. As a result, 3-D problem for the layer is reduced to the 6 extended order hyperbolic operator for bending waves in plate which includes as particular cases the known Timoshenko-Mindlin (4 order) and Kirchhoff models. The similar approach is used to construct extended degenerated close to hyperbolic model for nonlinear water wave propagation in the fluid of variable depth including known models for solitary wave propagation.

Application of Numerical Methods for Analysis of Propagation of Vibrations Generated by Moving Load

SM11S_11381

Thu • 15:05 • 231

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Two numerical methods are presented to analyze dynamic response of the free field nearby railway lines induced by the specific moving loads acting on the surface of a layered and homogeneous halfspace with different material properties. A three dimensional (3D) modelling approaches are performed by Thin Layer Method / Flexible Volume Method (TLM / FVM) and by Boundary Element Method (BEM). Both simulation models based on substructuring approach employ frequency domain algorithms. The validity of each method is demonstrated by comparison with results of analytical solution. An extensive numerical investigations have been carried out on the influence of different parameters on the effectiveness of open trench barriers at the ground surface in reducing adverse effects of high frequency vibrations.

Rayleigh-Like Surface Waves on a Nonlinear Layered Elastic Half Space

SM11S_10891

Thu • 15:10 • 231

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The work considers the propagation of small but finite amplitude Rayleigh-like waves on an elastic half space covered by a different elastic layer of uniform and finite thickness. It is assumed that the free boundary of the layered half space is free of tractions, and stresses and displacements are continuous at the interface between the layer and the half space. Then the nonlinear modulation of a group of surface waves centered around a wave number is examined by employing the method of multiple scales. It is shown that the first order slowly varying amplitude of the wave modulation is governed asymptotically by a nonlinear Schrodinger (NLS) equation. Then the dependence of the stability of the solutions and of the existence of solitary wave-type solutions of NLS equation on the nonlinear material parameters is investigated numerically for both hypothetical and real material models.

SM12

Material instabilities

Chairpersons: D. Bigoni (Italy), H. Petryk (Poland)

Ultrastiff Elastic Composites via Negative Stiffness Inclusions, and Material Stability Implications

SM12L_12025
Wed • 08:30 • 213

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Composite materials of extremely high stiffness, far higher than that of either phase and exceeding that of all standard bounds (e.g., those of Voigt and Hashin-Shtrikman), can be produced by employing one phase of appropriately-tuned negative stiffness. We show this via several exact solutions within linearized and also fully nonlinear elasticity, and via the overall modulus tensor estimate of a variational principle shown to be valid in this case. The specific type of composite considered is a matrix-inclusion composite in which the matrix material is positive-definite, and this contains a very small volume fraction of negative-stiffness (non-positive-definite) inclusions. The composite stiffness can exceed that of the bounds because the usual assumption of positive-definiteness of all the components is relaxed. A negative-stiffness component is unstable by itself, but we argue that a composite material containing negative-stiffness inclusions can have overall stability under appropriate conditions.

Computational Characterization of Micro- to Macroscopic Mechanical Behavior of Carbon Black-Filled Rubber

SM12L_11432
Wed • 08:50 • 213

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The deformation behaviors of rubber under macroscopically uniform tension, and of a plane-strain rubber unit cell containing cylindrical carbon black were investigated by computational simulation with the nonaffine molecular-chain network model. The results revealed the mechanisms of the enhancement of deformation resistance and hysteresis loss, i.e., Mullins effect, occurring in stress-stretch curves under cyclic deformation processes. The increase of volume fraction and of the heterogeneity of the distribution of carbon black substantially raises the resistance to deformation and hysteresis loss. The concentration of deformations and orientation hardening in the rubber phase are responsible for these characteristic behaviors.

Material Instabilities of Fiber-Reinforced Nonlinearly Elastic Solids

SM12L_11705
Wed • 09:10 • 213

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Material instabilities for fiber-reinforced nonlinearly elastic solids are examined under plane deformation. In particular, the materials under consideration are isotropic nonlinear elastic models augmented with a function that accounts for the existence of a unidirectional reinforcing. This function gives the anisotropic character to the material and is called a reinforcing model. The onset for failure is given by the loss of elliptcity of the governing differential equations. Previous work has dealt with the analysis of specific reinforcing models. It was established that the loss of ellipticity for some augmented isotropic materials requires contraction in the reinforcing direction. The loss of ellipticity was related to fiber kinking. Here we generalize these results and establish sufficient conditions that guarantee the ellipticity of the governing equations of equilibrium for more general reinforcing models. The two cases of compressible and incompressible materials are considered. The incipient loss of ellipticity is interpreted in terms of fiber kinking, fiber debonding, fiber splitting and matrix failure in fiber-reinforced composite materials.

Strain Localization at the Brittle–Ductile Transition of the Earth's Continental Crust.

SM12L_12751
Wed • 09:30 • 213

Yves M. Leroy(1), Frédéric Gueydan(2), Laurent Jolivet(3)

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Distributed midcrustal shear zones are characteristic of post-orogenic extension and lead to the formation of detachment planes. The objective of this talk is to show that these shear zones result from strain-localization. The destabilizing deformation mechanism is the transformation of fractured feldspar grains into mica. The model problem solved by numerical means combines simple shear and extension. The rheological model accounts for dislocation creep of quartz, feldspar and mica, the feldspar-to-mica reaction and the fracturing detected by the Mohr-Coulomb criterion. The 2D solution reveals a periodic system of extensional shear bands, dipping at 30o at the depth of 12 to 14 km. They do not propagate to greater depths because the pressure prevents the fracturing and thus the reaction. The periodic system of shear bands defi nes a mid-crustal flat weakened zone within which brittle fracture could occur explaining therefore the seismicity monitored at these depths in regions of active extension.

Material Instabilites in Thermo-Mechanical Processes

SM12L_10265
Wed • 09:50 • 213

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Strain localization and the developement of material instabilities are investigated to highlight the roles of thermal effects and thermomechanical couplings. During a loading process, it is shown that two conditions play the essential roles and correspond to the singularity of the isothermal and the adiabatic acoustic tensors. Under quasi-static conditions, strain localization (in a classical sense) may occur when either of these two conditions is met. It involves a jump in temperature rate in the latter case, whereas temperature rate remains continuous in the former, but a discontinuity in the spatial derivatives of the heat flux must occur.This is consistent with the condition of stationarity of acceleration waves, which are shown to be homothermal and propagate with a velocity related to the eigenvalues of the isothermal acoustic tensor. A linear perturbation analysis further clarifi es the above fi ndings.

Incremental Energy Minimization in Material Instaqbility Problems

SM12L_10996
Wed • 10:10 • 213

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Recent theoretical developments of the incremental energy minimization and its novel applications to material instability problems in time-independent inelastic solids are presented, following the concept and computational method developed earlier by the authors. Necessity of imposing a symmetry restriction on the constitutive law is discussed. In the internal-variable formulation of multi-mode inelasticity, theorems are formulated and proven that provide a novel justifi cation of the second-order incremental energy minimization as the condition necessary for stability of a solution path. New examples are given that show how instability of a uniform deformation path can lead to the formation of a higher-rank laminated microstructure in an initially homogeneous inelastic material. As a conclusion, the non-convex minimization of incremental energy yields a natural criterion of selection of the post-critical deformation pattern and provides a computational method for determining deformation paths with automatic branch switching.

On Convexity Conditions in Spatial and Material Settings of Hyperelasticity

SM12L_11277
Thu • 09:30 • 213

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In this contribution convexity conditions for the spatial and material motion problem are investigated. Whereas the spatial motion problem corresponds to the usual equilibrium equations, the material motion problem is driven by the inverse deformation gradient, thus it deals with material or configurational forces that are energetically conjugated to material variations, i.e. variations at fixed spatial positions. The duality between the two problems is elaborated in terms of balance laws, their linearisations including the consistent tangent operators and in particular the so-called acoustic tensors. Issues of convexity and in particular of rank-one-convexity are discussed in both settings. As a remarkable result it turns out, that if the rank-one-convexity condition is violated, the loss of well-posedness of the governing equations occurs simultaneously in the spatial and in the material motion problem. Thus, the inclusion of the material motion problem does not lead to additional requirements to maintain rank-one-convexity or ellipticity. The results are developed for the hyperelastic case in general and highlighted analytically and numerically for a material of Neo-Hookean type.

On the Concept of "Dynamic (In)Stability of Quasi-Static Paths"

SM12L_12682
Thu • 09:50 • 213

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A concept of dynamic stability of quasi-static paths is proposed that takes into account the existence of fast (dynamic) and slow (quasi-static) time scales. A change of variables is performed that replaces the (fast) physical time t by a (slow) loading parameter λ, whose rate of change with respect to time, $\varepsilon = d\lambda/dt$, is decreased to zero. This leads to a system of dynamic equations defining a singular perturbation problem: the highest order derivative with respect to λ appears multiplied by ε. The proposed definition is essentially a continuity property with respect to the smallness of initial perturbations (as in Lyapunov stability) and loading rate ε (as in singular perturbation problems). Three mechanical examples (the Ziegler and Shanley columns and a pin-on-flat friction apparatus) are presented to illustrate similarities and differences between "dynamic stability of quasi-static paths" and Lyapunov stability of some related equilibrium configurations or dynamic trajectories.

Dynamics of Perturbations and Shear Band Instabilities

SM12L_11254
Thu • 10:10 • 213

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The dynamic Green's function is obtained for an infinite nonlinear-elastic, incompressible solid homogeneously deformed and subject to time-harmonic incremental perturbations. The formulation is employed to investigate the effects of perturbations on the dynamic behaviour of solids near the shear band formation threshold. Results shed light on the problem of interaction between dynamics and shear band formation.

Dynamical Systems Theory in Material Instabilities

SM12S_10314
Thu • 14:30 • 124

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The study of instability in plastic solid continua can be traced back to Drucker and Hill and has re-appeared at Rice on shear bands. Since then there are a lot of papers pubished and several stability definitions are applied. These can be originated in either energy or kinematic conditions. The way of stability analysis is mainly determined by such definitions. This paper uses Lyapunov stability. Then a set of partial differential equations is derived from the fundamental field equations of continuum mechanics. These are interpreted as an infinite dimensional dynamical system for basic functions satisfying the boudary conditions. Lyapunov's indirect method is applied for that system. By using our methodology a few material instability phenomena are studied: strain localization, flutter, and a kind of mathematical interpretation can be obtained. It makes possibile to explain the origin of mesh dependence in numerical studies of post-localization and the role of internal length.

An Idea and Theory of Hypothetical Device for Investigating the Localization Phenomena

SM12S_10867

Thu • 14:35 • 124

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Suggested is an idea of the lamination shear device for investigating the localization phenomena in bulk or soft plastic media. The device consists of apile of laminae with a cavity of rather arbitrary shape cut in it. The cavity isfi lled with a medium examined which forms the specimen of rather arbitraryshape. The prescribed uniform shearing of the pile induces the basic shearprocess in the specimen, which is also uniform unless its stability is violated.By means of author's modifi cations of the well-known Van Hove's theorem, the stability is proved to be preserved up to the loss in strong ellipticity for thematerial deformed, which stipulates the onset of localized instability. Thus, the localization pattern arises on the background of a homogeneous state of thespecimen and is influenced mostly by its shape. Such a combination of theoreticallysubstantiated properties enables in principle to investigate the dependence ofthe localization pattern on the shape of domain of deformation. The stated stillopen question is of great interest for mechanics of the localization phenomena.

Stability of Ideal Infinite Crystal Under Finite Uniform Deformation

SM12S_12223

Thu • 14:40 • 124

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Strong deformation and fracture are very diffi cult to describe using macroscopic continuum methods. Lack of a material continuousness makes description of such processes to be a serious challenge. In the current paper the onset of the material fracture is studied from both micro- and macroscopic points of view. First an ideal infi nite crystal lattice is considered. Transfer from microstructure to continuum mechanic is made using long-wave approximation. This allows obtaining nonlinear continuum equations of the infi nite crystal under fi nite uniform deformation. These equations are found without limitation to the space dimension. For the stability verifi cation a small deformation is superposed to a fi nite deformation of the crystal lattice being described by the obtained nonlinear macroscopic equations. Criterions of the material stability and their relevance to the crystal structure are obtained.

Explosive Instabilities in a Class of Hyperelastic Materials with Higher-Order Gradients

SM12S_12419

Thu • 14:45 • 124

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We establish a continuum mechanics framework for three-dimensional analysis for the onset of material instability in second-gradient hyperelasticity based on a linear stability analysis of governing fi eld equations. The essence of the method presented in the paper is to consider an evolution of exponential disturbances and their growth or decay from homogeneous states, which are defi ned by a set of relations describing isothermal hyperelastic behavior of the material with the second-gradient type of deformation. Instability develops as a result of explosive growth of imposed disturbance of governing fi eld equations. If the material in the elastic range exhibits a certain amount of non-local interaction with surroundings, the velocity dependence of propagating waves through such a medium depends on the wavelength and it is non-trivial. Consequently, special attention must be given to the detection of critical conditions leading to the standard and the symmetry breaking bifurcation. We display a derivation of a general dispersion relation of the expanded stability equation and also discuss some particular issues regarding critical conditions leading to the spatial heterogeneity in the evolution of fluctuation.

SM13

Mechanics of composites

Chairpersons: S. Adali (South Africa), N. Fleck (UK)

Interfacial Properties of Nanowire-Polymer Composites

SM13L_10244
Tue • 11:00 • 208

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Nanocomposites with elongated structural fillers have recently attracted many investigations. A focus is exclusively on nanocomposites with carbon nanotubes due to carbon nanotubes unique physical properties, including mechanical, thermal, optical and electrical. However, after nearly a decade of research, their potential as reinforcement for polymers has not been fully realized; the mechanical properties of derived composites have fallen short of expectations. Nanowires, having a diameter comparable to carbon nanotubes, aspect ratio close or above 1000 and a few hundred times more surface area per volume than a classical fiber reinforcement, may be considered as a new family of a reinforcing phase for nanocomposites. The mechanical performance of composite materials is critically controlled by the interfacial characteristics of the reinforcing phase and the matrix material. Her we report a study on the interfacial properties of a silicon nanowire-reinforced polystyrene nanocomposite system through molecular mechanics simulations. Results of a nanowire pullout simulation suggest that the interfacial shear transfer stress of this novel system is significantly higher than for many traditional fiber reinforced composite systems. The adhesion energy and the interfacial shear stress has been determined indicating significant bonding quality. Further improvement of the shear stress transfer could be achieved with functionalization of silicon nanowires with coupling agents.

Plane Harmonic Waves in a Microperiodic Layered Thermoelastic Solid Revisited

SM13L_10347
Tue • 11:20 • 208

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Modeling of plane harmonic waves in a microperiodic layered infinite thermoelastic solid via an eight-order in time partial differential equation involving a high intrinsic mechanical frequency Ω_M and a high intrinsic thermal frequency Ω_T was proposed by the present author before [see J. Ignaczak, Proceedings TS2003, TS2003, June 8–11, 2003, Blacksburg, VA, U.S.A.]. It was shown there that there are two harmonic waves of a given frequency ω propagating in a positive direction normal to the layering when $\Omega_M \to \infty$ and $\Omega_T < \infty$, or $\Omega_M < \infty$ and $\Omega_T \to \infty$. In the present paper the existence of two dispersive and attenuated harmonic waves of a given frequency ω is proved when $\Omega_M < \infty$ and $\Omega_T < \infty$. Also, a closed-form of the associated velocities and attenuation coefficients is obtained. Numerical results illustrating the two waves for a particular composition of the microperiodic layered thermoelastic solid are included.

Damage Progression by the Element-Failure Method (EFM) and Strain Invariant Failure Theory (SIFT)

SM13L_10412
Tue • 11:40 • 208

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The element-failure method (EFM) is a novel finite element-based method for the modelling of damage, fracture and delamination in fibre-reinforced composite laminates. The nature of damage in composite laminates is generally diffused and complex, characterized by multiple matrix cracks, fibre pullout, fibre breakage and delaminations. It is usually not possible to model or identify crack tips in the conventional fashion of fracture mechanics. The central idea of the EFM, on the other hand, is to model the damaged portions with partially failed elements, whose nodal forces have been modified to take into account the local damage modes. This has the additional benefit of unconditional computational stability compared to other methods such as material property degradation (MPD) models. Here, we present the application of EFM with a recently-

proposed failure criterion called the Strain Invariant Failure Theory (SIFT) in the prediction of damage progression in a composite laminated structure, and show that the damage patterns are in very good agreement with experiments. It is also shown that the EFM is more versatile and general than the MPD method.

Reissner-Mindlin-Von Karman Type Plate Modle for Postbuckling Analysis of Laminated Composite Structures

SM13L_10667
Tue • 12:00 • 208

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Postbuckling behaviour of laminated composite structures using Reissner-Mindlin-Von Karman type plate model is considered. The potential energy functional where the linearized strain tensor has been replaced by nonlinear functions, i.e., the Von Karman model for large deformation is formulated. The fourth-order tensors connecting membrane stress resultants and bending moment resultants to membrane strains and curvatures, respectively, and the coupling one for in-plane and flexural behavior as well as the second-order tensor connecting transverse shear forces to transverse shear strains are defined according to the Classical Lamination Theory. In the FE-implementation linear triangular elements are used. The transverse shear strains are discretized by the stabilized MITC-technique of Brezzi, Fortin, and Stenberg. The normal rotation (drilling rotation) is introduced as an auxiliary function and discretized by the stabilized method of Hughes and Brezzi. Load-displacement behaviour of the structure as well as the failure prediction and the identification of the critical areas of the model are illustrated with numerical examples.

Aspects of the Mechanical Response of Randomly Reinforced, Chopped Fiber Strand, Polymeric Composites

SM13L_11014
Tue • 12:20 • 208

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The modulus of randomly reinforced composites exhibits an unusually high scatter, which depends on the length of the measuring device. A high degree of scatter is also noted for the composite's strength. The random geometry was modeled by a random generation of the locations and orientations of fiber strands and projecting their configurations on sequentially stacked layers, until attaining the desired thickness of the structure. The stiffnesses of the modeled structure were evaluated by transforming the principal moduli of each randomly oriented strand into the common structural coordinates, while accounting for its volume fraction. In this manner it was possible to compute the well-known laminate-level stiffnesses A, B, and D. With these properties at hand it was possible to evaluate departures from isotropy and homogeneity in relation to sample size and spatial distances. Failure was modeled by means of a strand discount method, utilizing the Tsai-Hill failure criterion. The model provided detailed insights into the behavior of random reinforcement and its predictions were in good agreement with experimental data.

Computational Modeling of Deformation and Damage in Particle-Reinforced Composites

SM13L_11080
Tue • 12:40 • 208

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The micromechanisms of deformation and fracture in particle-reinforced composites are studied through the finite element simulation of 3D multiparticle cubic cells. The particle distributions within the cell were generated to represent composites with homogeneous and heterogeneous (clustered) microstructure. Damage in the matrix was introduced by the modified Gurson model while reinforcement fracture and decohesion at the matrix/reinforcement interface were included using three-dimensional interface elements, the interface and/or particle strength and toughness being given by the constitutive equation of the cohesive crack. The simulations provided new insights on the role played by reinforcement clustering and damage (particle fracture, interface decohesion, ductile matrix failure) on the overall composite tensile response as well as on the micromechanisms of damage nucleation and growth.

Elastic Interaction of Multiple Delaminations in Laminated Structures

SM13L_11162

Tue • 17:00 • 208

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The elastic interaction of multiple delaminations in laminated structures subject to out of plane loading has been investigated by utilizing beam theory approximations of elasticity. Shielding and amplification of the energy release rate of cracks has been quantified for a cantilever beam. These phenomena are controlled by regions of opening and contact that develop along the crack faces. Results show important short and long range interactions between these cracks, depending mostly on their transverse spacing and have some similarity to the results of other investigators for the interaction of cracks in infinite bodies, but with strong modification of certain characteristics by mode ratio and thickness effects. Shielding and amplification strongly influence the propagation of the system of cracks leading to local instabilities, local strain hardening and crack arrest. Maps of these behaviors have been constructed, allowing for easy qualification of shielding and amplification and crack propagation events. The results are being validated using finite elements.

Damage Tolerance of Composite Structures with Thermal Shield

SM13L_11180

Tue • 17:20 • 208

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Accidental damages, like impact of foreign objects, on the aeronautical and spatial composite structures cause drastic reductions in the residual strength. Consequently, it is essential to define a damage tolerance concept during the project design. The aim of this paper is to study the influence of the cork thermal shield on the damage tolerance concept of composite panels. Indeed, cork thermal shield stuck on the composite panels used for civil and military launchers' fairing, modify the structure mechanical behaviour during impact of foreign objects. The results show the good mechanical behaviour of the thermal shield during the impact. Indeed, the thermal protection acts like a mechanical protection during the impact and reveals it before having damage in the laminate. In particular, with the studied thermal shields, damage threshold appears at a higher permanent indentation than the BVID (Barely Visible Impact Damage) aeronautic threshold of 0.6 mm.

Can it Be Made? Predicting the Formability of Textile Composite Components

SM13L_11387

Tue • 17:40 • 208

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There are many ways of forming components from composite materials. These include injection moulding, hand lay-up, diaphragm forming, stamping, pultrusion, resin transfer moulding, filament winding, and vacuum forming. In recent years, attention has been focused on optimising the structural properties of composite components by using continuous fibres. Producing materials that can be formed with minimum force to produce high quality components is a challenging task. In this study, a constitutive model is developed which predicts the force required to form various composite components from continuous fibre reinforced composites. The model is based on easily measurable physical quantities such as the tow spacing, fibre volume fraction and matrix rheology. The constitutive model is implemented in an energy based drape model to predict the formability of various demonstrator components. Finally, forming limit diagrams and design guidelines for producing components from textile composites are discussed.

Three-Dimensional Thermoelastic Analalysis of Plain Weave Glass/Epoxy Composities with Cracks at Cryogenic Temperatures

SM13L_11610

Tue • 18:00 • 208

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This paper examines the thermo-mechanical behavior of cracked G-11 woven glass/epoxy laminates with temperature-dependent material properties under tension at cryogenic temperatures. Three-dimensional finite elements are employed

to model the architecture of the two-layer woven laminates. It is assumed that the cracks are confined to individual fiber bundles oriented transverse to the tensile load direction and span the thickness of the fiber bundles. The effects of residual thermal stresses caused by differences in the coefficients of thermal expansion of the composite constituents, and cracks on the mechanical behavior of two-layer G-11 woven laminates at cryogenic temperatures are explored. Numerical results for the Young's modulus and Poisson's ratio of the woven laminates are obtained and discussed. A discussion on the findings from the three-dimensional finite element analysis are also given, with particular focus on the stress distributions and concentrations inside the woven composites under combined mechanical and thermal loads.

Advanced Beam Model for Fiber-Bridging in Unidirectional Composite Double-Cantilever Beam Specimens

SM13L_11747
Tue • 18:20 • 208

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Linear beam analysis accounting for fiber-bridging in composite DCB specimen was carried out. A simple solver was written based on beam equations. The location and number of bridgings is required as input data. Experiments were made on unidirectional glass/polyester specimens. Initiation and propagation tests were conducted. Initiation test results show very good agreement with previous beam model predictions. In contrast based on propagation test data beam models seemed to be inappropriate for predicting both the specimen compliance and the fracture toughness. The contradiction was attributed to the fiber-bridging phenomenon. The bridging law was determined from experiment and also from beam analysis. Comparison between them shows good agreement. According to the beam analysis the number of bridging fibers and the total force exerted by the bridgings can approximately be predicted. These two parameters show similar behavior, i.e. exhibit a peak value and after a steady-state behavior.

Interfacial Jump Conditions in Strain-Gradient Plasticity and Relations of Hall-Petch Type

SM13L_11782
Tue • 18:40 • 208

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Strain-gradient plasticity requires boundary conditions, and jump conditions across interfaces, additional to those required in ordinary plasticity. In the work to be described, we penalise dislocations crossing the interface by admitting an interfacial potential that is a function of the plastic strain; this induces a jump in the higher-order traction, which is analogous to allowing dislocations to pile up. The theory is illustrated by a number of simple one-dimensional examples. The microstructure is taken to be periodic and the homogenised, or effective, response is studied by taking the total strain to be periodic with prescribed mean value; the plastic strain is likewise periodic but its mean value is obtained from the solution. A pronounced scale-dependence of effective flow stress – a kind of Hall–Petch relation – is obtained in every case. Work in progress includes allowance for randomly-distributed interfaces, and extension to problems in two and three dimensions.

A Study of Particle Debonding with Anisotropy

SM13L_11794
Wed • 08:30 • 208

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Reinforcement of materials by adding second phase particles usually causes the fracture toughness to decrease due to void nucleation and growth by debonding along the particle-matrix interface. This work applies a unit cell model with periodical boundary conditions to numerically investigate effects of plastic as well as geometrical anisotropy on this failure mechanism for an elastic-viscoplastic matrix containing rigid inclusions. The periodical boundary conditions allows for any choice of initial angle between the tensile direction and the principal axes of anisotropy. Geometrical anisotropy is induced by the shape and the distribution of the inclusions. The average stress-strain response of the cell is evaluated and debonding is observed as a sudden stress drop. Depending on the initial orientation of the principal axes of plastic anisotropy, debonding in the present material is significantly delayed due to a reduced yield stress. Some results show identical stress-strain responses but laterally reversed deformation modes.

Nonlinear Affine Extension of the Three-Phase Sphere Model

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SM13L_11805
Wed • 08:50 • 208

To model the nonlinear behaviour of particulate composites, the classical procedure of transforming, at a given strain, a nonlinear problem into a linear one has been used. The chosen linearisation method is the recently proposed affine formulation which has been coupled to the three phase self-consistent estimate of the linearised overall properties, in the case of uniaxial loading. Due to the anisotropic tangent behaviour, the linear three-phase self-consistent estimate is computed numerically. This treatment has been applied to two-phase composites with nonlinear elastic behaviours described by power-law stress-strain relationships, but the same developments are still valid for viscous materials.

Three-Dimensional Analytical and Semi-Analytical Investigation of Free-Corner Effects

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SM13L_11879
Wed • 09:10 • 208

Stress fields at interfaces of dissimilar layers near free edges and corners of composite laminates are of a localized 3D singular nature (free-edge and free-corner effects). Numerical studies of such stress concentration phenomena require vast computational effort, hence it is of particular interest to develop approximate analysis methods requiring reasonable computational expenses yet performing with high accuracy. In the present contribution, analytical and semi-analytical approaches to 3D laminate corner effects are presented. First, an analytical method in the form of a layerwise assumed-stress approach for rectangular plates with arbitrary layups is used. Second, a hybrid layerwise displacement-based variational formulation proves to be highly efficient for rectangular cross-ply plates. As a closure, a novel semi-analytical approach to the 3D asymptotic corner behaviour is presented using the boundary finite element method which in essence is a fundamental-solution-less boundary element formulation based on finite elements.

On the Role of Inter-Granular Layers in Polycrystalline Ceramics

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SM13L_12141
Wed • 09:30 • 208

Ceramic polycrystalline materials have a non-linear and complex response to applied loads due to their internal structure. The inter-granular layers significantly change the macro-response of the material. The aim of the paper is to present a new constitutive model for the case of uniaxial tension of the polycrystalline materials, including the inter-granular metallic layers that create its internal structure. The quasi-static deformation process of a material comprises of: – elastic deformation of brittle grains, – elasto-plastic deformation of intergranular layers, – additional deformation due to micro-porosity development in layers A Representative Volume Element (RVE) was analysed taking into consideration an initial internal structure of the material obtained from SME photographs. Owing to the high complexity of the internal structure of the composite material, the FEM technique was used to obtain macroscopic stress-strain correlations.

A Homogenization Based Laminated Beam Theory

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SM13L_12148
Wed • 09:50 • 208

A sequence of theories is developed for laminated (including sandwich) beams. An homogenization approach is used in conjunction with far-field stress and strain solutions resulting from constant, linear, ..., n^{th} degree bending states; these solutions are called Fundamental Solutions. Based on the Fundamental Solutions, through-thickness stress and strain moments are used to obtain definitions of homogenized flexural and shear stiffness, homogenized transverse Poisson's ratio as well as a unique shear strain moment correction. All developed models adopt a form similar to that of Classical Timoshenko Beam Theory; however, the system parameters of the present and the Timoshenko model have different meanings. Numerical comparisons are made with 'exact' two-dimensional finite element results for a sequence of cantilever sandwich-beams.

It is shown that all stress and strain components (in-plane, transverse and shear) are obtained with consistent and excellent accuracy which goes beyond the capability of conventional beam theories.

Compressive Strength of Fiber Composite with Porosity

SM13L_12214
Wed • 10:10 • 208

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The compression strength of fiber composites is analysed using a finite element model with a separate discretization of fiber and matrix. The analysis is carried out under the assumption of plane strain. The fiber material is considered elastic while the matrix material is described by a finite strain version of J_2-flow theory. A geometric imperfection is introduced as a band transverse to the fibers to initiate the development of a kink band. The sensitivity of the compression strength to the fiber misalignment angle is investigated and the most critical kink band angle is studied. Finally, porosities are included in the model to analyse how this material imperfection influences the compressive strength of the composite. Analyses are performed with different amount and location of the porosities and the results indicate that the presence of porosities reduces the compressive strength somewhat.

Composites with Planar Random Fiber Arrangements

SM13L_12321
Wed • 11:00 • 208

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A short fiber reinforced composite material with particular fiber arrangement is investigated by means of a numerical unit cell approach as well as by an analytical mean field type approach. Homogenization and localization is performed for Carbon fiber reinforced Copper with respect to the linear thermoelastic and thermal expansion properties. Simulation results are compared and their applicability is assessed.

Thermal Fatigue of MMC Induced by Laser Heating

SM13L_12496
Wed • 11:20 • 208

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The thermal fatigue of particle reinforced metal matrix composites (MMC) induced by laser heating and applied mechanical load was experimentally and numerically studied. It was found that the initial fatigue damage took place near the edge of laser-irradiated region. The initial damage was the form of the void nucleation, growth and subsequent coalescence in the matrix or the interface separation. The fatigue cracks were constituted of void in the matrix, interface separation and particle fracture. The fatigue damage parameters were determined by ultrasonic method. The plane of mechanical load with the times of pulsed laser heating could be divided three regions, i.e. non-damage region, damage region and failure region. The damage processing was numerically investigated by finite element method. The fields of temperature, macroscopical stress and microscopical stress induced by the laser heating and tensile load were numerically obtained. The simulative results were good agreement with the experimental results. KEYWORDS: MMC, Thermal fatigue, Ultrasonic, Laser heating

An Anisotropic Damage Model for the Prediction of the Degradation Behaviour of Novel Textile Reinforced Composites

SM13L_12576
Wed • 11:40 • 208

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Novel textile reinforced composites are very suitable for applications in lightweight structures, since they can resist high mechanical and thermal load. In this paper a phenomenological damage-mechanics-based model for these composites is presented. Damage variables are introduced to describe the evolution of the damage state and as a subsequence the degradation of the material stiffness. Special emphasis is given to the interaction between fibre failure due to fibre stress and matrix failure due to transverse and shear stress. The predictive capability of the presented model is evaluated by carrying out a series of tensile tests using acoustic emission techniques to detect the strength and the failure behaviour of

CF/PEEK, GF/RP and CF/RP. The performance of the model strongly depends on the correct determination of the material parameters. Thus, model parameters may be determined either by experimental measurement, by micromechanical models or by crack density studies.

Crack Tunneling in Laminates

SM13L_12680
Wed • 12:00 • 208

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Steady-state tunneling and plane-strain delamination of an H-shape crack are examined for elastic, isotropic multi-layers. Both tunneling and delamination are analysed by employing linear elastic fracture mechanics within a 2D finite element framework. Failure maps are produced to reveal the sensitivity of cracking path to the relative toughness of layer and interface, and to the stiffness mismatch of layers. Closed-form expressions are derived for the critical stress level for steady-state plane-strain delamination. It is shown that the numerical predictions asymptote correctly towards the closed-form expressions for large delamination lengths. A comparison with experimental values taken from the literature shows that the model results are useful in the determination of the residual strength and the fatigue crack growth rate in elastic multilayers.

Study of the Usability of Various Cruciform Geometries for Biaxial Testing of Fiber Reinforced Composites

SM13L_12818
Wed • 12:20 • 208

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Experimental investigation of fibre reinforced composites was predominantly performed using uniaxially loaded specimens. However, in real applications composites are often loaded in more directions. Consequently, experimental investigation of these materials should consider biaxial tests. For this reason a biaxial testing facility for planar cruciform specimens was developed at the Free University of Brussels. A valid biaxial test avoids premature failure in the uniaxially loaded arms and gives a large region of uniform strain in the biaxially loaded zone. These conditions are not easily obtained and so the design of a suitable cruciform geometry is the subject of this paper. Finite element simulations in combination with experiments on different geometries, led to the selection of a suitable geometry with a reduced thickness in the central region of the specimen in combination with a rounding radius between two arms inside the material. In that way failure occurs in the biaxially loaded zone.

Complex Potential Formalism for Flexure of Inhomogeneous Plates Including Transverse Shear Deformation

SM13L_10946
Wed • 12:40 • 208

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The elegance of the Eshelby-Stroh sextic formalism in dealing with equations of plane strain elasticity motivated several investigators to extend its applicability towards the complex potential treatment of the classical laminate plate theory (CLPT) equations. CLPT is however adequate for accurate prediction of through thickness averaged displacements as well as force and moment resultants of very thin plates only. There is therefore much greater scope in using complex potential formalisms in connection with refined than CLPT equations. This paper is the first attempt towards the development of complex potential formalisms in association with refined plate theory equations. The development is based on the equations of a generalized plate theory that has been found adequate even for stress analysis studies of moderately thick laminated composites. Corresponding complex varible formalisms concerned with earlier but less accurate refined plate theories are also obtained as particular, though nontrivial cases of the present development.

Numerical Evaluation of Mixed Mode Delamination in a U.D. Glass/Epoxy Composite in 2D and 3D States

SM13S_10189
Tue • 14:30 • 213

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In this paper the delamination phenomena in the mixed mode I+II that is one of the important causes of failure in multilayer composites, is studied. The composite is a glass fiber reinforced plastic and is studied under static monotonic loading.Using Irwin-Kies criteria, usual laws of elasticity and VCCT (Virtual Crack Closure Teqhnique), based on finite element method, the SERR (Strain Energy Release Rate) in mode I, mode II, and four ratio mode (GI/GII) is evaluated.The finite element analysis of test bars is carried out using ANSYS5.5 software in two dimensions, and boundary conditions are chosen to bring the analysis in the vicinity of reality. Our numerical results are compared with existing experimental ones and with application of the local effects, such as 3D effect in the width of the test bar with the shape of MMB (Mixed Mode Bending) specimen, the scattering between experimental and numerical results is evaluated and discussed. For the three-dimensional effect, the variation of the stress components in the plan of delamination versus the width of specimen is obtained. Then the variation of strain energy release rate in the different ratio modes, in the width of test bars is calculated.

Effective Properties of Solids Containing Randomly Distributed Multi-Phase Spherical Particles

SM13S_10483
Tue • 14:35 • 213

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In this paper, the micromechanical method of homogenization is used to estimate the overall mechanical behaviour of solids containing high concentration of heterogeneous spherical particles. The previous treatments in the literature have failed to account for the long and short range interactions of thickly coated particles rigorously. Recently, based on the extension of Eshelby's equivalent inclusion method (EIM) to multi-inhomogeneities, the overall behaviour of solids with periodic distribution of multi-phase interacting particles has been estimated by the authors, which involved the Fourier series expansions of the eigenstrains. In this work, an accurate formulation suitable for composites containing non-dilute distribution of thickly coated particles with random microstructure is presented. The theory incorporates the complex interaction of many interacting multi-inhomogeneities, a scenario encountered when dealing with non-dilute concentration of multiple coated fiber reinforced composites.

Porous Anisotropic Composites under Microfructures

SM13S_10555
Tue • 14:40 • 213

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The aim of the present paper is to study the behaviour of composite materials with ellipsoidal inclusions. It is supposed that the components have transversally isotropic of physical and mechanical properties It is assumed that the matrix is porous and the loading processes leads to accumulation of damage in it. Fractured microvolumes are modeled by a system of randomly distributed quasispherical pores. As basic relations are taken the porosity balance equation and relation described effective elastic moduli in the case of transversally isotropic components. Effective moduli of such material are determined by using stochastic equations of elasticity theory and the method of conditional moment functions. The fracture criterion is considered as the limit value of intensity of average shear stresses occurring in the undamaged part of the material. Moreover, it is assumed that the strength limit is the random function of coordinates. The distribution of the functions is given by power-exponential formula. Algorithm enabling to calculate nonlinear elastic characteristics of the considered composite was constructed on the basis of the combined iterative method. The results of numerical calculations are presented in the form figures which depict the dependence of macrostresses on macrodeformations was found for various factors such as porosity, volume concentration of fazes and parameters of material strength scatter.

Three-Dimensional Transmission in Plane Layered Elastic Composites

SM13S_10745
Tue • 14:45 • 213

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Starting from a basic theorem which explicitly expresses the displacement induced in two perfectly bonded semi-infinite isotropic elastic solids in terms of the corresponding displacement induced in the homogeneous elastic whole space, what-

ever be the mechanism of loading, we derive in a stepwise fashion a well-structured series representation for the three-dimensional elastic field induced by an arbitrary singularity which is operative in or near a thick layer separating two other dissimilar semi-infinite isotropic elastic solids. The main objective is a physical interpretation of the seemingly complex solution in terms of fundamental singular fields. Several illustrative examples are given, including the image system produced by an arbitrary singularity in a slow steady viscous flow between two no-slip parallel plates.

Overall Properties of Periodic Biocomposites

SM13S_11176
Tue • 14:50 • 213

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The problem of predicting the electromechanical properties of composites whose constituents are biomaterials is addressed in this paper. A two-phase parallel fiber-reinforced periodic composite is considered here in either a square or hexagonal array. The materials are anisotropic. Their electroelastic properties are taken to belong to the hexagonal system, classes 622 or 6. The fiber cross-section is circular. Simple closed-form formulae are obtained for the overall properties of the composite using the asymptotic homogenization method. The local problems that arise upon the aplication of this method are solved using potential theory of a complex variable and properties of doubly periodic elliptic functions of periods 1, i (1, $\exp(i\pi/3)$) for a square (hexagonal) array. Some examples of the numerical results will be shown for several combinations of biomaterials, such as, collagen, collagen-hydroxyapatite, hydroxyapatite, etc. of interest in medical applications.

Electroelstic Fields Concentrations and Polarization Switching by Circular Electrodes in Piezoelectric Disk Composites

SM13S_11426
Tue • 14:55 • 213

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The electroelastic fields concentrations due to circular electrodes at the interface of piezoelectric disk composites have been discussed through theoretical, numerical and experimental characterizations. This paper consists of two parts. In the first part, the problem of an internal electrode embedded at the interface of two dissimilar semi-infinite piezoelectric solids was formulated by means of Hankel transforms and the solution was solved exactly. In the second part, finite element analysis was carried out to study electroelastic fields in piezoelectric disk composites containing circular electrodes of different radii by introducing a model for polarization switching in local areas of fields concentrations. A nonlinear behavior induced by localized polarization switching was observed between the strain and the voltage applied to the electrode. Experiments were also conducted to study the strain state near the electrode tip in piezoelectric disks. Comparison of the predictions by the present model with experimental data is conducted.

Fuzzy Set Approach to Modelling Composite Mechanical Properties

SM13S_11457
Tue • 15:00 • 213

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Abstract In the analysis of engineering problems three different approaches are used depending on the nature and extent of uncertainty by the introduction of the uncertainty triangle: probabilistic methods, a fuzzy set approach and an anti-optimisation. In the paper we intend to present qualitative and quantitative differences of results (understood in the sense of composite mechanical properties) comparing two models: a deterministic and the second, which is based on the fuzzy, set approach. They are used in the description of two composite materials – a unidirectional and a textile (a twisted yarn composite). In both cases, the fuzziness of variables is expressed by the triangular membership function. The variability (understood as the fuzziness) of material and geometrical parameters is taken to be equal to $\pm 10\%$, whereas the nominal (average) values correspond to á=1 and are equivalent to the deterministic description. The vertex method associated with the á-cuts representation of the membership functions is used to derive the upper and lower bounds of fuzzy output variables.

Evaluation of Linearization Procedures Sustaining Nonlinear Homogenisation Theories

SM13S_11507
Tue • 15:05 • 213

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This study aims at defining a methodology and a numerical tool for a systematic evaluation of various existing homogenization methods for nonlinear composites. Since the crucial step of such methods lies in the linearization procedure which leads to the definition of a heterogeneous linear comparison material (LCM), we have chosen a composite with a periodic microstructure. This allows us to derive numerically the exact solution of the nonlinear homogenization problem and to define a periodic LCM, whatever the linearization method, for which the exact solution can also be derived. Attention can then be focussed on the relative relevance of the chosen linearization procedure. The reported results refer to the overall stress-strain response of a two-phase periodic composite under tension with a power-law matrix and aligned identical elastic inclusions. The exact solution is compared to predictions derived from the 'modified secant' formulation and from various versions of the 'affine' procedure.

Thermal Residual Stress in Al2O3/SiCnano Ceramic Composites Measured by Nanoindenter

SM13S_12242
Tue • 15:10 • 213

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Thermal residual stresses in Al2O3 ceramics containing SiCnano particles were measured by nanoindentation instrument. As comparison, pure Al2O3 ceramics was selected as a reference without thermal residual stress. Considered the contact stiffness would vary due to local heterogeneities of microstructure in current composites, data on the surface sensitivity of a series of samples probed at different peak depths were collected. The experimental results on the residual stress of two composites in local region probed by indenter were obtained. Also the influence of volume fraction of SiC particles to the magnitude of thermal residual stress and the external work and deformation energy during penetration were investigated.
Key words: nano-ceramic composite, thermal residual stress, nanoindentaion experiment

H-Convergence and Multilayering in Piezocomposites

SM13S_11895
Tue • 15:15 • 213

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The development of homogenization as well as their applications to micromechanics, mechanics of composites and porous media, and to optimal design provides new possibilities of micro-macro modeling. The extension of results to piezoelectricity is important due to the straightforward applications in high technology (smart materials). The main aim of the present contribution is to present the following new results: extension of the notion of H-convergence to piezocomposites and derivation of the formula for the effective moduli of p-times laminated piezoelectric composite. The second aim is to formulate the optimization problem for minimum compliance in the case of composites made of two piezoelectric materials. In such a case the compliance functional involves also electric field.

Bounds for Expansion Coefficients of Composites

SM13S_12448
Thu • 14:30 • 213

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A method is suggested to bound the anisotropic effective stiffness and extension tensors of a multiphase composite made of expandable materials. The bounds are valid for composites of any microstructure. It is shown that the expansion coefficients vary an ellipsoid which parameters depend on properties of the phases, their fractions, and the effective stiffness of a composite. The obtained tensorial inequalities generalize bounds by Schapery, Rozen and Hashin, and Gibiansky and Torquato. Particularly, the bounds for the mixtures with voids are obtained.

Long-Term Stress–Strain Relations of the Cement-Matrix Composite

SM13S_12478
Thu • 14:35 • 213

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A micromechanics-based model is proposed to determine the nonlinear stress–strain relations of the cement-matrix composites due to the effects of the volume concentrations and the material ages. When the nonlinear stress–strain curve of the binders is determined by means of the four-parameter Burgers model at different material ages, the secant moduli of the nonlinear binders are then used in a two-phase composite model to find the overall secant moduli of the composite as a function of the volume concentration and the shape of the aggregates. The results show that the predicted stress-strain relations of the mortar depending on the material ages are suitable for the volume concentration up to 70% of the aggregates and the range lower than 80% the peak strength of the composite.

Inclusion Dispersion: Effects on Stress and Effective Properties

SM13S_12489
Thu • 14:40 • 213

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A 3D stress analysis method based on Mura's eigenstrains and Eshelby's equivalency principle is proposed. Multiple inclusion interaction is considered, thus the eigenstrains in each inclusion are no longer uniform. The multiple inclusion problem is solved from the governing elasticity equations to give a set of coupled singular integral equations in the unknown eigenstrains of each inclusion. The set of coupled singular integral equations are solved using numerical integration, to give the unknown eigenstrains. For illustrative purposes the inclusions are dispersed in a regular cubic arrangement with 27 inclusions. 4 different inclusion separation distances are considered and in each of the 4 situations 3 different inclusion stiffnesses are considered. The stresses from the analysis are seen to be highly influenced by inclusion separation. It is found that the center inclusion is shielded by the other inclusions and this shielding effect displays a local minimum as the separation distance changes.

Thermo-Mechanical Stability and Vibration Analysis of Composite Shells

SM13S_12531
Thu • 14:45 • 213

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The present study is focused on postbuckling and postbuckled vibration analysis of curved panels subjected to thermo-mechanical loading. The formulation is based on the modified Sander's theory incorporating the geometric nonlinearities. The higher-order shear deformation displacement field used in the present study accounts for parabolic distribution of the transverse shear strains through thickness of the shell and tangential stress-free boundary conditions on the boundary surfaces of the shell. The multi-term Galerkin's technique is used to obtain the true postbuckled shape of the shell and postbuckled frequencies and associated modeshapes. Numerical results are presented for composite panels with and without initial geometric imperfections. The modal participation of each mode in the postbuckling deflection is presented using multi-term Galerkin's procedure. The results show the thermo-mechanical load interaction on buckling, limiting points and snap-through buckling.

New Trends in Optimal Design of Composite Materials

SM13S_12560
Thu • 14:50 • 213

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The current trends in machine design demonstrate that a centre of gravity is continuously shifted from a structural design towards a material design mainly due to an increasing number of new materials and a development of new technologies enabling us to produce required machines. It is worth to emphasise that the optimal material design should take into account not only the required functional properties of machines but also the availability of technological processes and their influence on the mechanical properties. The aim of the paper: A) to show the possibility of optimisation of technological processes in order to eliminate or to enhance the effects of induced internal stresses during production of composite structures, B) using homogenisation approach to discuss the problem of fibre shape optimisation to obtain the required material properties. Problems are analysed in the elastic range using variational formulations with Lagrange's coefficients. Numerical examples have been solved to illustrate the effectiveness of the method.

Asymtotic Study of Imperfect Interfacial Bonding in Periodic Composite Materials

SM13S_12588
Thu • 14:55 • 213

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An asymptotic approach for analytical study of the mechanical behaviour of composite materials is proposed. As illustrative examples we consider longitudinal-shear deformation of regular arrays of circular fibres. We start with the asymptotic homogenization method. The cell problem is solved by means of a boundary perturbation technique. In order to study the phenomenon of the imperfect interfacial bonding we introduce an artificial layer between the components and tend its thickness to zero. In the asymptotic limit varying the elastic properties of this layer we simulate different types of the interface response. As the results effective moduli, local stresses and effective initial yield limits are evaluated for all values of the components' volume fractions and properties. The developed analytical solutions stay valid in cases when rapid oscillations of physical fields occur on the micro level (e.g., in the case of perfectly rigid nearly touching fibres), when FEM simulations may face difficulties.

Analytical Models for Stress and Failure Analysis of Notched Hybrid Composites

SM13S_12612
Thu • 15:00 • 213

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The design of notched high-performance composites with fibre and textile reinforcement requires a special stress analysis and a proof of their notched strength, which includes the structural parameters of the component combination, material orientation and layer arrangement. For the description of the notch stress behaviour of hybrid constructions, analytical calculation methods are developed at the Institut für Leichtbau und Kunststofftechnik (ILK). The model presented here is based on the enhanced laminate theory combined with the method of complex-valued displacement functions and the method of conformal mappings, from which adapted approaches for the stresses and displacements can be obtained. Extensive experimental research is also conducted. For developing of more accurate failure models an improved stress analysis of notched anisotropic plates combined with a physically based strength analysis is used. The discussed approach is demonstrated here for the example of textile-reinforced timber constructions.

T-Inclusion Regions for the Effective Transport Coefficients of Two–Phase Media

SM13S_12667
Thu • 15:05 • 213

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By starting from several truncated power series we derive by means of a special T-multipoint continued fraction technique the general T-inclusion regions estimating in a complex domain the effective transport coefficients Q of the two-phase media such as dielectric or diffusion constants, thermal or electrical conductivities, magnetic permeabilities. The incorporation into the T-inclusion regions of the power series expanded at infinity have not been investigated in literature. Hence the T-inclusion relations derived are new. They provide the best estimates of Q with respect to the given input data. In special cases they reduce to the well known complex bounds reported in literature. Numerical examples exhibiting the usefulness of the results obtained are also provided.

Thermoelastoplastic Behavior of Discontinuously-Reinforced Composites Considering Reinforcement Damage

SM13S_12684
Thu • 15:10 • 213

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The particle and short-fiber reinforced composites are used in different engineering applications. Therefore, in the analysis of the composite materials not only the mechanical loading but also the thermal loading should be studied. Due to loading conditions, some reinforcement may be cracked and/or debonded from the matrix. Consequently, the load carrying capacity

of the reinforcement depends on whether the reinforcement is intact, cracked or debonded from the matrix. The constitutive equation of composite material which take into account the damage process and the change in temperature is necessary in order to solve these phenomena. In this paper, an incremental constitutive equation of the particle and short-fi ber reinforced composites with progressive cracking damage of the reinforcement has been developed considering the temperature change and elastoplasticity. By modifying the load carrying capacity of the damaged reinforcement, the present constitutive equation can describe the cracking damage and the debonding damage of the reinforcement as well as the perfect composite.

Macroscopic Relations for Nonlinear Thermodiffusion in Heterogeneous Elastic Medium

SM13S_12732
Thu • 15:15 • 213

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Thermodiffusion in heterogeneous elastic body with periodic microstructure in the case of temperature (T) and concentration (c)dependent phenomenological coeffi cients is considered. The primal system of equations describing the thermodiffusion in such a nonlinear elastic composite is derived on thermodynamical basis. Next, by using homogenization methods macroscopic coeffi cients are derived. The special cases of linear dependence of coeffi cients on T and c, as well the case of the Arrhenius and non-Arrhenius temperature dependency are studied. To illustrate the general results, the microperiodic layered composite is studied and exact analytical formulae for the overall coeffi cients are obtained.

Incremental Effective Constitutive Law for Composite Material in the Form of Artificial Neural Network

SM13S_12970
Thu • 15:20 • 213

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Description of effective behaviour of composites in the form of a suitably trained Artifi cial Neural Network is presented in this paper. We assume an incremental form of constitutive relationship approximated by ANN. We propose two methods of acquisition of data for training the ANN. The fi rst one furnishes the pairs: average stress – average strains and their increments – resulting from the solution of boundary value problem defi ned over a representative volume, with given mean strain imposed. The second method we propose bases on sampling of global behaviour of the composite material. The presented approach is fully numerical. The corresponding algorithm seems to be applicable for a large class of composites. The representation of the constitutive law by ANN can be included as a subroutine into any FE code. Example shows the application of the method for Neo-Hookean material.

Analysis of Thick Laminated Panel With Piezoelectric Sensors Based on Three-Dimensional Theory of Elasticity

SM13S_13009
Thu • 15:25 • 213

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In recent years, smart structures with piezoelectric sensors and actuators have attracted serious attention for they can sense and alter the mechanical response during in-service operation. On the other hand, light-weight shell and panel structures may be one of the most popularly used structures in space vehicles. For these reasons, shell-type smart structures have become the subject of focus for many researchers. A study on the elasticity solution of shell panel with piezoelectric sensors is presented. In this paper, the structure is simply supported at four sides, orthotropic and under pressure excitation on outer surface. Three-dimensional equations of equilibrium, which are coupled partial differential equations, are reduced to ordinary differential equations with variable coeffi cients by means of Fourier series expansion in circumferential and axial directions. The resulting ordinary differential equations are solved by Galerkin fi nite element method. Finally three layered panels with one piezoelectric layer[0/90/P] are solved and the results are compared with latest published results.

SM14

Mechanics of phase tranformations (jointly with IACM)

Chairpersons: F. Fischer (Austria), A. Molinari (France)

A Micromechanical Model for Single-Crystal Shape-Memory-Alloys

SM14L_12077

Tue • 11:00 • 213

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We developed a continuum-mechanical model for shape-memory-alloys which utilises only physically well defined quantities. Therefore we define an averaged energy density of a representative volume element (RVE) which can consist of austenite and several variants of martensite. Instead of using a homogenous strain-state for the whole RVE, that would lead us to a non-convex problem, we apply a certain microstructure by separating the RVE into different regions, called laminates, which consist of one of the phases. We obtain new variables, where some of them will be considered as minimizers of the averaged energy density. This minimization process will define a relaxed energy functional. All remaining variables are related to dissipative energy terms because we want to simulate the characteristic hysteretic behaviour. For that reason we can derive evolution equations from the least-action principle. We verify the algorithm in a material-point computation and apply it to the FEM.

Stress-Induced Martensitic Phase Transition Front Propagation

SM14L_11393

Tue • 11:20 • 213

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A non-equilibrium description of states of computational elements and their interaction is proposed for the numerical simulation of stress-induced martensitic phase transition front propagation in thermoelastic solids. This description is based on the generalization of the thermodynamics of discrete systems to the thermoelastic case. A finite-volume numerical scheme is then constructed by means of corresponding contact quantities. Additional constitutive information is introduced by means of certain assumptions about the entropy production at the phase boundary. Results of numerical simulations capture experimental observations.

On Modeling the Longitudial Impact of Two Shape Memory Bars

SM14L_11852

Tue • 11:40 • 213

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We study the propagation of phase transformation fronts induced by the longitudinal impact of two shape memory bars. The corresponding wave structure is investigated by using the non-monotone elastic model versus a Maxwell's rate-type model containing a rate sensitivity parameter and a time of relaxation of kinetic origin. We focus on the numerical results which can be compared with experimental data: the time of separation (optical methods), the velocity at the end of the target bar (interferometry), the stress at the impacted end (piezoelectric wafers), the variation in time of the strain at various cross-sections (diffraction gratings). We put into evidence how an experimental investigation on the influence of the impact velocity on the time of separation of the bars and on the velocity time profiles at the free end of the target could clarify some aspects connected with the dynamic nucleation of phases.

Shape Memory Alloy Under Strain and Stress Controlled Conditions – Thermomechanical Aspects of Martensite and Reverse Transformations

SM14L_11308
Tue • 12:00 • 213

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Thermomechanical aspects of martensite and reverse transformations in shape-memory alloy subjected to strain and stress control were investigated. The temperature distributions on the specimen's surface were determined by using an infrared camera. The results differ in mechanical behavior, however at both approaches, a heterogeneous temperature distributions, related to the nucleation and developing of the new phase, were observed. After the initial uniform temperature distribution, the temperature increased in the central area of the sample, followed by an inclined line of significantly higher temperature. Next lines, parallel to each other, developed towards the grips, as well as a second "family" of them, developing in perpendicular direction. At higher strain, the regions of increased temperature became less clearly defined, due to the martensite developing in the whole material volume and the heat flow. The similar heterogeneous effects were observed during unloading, while the reverse transformation took place, accompanied by significant temperature decrease.

Determination of Phase Transformation Yield Surface of Anisotropic Shape Memory Alloys

SM14L_12225
Tue • 12:20 • 213

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The superelastic behavior of Shape Memory Alloys (SMA) is useful for several industrial applications. To determine the behavior of SMA structures, the development of specified phenomenological constitutive models is necessary. In particular, the definition of the criterion in order to detect the elastic behavior from the non-linear one related to the martensitic transformation is required. Recently, a macroscopic model, based on the concept of two transformation surfaces (a first surface drives the forward transformation and the second drives the reverse transformation) has been proposed and validated on a large data base of experimental results under uniaxial and multiaxial loadings. This model, in its initial version, is only valid for the pseudoelastic behavior of isotropic polycrystalline SMA. However, it is well-known that the initial crystallographic texture is an important parameter in the behavior of SMA and in particular in the shape of the transformation yield surface. The aim of this paper is to present some results concerning, on the one hand, the determination and the modeling of the transformation surface of polycrystalline textured SMA and, on the other hand, the relation between the volumic fraction of martensite and the macroscopic transformation strain. Comparisons between experiments and the two theoretical investigations will be done on Cu-Al-Zn and Cu-Al-Be polycrystalline shape memory alloys.

The Nature of Stress and Strain Fields in Shape Memory Polycrystals

SM14L_10721
Tue • 12:40 • 213

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Predicting the recoverable strains of shape memory polycrystals is a central open problem in the study of shape memory alloys. This in turn requires an understanding of the possible stress and strain fields that arise in such polycrystals. We show that for polycrystals made of materials undergoing cubic-tetragonal transformations the strains fields associated with macroscopic recoverable strains are related to the solutions of hyperbolic partial differential equations. We explore consequences of this relationship and connections to previous conjectures characterizing those polycrytals with non-trivial recoverable strain. We also show that stress fields in such polycrystals could be concentrated on lower-dimensional surfaces (planes and lines). We do this by proving a dual variational characterization of the recoverable strains of shape memory polycrystals and presenting several examples. Implications of this characterization for effective properties and the development of numerical methods are discussed.

A Numerical Approach to Martensitic Phase Transformations

SM14L_10088
Tue • 17:00 • 213

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Martensitic phase transformations triggered either thermally or mechanically entail a series of peculiar effects on the macroscale. A thermodynamic criterion, deciding upon the formation of a new martensite variant as a function of the stress state, the temperature and the martensite fraction already present, can be interpreted as transformation surface bounded by planes, which can be adapted for use as a material subroutine in a finite element program. In combination with flow-plasticity such a concept enables to explain the overall mechanical consequences of transformation induced plasticity also in the case of non-proportional thermo-mechanical loading histories. Furthermore, the computer algorithm allows to keep track of each particular variant which provides a physical reasoning for the orientation effect known e.g. in shape memory materials. The numerical predictions are in agreement with experimental observations in the case of a maraging steel.

High Pressure Mechanochemistry: Conceptual Multiscale Theory and Interpretation of Experiments

SM14L_11325
Tue • 17:20 • 213

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A simple multiscale (nano-, micro- and macro-) continuum thermodynamic theory for strain-induced phase transitions (PT) and chemical reactions (CR), as well as closed form solutions were developed which explain a number of mechanochemical phenomena. Specifically, the theory explains why the superposition of plastic shear and high pressure in rotational diamond anvil cell leads to: (a) a significant (by a factor of 3-5) reduction of PT and CR pressure and pressure hysteresis, (b) the appearance of new phases, which were not obtained without additional shear, (c) the substitution of a reversible PT by an irreversible PT, and (d) strain-controlled kinetics, (e) nanostructured phases, and (f) pressure self-multiplication effect. Additionally, the results enabled the development of new methods for control of PT and CR under plastic deformation, some of which have experimental confirmations. The results also predict the unique potential of plastic straining to produce high-strength nanostructured phases.

Modeling Martensite Transformation in the Elasto-Plastic Material at Finite Strain

SM14L_11395
Tue • 17:40 • 213

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In this paper, a model of martensitic transformation in TRIP steel was established in the framework of the continuous mechanics and thermodynamics at a large strain. The model is based on the concept of a laminated microstructure composed of the martensitic plate and austenite layer. The internal structure of the martensite and austenite composite is variable and changes with moving interface. The model includes the essential features of the deformation induced martensitic transformation and provides a local kinetics description of martensite growth. A distinctive feature of the current model is that each phase is characterized by its own material constitutive model, and therefore, the evolution of the stress in both phases as the martensite transformation proceeds under a given deformation gradient can be properly predicted.

Multiscale Modeling of Steels assisted by Transformation-Induced Plasticity

SM14L_10648
Tue • 18:00 • 213

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The favorable combination of strength and ductility in carbon steels whose mechanical response is enhanced by transformation-induced plasticity has been attributed to the effect of islands of retained austenite in the initial microstructure. The mechanical response of these steels depends on the interaction of several phases present in the mesoscale structure (ferrite, bainite and retained austenite). In turn, the evolution of retained austenite depends on smaller scale phenomena, particularly its transformation into twinned martensite. We develop a model for retained austenite where the effects of the substructures is accounted for via a homogenization procedure and the mesoscale behavior is modelled numerically via

a three-dimensional analysis of a representative inclusion. The analysis is carried out for different morphologies of the islands of retained austenite as well as the surrounding phases.

Numerical Analyses of the Interaction Classical Plasticity – TRIP

SM14L_12747
Tue • 18:20 • 213

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The effect of classical plasticity on TRIP is analyzed considering martensitic transformation of ferritic steel. It is experimentally shown that TRIP is influenced by the previous strain hardening of the parent phase. This has been shown through tests consisting in significant strain hardening of the austenitic phase during cooling and before the metallurgical transformation occurs followed by the transformation without applied load. As the obtained results do not seem to be easily explainable in the light of the existing models in the literature, the objective of this paper is to contribute to a better understanding of the mechanisms at the origin of the observed discrepancies. For that, we consider in a first stage a classical finite element micromechanical approach already used (see for instance Ganghoffer et al., Mech. Of Mat., 1998). Having experiments as reference, the results show the essential role played by the choice of the numerical parameters.

Temperature and Strain Rate Effects on TRIP Sheet Steel. Measurement of Temperature by Infrared Thermograph

SM14L_10046
Tue • 18:40 • 213

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More and more, new sheet steels are design to assume a high energy level absorption as DP steel or TRIP steel. The energy level absorption of this materials is due to high stress level with large ductility. However, some problems appears to define precisely analytical behaviour of TRIP steel since the behavior is strongly dependency of the phase transformation which occurs during plastic deformation. To obtain a complete knowledge of the behavior affected by the phase transformation, an experimental analyse has been performed in tensile test and shear test for different strain rates, temperature at low and high strain rates. Moreover, in the same time, a thermographic set-up has been used during tests to measure the temperature increase during plastic deformation. This complementary information may be used to explain and understand the phase transformation of TRIP steel during plastic deformation. Moreover, an analyse of the temperature gradient effect on the plastic behaviour has been realised in relaxation tests.

Macro-, Meso- and Micro-Scopic Metallo-Thermo-Mechanics

SM14L_10434
Thu • 09:30 • 219

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Evolution of material structure, temperature and mechanical fields undergoing phase transformation are coupled each other as is termed metallo-thermo-mechanical coupling. Three kinds of approach from maro-, meso- and micro-scopic viewpoints are presented, in this paper, to determine the fields, and fundamental governing equations are briefly introduced in the framework of metallo-thermo-mechanics respectively based on the methods of finite element, phase field and molecular dynamics. Some examples of simulated results are illustrated: Quenching of gear wheel and Japanese sword as well as continuous casting by twin roll method by FEM and forging of billet and gear by FVM; cooled plate with induced stress and dendrite growth from molten state by PFM; and melting of a bar, crystallographic change in optical memory device and shape memory effect by MDM.

Numerical Determination of Diffusional Transformation Induced Plasticity from Computations of Random Microstructures

SM14L_12421
Thu • 09:50 • 219

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Current theories for the modeling of transformation induced plasticity still fail to reproduce experimental results in cases where the material has undergone permanent strain preliminar to transformation process. There is no such discrepancy when

using Finite Elements modeling with classical plasticity; furthermore this approach allows to control the nucleation rate and spatial distribution of the product phase, its morphology and its growth rate. Its drawback is the possible dependancy of results to computation parameters (mesh size ...), an aspect that has been addressed in details so to determine valid configurations of computations. We have observed that one should resort to a huge mesh to get a response representative of an effective medium in the case where nucleates are randomly positionned. Assuming ergodicity, this problem is circumvented by performing ensemble averages over sub-domains extracted randomly from the bulk material, a classic method adapted for phase transformation for the first time.

Modeling of the Microstructural Evolution in Cr-Mo Steels During Tempering and Hydrogen Exposure

SM14L_11625
Thu • 10:10 • 219

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Hydrogen attack is a dangerous material degradation process that occurs in steels subjected to high pressures of hydrogen at elevated temperatures. A detailed study of the coupled processes responsible for hydrogen attack requires a combination of continuum mechanics with solid solution thermodynamics, kinetics and chemistry. This paper is concerned with the development of numerical models that combine these ingredients. First, a relatively simple microstructural model is presented which takes into account these processes within the framework of a multi-component, multi-phase continuum description. The numerical model is developed for microstructures built up by a ferritic matrix and carbides such as M_7C_3, $M_{23}C_6$, M_6C and M_2C. This model is applied to predict the microstructural evolution in low alloy Cr-Mo steels during tempering and hydrogen exposure. Secondly, the first steps in the development of a finite element code for a second more sophisticated model will be addressed.

New Model of the Phase Transition Kinetics in Solids

SM14S_11521
Thu • 14:30 • 152B

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One of the main feature of phase transition (PT) in solids is the entropy sources concentrated on interface and connected to PT hysteresis. To clarify the dependence of these sources on interface velocity and material properties the kinetic model of thermoelastic material is considered. The kinetics is based on the local balance of energy. The energy release is connected to material unloading in vicinity of new phase inclusions. The energy absorption is determined by change of latent energy. The model satisfies to general requirements: non-negativity of PT dissipation; thermomechanical threshold, which overshoot is accompanied by formation of new phase inclusions; thermomechanical limit, which achievement corresponds to complete transition; interrelation of the new phase growth with thermoelastic modules; dependence of the PT character (reversibility and irreversibility) on kinetic parameter. This fact is essentially new.

Equilibrium and Stability of Two-Phase Deformations within the Framework of Phase Transition Zones

SM14S_11837
Thu • 14:35 • 152B

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The phase boundaries in nonlinear elastic solids are considered as surfaces of discontinuity in deformation gradient at continuous displacements. The analysis of the conditions on the equilibrium interface leads to the concept of phase transition zones (PTZ). Given a material, the PTZ represents all deformations allowed on the equilibrium interface. Every point of the PTZ corresponds to some piece-wise homogeneous two-phase deformation. We develop a procedure to examine the stability of such deformations that gives necessary stability conditions in a general case. The stability is investigated with the aid of two criteria. One is a kinetic stability criterion, the other one is the energy criterion. The difference between the stability of two-phase deformations and deformations in a joint body is clarified. Spherically symmetric two-phase deformations are studied in detail to demonstrate efficiency of the approaches developed. Deformations which correspond to stable and unstable two-phase configurations are related with the PTZ.

Simulation of Discontinuity Movement by Boundary Elements

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SM14S_12121
Thu • 14:40 • 152B

For problems involving the movement of a discontinuity in a continuum, the explicit knowledge of its position is often of vital importance for the numerical simulation of the material response. The movement of this discontinuity can usually be expressed in terms of the state in its direct vicinity. However, this local state may be heavily influenced by the behavior of the bulk material. Thus, for an accurate description of the material response, both aspects may have to be taken into account. A numerical scheme which describes the movement of a discontinuity as well as the behavior of the bulk material is presented. The same discretization is used for the description of the interface propagation and the bulk behavior by employing a moving finite element scheme and the boundary element method. Results obtained using a three dimensional implementation of the scheme described above for a phase transformation problem are presented.

Nucleation and Motion of Phase Boundary in Shape Memory Alloy Microtubes

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SM14S_12881
Thu • 14:45 • 152B

Experimental phenomena and deformation mechanism of helical-type martensite band nucleation and propagation in superelastic NiTi SMA microtube under tension and torsion are investigated using a continuum theory. A simple constitutive relation with intrinsic strain softening is employed to approximate the material behavior during stress-induced transformation. 3D FEM simulation of the tube is performed and a combined analytical-experimental approach is used to extract the constitutive parameters of the material from the experimental measurement. The observed phase boundary motion and deformation patterns are clearly reproduced in the simulation. The results demonstrated that both material and geometric instabilities are responsible for the observed martensite band nucleation and growth. Compared with previous investigations, the issue of mesh sensitivity is demonstrated and addressed in the present simulation, which needs to be solved by a non-local constitutive theory in the future investigation where the interface free energy is taken into account.

SM15

Mechanics of porous materials

Chairpersons: W. Ehlers (Germany), J. Huyghe (Netherlands)

Biodegradation in Porous Landfill Bodies

SM15L_10198
Thu • 11:00 • 208

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In this contribution a constitutive model based on the macromechanical Theory of Porous Media (TPM) for a saturated thermo elastic porous body has been developed. The body under investigation consists of an organic and inorganic moisturized phase and a gas phase. Based on a consistent thermomechanical treatment the governing equations and constitutive equations will be given. Thus, we obtain a mathematical concept to describe the motion of the solid phases, the pressure of the gas phase, the temperature of the mixture and the biodegradation of organic material into a gas mixture of methane and carbon dioxide produced by bacterial decomposition during stable methane fermentation (biogas). Nevertheless, the calculation concept must be fit for specific tasks, whereby an absorbed comprehension of the investigated problem is required. Therefore, we practice an interdisciplinary cooperation with the Institute of Waste Management in Essen, Germany, so that we are able to present first emboldening results.

Localization and Stability of Unsaturated Soil

SM15L_10792
Thu • 11:20 • 208

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Unsaturated soil plays a dominant role in geotechnical engineering, since the state of saturation significantly influences the effects of draining, deformation and localization of the subsurface. From the mechanical point of view, unsaturated soil is characterized by a triphasic material consisting of a porous solid matrix (the soil) together with the pore-water and the pore-gas. Based on a continuum mechanical approach, unsaturated soil can be described within the well-founded framework of the Theory of Porous Media (TPM), thus including saturated soil (solid matrix and pore-water) and empty soil (solid matrix and pore-gas) as special cases. Based on quasi-static situations, the numerical computations make use of weak formulations of the momentum balance of the overall triphasic medium together with the mass balance equations of the pore-fluids and Darcy-like relations for the seepage velocities. Proceeding from a materially incompressible elasto-viscoplastic soil skeleton, the numerical examples exhibit the draining, the deformation and the localization behaviour of unsaturated soil with a particular focus on embankment stability problems.

Convolution Quadrature Based Boundary Element Method for Quasi-Static Poroelasticity

SM15L_11119
Thu • 11:40 • 208

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The reasons to use a CQM-based BEM instead of usual time-stepping procedures are either to include inelastic material behavior or to improve the stability of the time-stepping procedure. The main difference to usual time-stepping BE formulations is the way to solve the convolution integral appearing in most time-dependent integral equations. In the CQM formulation, this convolution integral is approximated by a quadrature rule whose weights are determined by the Laplace transformed fundamental solutions and a multi-step method. For quasi-static problems in poroelasticity there is no need to apply the CQM because time-dependent fundamental solutions are available. However, these fundamental solutions are highly complicated yielding to very sensitive algorithms. Therefore, it is promising to apply the CQM also on the quasi-static integral equations in poroelasticity. Applying the usual spatial discretization on the poroelastic integral equations and

using the CQM for the temporal discretization yields a time-stepping algorithm. The algorithm shows no stability problems and behaves well over a broad range of time step sizes.

Theory and Numerics of Multicomponent Mixture Models for Soft Biological Tissues

SM15L_11194
Thu • 12:00 • 208

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One natural category of porous materials is represented by biological soft tissues, such as cartilage, lung or skin. The challenge of describing these materials lies in their complex inhomogeneous microstructure consisting of mostly ionized water and collagen fibers embedded in an extracellular meshwork of charged protein compounds. In order to describe the physiological behaviour of soft tissues on the macroscale, the electro-chemomechanical couplings between the constituents as well as the viscoelastic and anisotropic properties of the extracellular matrix must be considered. In order to meet these requirements, the well-founded Theory of Porous Media (TPM) is applied, which consistently allows for the description of multiphasic continua with internal interactions. For the efficient numerical treatment within the FEM, the governing set of multi-field equations is rewritten in weak form including physically meaningful boundary terms. The overall applicability of the multicomponent mixture approach is finally shown by representative numerical examples.

Thermo-Hydro-Chemical-Mechanical Analysis of Concrete at High Temperatures

SM15L_12114
Thu • 12:20 • 208

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This paper presents an experimental and numerical analysis of a hollow cylinder submitted to high temperatures. The evaluation of heat and mass transfers, evolution of the phases constituting the porous medium, mechanical performances of concrete are taken into account in a full three phases coupled analysis. A hollow cylinder has been heated up to $523.15K$ ($250°C$) at a $5K/h$ velocity on the internal side and submitted to gas pressure/temperature measurements. A numerical simulation of the cylinder has been performed, showing a good correlation with the experimental observations.

Mechanics of Saturated High Porosity / Soft Materials

SM15L_12577
Thu • 12:40 • 208

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High porosity materials are considered. The studies are motivated by results for trabecular bones or soft materials such as foams, gels or structured liquids. The particular behaviour of such porous materials results from a specific distribution of loads, role of viscous dissipations in fluid phase due to its deformation, interactions between phases represented by couplings in stress tensors and drag or dynamic couplings. Experimental studies show significant dispersion of waves and attenuation of fast wave being higher than that for slow wave in some frequencies range. Moreover a maximum attenuation is observed for certain porosities. The effective medium approximations are applied in order to evaluate elasticity parameters and microscopic considerations along with averaging to assess interaction forces of the two-phase model. Results for wave propagation parameters as functions of porosity, frequency and parameters of structure of solid skeleton are analyzed and compared with available experimental data.

Mesoscale Predictions for the Thermomechanics of Granular Energetic Composites

SM15L_12771
Fri • 11:00 • 208

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A finite-element analysis is performed to characterize both the grain and bulk scale thermomechanical response of explosively (RDX) coated aluminum (Al) microspheres due to mild and strong impact. The bulk material response is given by the average manifestation of the grain-scale predictions over representative elementary volumes. Emphasis is placed on accurately describing and numerically resolving stress, strain, and temperature fluctuations occurring near intergranular contact surfaces and near internal Al-RDX interfaces for various values of RDX mass fraction. The commercial software

package ABAQUS/Explicit was used to model the grain geometry and materials and simulate dynamic loading conditions. A two-dimensional model of the grains is utilized, and the compaction process is simulated as a rigid piston-cylinder device. Preliminary results for the grain-scale temperature field were obtained for a representative case; the data indicates that thermal diffusion effectively reduces RDX temperatures significantly at the piston interface, where the largest local temperatures occur.

The Structure of Constitutive Laws for Powder Metallurgical Components

SM15L_12903

Fri • 11:20 • 208

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In this paper we examine the structure of constitutive laws for the compaction response of particulate materials, where deformation results from the plastic deformation of the individual particles. Micromechanical modelling suggests a number of different structures for the constitutive laws. A deformation theory model is described which is based on the construction of surfaces of constant complementary work density in Kirchhoff stress space determined by following extremal work paths to the current state. Alternatively, an incremental anisotropic constitutive law can be constructed based on the existence of a yield surface, whose size and shape evolves as the powder compact is deformed plastically. It is demonstrated that the yield surfaces nest inside surfaces of constant complementary work density. The models are calibrated using data for a commercial steel powder generated in a triaxial cell. The nesting character of the different types of surface is demonstrated and the relative merits of the different types of model is discussed.

Experimental Characterisation and Numerical Modelling of Density Distribution in Tablets

SM15L_12917

Fri • 11:40 • 208

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Density gradients in pharmaceutical tablets are important for they affect the local properties of the material which in turn influence the mechanical response of the tablet during post-compaction operations, such as coating, packaging, transport, storage or use. Experimental density maps obtained using techniques such as indentation hardness and X-ray computed tomography (CT) are presented. Constitutive models have been developed and calibrated to describe the compaction behaviour of the powder and the friction interaction between powder and die wall. The results are implemented in the finite element program ABAQUS/Standard. It is shown that different die wall lubrication conditions induce opposite density distribution trends in identical tablets (weight, height and material) and this affects the break force, failure mode and friability: it is then demonstrated that for a given average tablet density the break force and failure mode are not unique. The methodologies presented are applicable for any powder system in general.

Stresses and Fractures in Capillary-Porous Materials Under Drying

SM15L_13006

Fri • 12:00 • 208

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A risk of fracture of saturated capillary-porous materials under drying was analyzed theoreti-cally and experimentally. The drying induced stresses were determined theoretically with the help of mechanistic model of drying developed in authors' earlier works. The viscoelastic be-havior of the material under drying based on the Maxwell model was assumed. The numerical calculations were carried out for the kaolin-clay sample shaped cylindrically. The theoretical time-evolution curves of the drying induced stresses were compared with the experimental time-evolution curves of the acoustic emission (AE) represented by the descriptors such as the intensity of AE events and the intensity of AE energy emitted by the material under drying. These two AE descriptors were monitored on line during convective drying of cylindrically shaped kaolin sample in laboratory drier. The analysis proved that the amount of emitted energy increased significantly at those periods, at which the theoretical stress curves reached their maximum. Since the energy of acoustic signals originates from micro- and macrocracks of the material structure, we conclude that the AE method may serve for identification of frac-ture intensity occurring in saturated capillary-porous materials during drying.

Coupling Between Permeability and Damage: a Micromechanical Approach

SM15L_11941
Fri • 12:20 • 208

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A self-consistent scheme is used in order to determine the effective permeability of a cracked porous medium. For weak values of the permeability of the uncracked porous solid phase, the order of magnitude of the effective permeability increases beyond a critical value of the crack density (damage) parameter. The self-consistent scheme thus proves to be able to capture the coupling between damage and permeability as well as the concept of percolation threshold. In the asymptotic case of an impervious solid phase, a simple analytical estimate of the effective permeability is derived as a function of the crack aspect ratio, of the crack opening and of the damage parameter. The micromechanical model also shows that both the evolution of the crack opening and the crack propagation process are controlled by Terzaghi's effective stress. The latter is therefore the appropriate parameter for the effect of the mechanical loading on the effective permeability.

Probabilistic Homogenization of Hyperelastic Solid Foams

SM15L_11463
Fri • 12:40 • 208

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The present study is concerned with a probabilistic homogenization scheme for amorphous hyperelastic solid foams at finite strain. The scheme is based on the multiple analysis of a small-scale representative volume with a randomized microstructure. The macroscopic stress-strain characteristics are determined numerically by means of a strain energy based homogenization procedure. This procedure assumes macroscopic mechanical equivalence of a representative volume element for the given microstructure and a corresponding volume element consisting of the effective medium if the average strain energy density is equal provided that the volume average of the deformation gradient for both volume elements is equal. The results are evaluated stochastically in terms of the stress mean values and the corresponding standard deviations describing the scatter band width. It is observed that the microstructural disorder has distinct effects on the effective stress-strain response of amorphous cellular solids.

Mandel and Cryer Problems For Fluid-Saturated Foams With Negative Poisson's Ratio

SM15S_10790
Thu • 14:30 • 134A

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The advent of various foams with negative Poisson's ratio has interested us in how they behave when saturated with fluid. To explore it, we have solved the 2D and 3D problems corresponding to those treated by Mandel and Cryer. The results show that much more remarkable Mandel-Cryer effect and additional unusual phenomena are observed for the negative Poisson's ratio than for the conventional one. In all problems, pore pressure at the sample center has a peak at some time after step-like loading. Similar behaviors are observed in circumferential stress at the sample center. Their peaks are higher for the Cryer problems than for the Mandel ones and for the 3D problems than for the 2D ones. In the Mandel problems, a sample having a negative Poisson's ratio expands laterally immediately after loading, then gradually contracts and finally becomes slenderer than the original in spite of axial compression.

Experimental Investigation of Dense Free Surface Granular Flow

SM15S_11150
Thu • 14:35 • 134A

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When the slope of a sandpile is tipped beyond a critical angle (30 degrees for dry particles) the grains of sand will begin to flow. This type of flow is important geologically (e.g. landslides and river sedimentation) and industrially (e.g. mixing pharmaceuticals and transporting grains). However, this flow is not well-understood, dense granular flow is very different from that of a conventional fluid in that granular flow is limited to a thin boundary layer. For this project boundary layer granular flow was studied in a slowly rotated drum mixer using different rotation speeds and bead sizes. A high speed digital camera was used to locate and track the particles in the top flowing layer. These trajectories show the boundary layer has a dominant ordered structure of layers of trajectories parallel to the free surface. The velocity and density profiles were calculated from the particle trajectories, and their dependence on rotation speed and bead size will be discussed.

A conventional scaling model does not appear to apply, though the stratified structure of the flow appears to determine some details of the velocity fluctuations and granular temperature.

A Fluid Inclusion in a Poroelastic Solid Susceptible to Void Compaction

SM15S_11848
Thu • 14:40 • 134A

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Experimental results by Zhu and Wong (J. Geophys. Res., 102: 3027-3041, 1997) suggests that void compaction can take place in materials such as sandstone leading to alterations in the elasticity the hydraulic conductivity properties. The poroelastic behaviour of these materials can be modelled by appeal to stress-dependent skeletal response. The stress dependent alterations of the elasticity and hydraulic conductivity values are determined through an evaluation of the experimental data for Berea Sandstone The computational results illustrate the influence of the void compaction process on both the amplification of the pressure in the fluid inclusion, which represents the Mandel-Cryer effect, and on the rate at which dissipation of the fluid pressure takes place.

FE-Investigations on Shear Localizations in Granular Bodies within Hypoplasticity

SM15S_12358
Thu • 14:45 • 134A

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Localizations of deformation in the form of narrow zones of intense shearing can develop in granular bodies during processes of granular flow or shift of objects with sharp edges against granular materials. An understanding of the mechanism of the formation of shear zones is important since they act as a precursor to ultimate failure. Classical FE-analyses of shear zones are not able to describe properly both the thickness of localization zones and distances between them since they suffer from a spurious mesh sensitivity (its size and alignment). To overcome this drawback, classical constitutive models require an extension in the form of a characteristic length to regularize the rate boundary value problem and to take into account microscopic inhomogeneities triggering shear localization. In the paper, a spontaneous shear localization in granular bodies is investigated with a finite element method based on a hypoplastic constitutive model. To simulate properly the formation of shear zones, a hypoplastic model was extended by polar, non-local and gradient terms to take into account a characteristic length. The extended hypoplastic models were directly compared on the basis of a FE-analysis of a compression test and earth pressure problem of a retaining wall with sand in conditions of plane strain. The numerical results were also compared to corresponding laboratory tests.

Modelling of Composites Processing Using a Two-Phase Porous Media Theory

SM15S_12518
Thu • 14:50 • 134A

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A framework for the modeling of various forming processes for biphasic fiber composites is proposed. The class of processes considered involve deformation of a fiber bundle network, wetting by penetration of resin into fiber bundles, and resin flow through the fiber bundle network. The model framework comprises the continuum formulation of a nonlinear compressible porous solid saturated with a compressible fluid phase, which consists of liquid resin with dispersed gas. In particular, we are concerned with the modeling of fluid pressure driven wetting of liquid into the fiber-bundles. The wetting process is considered as an irreversible dissipative mechanism that leads to the compaction of solid phase due to the exclusion of voids and "elastic" packing of the fibers. Additionally, anisotropic macroscopic Darcian flow of the resin is accounted for. A finite element analysis creep test representing the press-forming processing of a polymer composite pressure vessel is demonstrated.

Wave Propagation in High Porosity Bones-a Cellular Model

SM15S_12566
Thu • 14:55 • 134A

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Experimental ultrasonic studies for high porosity cancellous bone give the results which can not be properly described in the wide frequency range (especially for high frequencies) using two phase macrocontinual models (Biot's or Schoenberg model). Hence, a cellular model for propagation of ultrasonic waves in such media is proposed. The sensivity analysis of

frequency dependent phase velocities and attenuations of both longitudinal ultrasonic waves is presented in order to extract physical properties and structural parameters of the cellular model which mostly influence wave parameters. The parameters calculated from the proposed model are compared with the data obtained from Biot's theory. It was shown that only for the long wave range (low frequencies) the predictions of both considered models are close to each other and that the results obtained from cellular model are in good qualitative agreement with the experimental data received from ultrasonic studies.

Soft Porous Media Model of Magnetic Fluid

SM15S_12567
Thu • 15:00 • 134A

Mariusz Kaczmarek[(1)], Tomasz Hornowski[(2)]
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(2) *Adam Mickiewicz University, Poznań, Poland*

An interesting intelligent materials are magnetic fluids in which under influence of magnetic fi eld certain amount of colloidal particles forms clusters which join into chains. The presence of chains induces stiffness and mechanical anisotropy. In order to describe the properties and incorporate interactions between clusters and surrounding liquid a model of soft porous media is considered. It is assumed that the two phases are the skeleton made of chains and the liquid composed of carrier liquid with free particles. The interactions between clusters are represented through components of stress tensor for the solid phase. The interactions of clusters with liquid are expressed as the sum of viscous, inertial and Basset force. Given the assumed symmetry of the medium (transversal isotropy) the harmonic wave studied and dependence of wave parameters on strength of magnetic fi eld, angle between directions of magnetic fi eld and wave, and on frequency are compared with experimental data.

A Three Layer Porous Media Model of Cutaneous Circulation with Application to Mechanical Skin Irritation

SM15S_12614
Thu • 15:05 • 134A

Daniela Bauer[(1)], Reinhard Grebe[(1)], Alain Ehrlacher[(2)]
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(2) *LAMI, École Nationale des Ponts et Chaussees, Marne La Valle, France*

Mechanical skin irritation induces vasodilatation on the line of stroke due to histamine release from mast cells and vasodilatation in the neighboring areas induced by pain receptor stimulation. Cutaneous vascular network has been described by a model consisting of three layers. First and last layer presenting irrigation and drainage of the system, are described as horizontal two-dimensional porous media. Intermediate layer, described by means of lumped parameter model, does not allow horizontal fluxes. This assumption is done in order to describe best cutaneous microcirculation. Capillaries in skin show, in contrary to muscle circulation, only very few connections between themselves. All vessels are compliant. Permeability depends on volume. Skin irritation is modeled by changing compliance. The model gives insight in changes in pressure and volume due to irritation. It also shows spatial flow fi elds before and after irritation.

Identification of Some Chemoporoelastic Parameters of a Reactive Shale from Experimental Data

SM15S_12713
Thu • 15:10 • 134A

J. Sarout, E. Detournay
Univ. of Minnesota

This paper is concerned with the experimental identifi cation of some chemoporoelastic parameters of a chemically reactive shale from data obtained in pore pressure transmission-chemical potential tests. The parameter identifi cation is carried out by matching the observed pressure response with a theoretical solution of the experiment. This solution is obtained within the framework of Biot theory of poroelasticity, extended to include physico-chemical interactions. A series of experiments on Pierre II shale (a shale from the Rocky Mountains in Colorado) has been carried out with the Membrane Effi ciency Screening Equipment (MESE) in the laboratory of CSIRO Petroleum, Australia. An analysis of the sensitivity of the theoretical solution to the parameters is carried out. The critical parameters are then brought out among all the parameters of the solution, i.e., the transport parameters which are the hydraulic permeability, the chemical diffusivity and, above all, the chemical reflection coeffi cient (membrane effi ciency). Two radically different methods are used for the quantifi cation of these parameters. First, a cost functional is defi ned by a least square difference between the theoretical solution and the whole set of experimental data. A systematic minimization method (typical inverse problem) is then applied to this functional.The robustness of the algorithm is also estimated through several numerical tests on simulated data. Eventually, a more pragmatic approach is deduced from this approach, e.g., the chemical reflection coeffi cient is directly correlated with the pressure drop during the chemical loading. Coherence of the results obtained with both methods is shown.

SM16

Mechatronics

Chairpersons: W. Schiehlen (Germany), M. Tomizuka (USA)

Improvement of Positioning Acuracy of Delat Parallel Robot

SM16L_10553

Fri • 11:00 • 123

Dominique Debalise, Cedric Baradat, Patrick Maurine, Vigen Arakelian
LMA2G / INSA, Rennes, France

In recent years, there have been promising applications of parallel structures in medical robotics and the machine-tool industry, which require high positional accuracy. In other words, more precise reproduction of predetermined end-effector positions, is strictly related to a higher manufacturing accuracy. For this purpose, in the present study, a new method of improving the positioning accuracy of the Delta parallel robot is developed. The suggested approach is based on geometrical calibration, which is carried out by the integration of the elastic deformations structure in the calibration process. At first, the robot structure is considered a rigid-body system. The end-effector location is calculated by the forward kinematic model. Then, the geometrical model of the robot is studied, taking into account the deviation due to the elasticity of links. Such a solution allows one to obtain a more exact geometrical model, and consequently, to improve the positioning accuracy of the Delta robot.

Dynamics and Control of a Hydraulically Driven Boring Plant

SM16L_10809

Fri • 11:20 • 123

Friedrich G. Pfeiffer
AMM, TU-Muenchen, Muenchen, Germany

In civil and underground engineering very large boring plants are used for drilling holes into the ground having a size of about 30 m depth and .5 m diameter. Today such machines possess hydraulically driven cable winches, which control both, the lifting and the lowering of the heavy drilling tools. One problem of the control process consists in an interaction of the hydraulic control and the mechanical system dynamics generating sometimes self-excited vibrations with large amplitudes. Another problem is connected with the groundwater contact when the drilling tool comes down rather fast. Both features may lead to slack cables, which must be avoided, anyway. To solve these problems an adaptive control was designed and implemented into the process control system of the boring plant. All machines produced by a Bavarian company since that time are now in operation without any problems. Older plants have been modified correspondingly. The presentation will give an overview of the problems involved, of the models used to describe the dynamics of the hydraulic and mechanical components, of the control design and also of a couple of experimental verifications performed with a big boring plant.

Investigation of Powerfull and High Precision Piezoelectric Actuator for Two-Dimensional Positioning

SM16L_10900

Fri • 11:40 • 123

Piotr Vasiljev[1], **Dalius Mazeika**[2], Genadijus Kulvietis[2]
(1) *Vilnius Pedagogical University, Vilnius, Lithuania*
(2) *Vilnius Gediminas Technical University, Vilnius, Lithuania*

The investigation of novel design high precision piezoelectric actuator for the object positioning in two-dimensional space is presented in the paper. Introduced piezostack-based actuator can achieve elliptical moving trajectories of the contact core in two perpendicular planes. Actuator operating principle is based on exciting the ends of the beam with two external harmonical forces that have the same frequency but different phases. The movement of such beam looks like a beam shaking. Investigated actuator consists of two perpendicular concatenated shaking beams. Depending on control of the power supply the linear, curvilinear and rotational motion of the positioning object can be achieved. Piezoelectric actuator has main advantages of large driving force, high dynamic resolution and small response time. Optimization analysis of piezoelectric actuator is carried out on purpose to find out optimal geometrical parameters of the actuator. A simulation, including a finite element analysis of the system, is used to analyze the actuator response to various input sets. Experimental model of piezoelectric actuator is built and its characteristics were compared to the results of theoretical analysis.

Gain-Scheduling Control of Machine Tools with Varying Structural Flexibilities

SM16L_11282
Fri • 12:00 • 123

Wim Symens, Hendrik Van Brussel, Jan Swevers
PMA, Mechanical Engineering Department, Katholieke Universiteit Leuven, Leuven, Belgium

The high accelerations of present-day machine tools are likely to excite the vibration modes of the machine structure of these tools. Therefore structural eigenfrequencies need to be incorporated in the controller design. An additional complication with machine tools is that the structural eigenfrequencies are not constant but depend on the position of the tool in the workspace of the machine tool, with as consequence that the machine model is position dependent. To control such linear time varying (LTV) systems, two approaches are possible: (i) the controller is robust with respect to system variations, and (ii) the controller incorporates the system variations, e.g. by gain-scheduling. In this paper a flexible beam with varying stiffness is controlled based on the gain-scheduling approach. Next to an ad-hoc scheduled H-infinity controller, analytically scheduled controllers are designed using a global LTV model of the set-up. Experiments finally show that gain-scheduling is necessary if high-performance is demanded.

A Systematic Load Identification Procedure for Parallel Robot Manipulators

SM16L_12417
Fri • 12:20 • 123

Horst Schulte, Patrick Gerland
University Kassel, Kassel, Germany

This paper presents a systematic load identification procedure for a class of parallel robot manipulators. It is considered as a regular dynamic robot identification problem since the load is rigidly fixed on the robot-platform. The estimation scheme uses the fact that the equations of motion are linear respect to the inertia parameters and the gravity term. Starting from the equations of motion of a rigid body, two identification equations are derived. The challenge is that the estimation must be based only on the measurements obtained through sensors at the actuators. No additional force-torque sensors mounted on the robot-platform are available. On this account we make use of the well-known kinematic relations and differential equations to transform the forces, positions and velocities of the actuators in torques represented in body fixed frame. The load identification procedure is exemplified by experimental studies with a calibrated test load based on periodic robot excitation.

Rapid Prototyping of Model Based Control Algorithms for Diesel-Engines with Turbocharger

SM16L_12758
Fri • 12:40 • 123

Matthias Weber, Rolf Isermann
Institute of Automatic Control, Darmstadt University of Technology, Darmstadt, Germany

A Control Prototyping system for the design of electronic control unit (ECU) functions for truck Diesel engines is presented. By this way the different steps of the control development can be optimized. As an application example, the design of a control algorithm for the charging pressure of a variable geometry turbocharger is described. The modelling process for the required dynamic nonlinear turbocharger model with variable turbine geometry (VTG) an the resulting control performance is shown in detail.

Stability Analyses of Electrostatic Torsional RF MEMS Switch

SM16S_10510
Thu • 14:55 • 124

Ya-Pu Zhao, Jian-Gang Guo
LNM, Institute of Mechanics, Chinese Academy of Sciences, Beijing, China

The stability analyses of the electrostatic torsional RF MEMS (radio frequency micro-electro-mechanical systems) Switch are presented in the paper with the consideration of van der Waals (vdW) force. The critical applied voltage and tilting angle are calculated by static equilibrium equations. Furthermore, the dynamic behavior of RF MEMS switch is studied by the qualitative analysis of nonlinear equation of motion.

Development of Positioning of Mechanisms with Piezoelectric Engines

SM16S_12546

Thu • 15:00 • 124

Alfredas Busilas(1), Romualdas Naumavicius(2)

(1) *Vilnius Gediminas Technical University, Vilnius, Lithuania*
(2) *Sutota Ltd, Kaunas, Lithuania*

Positioning mechanisms with carts moving in a horizontal plane and with piezoelectric vibroengines analyzed in the article form a group of mechanisms, having elastic and dissipative links and carts moving between defectors, which interact with the engine without intermediate transference links. Positioning mechanism piezoelectric vibroengine of original construction has been developed, which eliminates looseness, energy losses and acoustic noises. Algorithm of positioning mechanism cart discrete shift without transition processes has been suggested and control task formulated. Control devices of precision positioning mechanisms with piezoelectric vibroengines, which form the optimal control law of the cart shift have been developed. An original precision positioning device with displacement transducer, piezoelectric vibroengine and controllable feeding voltage formation scheme, which considerably increases speed evenness and precision of cart position registration while shifting the cart under a freely chosen program, has been demonstrated.

Hierarchical Tracking Control of Wheeled Mobile Robot

SM16S_12712

Thu • 15:05 • 124

Pu-Sheng Tsai(1), **Li-Sheng Wang**(2), Fan-Ren Chang(1)

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(2) *Institute of Applied Mechanics, National Taiwan University, Taipei, Taiwan*

For a mobile robot or a vehicle moving with rolling-without-sliding wheels, nonholonomic constraints need to be dealt with in order to design an effective controller. Based on Jourdain's variational equation and Appell's approach, it is possible to formulate the dynamics of the vehicle in terms of the privileged coordinates which satisfy the reduced Appell's equations. If this set of equations is decoupled from the other non-privileged coordinates, we may design a controller to track the privileged coordinates of the given desired trajectory. On the other hand, to track the non-privileged coordinates, the kinematic conditions of constraints are re-structured from which the compensations for the desired values of privileged coordinates are computed. The updated reference values for the privileged coordinates are then fed into the controller for the reduced Appell's equations. The proposed hierarchical tracking control thus treats the dynamical equations and the kinematic equations at different stages. From the simulation results, it is shown that such hierarchical tracking control strategy indeed gives rise to an effective algorithm for dealing with tracking problem.

Development of High-Performance Motion Simulator for Virtual Reality Systems

SM16S_12929

Thu • 15:10 • 124

Dzmitry O. Tsetserukou(1), **Alena V. Neviarouskaya**(2)

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(2) *Department of Marketing, Invention and International Contacts of IMRM of NAS of Belarus, Minsk, Belarus*

The paper is concerned with development of the high-performance and simple system of the motion effect simulation on the operator. These mechanisms are widely applied in virtual reality systems: trainers for truck drivers and aircraft pilots; entertainment; medical research application. The new construction of the spherical motion platform on the basis of four-bar linkage has been developed with simple structure, sufficient fidelity of motion and small energy consumption. In the paper the force analysis of spherical motion platform has been presented. The three-dimensional model of developed motion simulator has been given.

SM17

Multibody dynamics

Chairpersons: M. Geradin (Italy), F. Pfeiffer (Germany)

Simulation of Contacting Spatial Polyhedral Particles

SM17L_12133
Thu • 11:00 • 231

Beate Muth[1], Peter Eberhard[1], Stefan Luding[2]
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(2) *Particle Technology Group, Delft University of Technology, Delft, The Netherlands*

It is goal of the work presented here, to investigate the dynamical behaviour of granular material or bulk solids, in order to simulate procedures in hauling engines, shaking machines, fi ller constructions, etc. Due to the fact, that a detailed simulation considering also the deformability of every single particle is very time consuming, methods from molecular dynamics (MD) are used, so that it is possible to determine the motion of many bodies. To describe the equations of motion, Multibody System Dynamics are used. Here, arbitrarily shaped polyhedron can be described easily. In the talk we want to address shortly both methods, want to talk about the combination of both methods, about the contact detection for non-convex polyhedron, and we want to present some of our results. Several animations will be shown, that straighten out possible appliances.

Contact Problems in Roller Chain Drive Systems.

SM17L_12569
Thu • 11:20 • 231

Sine Leergaard Pedersen
Technical University of Denmark, Kgs. Lyngby, Denmark

A model of a roller chain drive is developed and applied to the simulation and analysis of roller chain drives of large marine diesel engines. The model includes the impact with guide-bars of the motion delimiter components of the roller-chain drive by the rollers and links of the chain strands between the sprockets. The main components of the model of the roller chain drive include the sprockets with different sizes and the chain made of rollers and links, which are represented by rigid bodies, mass particles and springs damper assemblies respectively. The guide-bars are modelled as rigid bodies being their contact with the rollers represented by a continuous force. The models proposed effectively represent the polygonal effect, always present in this type of drives, and therefore, all vibration dynamics associated to it.

Analysis of Grazing Bifurcations in Impact Microactuators

SM17L_11020
Thu • 11:40 • 231

Xiaopeng Zhao, **Harry Dankowicz**
Virginia Polytechnic Institute and State University, Blacksburg, USA

Impact microactuators rely on repeated collisions to generate large displacements of a microelectromechanical machine element without the need for large applied forces. Their design and control rely on an understanding of the critical transition between non-impacting and impacting long-term system dynamics and the associated changes in system behavior, known as grazing bifurcations. In this paper, we present three characteristically distinct transition scenarios associated with grazing conditions for a periodic response of an impact microactuator: a discontinuous jump to an impacting periodic response (associated with parameter hysteresis), a continuous transition to an impacting chaotic attractor, and a discontinuous jump to an impacting chaotic attractor. A theoretical normal-form analysis is presented that predicts the character of each transition from a set of conditions that are computable in terms of system properties at grazing. This analysis is validated against results from numerical simulations of a model impact microactuator.

Plastic Deformation by Impacts in Multibody Systems

SM17L_12134

Thu • 12:00 • 231

Robert Seifried, Werner Schiehlen

Institute B of Mechanics, University of Stuttgart, Stuttgart, Germany

In machine dynamics, the multibody system approach proves to be most efficient for the dynamical analysis of the overall motion. Collisions in multibody systems might result in impacts between the system's bodies and the coefficient of restitution is generally used to describe the energy loss during impact. The loss of kinetic energy is due to the initiation of elastic waves in the bodies and local plastic deformation resulting from high forces in the contact region. However, the coefficient of restitution cannot be computed within the multibody system approach. In this paper a numerical method on a fast time scale is presented to evaluate the coefficient of restitution considering plastic deformation in the contact region and wave propagation in the bodies. Numerous longitudinal impacts of a steel sphere on different aluminum rods are used as benchmark for the presented approach and the results are verified by measurements, too.

Modeling Ballast Behavior Using a Three-Dimensional Polyhedral Discrete Element Method

SM17L_11361

Thu • 12:20 • 231

Gilles Saussine(2), Jean-Jacques Moreau(1), Frederic Dubois(1), Catherine Cholet(2), Claude Bohatier(1), Pierre-Etienne Gautier(2)

(1) *University – L.M.G.C, Montpellier, France*
(2) *S.N.C.F (Research Department), Paris, France*

Ballast is an important component of a railway track structure. It comes from the cruhing of rocks, and it ensures, from a mechanical point of view, the transmission of static and dynamic efforts induced by running of trains to the platform. The deterioration of the railway track under a large number of running of trains, in particular the settlement mechanism of the ballast layer or the lateral buckling of track, remains insufficienly known. In order to study the behavior of ballast layer a three-dimensional Discrete Element Method (DEM), based on the Non Smooth Contact Dynamic (NSCD) approach has been developed. Ballast grains are considered as rigid bodies with polyhedric shapes and the contact between grains is modeled by unilateral contact and dry Coulomb's friction laws. This model enable us to perform very specific investigations on railway track samples, with up to 30000 digitized grains, in order to understand local phenomenon and to propose rupture criterium.

Efficient Generalized Speeds in a Recursive Formulation of Flexible Multibody Dynamics

SM17L_11375

Thu • 12:40 • 231

Arun Banerjee, Mark Lemak

Lockheed Martin ATC, Palo Alto, USA

Certain choices of variables describing the motion rather than the configuration of a multibody system have been shown in recent literature to lead to simpler dynamical equations. These include generalized speeds for rigid bodies connected by revolute joints, Hooke's joints, and spherical joints, and those for elastic motions of flexible bodies undergoing large overall motion. This paper incorporates these generalized speeds in a recursive formulation for the dynamics of a system of flexible bodies connected by rotational and translational joints. The result is a set of dynamical equations with block-diagonal mass matrices that are not symmetric, and kinematical equations that are slightly more complicated than those for customary choice of variables. Overall numerical efficiency of the formulation is demonstrated by means of examples of large motions of a single flexible spacecraft and an articulated four-body spacecraft with three flexible appendages connected to the bus by three types of rotational joints

Low Energy Control of Periodic Motions in Manufacturing

SM17L_11223

Fri • 09:30 • 231

Nils Guse, Werner Schiehlen

Institute B of Mechanics, University of Stuttgart, Stuttgart, Germany

Flexible manufacturing processes require different periodic motions which may be realized by an active robot. A well established robot control principle is inverse dynamics which is used to overcome the high nonlinearities typical for mechanical systems undergoing large displacement motions. However, this principle results in high energy demand. This paper presents two methods for designing linear and nonlinear springs as local energy storage devices to improve the efficiency of nonlinear rheonomic systems such as assembly robots. Firstly, the shooting method is applied to find parameters of a mechanical system resulting in a conservative limit cycle close to the desired trajectory. The second method describes an alternative

approach to design a system with low energy consumption by fitting the spring characteristics to an optimal force function calculated by inverse dynamics. Both methods yield impressive energy savings despite of the additional fine tuning control.

Configuration Control and Dynamic Analysis of Redundant Link-Type Manipulators

SM17L_11700
Fri • 09:50 • 231

Kazuo Yamamoto(1), Masashi Okada(2), Kazuo Tanizawa(1)
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(2) *Graduate School of Kinki University, Nagagun, Japan*

Configuration control and dynamical behavior are examined by numerical simulations focusing on redundant link-type manipulators which are boarded on the spacecraft and make an operation to move their end effecter toward the target position avoiding obstacles in the work area. Simulations are limited for two-dimensional model and are composed of four stages; 1) Determination of end effecter orbit, 2) Determination of link configuration, 3) Dynamical behavior for rigid link system and 4) Influence of link elasticity to the motion. In the determination of the orbit and link configuration, artificial potentials are given that are inversely proportional to the distance with the obstacles. The elastic deformation is modeled by finite element approach. As results of simulations, end effecter orbits and link configurations were obtained which can avoid the obstacles, and influence of the link elasticity were clarified for the avoidance of obstacles and the final positioning.

Motion and Vibration Control of the Lift Mechanism of a Ladder Truck

SM17L_12582
Fri • 10:10 • 231

Katsuhisa Fujita(1), Yasuhiro Shiono(1), Mitihiro Itihara(2), Takuro Koseki(2)
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(2) *Morita Co. Ltd., Japan*

A ladder truck with lift mechanism has played an important role in life-saving and fire-fighting. Although the quicker operation mechanism is requested for these demands, the lift operation generates a lot of vibration at the time of the extending and retracting motions, the ascending and descending motions, and turning motion. In this paper, though an actual ladder truck is composed of five sections, a two-sections ladder model is investigated to make the physical understanding easier. A coupled equation of the model is derived using the differential algebraic equation. Performing the numerical simulations taking the dimensions of the model and the modification of the input motion as parameters, the physical meaning of the dynamic behavior at the time of the lift operation is discussed. Moreover, the optimal control method for minimizing the vibration and the moving time of a ladder simultaneously is discussed.

A Geometrical Framework for Modeling and Simulation of Nonholonomic Mechanical Systems

SM17S_10026
Tue • 14:30 • 124

Wojciech Blajer
Technical University of Radom, Radom Poland

Many studies on dynamics of nonholonomic (NH) systems are strongly influenced by various historical approaches and the mathematical description which are rather arduous in practical/computer applications. A large variety of formulations for NH systems may also be misleading, causing possible difficulties in choosing the proper/best method when solving a given problem. A frequent belief is also that disparate approaches to H and NH should be used, while a unified treatment of systems subject to H and/or NH is possible. The aim of this contribution is to present a systematic geometrical framework for effective modeling and simulation of NH systems. Different types of equations of motion in dependent and independent variables are obtained in compact matrix forms. Some relevant aspects – the constraint violation problem, the involvement of independent velocities, and the determination of constraint reactions – are also addressed. Two classical examples of NH systems are reported.

Selected Problems of Discrete-Continuous Mechanical Systems with Local Nonlinearities

SM17S_11352
Tue • 14:35 • 124

Amalia Pielorz
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The paper concerns dynamic investigations of nonlinear discrete-continuous systems representing various elements of machines and mechanisms. Such systems consist of rigid bodies connected by means of elastic elements which are torsionally,

longitudinally or transversally deformed, and the classical wave equation is used for the description of their motion together with the solution of the d'Alembert type. Nonlinearities in the systems are of a local type and have softening characteristics. Two sets of nonlinear functions are proposed for the description of local nonlinearities, including the polynomial of the third degree and irrational functions. The determination of displacements and strains in arbitrary cross-sections of the elastic elements is reduced to solving nonlinear equations with a retarded argument. Exemplary numerical results are presented for a multi-mass torsional system and for a single gear transmission. It is shown that certain functions have some restrictions for their application.

Intrinsic Formulation of Dynamics of Curvilinear Systems

Jean Lerbet
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SM17S_11674
Tue • 14:40 • 124

The paper concerns the dynamics of curvilinear systems which are often met in mechanical systems (robots, artificial satellites and so on). We only suppose that each section is rigid. Using Lie group theory, a general curvilinear system is then equivalent to a distribution $(\sigma,t) \mapsto D(\sigma,t)$ of displacements, elements of the Lie group D of Euclidean displacements the algebra of which may be identified with the Lie algebra of screws. The kinematics is enterely described by the lagrangian field of deformations $\mathcal{E}(\sigma,t) = \mathbf{D}(\sigma,t)^{-1} \circ \frac{\partial D(\sigma,t)}{\partial \sigma}$ and the lagrangian field of velocities $\mathcal{V}(\sigma,t) = \mathbf{D}(\sigma,t)^{-1} \circ \frac{\partial D(\sigma,t)}{\partial t}$ and with standard hypotheses about the distribution of external forces, the intrinsic equations are obtained, the displacements or deformations being small or large. Last, the elements to automatically obtain scalar equations are given.

Generalized Newton–Euler Dynamic Equations

Evtim Zahariev
Bulgarian Academy of Sciences, Sofia, Bulgaria

SM17S_11446
Tue • 14:45 • 124

Novel generalized Newton–Euler dynamic equations of rigid and flexible multibody systems are proposed. The inertia forces in the equations are with respect to the quasi-velocities and accelerations. Body mass properties are presented by generalized dense mass-matrices used in finite element discretization and other kinds of mass reduction. Lagrange's equations are applied. The kinetic energy is differentiated with respect to generalized coordinates, velocities and time. The final form of the generalized Newton–Euler equations is obtained substituting the generalized coordinates in the expressions so obtained by quasi-velocities and accelerations. Examples of modeling large flexible deflections are solved implementing different algorithms. The equations are consistent with any commercially available computer programs for finite element discretization and solve in general the problem for deriving the dynamic equations of rigid and flexible systems.

On Approximate Jacobian Matrices in Simulation of Stiff Multibody Systems

Dmitry Pogorelov
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SM17S_11640
Tue • 14:50 • 124

Simulation of stiff multibody systems requires Jacobian matrices (JM) of equations of motion. Evaluation of the JM by finite differences is a very CPU time-consuming operation. Use of approximate JM taking into account stiff forces reduces considerably the computational efforts. Analytic expressions for the corresponding matrices are obtained. Block-diagonal approximations of the JM are introduced to apply implicit solvers to the scheme of the articulated body algorithm as well as to simulate system of thousands of bodies undergoing contact interactions. Models of a fright coach and a ballast system illustrate implementation of the developed approaches.

The Absolute Coordinate Formulation with Reduced Strain and Stiffening

Johannes Gerstmayr, Hans Irschik
Institute for Technical Mechanics, University of Linz, Linz, Austria

SM17S_12029
Tue • 14:55 • 124

The present work contributes to the field of multibody systems with respect to the absolute coordinate formulation (ACF) with a reduced expression of the strain energy. The ACF is known to be advantageous with respect to the description of constraint equations and the constant mass matrix. Absolute coordinates are used as unknowns, similar to nonlinear finite element methods. In the present work, a consistent linearization of the equations of motion with respect to small deformations but large rigid-body motions is performed. This formulation leads to a constant mass matrix while the nonlinear stiffness matrix is composed of the constant small strain stiffness matrix rotated by the underlying rigid body rotation.

The equations of motion are derived for the case of a constrained multibody system and geometrical stiffening terms are introduced.

Generating Optimal Motions of Constrained Multibody Systems

SM17S_12539

Tue • 15:00 • 124

Guy Bessonnet, Pascal Seguin
LMS, University of Poitiers, France

A general approach to optimal motion synthesis of controlled multibody systems is presented. It applies to a wide range of actuated mechanical systems such as industrial manipulators, parallel robots and walking machines. The method is developed in order to account for time-varying topology of systems having closed kinematic chains possibly subjected to one-sided contacts. Based on Lagrangian dynamics of constrained mechanical systems, an optimal control problem is stated. It consists in minimizing an integral amount of actuating torques while satisfying a complete set of constraints defining feasible movements. A parametric optimization technique based on approximating joint motion coordinates using spline functions of class C3 is developed to solve this primary problem. Optimization parameters are the values of generalized coordinates at control points. The original optimal control problem is recast as a non-linear constrained optimization problem. The latter can be solved efficiently using computing codes implementing SQP algorithms.

Simulation of Constrained Rigid and Elastic Bodies Without Constraint Equations

SM17S_10893

Tue • 15:05 • 124

Oleg Dmitrochenko[1], Dmitry Pogorelov[1], Su-Jin Park[2], Wan-Suk Yoo[2]
(1) *Bryansk State Technical University, Bryansk, Russia*
(2) *Pusan National University, Busan, Korea*

Equations of motion of connected rigid and elastic bodies usually contain an algebraic part for constraint equations (DAE). Although methods of reliable solving DAE are well known, it is worth to avoid them if possible. A rigid body is usually modeled by Newton-Euler equations using any triplet of orientation angles. We consider large displacement finite-element (FE) approaches for simulation of elastic bodies. In the large rotation vector formulation, which uses rotation angles, the generalized coordinates for both rigid and elastic bodies are compatible and we can apply the assembling procedure to obtain ordinary differential equations instead of DAE. The recently introduced absolute nodal coordinate formulation (ANCF) uses finite slopes instead of rotation angles. When a rigid body is attached to ANCF FE without restrictions for relative orientation (revolute joint in 2D, spherical joint in 3D) we still can directly use the assembling procedure. If there are such restrictions we develop new rigid-body elements that employ ANCF nodal slopes as generalized coordinates. These elements can be easily assembled with elastic ones.

Research of Movement of the Mechanism Sufficient with Elastic Part

SM17S_10533

Tue • 15:10 • 124

Gakhip Ualiyev[1], Zair G. Ualiyev[2]
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In the given work some principles of drawing up of mathematical models of transfer and executive mechanisms of independent movement with elastic parts are resulted. In mechanisms with considerable elastic parts the complete cycle of their movement is supposed to be considered as separate periods. In the various periods of movement the elastic parts are represented both as communication, and as source of movement. The questions of drawing up of mathematical models of resulted executive mechanisms of independent movement and definition of inertial parameters of separate mechanisms of variable structure with elastic connections are considered. In the given work the questions of definition of elastic forces of longitudinal deformable connecting-rod of 4-part mechanism are considered, also the equation of movement of flat 2-rocker mechanism in view of weight of elastic connecting-rod is drawn up. The system of the equations describing the movement of 2-rocker mechanism with elastic connecting-rod.

Expression on the Deflection of a Flexible Thin Rod and It's Measurement

SM17S_12464
Tue • 15:15 • 124

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Many mechanical systems such as industrial robots, automated production systems, and crane systems which containing cable elements, power cable, a distributing cable and cable carrier are able to perform variable and large transformation and rotational displacements. Along with a recent speeding up or high performances of these mechanical systems, these cable elements to meet the severe condition is required. In these cases, cable elements are strained with bending deformation accompanied with a torsional deformation. Since it is diffi cult to estimate directly the torsion and the curvature of deformable cable elements, to obtain a broad view of their motion is an effective measurement. In this study, useful methods are investigated for the kinematical measurement of torsion and curvature of a circular cable element which is recorded by two high-speed video cameras. The measurement of cable element, suggested here, may be available for a motion analysis of cable structures.

Homoclinic Orbits Layering in the Coupled Rotor Nonlinear Dynamics and Chaotic Clock Models: a Paradi

SM17S_10624
Thu • 14:30 • 134

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For examine natural clocks of reductor, as well as source of nonlinear vibrations and noise in its dynamics, it is necessary to investigate properties of nonlinear dynamics, and phase portraits, as well as structures of homoclinic orbits, layering and sensitivity of this layering of homoclinic orbits and bifurcation of homoclinic points. In the paper mass moment vectors introduced by author at ICTAM Haifa 92, are used to present a vector method for the analysis of kinetic parameter dynamics of coupled rigid rotors with deviational properties of mass changeable distribution and with couple rotations.A numerical experiment with the use of derived analytical expressions and of MathCAD program was used to create a visualization of phase portraits of nonlinear dynamics of coupled rotors and the layering of homoclinic orbits with respect to the system parameters change.

Stabilization by Rotating Rigid Bodies for Unstable Rotation of a Rigid Body with Cavities Containing a Fluid

SM17S_10779
Thu • 14:35 • 134

Yuriy N. Kononov, Tanya V. Khom'yak
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In Y.N.Kononov's work there is shown a possibility of rotation stabilization of the gyroscope by introduction in a cavity transversal and coaxial partitions. However, in practice it cannot always be carried out. Other possibility of stabilization for unstable rotation of a rigid body with a fluid can be the rotating rigid bodies connected with the basic body by a common point and the elastic regenerating moment. – The cases of free and not free (there is a fi xed point) rotations of the Lagrange gyroscope with an ellipsoidal or cylindrical cavity containing a perfect fluid are considered. One or two rotating rigid bodies are connected by means of an elastic spherical joint with the gyroscope. – The possibility of stabilization by rotating rigid bodies for unstable rotation of a rigid body with a fluid is shown. The effect of angular velocities of rigid bodies rotation as well as the factors of elastic regenerating moments effecting stabilization are obtained.

A Study on the Brush Noise Reduction of a DC Motor Using Multi-Body Dynamics

SM17S_11789
Thu • 14:40 • 134

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The DC Motor of a vehicle can cause noise and vibration due to high-speed revolution, which can make a driver feel uncomfortable. There have been various studies that attempted to solve these problems, focusing mostly on the causes of noise and vibration and the means of preventing them. The CAE methodology is more effi cient than a real test for the purpose of looking for various design parameters to reduce the noise and vibration of the DC motor. In this study, a design process for reducing brush noise is presented with the use of a computer model which is made by using multi-body dynamics program (DADS). The design parameters to reduce the brush noise and vibration were proposed using a computer model. They were used to reduce the noise and vibration of a DC motor and verified using the test results of a fan DC motor in a vehicle. This method may be applicable to various DC motors.

Simulation of Track Ballast

SM17S_11688
Thu • 14:45 • 134

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Railway ballast simulation algorithms are presented in the paper. The ballast is a system of planar rigid bodies with both convex and non-convex shapes. Contacts of interacting bodies are computed as force elements, which consist of a viscous-elastic normal part and a dry friction tangential part with sliding and sticking modes. Collision detection consists of two levels: neighbor and far ones. The far collision level detects contacts of polygon hulls by the linked linear list method. The neighbor collision level is an approach for detecting polygon penetrations by the sensitivity cell method. Simplified Jacobian matrices are used to accelerate the integration of stiff equations of motion. The ballast model can include up to some thousands of bodies and allows simulating processes of the ballast laying, compaction and so on. Some simulation results are presented.

Design of the Rear Carriage Stabilizer of a Low-Floor Articulated Trolleybus

SM17S_10647
Thu • 14:50 • 134

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In the course of ŠKODA 22 Tr low-floor articulated trolleybus modernization other type of the articulation and driving axles was used in construction among others. During test drives with the modernized trolleybus focused on the vehicle driving stability considerable rolling of the rear carriage appeared during all the driving manoeuvres. Using a stabilizer in the rear carriage is a suitable constructional solution. Verification of the suitability of its constructional solution from the point of view of the required effect on the driving stability was performed using the computer simulation with the trolleybus multibody models. Multibody models of the trolleybus with the rear carriage stabilizer are created in the alaska software. On the basis of the results of the test drives simulations the optimum diameter of the steel rod used for the stabilizer production was proposed and the suitability of the complete constructional solution of the rear carriage stabilizer for improving its driving stability was confirmed.

Stability Analysis of a Tethered System

SM17S_12071
Thu • 14:55 • 134

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Space-tethers are very slender and flexible structures that are deployed in space. One of such structures is the SET (Short Electrodynamic Tether). The distinguishing characteristic of the SET is that it orbits with the longitudinal axis normal to the orbit plane. The SET is in continuous rotation about this same axis, which allows it to maintain the aforementioned operating position. The SET is not perfectly straight after deployment. This fact could make the system structurally unstable, as predicted by the linear study of unbalanced rotors when hysteretic damping appears in the shaft (supercritical velocities). However, if non-linear elastic and internal damping forces are considered in the model, the resulting motion of the structure could remain bounded. This assertion was shown in a previous study by the authors using multibody dynamic simulations. In order to confirm these results, the present work studies the stability of the SET's solutions analytically. A modified Jeffcott model will be the object of this study.

A Systematic Model Reduction Method for the Control of Flexible Multibody Systems

SM17S_12208
Thu • 15:00 • 134

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The development of parallel kinematic mechanisms is a major advance in the field of high-speed machine-tools and manipulators. The natural vibration modes may be excited during the fast motions so that the flexible behaviour has a significant

influence on the performances. In order to drive those complex mechanisms efficiently, the design of the control algorithm requires high-quality mechanical models in terms of accuracy, efficiency, and conciseness. The new modelling method presented here leads to a better compromise between those conflicting criteria. The number of degrees of freedom associated with the deformations is reduced by component mode synthesis, and an interpolation is performed to get an explicit description of the mechanical model in the configuration space. Selecting the number of component modes and the interpolation precision level, the user is able to balance accuracy against efficiency and conciseness. The relevance of the method is illustrated with a few examples.

Dynamic Analysis and Vibration Control of The Planar Beams Moving Along the Axial Direction

SM17S_12537

Thu • 15:05 • 134

Naoki Sugano, Etsujiro Imanishi

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In this paper, dynamic simulation method and vibration control technique are proposed for flexible body moving along the axial direction, such as the plates and the wire rods in the mill. At first, for the purpose of analyzing the dynamics of this flexible body, the FEM beam model that takes account of the movement of the axial direction and geometric nonlinearity is proposed. Calculation result shows that the vibration phenomena appears when the cantilever beam is pulled into the fixed area. Next, the optimal damper-spring support property for controlling the vibration of the beam is obtained by the complex eigenvalue analysis. Finally, the vibration control method is proposed and the effect of the control is verified by numerical simulation using the finite element model proposed above. In the consequence, it is verified that the vibration of the beam are reduced by the proposed vibration control method.

SM18

Plasticity and viscoplasticity

Chairpersons: E. van der Giessen (Netherlands), P. Perzyna (Poland)

Physically Based Thermomechanical Modeling of Metals over a Wide Range of Strain Rates and Temperatures

SM18L_10393
Tue • 11:00 • 206

George Z. Voyiadjis, Farid H. Abed
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Microstructural physical based constitutive models are developed in this work in order to characterize the thermomechanical response of different types of metals subjected to low and high strain rates and temperatures. The concept of thermal activation energy as well as the dislocations interaction mechanisms is used in the derivation procedure taking into consideration the effect of the mobile dislocation production as well as the dislocation speed on the flow stress of the deformed material. The model is verified using different sets of experimental data for the same material parameters obtained from other independent tests. Good correlation is observed between the model predictions and the experimental observations. The plastic flow is considered in the range of temperatures and strain rates where diffusion and creep are not dominant.

Simulation of Dynamic Polycrystalline Thermoelastoviscoplasticity and Fracture

SM18L_10955
Tue • 11:20 • 206

John D. Clayton
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Presented is a constitutive framework for addressing the dynamic response of polycrystalline microstructures, posed in a thermodynamically consistent manner and accounting for finite deformations, rate dependence of flow stress, thermal softening, thermal expansion, heat conduction, and thermoelastic coupling. Assumptions of linear and square-root dependencies, respectively, of stored energy and flow stress upon the total dislocation density enable calculation of the time-dependent fraction of plastic work converted to heat energy. Fracture at grain boundary interfaces is represented by cohesive zones. Dynamic finite element simulations demonstrate the influences of texture, morphology, and interfacial strengths on the deformation and failure behaviors of an actual two-phase material system consisting of comparatively brittle pure tungsten grains (BCC) embedded in a more ductile matrix of tungsten-nickel iron alloy (FCC). Aspects associated with constitutive modeling of the homogenized material system, including a macroscopic theory for finite anisotropic damage deformation, are discussed in light of the computational results.

Assessing Different Self-Consistent Approximations by Comparison with Full-Field Simulations in Viscoplastic Polycrystals

SM18L_11005
Tue • 11:40 • 206

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In this work we compare full-field numerical simulations for the effective behavior and the statistical field fluctuations in viscoplastic polycrystals with various estimates of self-consistent (SC) type. The full-field simulations make use of a recently introduced technique, based on Fast Fourier Transforms (FFT), which allows obtaining the mechanical response of heterogeneous materials in a very efficient fashion. Results are shown for linear and power-law 2D and 3D polycrystals. For linear systems, the above comparison demonstrates the accuracy of the standard SC approximation, even for relatively large grain anisotropy, when the fluctuations become significant. On the other hand, of the various non-linear self-consistent formulations, the recent second-order method, which is based on a linearization scheme taking into account both the first and second order moments of the mechanical fields, gives the best overall agreement with the full-field simulations, for both the effective behavior and the statistical field fluctuations.

Three-Dimensional Modelling of Thermo-Elasto / Viscoplastic Solids Containing Adiabatic Shear Bands

SM18L_11110
Tue • 12:00 • 206

Patrice Longere[(1)], **Andre Dragon**[(1)], Herve Trumel[(3)], Thibaut de Resseguier[(2)], Xavier Deprince[(4)]
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(3) *CEA/DAM Le Ripault, France*
(4) *GIAT Industries, France*

Adiabatic shear banding is here considered as an anisotropic continuous damage process in the context of finite anisotropic elasto-irreversible strains. The anisotropic mechanical degradation induced by the bands is dealt with by using a tensorial damage variable, and the kinematic consequences of the presence of the bands are described by means of the corresponding part of the velocity gradient. Constitutive equations are derived from thermodynamic potentials namely the free energy and dissipative potentials. The hypothesis of a single yield function has been put to describe the strong coupling between plasticity and damage. The conditions of adiabatic shearing initiation and band orientation are obtained from a simplified analysis based on the linear theory of perturbations. The three-dimensional constitutive model has been implemented in the finite element code LS-DYNA. Its predictive capabilities are encouraging considering numerical simulations performed on boundary value problems related to dynamic hat shape structure test.

Thickness Dependent Yield Strength of Thin Films

SM18L_11410
Tue • 12:20 • 206

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Experiments have showed that the yield strength and hardening of thin films may depend on the film thickness. This thickness dependence cannot be explained by standard local plasticity or viscoplasticity theories. Micro structural length scales must be taken into account. There are several ways to incorporate micro structural length scales. Gudmundson has presented a theoretical framework that covers some of alternative theories as special cases. A particular feature of this theory is that the structural dimension influences both the elastic range and the hardening. The theory is implemented in a finite element programme and it is demonstrated by application to two thin film problems. A thin film on a thick elastic substrate is considered. Firstly, the film is subjected to a pure shear loading. Secondly, a prescribed biaxial strain of the film-substrate is considered. The results are compared to experiments and alternative models.

Size-Effects in Void Growth

SM18L_11790
Tue • 12:40 • 206

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The size-effect on ductile void growth in metals is investigated. The analysis is based on unit cell models both of arrays of cylindrical voids under plane strain deformation, as well as arrays of spherical voids using an axisymmetric model. A recent finite strain generalization of two higher order strain gradient plasticity models is implemented in a finite element program, which is used to study void growth numerically. The results based on the two models are compared. It is shown how gradient effects suppress void growth on the micron scale when compared to predictions based on conventional models. This increased resistance to void growth, due to gradient hardening, is accompanied by an increase in the overall strength for the material. Furthermore, for increasing initial void volume fraction, it is shown that the effect of gradients becomes more important to the overall response but less important to the suppression of void growth.

On the Accounting of Dislocation Internal Stress in Continuum Plasticity

SM18L_11820
Tue • 17:00 • 206

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We discuss existing gradient plasticity proposals that are intended to represent internal stress effects of dislocation distributions, and show by a common and simple example that all such proposals overestimate the strain energy or stress of a dislocated medium by the introduced phenomenology. Based on the above observation, we propose a model of crystal plasticity of unrestricted nonlinearity, both in material response and kinematics, that does not have the above defect. The model phenomenologically accounts for short-range interactions through the usual strength-based hardening assumptions of conventional crystal plasticity and calculates the long-range stress and evolution of so-called geometrically necessary

dislocation distributions, at the desired scale of resolution, in a mechanically rigorous manner. We present computational results for a simplified version of the model. The development of microstructure is a natural consequence of the model.

Mean Field Homogenization of Elasto-(Visco) Plastic Composites: Formulation for Time-Dependent and Independent Behaviors

SM18L_11886
Tue • 17:20 • 206

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Different formulations for the homogenization of elasto-(visco)plastic composites are examined. In the rate-independent case, a robust and generic incremental formulation using algorithmic tangent operators and implicit time-discretization has been developed. One particularity is that the Eshelby's tensor is computed with the isotropic part of the tangent operator. All the other computations are performed with the anisotropic algorithmic modulus. An extensive validation of this method has been achieved. For rate-dependent elasto-plasticity, an affine formulation is adopted. By the help of Laplace–Carson transform, the constitutive law is changed into a fictitious thermo-elastic one. The homogenization is performed in the Laplace domain, a numerical inversion is achieved to get the equivalent temporal functions and finally, the macroscopic response can be computed.

Strain Gradient Crystal plasticity Incorporating Grain Boundary Effects

SM18L_11963
Tue • 17:40 • 206

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This paper focuses on a strain gradient enhanced crystal plasticity model that incorporates the intrinsic role of dislocations in their various roles (statistically stored dislocations, geometrically necessary dislocations, grain boundary dislocations) in FCC metals. The crystal plasticity model presented is based on an extended slip law, incorporating a slip resistance and a back-stress, that emerge from the evolution of the three considered types of dislocation densities. The main principles of the underlying framework are outlined and some aspects of the computational solution strategy are emphasized. An example is given that illustrates the non-homogeneous inter- and intragranular deformation in a polycrystalline sample. The explicit incorporation of the grain boundaries and the dislocations accommodating the lattice mismatch of neighbouring grains, is considered as an original contribution. It is shown that the proposed strain gradient crystal plasticity model provides meaningful micromechanical predictions of the associated size or strengthening effects.

Limit and Shakedown Analysis with Decohesive Effects

SM18L_12058
Tue • 18:00 • 206

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Local failure of composite materials under variable loading can be considered as being caused by repeated, dissipative events occurring on the micro-structural level. The interaction between the composite components determines the local response of the material, in particular the mechanisms leading to local damage and overall failure. Therefore, the study of these mechanisms on the micro-level under complex loads can be helpful to better understand the causes of failure. It is shown in this work, how direct methods can help to assess and how can be used in a constructive manner for the design of such materials. It is based on a two-scale approach: On the macroscopic scale, the global response of the composite is analysed. On the microscopic scale, the influence of each component on the global behaviour is investigated. The two principal used ingredients are averaging techniques combined with direct methods applied to a representative volume element on the micro-level.

A Constitutive Law for Glassy Polymers and Blends

SM18L_12339
Tue • 18:20 • 206

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In this study, a modelization of the viscoplastic behaviour of glassy polymers is proposed, from an approach originally developed for metallic alloys at high temperature and in which state variable constitutive equations have been modified. A procedure for parameters determination is developed. Experimental tests in tension on an RT-PMMA material have been

achieved under constant true strain rate. Video measurements allows evaluation of the volume variation in real time during the deformation. The viscoplastic constitutive equation describing the mechanical behaviour of the matrix is combined with a micromecanical model to account for both the influence of damage mechanisms in the RT-PMMA and subsequent yielding of the matrix around the particles. The model includes the effect of strain rate sensitivity, strain softening, strain hardening and the void volume fraction evolution. A quite nice agreement is observed between experimental results and the predicted behaviour given by our model.

Plastic Properties Identification With Plural Sharp Indenters

SM18L_10652
Tue • 18:40 • 206

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An identification method for elastic-plastic material constants that obey the power-law hardening rule, from a couple of instrumented sharp micro-indentation tests, is proposed. Based on a similarity function that is determined from the 3D-FE calculation, it is shown that for plural triangular pyramid indenters with different apex angles, unique values of representative strain correspond to each apex angle. Based on these results, we propose a new method for the material constants determination, utilizing two triangular pyramid indenters with different apex angles. This method allows us to determine the material constants with more stability than with the single indenter method. We also show that the dimensionless function pi, which characterizes the relationship between indentation load and Young's modulus of the material, can be expressed as an interpolation between two analytical extremes: the elastic solution and the rigid/perfectly plastic solution. An experimental validation for this method with actual metal is also given.

Calibration of Anisotropic Elastic-Plastic Models for Thin Layers and Foils in Microtechnologies: Two Novel Techniques

SM18L_10797
Fri • 09:30 • 213

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The methods presented in this paper for the identification of material parameters in anisotropic elastoplasticity at the microscale exhibit the following new features in their experimental stage: data gathered from both indentation curves and imprint mapping in the former technique, which is intended for the mechanical characterisation of thin layers on substrate; in the latter, a device which pressurises a free foil specimen and measures the geometry of the inflated membrane by a laser profilometer. At the computational stage, traditional least-square techniques are employed for the inverse analysis based on finite-element large-strain simulations, which are used also for sensitivity analyses.

Metal Forming Processes Conditioned by Cyclic Loading. A New Challenge for the Theory of Plasticity

SM18L_10064
Fri • 09:50 • 213

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Since early works of cyclic plasticity, it was observed that stress-strain cycles of large amplitude imposed on the cold-worked specimens of metallic materials produce cyclic softening. Korbel and Bochniak proposed the improvement of a method for plastic forming operations conditioned by cyclic loading. The experimental investigations led to the identification of shear banding as the basic mechanism responsible for plastic softening. Our aim is to study this problem from the point of view of cyclic plasticity accounting for multiscale description of shear banding. A new approach to the theory of plasticity describing the discussed above phenomena is proposed and an example illustrating its predictive power is presented. In particular, the parameters controlling cyclic loading under torsion: the amplitude of the cycle and its frequency are related with the microscopic model of shear banding. The optimal ranges of these parameters from the point of view of required plastic softening are estimated.

Development and Identification of a Probabilistic Two-Scale Model for High Cycle Fatigue Prediction

SM18L_12469

Fri • 10:10 • 213

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The present paper is concerned with the development of a probabilistic two-scale model for HCF that accounts for the failure of sample but also for the thermal effects during cyclic loadings. We assume that HCF damage is localized at the microscopic scale. So the microplasticity appears without affecting the behaviour of the material at the macroscopic scale. The development of the model is presented in three successive stages. In the first one, the model is deterministic and we show how to interpret the thermal effects by integrating the conduction heat equation. So we justify the empirical method proposed to estimate quickly the mean fatigue. We improve then the model by introducing a probabilistic characteristic at the microscopic scale. We assume that the number of active sites, i.e. a site whose the microplasticity appears, follows a Poisson process. We show that the new model represents better the thermal effects than the first model. With this approach the scatter can be determined but not the mean fatigue limit of a fatigue sample. A method of identification is also proposed. It is based on the analysis of the thermal effects for the scatter and is applied on a dual-phase steel. A first validation of the model is effected by predicting the scatter of the S/N curve. And a second validation is proposed by showing a good agreement between the experimental result and the predicted model for bending fatigue test.

A Visco-Plastic Constitutive Model for Cyclic Hardening Materials and Its Finite Element Implementation

SM18S_10036

Tue • 14:30 • 160

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A visco-plastic constitutive model was extended to describe the strain-range-dependent cyclic hardening behavior and the ratcheting of SS304 stainless steel. Then the extended model was implemented into the finite element code and the simulating capability was verified by comparing with some experimental results.

Quasi Rate-Independent Viscoplastic fcc-Polycrystals

SM18S_10383

Tue • 14:35 • 160

Milan Micunovic
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Geometry and kinematics of intragranular as well as intergranular plastic deformation of polycrystals are discussed. Elastic strain is covered by the effective medium homogenization method inside a representative volume element (RVE). Evolution equation formed by tensor representation is derived from very simple micro-evolution equation. It has incremental form obtained by Vakulenko's concept of thermodynamic time. The rate dependence takes place by means of stress rate dependent value of the initial yield stress. Strain geometry is based on constrained micro and free macro rotations in intermediate reference configuration. This leads to the fact that evolution equation for plastic spin of RVE is an outcome of evolution equation for plastic stretching. The theory is applied to slightly disordered fcc-polycrystals. For some characteristic given stress histories (with low, medium and high strain rates) the micro-meso transition is tested and number of active slip systems grains are found and compared with so-called J2-approach.

A Viscoplastic Model for Thermoplastic Polymers Under Uniaxial Monotonic and Cyclic Straining

SM18S_10729

Tue • 14:40 • 160

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The thermodynamic approach of the continuous medium and the local state method were widely used for the study of the mechanical behavior of metal alloys under complex triaxial loading conditions. The purpose of this paper is to show that these classical models can be modified then used for modeling mechanical behavior of polymers. Viscoplastic constitutive equations are proposed into the restrictive framework of standard generalized materials and the field of the small deformations. A yield criterion is established. It is based on the first stress invariant and the second and the third invariant of deviatoric stress. First invariant allows the description of hydrostatic pressure effects on the polymers yielding while

the third invariant is used to delineate the experimentally observed stress state dependency effects. A non-linear kinematic hardening rule is proposed to describe cyclic softening that several polymers exhibit under strain controlled cyclic tests.

Advanced Thermo-Visco-Plastic Constitutive Relations for Direct Applications in Numerical Analyses

SM18S_10734
Tue • 14:45 • 160

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Abstract: In this contribution thermo-visco-plastic constitutive relations are proposed. This phenomenological approach is partly based on theory of dislocations and processes of thermal activation. The main advantages of such constitutive relation are reduction of number of material constants in comparison with the complete approach based on materials science (theory of dislocations). In the proposed formulation, the total stress is a sum of two contributions, the internal stress and the effective stress which define respectively the strain rate and temperature-dependant hardening and the direct coupling strain rate-temperature during plastic deformation. This constitutive relation has been used so far many times in finite element codes to simulate dynamic processes of impact loading and an original algorithm using theory has been recently proposed by Zaera et al. (2004).

Energy Storage Rate in Non-Homogeneous Deformation

SM18S_11185
Tue • 14:50 • 160

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The energy storage rate, defined as the ratio of the stored energy increment to the plastic work increment, versus strain are experimentally estimated in the range of homogeneous deformation as well as in the range of non-homogeneous one. It has been shown, that during straining the material reaches the state at which the energy storage rate is zero and after that it is negative. This means that a part of energy stored during previous deformation begins to release. It has been found that the point where the energy storage rate is zero corresponds to the point of Considère stability criterion. Therefore the release of stored energy could be used as an indicator to describe the progressive predominance of damage leading to the fracture of material. This confirms Considère construction that specimen will undergo stable deformation up to the point on the stress-strain curve for which the strain hardening rate is equal to the flow stress.

Dynamic Behavior of Many-Dislocation Systems in Silicon

SM18S_11295
Tue • 14:55 • 160

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The most remarkable feature of a silicon crystal deformed at a constant strain rate is the appearance of a Steady State of Deformation (SSD). The SSD appears shortly after the lower yield point and continues throughout stage I of the stress-strain curve. In this state the value of effective stress (the mean of the stresses acting on all the moving dislocations) remains constant irrespective of increase in dislocation density. The steady value depends on strain rate and temperature, but not on deformation history of the crystal. The present study simulates dynamic behavior of dislocations in silicon crystals deformed at constant strain rates, using a two-dimensional discrete-dislocation model. The model consists of infinitely repeated cells, each of which contains the same number of positive and negative mobile dislocations. Calculated results indicate that the experimentally observed SSD corresponds to the dislocated state that maximizes the mean internal stress on moving dislocations.

The Eshelby Problem for Elastic-Viscoplastic Materials

SM18S_11309
Tue • 15:00 • 160

Sebastien Mercier, **Alain Molinari**, Nicolas Jacques
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Micro-macro schemes contain two important steps. First, the localization process consist to solve an Eshelby type problem, that is to link the fields inside an ellipsoidal inclusion to those applied in the surrounding infinite matrix. Secondly, an averaging process is used to derive the macroscopic behavior. For elastic viscoplastic materials, no exact solution exists for

the first step. In this work, we adopt a simple but salient interaction law proposed by Molinari (2002). To validate the interaction law, Finite element comparisons are conducted for different inclusion shapes, values of the material parameters. and for incompressible and compressible elasticity. It is observed that the localization step (non-linear Eshelby problem) is well described. Finally, the proposed interaction law is used in association with averaging schemes, to obtain the macroscopic behavior of multiphase elastic-viscoplastic materials.

Multiscale Modeling of the Structure-Property Relationship for Semicrystalline Materials

SM18S_11344

Tue • 15:05 • 160

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A micromechanically-based numerical model for the elasto-viscoplastic deformation and texture evolution of semicrystalline materials is developed. A distinction between three different scales is made. The constitutive properties of the material are identified at the microscopic scale for the individual crystallographic and amorphous components. At the mesoscopic scale, an aggregate of individual phases is formed. To bridge between those scales, an elasto-viscoplastic two-phase composite inclusion model is formulated. The microscopic fields are related to the mesoscopic fields of the aggregate by a hybrid interaction law. A full micro-meso-macrolevel bridge is obtained by using an aggregate of composite inclusions in each integration point of a macroscopic finite element model. The full multiscale model is employed to study the mechanics of intraspherulitic deformation for polyethylene, to simulate the influence of a stacked lamellar microstructure on the macroscopic behavior of extruded material, and to investigate the toughening effect of the microstructure in particle-modified materials.

Modeling of Viscoplastic Constitutive Equation for Polymers by Taking Into Account Strain Recovery

SM18S_11350

Tue • 15:10 • 160

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Polymers reveal significant viscoplastic deformation at the room temperature. Peculiar strain recovery is shown during unloading in particular, and it is quite different behavior from what is shown in metals. In order to describe such characteristic deformation of polymers, a viscoplastic constitutive equation which is formulated by combining the kinematic hardening creep theory of Malinin and Khadjinsky with the nonlinear kinematic hardening rule of Armstrong and Frederick is employed, and the evolution equation of a back stress is modified. In the present study, a loading surface is defined in a viscoplastic strain space, and a criterion of loading-unloading is defined by using the loading surface. Moreover, a parameter is defined by using the loading surface, and the evolution equation of a back stress is modified by using the parameter. Then, experimental results are simulated by using the constitutive equation, and the validity of the modification is confirmed.

Yield Surfaces Using an Extension of the Regularized Schmid Law to Polycrystalline Materials

SM18S_11498

Tue • 15:15 • 160

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Generally, the classical Schmid law is used for elastoplastic polycrystals. A micromechanical model based on an extension of a “regularized” Schmid law to polycrystalline materials is presented. A new plastic multiplier having a crystallographic nature is then defined. The scale transition is based on an affine formulation and particularly the “Transformation Field Analysis” (TFA) is used where the effective elastic properties are deduced from a classical self-consistent scheme. Each crystal is characterized by its volume fraction and its crystallographic orientation and intra granular plastic anisotropy is taken into account through a multiple slip framework. Intra crystalline strain hardening well describes stage II for FCC single crystals. Yield surfaces have been generated for isotropic and textured FCC polycrystals and are in good agreement with the ones obtained with the classical Schmid law.

Steady-Flow of a Non-Homogeneous Bingham Material Over a Wedge

SM18S_11930
Thu • 14:30 • 160

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A study of the steady-state motion of a porous medium over a rigid wedge-shaped penetrator was conducted. In order to describe the combined effects of strain rate and compaction on yielding of porous materials, a rigid viscoplastic constitutive equation was used. The deviatoric response of the target medium was modeled with a non-homogeneous Bingam type equation with shear yield limit dependent on the current density. The system of partial differential equations consisting of the constitutive equation, the continuity equation, and the balance of momentum was solved for different interface conditions. The resistance to penetration as a function of the striking velocity, target properties (density dependent yield, locking pressure, locking density), friction coeffi cient as well as wedge semi-angle was obtained. The wedge semi-angle corresponding to a minimum in resistance to penetration in mortar for various impact conditions also resulted from this investigation.

Parameters Identification of Viscoplastic Models Using Evolutionary Algorithms

SM18S_11945
Thu • 14:35 • 160

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The constitutive models of viscoplastic fbw involve several material constants, diffi cult to be determined experimentally for the whole range of application. In this work a method for parameters identifi cation of viscoplastic laws is presented, using the results of standard experimental tests only. The solution of the resulting inverse problem applies optimization techniques based on evolutionary algorithms. This stochastic search method, inspired by natural evolution, is applied to minimize the difference between simulated curves and measured experimental data. The metal alloys are investigated in the numerical examples and the experimental curves of tension tests at different strain rates are used. The identifi cation of parameters is carried out for the viscoplastic law of Bodner-Partom, Chaboche and Perzyna. Several independent runs of the optimization procedure have been performed in order to evaluate the effi ciency of the approach. Very good results have been obtained for relatively large limits of parameters variation.

Modelling of Elastic-Plastic or Viscoplastic Materials Sensitive to the Type of Processes – Different Approaches

SM18S_11953
Thu • 14:40 • 160

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Sensitivity to the type of the process is universal property well known in many practical cases. The presentation of this property is like different behavior of the nonelastic material during fore example: extension or compression; loading or unloading; hardening or softening; plastic deformation with athermal or thermofluctuational micromechanismes; relaxation or creep; etc. The principle of the modeling of this type of material behavior is based on the introducing models with different material constants according to the type of process in consideration. In this paper we will give two approaches: (1) First: It is more or less classical approach, using nonsymmetric yield surfaces in the stress space; (2) Second: It is on the base of extended strain space, introducing the process type indicators and incremental constitutive relations with different material functions for different process types. We present, like examples, some characteristic models with experimental verifi cations.

Metal Forming and Texture Development Modelling

SM18S_11975
Thu • 14:45 • 160

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A description of plastic anisotropy evolution due to texture development during metal forming processes is presented. It bases on a model of single crystal with the regularized Schmid law and a model of polycrystal behaviour with the Taylor assumption. The description makes possible to predict the texture development at each step of the plastic deformation

process. The evolution of plastic anisotropy in drawing wires, rolled sheets, and sheets under pure shear, associeted with the accompanying texture development, is discussed in details.

Modeling the Crystallographic Texture Evolution Based on the Maximum Entropy Method

SM18S_12549
Thu • 14:50 • 160

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The distribution of crystal orientations is an important microstructural feature which affects the overall properties of polycrystalline metals. Phenomenological models seem to be generally unable to adequately represent the evolution of the crystallite orientation distribution. Therefore, if the evolving texture has to be taken into account in the context of finite element simulations, e.g. of deep drawing processes, in most cases mixture theories (Taylor, Sachs) are applied. The disadvantage of such an approach is that at each integration point of the finite element mesh, large systems of (algebro-)differential equations have to be integrated. We present an alternative approach that is based on a tensorial Fourier expansion of the crystallite orientation distribution function (CODF) [Adams et al. 1992, Böhlke and Bertram 2003], which is the one-point correlation function of crystal orientations. The general evolution equations for the Fourier coefficients are derived. The evolution equations contain only microscopic parameters. By this approach the texture evolution can be described by modeling some low order Fourier coefficients and by estimating the higher-order coefficients based on the maximum entropy method. It will be shown that such a low dimensional approach of the CODF yields a reasonable description of the texture evolution and represents a versatile alternative to the above mentioned mixture theories.

B.L. Adams, J.P. Boehler, M.Guidi, and E.T. Onat: Group theory and representation of microstructure and mechanical behavior of polycrystals. J. Mech. Phys. Solids, 40(4), 723–737, 1992

T. Böhlke, A. Bertram: Crystallographic texture induced anisotropy in copper: An approach based on a tensorial Fourier expansion of the CODF. Journal de Physique IV, 10, 167–174, 2003

An Elastoplastic Model for Prediction of Permanent Deformations of Unbound Granular Pavement Layers

SM18S_12634
Thu • 14:55 • 160

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This paper presents a simplified method for modelling of permanent deformations in order to estimate the rutting of unbound layers. This method is based on three steps: first, the material is characterised using repeated load triaxial tests, with different stress levels. Then, the tests results are analysed using an elastoplastic model of prediction of permanent deformations recently developed. Finally, a finite element analysis, with the program CESAR-LCPC, is used to determine the stress distribution in the pavement, and subsequently the permanent deformations. The calculation is performed with a CESAR's module, which includes non linear elastic models for unbound granular materials, and visco-elastic models for bituminous materials. The stresses calculated at different points in the structure allow to determine the permanent vertical strains at each point, by applying the permanent deformation model. Finally the permanent strains are integrated along the vertical direction to obtain the vertical displacements in the structure (i.e. rutting of the layer). The elastoplastic model is used to analyse repeated load triaxial tests performed on an unbound granular material tested on the LCPC accelerated pavement testing facility. The effect of the different model parameters on the modelling predictions is analysed and discussed. Finally, the model is applied to simulate the rutting of pavements with different thicknesses of bituminous materials.

Intragranular Kinematic Hardening Modelling and Validation

SM18S_12697
Thu • 15:00 • 160

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Various deformation induced dislocation microstructures often appear in deformed metals and alloys (cyclic/monotonic loading). Each is composed of a soft phase with a low dislocation density (cell interiors, channels) and a hard phase (dense walls). These dislocation microstructures induce backstresses, which give kinematic hardening on the specimen scale. A two-phase localization rule is applied in this paper for computing these intragranular backstresses. It is based on Eshelby's inclusion problem and the Berveiller-Zaoui approach. It takes into account an accommodation factor which

permits the computation of reasonable backstress values for large plastic strains. This model is validated by comparing with a number of experimental backstress measures on single crystals. Despite the lack of an adjustable parameter, the agreement of the model with experiments is encouraging. Finally, the model is used for evaluating the division of polycrystal backstress into inter- and intragranular components and the results are compared with neutron diffraction measurements. This kind of physical intragranular kinematic hardening model could help to improve the prediction of polycrystalline homogeneization models.

Modelling of Molecular Processes in Creep of an Oriented Linear Crystalline Polymer

SM18S_13002
Thu • 15:05 • 160

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Molecular models of chain slippage and rupture, interrelation of these molecular processes in high-oriented loaded amorphous-crystalline polymer is suggested. It is taken into account complex interaction between slippage and rupture of interconnecting polymer chains. An oriented crystalline polymer with homogeneous chemical structure of type of linear polyethylene is examined. The crystalline polymer is considered as two-phase one with interchanging amorphous and crystalline regions. Using Frenkel-Kontorova's dislocation or soliton models the tension and slippage of macromolecules is considered. According to the molecular model in polymer sample creep the leading elementary process is mechanically stimulation of thermo-fluctuation slippage of interconnecting molecular chains. It is valid for flexible chain polymers at least. The activation energy of the slippage and the thermo-fluctuation rupture of the linear chain is calculated by using Morza's potential for the covalent bond. It is considered conditions thermo-fluctuation interconnection molecular chain rupture. The conditions and molecular creep processes are complexly dependent on load, conformation structure, concentration of chain ends, entanglements and cross -links, and on other molecular and super-molecular parameters of polymer sample.

SM19

Plates and shells

Chairpersons: E. Ramm (Germany), H. Mang (Austria)

A Cohesive Approach to Thin Shell Fragmentation

SM19L_10038
Mon • 16:00 • 226

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We propose a cohesive approach to the finite element simulation of static and dynamic fracture in Kirchhoff-Love thin shells. Shells are spatially discretized with subdivision shape functions, as originally proposed in Cirak *et al.*, 2000; and Cirak and Ortiz, 2001. Fracture is allowed only along element boundaries, and the progressive separation of the fracture surfaces is governed by cohesive elements. The irreversible cohesive law accounts for the normal and tangential opening displacement of the crack flanks, and it is able to distinguish between bending and tearing modes of fracture. Owing to the non-locality of the subdivision functions, the topological transitions attendant to fragmentation are difficult to account for. We provide an approach that allows simply for arbitrary topological transitions, fragmentation patterns and their evolution. In particular, the shell remains fully coherent up to fracture initiation. The efficiency of the approach is demonstrated through the simulation of petalling experiments in aluminum plates.

Some New Thoughts on the Buckling of Thin Cylindrical Shells

SM19L_10233
Mon • 16:20 • 226

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The classical theory of buckling of axially loaded thin cylindrical shells predicts that the buckling stress is directly proportional to the ratio of thickness to diameter (t/R), other things being equal. But the empirical data show that the buckling stress is proportional to (t/R)1.5, other things being equal. Also there is wide scatter in the buckling stress data. The “imperfection-sensitive”, “non-linear” behaviour is thought to be the cause of the above. Experiments on self-weight buckling of open-topped cylindrical shells agree well with the mean experimental data from the literature. The less scatter in the self-weight buckling data is attributed to the “statical determinacy” of the situation, which allows a post-buckling dimple to grow at a well-defined “plateau load”. Whereas the large scatter in tests on cylinders with closed ends (most of the literature data) may be attributed to the lack of static determinacy. The hypothesis has been verified by a non-linear finite-element analysis.

Continuity Conditions in Elastic Shells with Phase Transformation

SM19L_10287
Mon • 16:40 • 226

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We develop the dynamically and kinematically exact non-linear theory of elastic shells with an account of phase transformation of the shell material. Independent field variables of our model are the translation vector, the rotation tensor, and the position vector of the curvilinear phase interface, all defined on the undeformed shell base surface. We formulate the equilibrium boundary value problem through the variational principle of the stationary total potential energy. In particular, new dynamic continuity conditions are derived at the phase interface. Special forms of the continuity conditions are given at the coherent and incoherent interface curves. The results are illustrated on examples of phase transition in an infinite plate with a circular hole, a simply supported circular plate and a circular cylindrical shell.

Sensitivity Analysis Concerning the Initial Postbuckling Behavior of Elastic Structures

SM19L_11021

Mon • 17:00 • 226

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The (initial) postbuckling behavior of imperfection-sensitive structures may be improved by converting them to imperfection-insensitive structures. Such a conversion can be achieved by specific modes of stiffening of the original structure. In this paper mathematical relations allowing to assess the sensitivity of the initial postbuckling behavior with respect to such modes of stiffening are presented. Koiter's initial postbuckling analysis is applied in the context of the Finite Element Method (FEM) to deduce these relations. An essential ingredient of a special form of accompanying linear eigenvalue analyses, previously used to compute estimates of stability limits on nonlinear primary paths, plays an important role in the derivation of these mathematical relations. They permit to determine whether or not a specific mode of stiffening will result in a transition from imperfection sensitivity to imperfection insensitivity. Two numerical examples serve as the vehicle to corroborate the theoretical findings.

Nonlinear Forced Vibration Analysis of Rectangular Plate Using Super Elements

SM19L_11932

Mon • 17:20 • 226

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Implementation of finite element methods in the analysis of engineering structures has been widely used in the recent years. In the case of large structures due to the application of a large number of elements and nodes, the method become unattractive. Design of new techniques and elements have been one of the important issues among the finite element engineers. In this regard, dynamic behavior of geometric nonlinear plates under external harmonic force, using super elements analysis is considered. A one-quarter model of the plate is proposed to reduce the runtime. Von Karman strain-displacement relations is used. The findings indicate using a few super elements, the same results can be obtained by a large number of regular elements. The computational model is a simple and efficient way to predict the dynamic behavior of the plate. The time required of dynamic analysis is significantly smaller than the regular finite element.

Nonlinear Vibrations of Shallow Shells and Thin Plates of Arbitrary Shape

SM19L_12350

Mon • 17:40 • 226

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Large amplitude free vibrations of thin plates and shallow shells which are described by Donnell–Mushtari–Vlasov differential equations are considered. For the solution of the problem for plates and shallow shells of the complex form an effective method are proposed. It consists in the approximating of solution of initial nonlinear system of the equations by single mode approximation, which is the product of the eigenfunction appropriate to the basic frequency of linear vibration and time-dependent function. As a result of an application of variational Galerkin procedure, the problem is reduced to research of the second order nonlinear ordinary differential equation with respect to amplitude parameter. The distinctive feature of the offered method is the defining eigenfunctions in an analytical kind by the R-function theory (RFM). This fact allows to find natural frequencies for the plate or shallow shell median surface in any form and various type of boundary conditions. The given numerical results and their comparison with well-known from other works confirms the reliability and efficiency of the suggested method.

Parallel Multilevel Solution of Large-Scale Nonlinear Shell Problems

SM19L_12606

Tue • 17:00 • 124

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The analysis of largescale nonlinear shell problems asks for parallel simulation approaches. One crucial part of efficient and well scalable parallel FE-simulations is the solver for the system of equations. Due to the inherent suitability for parallelization one is very much directed towards preconditioned iterative solvers. However thin walled structures discretized by finite elements lead to illconditioned system matrices and therefore performance of iterative solvers is generally poor. This situation further deteriorates when the thickness change of the shell is taken into account. A preconditioner for this

challenging class of problems is presented combining two approaches in a parallel framework. The first one is based on a scaling of the shell director only for solution purpose. The second approach utilizes an aggregation multigrid concept. It is demonstrated by several numerical examples that both approaches allow to remedy the illconditioning of the underlying problem.

A Doubly Curved Element for Laminated Composite Shells Undergoing Finite Rotation

SM19L_12791
Tue • 17:20 • 124

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A finite element formulation via tensor notation for geometrically exact nonlinear laminated composite shells is presented. The present 5/6-DOF shell theory is based on total Lagrangian concept where the Green-Lagrange's strain tensor and and the work conjugate 2-nd Piola-Kirchoff stress tensor plays the central role. The two parametric incremental material rotation vector is considered to be orthogonal to the shell director. To improve the performance of the present 4/9-noded element, EAS scheme combined with ANS scheme is employed. The update procedure of the nodal rotation is kept additive within a load increment step. To avoid the singularity problem the load increment size is restricted to render the rotation magnitude less than π. The performance of the element is found to be exciting in linear and nonlinear regime for a wide class of structural problems. New results are presented for different structural problems under thermo-mechanical loads.

A New Triangular Element for the Analysis of Composite Plates

SM19L_12792
Tue • 17:40 • 124

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A triangular element based on the Mindlin's plate theory has been developed for the analysis of composite plates. The element has six nodes (at the vertices and mid-sides of the triangle) each containing five degrees of freedom – in-plane displacements u, v, transverse displacement w, and cross-sectional rotations θ_x $(= \frac{\partial w}{\partial x} + \gamma_x)$ and θ_y $(= \frac{\partial w}{\partial y} + \gamma_y)$. The key concept of assuming independent shear rotations γ_x and γ_y enables a high order of displacement to be modelled with relatively fewer degrees of freedom. Representing the field variables u, v, w, γ_x and γ_y with complete polynomials of suitable order maintain the proper hierarchy of deflection, rotation, moment and shear, and averts shear locking. C_1 compatibility required in the element is kept unsatisfied. On the other hand patch test is passed and the element is free from spurious modes. Numerical examples on deflection of composite plates prove the efficacy of the proposed element.

An Natural Hybrid-Mixed Model with Shear Projection for Curved Shells

SM19L_12838
Tue • 18:00 • 124

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A new natural hybrid-mixed variational approach, applied to a degenerated 4-node shell finite element, is presented. The membrane part is natural hybrid with an improved stress field. The bending part is mixed based on the classical Hellinger-Reissner principle. The transverse shear part is partially hybrid with the satisfaction of two 3D-equilibrium equations. To eliminate the shear locking, the Assumed Natural Strain method is used for approximating shear strains. The results of a pinched cylinder are presented.

The Stress Analysis of the Multilayered Plates and Shells with Defects of the Structure

SM19S_10071
Tue • 14:30 • 134B

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The laminated composite shells have high strength properties. However technological processes of their manufacture are difficultly automated, that causes the increased probability of manufacturing of thin-walled elements of structures with local defects. Such local imperfections can produce essential influence on the strength of the total shell. The variant of the theory of laminated anisotropic plates and shells is offered for the analysis of such situations. The high order kinematics model reflects nonlinear character of distribution of displacements on thickness of rigid layers. These layers are connected by the thin glue layer. For glue layers the linear distribution of displacements is assumed. It is supposed, that on some local area of the shell glue layer is absent, therefore in this area the unilateral contact between rigid layers is taken into account. The problem is solved on a basis of the geometrically nonlinear theory of the shells The stress analysis is considered for anisotropic toroidal shell loaded by internal pressure. The numerical researches are executed for two examples. In the first two-layer shell with two rigid layers has no defects in glue layer, and in second example the connection is absent on some area of the shell. The characteristics of the stressed behavior of the shells are investigated in depending on the sizes and positioning of defects.

Nonlinear Analyses of Rhombic Plates subjected to a Concentrated Load

SM19S_10583
Tue • 14:35 • 134B

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The theoretical formulations are presented for a rhombic plate subjected to a concentrated load. Several numerical modeling analyses are carried out. Numerical solutions of the present theoretical formulations are shown and compared with the available results using finite element analysis for various plates with different length to width ratios, thickness and supported edges. Some excellent agreements are achieved. It is seen that the accuracy and efficiency of the proposed new theory formulation are confirmed.

Analytical Solution of Bending of a Clamped Elliptical Plate Under Lateral Load and In-Plane Force

SM19S_10770
Tue • 14:40 • 134B

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On the basis of the ordinary thin plate theory, the exact analysis on the bending problem of a clamped elliptical plate is performed by means of introducing the elliptical cylinder coordinates. The elliptical plate is subjected to the uniform lateral load and in-plane force simultaneously. The analytical solution for the deflection due to bending is obtained in the form of an infinite series of Mathieu functions and the coefficients of the series involve the circular, hyperbolic and modified Mathieu functions. The expressions for the bending moments are also derived analytically. It should be noted that the orthogonality of Mathieu functions is used in the process of leading to the expressions for the deflection and moments. Numerical calculation results for the dimensionless deflections and moments will be presented in figures for various values of in-plane force and axial-length ratio. The special case of circular plate will be also discussed in detail

Meshless LBIE Formulations for Viscoelastic Thin Plates

SM19S_11238
Tue • 14:45 • 134B

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In this paper, simply supported and clamped thin viscoelastic plates are analyzed. Linear viscoelasticity has been considered for which the correspondence principle is applied. In Laplace transform domain the governing equation is the PDE of forth order. In case of plates with clamped edges and/or simply supported straight edges, it is possible to decompose the governing equation into a system of two Poisson equations for Laplace transforms of deflection and its Laplacian, respectively.In this paper a new approach based on local boundary integral equations (LBIEs) is presented. Nodal points are randomly distributed over the domain of the plate. Each node is the center of a circle surrounding this node. The LBIEs are applied to each circular subdomain.

Asymptotic Behavior of Piezoelectric Plates

SM19S_11711
Tue • 14:50 • 134B

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We extend to the linearly piezoelectric case the mathematical derivation of the linearly elastic behavior of a plate as the limit behavior of a three-dimensional solid whose thickness 2e tends to zero. Due to classical assumptions on the exterior loadings, a suitable scaling is defined by to study the limit behavior as e goes to 0. Note that the assumptions on the forces are those which provide Kirchhoff-Love limit plate theory while those on the electrical loading involve an index p running over 1, 2 that will imply two kinds of limit models according to the nature and the magnitude of the data. We show that the scaled states converge in a suitable topology to the unique solution of the limit problem indexed by p. These limit problems (p = 1 or 2) are connected with the physical situations where the thin plate acts as an actuator or a sensor.

Effect of a 'Static' Resonance in Elastic Thin-Walled Cylinders

SM19S_11815
Tue • 14:55 • 134B

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The results of experimental investigation (using qualitative small-sized steel samples) of influence of periodic non-homogeneity in a circumference direction onto deformation and buckling of longitudinally compressed elastic circle cylindrical shells are discussed. This non-homogeneity was caused by three different factors: by loading scheme (1), by initial imperfections of the mode of smooth cylinders (2) and by variability of the sign of an eccentricity of ribs of stringer modules (3). Analysis of experimental data showed, that the periodic non-homogeneity results in the beginning and development of periodic bending nonlinear deformations in the loaded shell. The most intensive deformations are developed at the non-homogeneities, the variability of which is close to the variability of the mode of the first tone of eigen lateral oscillations of a shell. The phenomena of increase of static lateral deformations of a shell, at the variability of non-homogeneity close to the variability to the first mode of eigen oscillations, can be called a "static" resonance.

Energy-Conserving Integration in Six-Field Shell Dynamics

SM19S_11890
Tue • 15:00 • 134B

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We propose an energy-conserving time-integration algorithm for dynamics of shell structures. The shell model is based on six-field non-linear theory, with three translations and three rotation parameters describing the shell motion. The spatial approximation is based on the finite element method. The temporal algorithm uses mid-point approximation of the rate equations expressed in state variables. The presence of rotation group in the definition of the configuration space requires special computational techniques. We present numerical simulation of a branched shell moving freely in space, undergoing multiple turns and large relative deformations. The classical extended Newmark integration scheme shows in this case some numerical instability. Application of the energy-conserving scheme gives here comparable results in the period of stable simulation and does not reveal any instability elsewhere. This allows one to extend the simulation period with the use of longer time steps.

Beam Theory for Analysis of Girders with Corrugated Steel Webs

SM19S_12046
Tue • 15:05 • 134B

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Prestressed concrete girder with corrugated steel webs is a new concrete-steel composite structural element that has been recently utilized in highway bridges in France and Japan. In the girders, considerable shear deformation in the webs and large relative longitudinal displacement of the upper and lower flanges are anticipated. This incurs warping in the cross section of the girder and invalidates the assumption on plane section remaining plane in the classical beam bending theories. In this study, an extended shear deformable beam bending theory for analysis of the girders is derived. The theory is basing on two displacement fields and the assumption on zero longitudinal stiffness of the corrugated steel webs. Numerical example on a box-section cantilever by the theory shows good prediction comparing with the classical beam theories. The theory is also capable to predict the shear lag phenomenon in the webs of the girder.

Mindlin Cylindrical Panels with Twist and Double Curvature

SM19S_12224
Tue • 15:10 • 134B

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An open cylindrical panel, which has a twist around the lengthways direction and double curvature in the radial and lengthways directions, is a better shell model of turbine blades. In order to analyze vibration characteristics accurately, a precise relationship between strains and displacement components of the shell model is derived on the general shell theory and the

first order shear deformation theory. By using the principle of virtual work and the Rayleigh–Ritz method, the governing equation for free vibration of the model is presented. The effects of parameters such as curvature and twist on vibration are studied.

Application of the Return Mapping Algorithm to Perzyna Viscoplasticity for Plane Stress

SM19S_12328
Tue • 15:15 • 134B

Zdzislaw Nowak, Krzysztof Wisniewski
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In the paper the elastic-viscoplastic constitutive relations of the Perzyna-type is investigated for plane stress problems. A fully implicit integration algorithm is adopted and the relevant expression of the consistent tangent operator for the von Mises yield criterion and flow functions of arbitrary type is derived. It is shown how the elasto-plastic rate equations of standard plasticity can be generalized to overstress-type models of viscoplasticity, where the stress point can be located outside the loading surface. Numerical example is given to reveal the differences and the similarities between the plastic and the viscoplastic overstress models.

A Perturbation Method for Nonlinear Vibrations of Structures

SM19S_12346
Tue • 15:20 • 134B

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A perturbation theory for the large amplitude vibration analysis of general, statically loaded imperfect structures is presented. The method is based on a perturbation expansion for both the frequency parameter and the dependent variables. The theory makes it possible to investigate the dependence of the natural frequencies of structures on finite vibration amplitudes, initial geometric imperfections, and a nonlinear static deformation. An extension to a multi-mode analysis is presented for perfect structures. The perturbation theory developed is applied to the nonlinear (large amplitude) vibration problem of anisotropic cylindrical shells including edge effects. The starting point of the analysis are the Donnell-type differential equations of an anisotropic circular cylindrical shell. Characteristic results of the buckling and nonlinear vibration analysis of isotropic and composite shells are shown, in order to illustrate the capabilities of the computational modules developed.

SM20

Rock mechanics and geomechanics

Chairpersons: Z. Mroz (Poland), I. Vardoulakis (Greece)

The Material Point Method in Soil Mechanics Problems

SM20L_10231
Thu • 11:00 • 206

Zdzisł aw Więckowski
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The dynamic soil mechanics problems like failure of a retaining wall and pile driving are investigated. As these problems are characterised by large strains, they are hard to analyse – due to severe mesh distortions – by the use of the fi nite element method (FEM) formulated in the Lagrangian frame, the most popular computational tool in engineering practise. This disadvantage of FEM is avoided in the present paper by applying the material point method (MPM) which can be regarded as FEM formulated in an arbitrary Lagrangian–Eulerian description of motion. Two kinds of space discretisation are employed in MPM: the motion of material points representing subregions of the analysed body is traced with respect to the Eulerian mesh. Such an approach makes the method very fl exible and capable to handle large strain problems. The case of non-cohesive models of the soil is analysed; the elastic–plastic and elastic–viscoplastic material models are applied.

Modeling of Coupling Between Induced Anisotropic Damage and Permeability in Rocks

SM20L_10702
Thu • 11:20 • 206

J.J. Zhou, **J.F. Shao**
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In this paper, we present a micromechanics based macroscopic modeling of the coupling between induced anisotropic damage and permeability in brittle rocks. The damage state is represented by a second order tensor. The evolution of damage is determined from a crack propagation criterion. The free enthalpy of cracked solid is deduced from micromechanical considerations. The constitutive equations of anisotropic damage model are then derived from this thermodynamic potential. For the coupling between induced damage and variation of permeability, it is assumed that cracks exhibit normal opening coupled with sliding and propagation due to crack surface asperity. The normal opening is contributing to the variation of permeability of rock. The overall permeability of the REV is obtained by a space integration method taking into account crack opening in each orientation.

Micromechanical Study of Macroscopic Friction and Dissipation in Idealised Granular Materials: The Effect of Iinterparticle Friction

SM20L_10866
Thu • 11:40 • 206

N.P. Kruyt[(1)], L. Rothenburg[(2)]
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Using Discrete Element Method (DEM) simulations with varying interparticle friction coeffi cient, the relation between interparticle friction coeffi cient and macroscopic continuum friction and dissipation is investigated. As expected, macroscopic friction and dilatancy increase with interparticle friction coeffi cient. Surprisingly, dissipation is present even for zero and infi nite interparticle friction coeffi cients when there is no microscopic frictional dissipative mechanism. Thus dissipation in idealised granular materials is not exclusively due to interparticle friction. By performing additional DEM simulations of unloading paths, the plastic strains were determined. The dependence of the dissipation-rate function on plastic strains is investigated. A specifi c form for the dissipation-rate function is formulated, based on the results of the DEM simulations. Furthermore, it is shown that there is no signifi cant recoverable plastic work.

Influence of Contact Phenomena on Structure–Subsoil Interaction: Finite Elements Method Analysis

SM20L_11584

Thu • 12:00 • 206

Marcin Maździarz

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The contact between structure and subsoil is formulated by using 3D elasto-viscoplastic relationships incorporating pore pressure. Finite element implementation is then performed for the geotechnical structure, subsoil and contact relationships. Contacts elements with zero thickness are carefully developed, allowing for slip and stick. Solid isoparamtric elements are also developed. The novelty of the contribution consists of using elasto-viscoplastic model incorporating pore pressure for 3D contact. Using implemented spatial elements in the program HYDRO-GEO elasto-viscoplastic analysis of interaction between structure and subsoil was carried out. Earth dam interacting with concrete weir and excursion trough in one of Polish earth dams (Dobczyce) was analyzed. Simulation of deformation of structure and slide of soil on surface of the retaining wall was studied.

Modeling of Static Liquefaction and Evolving Failure Modes

SM20L_11667

Thu • 12:20 • 206

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Considered are the elasto-plastic and a new elasto-viscoplastic version of the Superior sand model for describing static liquefaction of water-saturated, loosely-packed granular deposits. The response of the model to undrained triaxial compression in strain- and stress-controlled loading as well as to creep is analyzed. The limit points at which static liquefaction identified with the loss of stability of the model are discussed. It is shown that the classical second-order work rate instability criterion valid for elasto-plastic models no longer applies to the rate-dependent version of the model; instability is governed by the first-order work acceleration. Examples of numerical simulations of the undrained plane-strain biaxial compression test using the model demonstrate the effect of the rate of loading and internal flow on the formation of shear bands. Also, the effect of the mass of the specimen and of the loading system on the post-stability response is discussed.

Development of Shear Banding in Sandstone

SM20L_11845

Thu • 12:40 • 206

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Closed-loop, servo-controlled compression tests were conducted to investigate the development of shear banding in Berea sandstone. The experiments were performed with a Vardoulakis-Goldscheider type plane-strain apparatus, designed to allow the shear band to develop in an unrestricted manner. Dilatancy and friction were evaluated at three confining pressures, and several tests were halted in the strain-softening regime. Thin section microscopy and digital image analysis provided direct observations of the shear band. Porosity increase within the shear band was 4-8 grain diameters wide and associated with intragranular microcracks; increased porosity did not extend beyond the tip of the shear band.

Incremental Nonlinearity in Constitutive Relation for Granular Media

SM20L_12462

Fri • 09:30 • 206

Yuji Kishino

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Recently, incrementally nonlinear models have been proposed for constitutive relations of geomaterials. To validate such constitutive models, we have to develop a sophisticated testing apparatus. Furthermore, to investigate general irrecoverable behaviors, we have to conduct a huge series of tests for numerous specimens regarded as identical. On the other hand, numerical tests with a suitable discrete element method enable us to extract general information on irrecoverable behaviors of an identical granular specimen. In this paper, the 3D Granular Element Method was utilized to conduct stress probe tests. It was found from these tests that, as far as the conventional tri-axial state concerns, the incremental plastic response is approximated by the non-associated flow rule, and that, for general true tri-axial stress-probes, the direction of incremental plastic strain is apparently dependent on the direction of incremental stress. The latter suggests the existence of multiple shear mechanisms in plastic deformation of granular media.

A High-Pressure Hish Strain Rate Elastic-Viscoplastic Model for Cementitious Materials

SM20L_12779

Fri • 09:50 • 206

Martin J. Schmidt(1), Oana Cazacu(2), Mark L. Green(1), Nicolaie D. Cristescu(3)

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A comprehensive experimental study aimed at characterization of the combined effects of high confinement and high strain rate on the deformation and strength of cementitious materials was conducted. Quasi-static triaxial compression tests for confining pressures ranging from 0 to 500 MPa were performed. Dynamic tests for strain rates in the range 60/s to 160/s under unconfined and confined conditions were conducted using a split Hopkinson pressure bar. A decrease in strain rate sensitivity with increasing confining pressure was observed. A new elastic/viscoplastic model that captures compressibility, dilatancy, and strain rate effects has been developed for concrete. There are no a priori limitations or restrictions regarding the specific expressions of the yield function and viscoplastic potential. A new flow rule was proposed. Procedures for determining the constitutive functions were developed. Comparisons between model predictions and data showed the proposed model describes with very good accuracy the high-pressure behavior of concrete.

From Dislocation Junctions to the Three Stages Curve

SM20L_11955

Fri • 10:10 • 206

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The strain hardening matrix of fcc crystals can be obtained from crystallographic continuum models deriving from the Kocks-Mecking framework. DD simulations were used to compute the coefficients of the interaction matrix between slip systems and to extend an existing model for stages II and III in order to also include stage I. Other parameters of the model are the mean-free path of the dislocations and their critical annihilation distance by cross-slip, which can be estimated from various sources. The resulting constitutive formulation is inserted into a numerical crystalline model using a FE code, which is used here to test single crystal behavior. As a result, parameter-free deformation curves can be obtained for fcc crystals, which depend in a known manner on the nature of the material, the orientation of the crystal and temperature. This is illustrated by a comparison between aluminum and copper crystals initially oriented for easy glide at room temperature. In this type of modeling, the internal variables are average dislocation densities per slip system. Thus, although dislocation patterning is not accounted for, the traditional three-stage stress vs. strain behavior is fully recovered. The present results seem to indicate or confirm that, as long as there is no change in strain path, there is no need to account for dislocation patterning when modeling strain hardening properties up to the end of stage III. This statement raises a few interesting questions.

Dynamic Behaviours of Soils and Rocks in a Wide Pressure Range

SM20S_10374

Tue • 14:30 • 219B

Anatoly M. Bragov(1), Andrey K. Lomunov(1), Ivan V. Sergeichev(1), **Leopold Kruszka**(2)

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Investigations of dynamic compressibility of soils were performed by two various experimental methods: the modified Kolsky method was used at strain rates about 103 s^{-1} and pressure up to 300 MPa, and the plane-wave shock testing was at higher strain rates and pressure up to 2GPa. Soils' specimens, including dry and wet sands, were placed in a steel jacket equipped additionally by strain gauges to test on split Hopkinson pressure bar (SHPB). As in these above methods deformation state is the same, then it is able to construct total stress-strain curves of dynamic deformation of soft soils in uniaxial strain condition in a wide range of pressure. Besides above testing, there are presented experimental analysis for two rocks' materials, i. e. the gabbro-diabas granite and two kinds of marble tested in compression as well as in tension (splitting tests) by SHPB at high strain rate about 103 s^{-1}.

The Localization of Plastic Strain and Rock Fracture

SM20S_10421

Tue • 14:35 • 219B

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Localization of strain and fracturing in rocks is considered from the aspects of rigidly plastic and elastoplastic body models based on the Coulomb-Mohr and Huber-Mises-Shleicher criterions. A system of differential equations of plasticity and conditions of hyperbolicity were obtained. At the moment of failure, stress values and angles, at which it occurs, in plane strain and in plane stress were determined. The directions of localization and fracturing are identified with characteristics of system of equations for velocities. For hardening elastoplastic rocks, the localization is associated with loss of ellipticity and the first transition to hyperbolicity of system of equilibrium equations in terms of velocities. In employing this approach, theoretical and experimental results coincide for brittle solids.

Mohr-Coulomb Yield Criterion for Cosserat Continua

SM20S_11427

Tue • 14:40 • 219B

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The classical yield criterions cannot be applied directly to Cosserat continua since that the strain tensor and the stress tensor in Cosserat continua are asymmetric. In this contribution the strain tensor and the stress tensor are decomposed into symmetric and skew-symmetric components, and the formulae of stress invariants are modified for Cosserat continua. A Mohr-Coulomb yield criterion for Cosserat continuum is established in detail, and the formulae of von Mises, Tresca and Drucker-Prager yield criterions for Cosserat continua are presented as well. Moreover, elasto-plastic finite element method based on these yield criterions is addressed. One numerical example shows the superior behavior of the established Mohr-Coulomb yield criterion, and demonstrates that the Cosserat model, which incorporates an internal length scale, is capable to resolve the mesh-dependence that exists in strain localization problem for classical continua.

On the Use of Second-Order Topological Information for Subsurface Imaging by Elastic Waves

SM20S_12364

Tue • 14:45 • 219B

Bojan Guzina, Ivan Chickichev
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This paper summarizes the generalization and application of topological derivative, rooted in structural shape optimization, to 3D inverse scattering involving elastic-wave identification of subsurface obstacles. Recently, elastodynamic expressions for topological sensitivity have been proposed for the imaging of both semi-infinite and finite solid bodies. Despite their utility, however, these developments are limited in the sense that they are restricted to the identification of subsurface cavities and do not provide an explicit link between the nucleated (infinitesimal) cavity and finite void(s) being sought. To deal with these impediments, the proposed generalization is two-fold and involves i) development of a formula for the nucleation of a solid inclusion, and ii) rigorous analysis of the second-order topological information that permits direct estimation of the obstacle size through the solution of a canonic least-squares problem established on the basis of (first-order) topological sensitivity. Numerical examples are included to illustrate the proposed developments.

The Influence of Teeth on the Earth-Working Processes

SM20S_12848

Tue • 14:50 • 219B

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The new experimental program of laboratory tests was presented, performed in a soil bin on cohesive soil. Model tools in a shape of an excavator's bucket equipped with teeth of different geometry were used in that study. The change in geometry simulated different subsequent stages of material wear. The experimental verification of the influence of teeth (number of teeth, and the position of teeth on the bucket's inside lip) on the efficiency of the digging cycle is discussed. Three different types of soil samples (dense, medium dense and loose) were used.

SM21

Solid mechanics in manufacturing

Chairpersons: B. Heimann (Germany), T. Inoue (Japan)

SM22

Stability of structures

Chairpersons: Z. Gaspar (Hungary), S. Kyriakides (USA)

Wrinkles in Square Membranes

SM22L_11097
Tue • 11:00 • 226

Yew W. Wong, **Sergio Pellegrino**
University of Cambridge, Cambridge, UK

This paper considers a thin, uniform, elastic, isotropic square membrane loaded at the corners by two pairs of equal and opposite forces (a simple model for a solar sail). Two wrinkling regimes are identified. The first regime occurs for symmetric and moderately asymmetric loading; it is characterised by small, radial corner wrinkles. The second regime occurs for strongly asymmetric loading and is characterised by a single, large diagonal wrinkle, plus small radial corner wrinkles. A simple analytical method for predicting wrinkle wavelengths and out-of-plane wrinkle displacements, and also in-plane corner displacements of the membrane, is presented. The analytical predictions are validated against experimental measurements and detailed finite element simulation results. The accuracy achieved by the analytical model is typically better than 20% on wavelengths and 40% on amplitudes. On the other hand, finite element simulation using thin shell elements is shown to be able to replicate physical experimentation with an accuracy better than 10%.

Dynamic Arrest of Propagating Buckles in Offshore Pipelines

SM22L_11600
Tue • 11:20 • 226

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Offshore pipelines are susceptible to local damage and collapse with the potential of propagation driven by the external pressure. Buckle propagation usually occurs at high velocities and can destroy large sections of the pipeline. An effective way to ensure that collapse, should it occur, affects only a small length of the pipeline, is the periodic placement of buckle arrestors along the line. These devices locally increase the circumferential bending rigidity of the pipe and thus provide an obstacle in the path of propagating buckles. The effectiveness of three different types of arrestors has been studied first under quasi-static and then under dynamic buckle propagation conditions using combinations of experiments and analyses. In all cases, inertial effects were found to enhance the arrestor performance; in other words, the pressure at which a given arrestor is crossed dynamically is higher than the quasi-static crossover pressure for reasons that will be outlined.

Elastoplastic Microscopic Bifurcation and Post-Bifurcation Behavior of Periodic Cellular Solids

SM22L_10692
Tue • 11:40 • 226

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In this study, a general framework to analyze microscopic bifurcation and post-bifurcation behavior of elastoplastic, periodic cellular solids is developed on the basis of a two-scale theory of the updated Lagrangian type. We thus derive the eigenmode problem of microscopic bifurcation and the orthogonality to be satisfied by the eigenmodes. By use of the framework, then, bifurcation and post-bifurcation analysis are performed for cell aggregates of an elastoplastic honeycomb subject to in-plane compression. Thus, demonstrating a basic, long-wave eigenmode of microscopic bifurcation under uniaxial compression, it is shown that the eigenmode causes microscopic buckling to localize in a cell row perpendicular to the loading axis. It is also shown that under equi-biaxial compression, the flower-like buckling mode having occurred in a macroscopically stable state changes into an asymmetric, long-wave mode due to the sextuple bifurcation in a macroscopically unstable state, leading to the localization of microscopic buckling in deltaic areas.

Twist Buckling and the Foldable Cylinder: An Exercise in Origami

SM22L_12688
Tue • 12:00 • 226

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The buckling of the thin circular cylindrical shell under torsion is one of the fundamental problems of elastic stability. But, unlike its counterpart loaded in axial compression, it develops a deflection pattern like a mechanism from origami, whereby the system can be folded completely flat with length reduced to zero. The mechanism is simply demonstrated by twisting a rolled length of paper between two rigid mandrels. The talk will explore the relationship between initial buckling, first-order post-buckling, and the final folding mechanism, in the twisted cylindrical shell. It will demonstrate that the circumferential wavenumber is decided at the point of instability and remains unchanged throughout. However, as the system moves to accommodate the fixed geometry of the final folded shape, the obliqueness of the wavepattern changes; crest and valley lines start parallel to one another, but rotate by different amounts to create the fold lines of the mechanism.

Coupling of Axisymmetric and 3D Shell Models for Non Linear Elastoplastic Buckling Prediction of Mainly Axisymmetric Shells

SM22L_11174
Tue • 12:20 • 226

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The axisymetric models are very efficient for prediction of non linear buckling of shells with generalised imperfections or loadings. The approximate the solution is expanded on a finite Fourier basis. This strategy has been extensively used by Wunderlich or Combescure for the analysis of axisymetric imperfect shells subjected to any load. In case of local geometrical imperfection or quickly varying load or local support condition the axisymmetric models are no longer efficient. The usual practice is to use 3D shell model. This method leads to heavy meshes if one desires a good precision. A special interface element is developed to combine a 3D analysis for the region of local strong discontinuity and an axisymetric coupled Fourier analysis for the rest of the structure. The method presented in this paper is developed for elasto plastic non linear buckling and some examples are compared with fully 3D analysis or with experiments.

Stability of Parametrically Excited Structures: New Results

SM22L_11939
Tue • 12:40 • 226

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Linear dynamical systems with many degrees of freedom with periodic coefficients also depending on constant parameters are considered. First and second order derivatives of the Floquet matrix with respect to parameters are derived in terms of matricians of the main and adjoint problems and derivatives of the system matrix. Then, linear vibrational systems with periodic coefficients depending on three independent parameters: frequency and amplitude of periodic excitation, and damping parameter are considered. For arbitrary matrix of periodic excitation and positive definite damping matrix general expressions for regions of the main (simple) and combination resonances are derived. Two important specific cases

of excitation matrix are studied. It is shown that in both cases the resonance regions are halves of cones in the three-dimensional parameter space. As an example of the developed theory Bolotin's problem on dynamic stability of a beam loaded by periodic bending moments is solved.

Buckling and Imperfection-Sensitivity of Axially Compressed Cylindrical Shells with Compliant Cores

SM22L_12084
Fri • 11:00 • 226

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The extent to which the mechanical properties and dimensions of compliant core materials influence the load-carrying capacity and imperfection-sensitivity of axially compressed circular cylindrical shells is analyzed numerically for a wide range of configuration parameters. Excellent qualitative and quantitative agreement with available analytical and experimental results is obtained, and the conclusion is reached that a comparatively thin layer of compliant core material is sufficient to achieve substantial increases in the respective buckling loads while at the same time the imperfection-sensitivity is significantly smaller than for the unfilled shell and similar weight-optimized constructions.

On the Stability of the Sky-Hook

SM22L_11816
Fri • 11:20 • 226

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The sky-hook, that is a string forming a connection from the surface of the Earth to a satellite in geostationary orbit, which may be used as track for an Earth to space elevator, is an old dream of mankind, originating about 100 years ago in Russia. Besides the question of feasibility from a technological point of view also the question concerning the stability of such a configuration has not yet been completely solved. Under the assumption that a proper material (carbon nanotubes) is available making the connection possible from the technological point of view, we address the question of stability of the radial relative equilibrium of a very long tapered string, which rotates synchronously with the Earth and reaches from the surface of the Earth up into the sky. The solution of the stability problem for different string materials is given by application of the Reduced Energy Momentum Method.

Stability of Shear-Flexible Frames

SM22L_12297
Fri • 11:40 • 226

Esben Byskov, Ronni Dam, Thomas Frost, Lars Hulsbæk
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Most studies of postbuckling and imperfection sensitivity of frame structures assume shear inflexibility. Here, we present theoretical, numerical, and experimental results for a shear-flexible sandwich realization of a particular frame, the socalled "Roorda Frame." When dealing with sandwich beams and frames it is very important noticing that the meaning of a rigid joint or a clamped support is different than for the case of shear inflexibility. For frames consisting of shear-inflexible materials the buckling loads are well separated, and separation decreases for increasing shear flexibility. Although experimental and numerical results of postbuckling behavior and imperfection sensitivity of frames of sandwich materials agree well, their determination entails serious difficulties in comparison with the equivalent problem for frames made of shear-inflexible materials. Modeling of the cross-sectional properties must be given special attention. Special finite elements must be used in order to avoid shear and membrane locking.

Generalised Beam Theory Formulation to Analyse the Post-Buckling Behaviour of Orthotropic Laminated Plate Thin-Walled Members

SM22L_12558
Fri • 12:00 • 226

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This paper presents the derivation and illustrates the application of a non-linear orthotropic GBT formulation, which is intended to perform post-buckling analyses of laminated plate FRP open-section thin-walled members. Different types of loading and end support conditions can be dealt with and the theory can handle the presence of arbitrary initial geometrical imperfections. One is able to determine "exact" and "approximate" (only a few modes) post-buckling equilibrium paths and the evolution, along those paths, of (i) displacements and stresses and, using the GBT unique mode decomposition feature, also of (ii) the deformation mode participation in the member deformed configuration. To validate and illustrate the

application and capabilities of the formulated GBT, numerical results, concerning the post-buckling behaviour of laminated plate FRP lipped channel members exhibiting different orthotropic behaviours, are presented and discussed. Some of them are compared with values obtained from finite element analyses, performed in the code ABAQUS and adopting shell element meshes to discretise the member.

Dynamic Instability of a High-Speed Flexible Shaft with a Massive Disc and Follower Load.

SM22L_12934
Fri • 12:20 • 226

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The paper is concerned with transverse flutter instability analysis of a flexible rotating shaft supported as a cantilever beam carrying a massive disc at the free edge. The system is subjected to concentrated follower load exerted on the disc. Such model corresponds to real rotating machinery like turbines or compressors in which medium flow can produce tension or compression in the shaft. The follower load and internal dissipation generate dynamic bifurcations of flutter type. A discrete-continuous model of the system is considered in which attention is paid mainly to the gyroscopic effect and the influence of the massive disc on the shape functions for the continuous shaft. The near-critical behaviour of the system is analysed as well under assumption of geometric system non-linearity. It is shown that the gyroscopic effect can dramatically change the flutter scenario of the system.

Statical Models to Illustrate Special Instabilities

SM22L_10915
Fri • 12:40 • 226

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Simple statical models are useful to understand different types of elastic instability phenomena. There are well-known models in the literature to analyze the limit point, the asymmetric, the stable- and unstable-symmetric, the monoclinal, anticlinal and homeoclinal point of bifurcation. The paper shows models to illustrate some special instability. Three models belong to the cusp catastrophe. They have point-like instability, stable-X or unstable-X point of bifurcation, respectively. Two models illustrate classes of the double cusp catastrophes, where the homogeneous quartic parts of the potential energy functions have two distinct or two coincident real roots. The equilibrium paths of the perfect and some imperfect structures and some imperfection-sensitivity curves will be presented.

Shallow Spherical Caps Under External Pressure

SM22S_10378
Tue • 14:30 • 152B

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The present study addresses the static stability of shallow spherical caps subjected to uniform and static external pressure. A series of six, carefully machined, mild steel spherical caps were chosen to complement the existing experimental data. The shallowness parameter, lambda, was chosen to be between 3.5 and 5.5. Caps were CNC-machined from 245 mm diameter solid billet. Shells had a heavy edge ring being integral with the wall. It was aimed here to model the fully clamped boundary conditions. The height-to-wall thickness ratio varied from 1.5 to 4.5 and the radius-to-thickness ratio varied from 300 to 1800. The above models were buckled through the application of quasi-static external pressure. All caps failed suddenly through a snap-through mechanism. Comparison of experimental failure pressures with numerical predictions was found to be good. The trend of experimental data on load versus the slenderness parameter, lambda, confirms a sudden dip in the load carrying capacity around lambda = 4.0 (i.e. contrary to some of the existing data which has been published on this controversy).

Nonlinear Dynamic Stability of Multi-Suspended Roof Systems

SM22S_11172
Tue • 14:35 • 152B

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The present work deals with the nonlinear dynamic stability aspects of initially imperfect dissipative multi-suspended roof systems under step loading. A fully nonlinear analysis is used to establish that global stability, being the main feature of multi-suspension roof systems, is captured by the proposed autonomous conservative models. For realistic geometrical combinations, stiffness and damping parameters involved, the plots presented in the paper show that all model cases, dealt with the global dynamic response, are stable. This is the primary advantage of multi-suspension roofs, captured by the proposed simulation. Moreover, the vertical vibrations evaluated were of small amplitude, the snap-through phenomenon totally absent and the effect of complementary fixed points were minimal, contrary to recently reported results concerning simple models of single-suspended roofs found in other papers. The results agree well with the ones concerning doubly-suspension roofs reported in a previous paper by the same authors as here. Thus, the proposed autonomous multi-DOF model can serve as an efficient tool for the understanding of the main features of multiple suspension roofs and offers a first insight into the well established advantages of this popular roofing system.

Bifurcation Buckling of Sandwich Plates and Shells in Plastic Range

SM22S_11653

Tue • 14:40 • 152B

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Exact bifurcation buckling analyses of sandwich plates and shells are presented. The particular caes considered are the complete circular plates and complete spherical shells subjected to uniform equi-biaxial compression. The high-modulus faces are allowed to undergo plastic straining; the low-modulus core remains elastic. Constitutive relations of the competing incremental and deformation theories of plasticity are employed. Transverse shear strains, important for sandwich structures, are accounted for by suitable kinematic hypothesis. Governing equations in kinematic variables are obtained by virtual work method and using Shanley's concept of plastic bifurcation under increasing loading. Analytical solutions are obtained for general non-axisymmetric buckling. The derived formulas generalize the classical results for homogeneous plates and shells by supplying transverse shear correction terms. Numerical results show that the deformation theory furnishes, as usual, a lower critical buckling pressure. However, interestingly, the results from the incremental theory are only slightly higher.

A Unified Treatment for the Elastoplastic Bifurcation of Structural Elements

SM22S_11962

Tue • 14:45 • 152B

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This work is devoted to a unified method for the analysis of the elastoplastic bifurcation and post-bifurcation of structural elements such as beams, plates and shells. The plasticity is described within the frame of generalized standard materials, obeying the von Mises yield criterion and a linear isotropic hardening. The bifurcation theory makes use of asymptotic expansions as introduced by Hutchinson. The presented results focus on the significant case of uniaxial stress which enables us to obtain analytical relations for the structural elements in hand. First, the method is illustrated with a Timoshenko beam under axial compression, from which the well-known results for the Bernoulli beam model are straightforward. Next, it is shown that the same method applies again to the plastic buckling of axially compressed plates and cylindrical shells. In each case, the three-dimensional bifurcation equation is solved, giving rise to the critical load, the eigenmode as well as the initial slope of the bifurcating branch which is essential for the stability analysis.

Instabilities of Initially Stressed Hyperelastic Cylindrical Membrane and Shell Under Internal Pressure

SM22S_12420

Tue • 14:50 • 152B

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This paper investigates the static nonlinear behavior and possible instabilities of cylindrical membranes and shells experimentally and numerically using the Finite Element Method. A detailed experimental analysis was carried out involving cylindrical membranes and shells with different initial axial forces, internal pressures and imperfections. The specimens used in the experiments are considered as an isotropic, homogeneous and hyperelastic rubber, which is numerically modeled as a Neo-Hookean, Mooney-Rivlin or Ogden incompressible material. The structure was analyzed using appropriate membrane or shell finite elements and the resulting nonlinear equilibrium equations solved using the FE software ABAQUS. A detailed parametric numerical analysis was also carried out to study the influence of the initial traction and geometric parameters on the non-linear behavior and load carrying capacity of the structure. The influence of different types of local imperfections was also studied in detail.

The Stiffness of Prestressed Frameworks: A Unifying Approach

SM22S_12669

Tue • 14:55 • 152B

Simon D. Guest
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Three different methods are commonly used to analyse the stiffness of prestressed frameworks that consist of bars and spherical joints. This paper will show that in fact the correct tangent stiffness matrix for a prestressed structure, as used in the computational literature, can be written as the sum of two terms. The first is a minor modification of a conventional stiffness matrix, that is best understood in terms of the equilibrium matrix that has been widely studied in the engineering mechanics literature. The second term is the stress matrix, that has been widely studied in the mathematical rigidity theory literature. Thus the extensive, but mutually exclusive, literature in these two areas is shown to be complimentary – giving useful insight into the response of prestressed frameworks; in combination, the two approaches can reproduce the complete, but less intuitive, results from the computational literature

On Stability of Systems Subject to Generalized Follower Force

SM22S_12931

Tue • 15:00 • 152B

Roman Bogacz[(1)], Szymon Imiełowski[(1)], **Włodzimierz Kurnik**[(2)]
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(2) *Warsaw University of Technology, Warsaw, Poland*

Stability and dynamics of columns and whirling shafts subject to a generalized follower force is considered in the paper. The generalized follower force is defined as one, that moves with the body on which it acts, and that always preserves the same attitude to the body as it moves. The both linear and nonlinear analysis are included. The first one relates to the influence of system parameters on the system response. It is shown that the shape of the eigenmodes depends of the value of loading. The nonlinear study is focus on the near critical behavior of the system under both tension and compression loads including analysis of the corresponding limit cycle, the effects relating to the double Hopf bifurcation are discussed.

Secondary Bifurcations and Localisation of Buckle Patterns

SM22S_12967

Tue • 15:05 • 152B

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The phenomenon of localisation is reasonably well understood in quantum physics or fluid mechanics but less so in the area of structural mechanics. In this contribution we revisit the effect of secondary bifurcations on the post-buckling response of a simple 3D system of elastically restrained beams. Our objective is to construct a uniform asymptotic expression for the localised buckling patterns experienced by this model. The main ingredients responsible for localisation here are the presence of a non-homogeneous pre-critical state together with the existence of certain turning points in the linearised buckling equation. This equation is formulated as a fourth-order eigenvalue problem with non-constant coefficients, and then a WKB technique is employed to construct the localised instability patterns.Numerical simulations supporting the analytical findings are included as well.

SM23

Stochastic micromechanics

Chairpersons: Y. Brechet (France), Y. Shibutani (Japan)

Creep Rupture and Fiber Breaks Accumulation in Unidirectional Composite

SM23S_10242
Thu • 14:55 • 152B

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The use of composites for pre-stressed reinforcement elements leads to an interest for creep-rupture investigations. In present paper a stochastic kinetic fiber break clusters accumulation model was developed. The analysis, based on Markov-type stochastic kinetic equations, leads to the development of closed-form analytical solutions for probabilities of obtaining adjacent fiber breaks of a particular configuration in the loaded composite material. The chain-of-bundles material model was used. In this approach, all possible geometrical varieties of clusters were considered (up to eleven adjacent broken fibers, with analytical approximation for larger fiber clusters) and form-dependent cluster distributions were obtained. Stress concentration calculations were performed using the influence function's approach. To apply the theory to real material volumes, a lower-tail probabilities analysis was made. A parametric analysis was realized and discrepancies of damage accumulation in different types of polymer matrix composite systems were analyzed. Simultaneously, Monte Carlo simulations were numerically realized. Theoretical predictions for composite lifetimes were compared with experimental data.

Modeling of Deformation and Fracture of Non Woven Felts

SM23S_12262
Thu • 15:00 • 152B

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A micromechanical model was developed to simulate the mechanical behavior of non-woven felts. The material is represented as a bidimensional network of straight fibres of finite length. The intersection between fibers formed the nodes of the model. Adjacent nodes were connected through rods that transferred load in the fiber direction. Additionally, torsional spring elements were added to penalize the angle variation between crossing fibers. Fibers were assumed to behave as non-linear elastic solids taking into account inelastic effects such us fiber buckling, fracture and fiber sliding. Computational simulations were compared with experimental data available on a non-woven felt made up of polyethylene fibers with different testing configurations

Homogenization of Plain Weave Composites with Imperfect Microstructure

SM23S_12380
Thu • 15:05 • 152B

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A simple computational framework is presented for the determination of a representative volume element (RVE) of plain weave fabric composites with disordered reinforcement. Although treated as periodic two-phase systems, the imperfect geometry of such materials often precludes a straightforward representation of the RVE in terms of a simple Periodic Unit Cell (PUC). In the present approach, morphology of such material systems is characterized by appropriate statistical descriptors. Then, in order incoprorate microstructure imperfections into selected idealized geometrical model, parameters of the model are found by minimizing the difference between statistical descriptors related to the original microstructure and to the idealized unit cell. Once the parameters are determined, the numerical homogenization method is used to predict the overall response of the composite by the homogenization method. The feasibility of the proposed methodology is verified by its application to artificial material systems to provide guide for modelling of real-world material systems.

Collective Prismatic Dislocation Loops Mechanism

Yoji Shibutani, Tomohito Tsuru
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SM23S_12571
Thu • 15:10 • 152B

Unstable displacement burst observed in the indent load and depth curve of nanoindentation is much possible to be related to the collective dislocation behavior. We have recently reported that the first critical indent load at the first burst is almost linear to the first burst width. To resolve the reason of this experimentally obtained linearity, we must understand the collective prismatic dislocation loops mechanism. In the present research, the dislocation emission and the subsequent prismatic dislocation loop formation of a single crystalline aluminum under nanoindentation are simulated by the molecular dynamics. Also, the collective prismatic loops emitted at the misfitting particle model are calculated, qualitatively and quantitatively comparing with the micromechanics considerations by Ashby and Johnson.

SM24

Structural optimization

Chairpersons: K. Choi (USA), J. Herskovits (Brasil)

Topology Optimization of Vibrating Structures with Hydrodynamic Surface Pressure Loading

SM24L_10433
Tue • 11:00 • 144

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This paper deals with the problem of topology optimization of continuum structures subjected to time-harmonic hydrodynamic surface pressure loading. This problem is an extension relative to traditional topology optimization, as both the locations and directions of the loading change as the structural topology changes. Maximization of the integral dynamic structural stiffness for given frequency and amplitude of the hydrodynamic pressure loading is the design objective in this paper. The boundary conditions, the material, and the total volume within the admissible design domain are also given. The volumetric densities of material in the finite elements in the design domain are the design variables. Illustrative optimum topology results are presented.

On Shape Optimization for Eigenvalue Problems

SM24L_10669
Tue • 11:20 • 144

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In shape optimization we change the reference domain of a structure, say the axis of a beam/bar or the mid-surface of a plate. The changes are continuous and thus cannot lead to topology optimization. For a broad class of static problems an optimality criterion of constant energy density along the designed boundary is proved earlier. In the present paper we prove a similar criterion for eigenvalue problems. Although most practical problems must be solved with the application of mathematical programming, the optimality criterion serve as the tool for more basic understanding and for idealized reference cases also as the basis for recursive procedures. Especially the evaluation of the optimality criterion for designs obtained by restricted/penalized parametrization or with geometrical constraints gives valuable information. As numerical verifications we solve finite element models of plate problems, optimizing the eigenfrequencies for in-plane vibrations as well as out-of-plane vibrations.

Shape Optimisation of Railway Wheel Profile

SM24L_11015
Tue • 11:40 • 144

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Delft University of Technology, The Netherlands

The paper presents a procedure for optimal design of a wheel profile based on geometrical wheel/rail contact characteristics. An optimized wheel profile is obtained as a solution of inverse (minimization) problem. A number of new wheel profiles are obtained. Their advantage compared with old one is shown. Keywords: Inverse problems, shape optimisation, wheel-rail contact, multipoint approximations

Shape Optimization of Thermomechanical Structures in the Presence of Convection and Radiation Using Parallel Evolutionary Computation

SM24L_11137
Tue • 12:00 • 144

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Shape optimization of heat conducting, elastic bodies subjected to thermal and standard loads is considered. Interaction of stress and temperature fields is modeled using the formulation of steady state thermoelasticity. The presence of heat radiation with mutual irradiation of the boundaries and the presence of shadow zones is taken into account. A parallel evolutionary algorithm is used to evaluate the optimal shape. The boundary element method is applied to discretize the thermoelasticity, conduction and radiation problems. Numerical tests for the problem of optimal shape of a heat radiation used to dissipate heat from electrical devices are presented. Two criteria of optimization are applied: (i) minimum volume of the entire domain with constraints imposed on maximum admissible temperature and equivalent stress fields and (ii) maximum amount of heat dissipated from a portion of the boundary with the constraint imposed on maximum volume of the structure.

Damage Identification in Structures by Means of Thermographic Methods

SM24L_11349
Tue • 12:20 • 144

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(2) *Institute of Fundamental Technological Research, Warsaw, Poland*

The prediction of location and size of any kind of damage in existing engineering structures is of great importance from the point of view of their serviceability and safety. Visual inspection and extensive testing can be employed to locate and measure the degradation of structure using the wide class of non-destructive techniques. In the present paper, the detection of surface, subsurface or internal cracks will be performed on the basis of analysis of thermal response of structure, and in particular by the measurement of temperature distribution along its external boundaries. In order to increase the number of available measurement data, the thermal multi-loading case is considered. On the basis of results of measurements, an inverse heat transfer problem is formulated and solved. In order to determine the location, orientation and size of single or multiple defects, the finite element model of a structure is constructed and used to predict temperature distribution, next used in the identification procedure. The novelty of the present approach is based on application of path independent sensitivity integrals used to detect position, orientation and size of the defect. Both steady and transient thermal fields can be used in identification procedure. Some numerical examples of defect identification in two-dimensional disks will be presented in order to justify the presented approach.

New Classes of Analytically Derived Optimal Topologies and Their Numerical Confirmation

SM24L_11623
Tue • 12:40 • 144

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Numerical FE-based derivation of optimal topologies can give grossly incorrect solutions for several reasons, particularly in the case of new classes of problems. Examples are checkerboard patterns, diagonal element chains and hinges in perforated plates with in-plane stresses and non-global optima due to singular topologies. For the above reasons, analytically derived optimal topologies for new classes of problems are of paramount importance for the conclusive verification of numerical methods in topology optimization. They are also useful in understanding the basic nature of optimal topologies. Unfortunately, the number of researchers understanding the theory of exact optimal topologies is becoming very small. The paper will discuss several new classes of optimal topologies, for problems with (a) new types of support conditions, (b) different permissible stresses in tension and compression, (c) variable external forces of nonzero cost, (d) several active displacement constraints, and (e) combination of external forces and selfweight. These exact, analytical solutions for optimal topologies will be verified by numerical, FE-based solutions using the SIMP method with checkerboard control.

Optimization of Beam Properties with Respect to Maximum Band-Gap

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SM24L_11744
Wed • 08:30 • 144

We study numerically the frequency band-gap phenomenon for bending waves in an infinite periodic beam using Floquet theory. The beam is supposed to consist of an infinite number of identical base cells made up of two different materials. The outcome of the analysis which is a dispersion relation is then subjected to an optimization problem in order to maximize these band-gaps. The band-gap maximization may be performed with respect to material parameters and cross-sectional geometry. We have numerically investigated a base cell with constant cross-section consisting of two materials with high contrast in Young's modulus (Zinc-Chromium) as well as a base cell consisting of two materials (Zinc-Silicon) with a high contrast in mass density in order to obtain preliminary results indicating which parameters might be of importance concerning the size of the band gaps.

Optimal Layout of Two Materials within the Core Layer of a Sandwich Plate. Relaxed Formulation and Its Computiational Algorithm

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SM24L_11760
Wed • 08:50 • 144

The paper deals with the minimum compliance problem of a sandwich plate with soft core. The aim is to find an optimal layout of two isotropic materials within the core layer. The relaxed formulation, derived by using homogenization, involves the non-linear hyperelastic constitutive relationships between shear forces and transverse shear deformations. In the numerical treatment of the relaxed formulation the core layer is modelled by a 2nd rank laminated composite. The effective transverse shear stiffnesses are determined by the formula of Tartar, applied iteratively. The equilibrium problem is solved with using the new DSG finite element, developed recently by Bletzinger et al. Additionally a proof is given that this element satisfies the Strang convergence criteria of consistency. The optimization has been performed with using COC. The optimal layouts of the area fractions and the underlying microstructures compare favorably with 3D layouts found within the relevant relaxed formulation by homogenization, according to the 3D algorithm by Czarnecki and Lewiński presented at the recent WCSMO-5.

Material Cloud Method for Topology Optimization

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SM24L_11826
Wed • 09:10 • 144

A newly developed material cloud method (MCM) for topology optimization is presented to overcome some difficulties in widely used traditional density distribution method (DDM) and improve a numerical efficiency in topology optimization procedure. In MCM, an optimal structure can be found out through modifying sizes and positions of material clouds, which are lumps of material having specified properties. A numerical analysis for a specific distribution of material clouds is carried out using fixed background finite element meshes. Application methodologies in this MCM are broadly categorized as three. One is to optimize sizes of material clouds (MCMS). Other is to optimize positions of material clouds (MCMP). The third is to sequentially optimize positions and sizes of material clouds (MCMPS). In MCMS, convergence and final result of material distribution can be improved as against those of DDM. Through applying MCMPS, an optimal design, which is with clear material distribution in an enlarged domain, can be efficiently obtained.

On Separation of Eigenfrequencies in Two-Material Structures

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SM24L_11936
Wed • 09:30 • 144

We present a method to maximize the separation of two adjacent eigenfrequencies in structures with two material components. The method is based on finite element analysis and topology optimization where an iterative algorithm is used to find the optimal distribution of the materials. Results are presented for vibration problems governed by the 2D scalar wave equation. Two different objectives are studied in the optimization; the difference between two adjacent eigenfrequencies and the ratio between the squared eigenfrequencies, respectively. In the 2D case we cannot use simple interpolation of material parameters but have to use a more involved interpolation, and results obtained with a new interpolation function are shown. The objective is reformulated into a double bound formulation due to the complication from multiple eigenfrequencies. It

is shown that some general conclusions can be drawn that relate the material parameters to the obtainable objective values and the optimized designs.

Structural Optimization of Composite Shell Structures Using a Discrete Constitutive Parameterization

SM24L_12098
Wed • 09:50 • 144

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The objective of this paper is to present a novel method for structural optimization of composite laminated shell structures where the design objective is chosen to be a global quantity such as maximum stiffness or maximum lowest eigenfrequency with a mass constraint. The problem is then to choose between a number of composite materials, oriented at given discrete angles, and foam materials, thereby allowing the formation of areas with sandwich structures. In order to solve this discrete design problem the mixed materials strategy suggested by Sigmund & Torquato (1997) where the total material stiffness is computed as a weighted sum of possible materials is used. Several new parameterization schemes have been developed, and examples involving challenging real life design problems such as wind turbine blades will illustrate the potential of the method to solve the combinatorial problem of proper choice of material, stacking sequence and fiber orientation simultaneously.

Optimal Design of Lossy Bandgap Structures

SM24L_12222
Thu • 11:00 • 144

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Elastic or acoustic (commonly refereed to as phononic) bandgap structures may find application for vibration suppression and for noise insulation purposes. The periodic arrangement of two materials with different properties may inhibit the propagation of waves at certain frequencies and for the infinite medium total reflection of the wave occurs. So far focus has almost entirely been devoted to the wave-reflecting properties and not to the effects, possibly beneficial for applications, of dissipation in the bandgap structures. This work presents a systematic method for the optimal design of bandgap structures for two objectives: 1) minimum wave transmission through the structure and 2) maximum dissipation of wave energy in the structure. The structures are obtained as optimal distributions of two materials where one is lossy, and the design methodology is based on the method of topology optimization, recently used to design bandgap structures with optimized wave reflection.

Design of Articulated Mechanisms with a Degree of Freedom Constraint Using Global Optimization

SM24L_12302
Thu • 11:20 • 144

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This paper deals with design of articulated mechanisms using a truss ground structure representation. The considered mechanism design problem is to maximize the output displacement for a given input force by choosing a prescribed number of truss elements out of all the available elements, so that the resultant mechanism has one mechanical degree of freedom when supported in a statically determinate manner. The mechanical degree of freedom constraint is included since it is essential for obtaining a proper articulated mechanism design. The Green-Lagrange strain measure is used to accommodate for large displacements. The problem is formulated as a non-convex mixed integer problem and solved using a convergent deterministic global optimization method based on branch and bound with convex relaxations.

Optimization of Functionally Graded Materials with Temperature Dependent Properties. A Meshfree Solution

SM24L_12789
Thu • 11:40 • 144

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In many applications, such as thermal protection shields or medical implants, the thermo-mechanical loading conditions are non-uniform and complex. The goal of this work is to numerically determine optimal material gradation of the FGM under such conditions. We take into account temperature-dependent material properties for the metal and the ceramic components. We consider points on the volume fraction curve as the design variables. We use a shape-preserving spline to interpolate through these points. The material composition at each point is determined by the spline function. For the local effective properties of the FGM we use the rule of mixtures and the Mori-Tanaka model. We minimize the mass while stresses are used as constraints. The solutions to the nonlinear thermo-elastic problems are obtained using a meshfree method that adds versatility. The design space of material configurations is unrestricted and we study convergence properties when the number of design variables increases.

Optimum Blank Design for Deep Drawing Using Interaction of High and Low Fidelity Simulation

SM24L_12870
Thu • 12:00 • 144

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This paper deals with the optimization of blank design for deep drawing processes. The developed design optimization system utilises the interaction of high- and low-fidelity finite element simulations of a deep drawing process, and the multi-point approximation technique based on the iterative response surface building. Approximation functions and a weighting scheme are introduced in order to correct the low-fidelity responses so they can be treated as high quality approximations. The approximated problem is then solved by the multipoint approximation technique, hence there are two levels of approximation in the optimization process. The system has been applied to the optimum blank design for deep drawing process of a rectangular box. The optimization problem is to determine the optimum initial blank design that minimizes the waste of material. The required computational effort was considerably reduced as compared to the use of high-fidelity simulations only without compromising on the quality of the solution.

The Concurrent Design of Materials and Structures for Cellular Materials on Efficiency of Heat Dissipation

SM24L_13013
Thu • 12:20 • 144

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This paper describes an analytical model for heat transfer of cellular materials and presents a method for optimal design of increasing its efficiency of heat dissipation. The method is based on topology optimization techniques and finds the optimal topology within a given design section and the volume constraint. Two classes of design variables, volume density and local aperture, are applied not only to optimize macro material distribution as well as the local material topology, so-called concurrent design, but also to avoid confused interpretation for the checkerboard patterns. Several numerical results for material distribution are described in detail by illustration. As a result, accurately and practicably, the numerical method would guide the design of optimum cellular structures that would maximize heat transfer per unit pumping power. This paper is divided into six major sections as follows. The first section is introduction. The problem is described by section 2. The optimization problem is explained in section 3. In the following section, the sensitivity analysis is carried out. Four numerical examples are showed in section 5. In the last section, we will draw the conclusion.
Key words: topology optimization, cellular materials, concurrent design of materials and structures, heat dissipation.

A Technique for Nonsmooth Optimization Based on the Interior Point Feasible Directions Algorithm

SM24L_10594
Thu • 12:40 • 144

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Nonsmooth functions are frequently present in Structural Optimization. This is the case with applications involving eigenvalues. Smooth optimization techniques generally fail in nonsmooth problems. A new method for minimization of convex functions, not necessarily differentiable, is presented. This approach defines a constrained optimization Equivalent Problem (EP) and a sequence of Auxiliary Problems (AP), where the constraints of EP are approximated by cutting planes. At each iteration a Search Direction for EP is obtained by computing a Feasible Descent Direction of AP. If the step length is short, AP is updated and a new search direction is computed. This procedure is repeated until a good step is obtained. The Feasible Directions Interior Point Algorithm for constrained smooth optimization, [1], is employed to compute the search direction. We prove global convergence and solve very efficiently several test problems. [1] Herskovits J. Feasible Directions Interior Point Technique For Nonlinear Optimization, JOTA, v99-1, 1998.

Shape Sensitivity Analysis for Fixed-Grid Analysis Based on Oblique Boundary Curve Approximation

SM24S_10048
Tue • 14:30 • 123

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Fixed-grid analyses equipped with a fictitious domain method can avoid remeshing for shape optimization, but stresses on domain boundaries cannot be calculated accurately if the boundaries are improperly represented. For improved stress evaluation, we consider the direct boundary curve approximation by piecewise oblique lines which can cross boundary elements. In this approach, the intersection points between the fixed girds and the approximated boundary do not necessarily coincide with the analysis nodes unlike in existing fixed-grid analyses. The objective of this investigation is to derive the analytic shape sensitivity of stresses for the direct piecewise oblique boundary approximation. Since the force term in the sensitivity equation is associated only with the elements crossed by the design boundary curve, only the design velocities of the intersection points between the curve and the fixed mesh are needed for sensitivity analysis.

Perturbation of the Compliance Functional Due to the Apperance of a Small Cavity in an Elastic Body

SM24S_10052
Tue • 14:35 • 123

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The paper proves that the known methods of assessing an increment of strain energy due to the appearance of small cavities in elastic solids lead to one equivalent result. The following approaches are discussed: the compound asymptotic method by Mazja, Nazarov and Plamenevskii, the topological derivative method and the method of Eshelby. A new method of computing the topology derivative relevant to weakening the domain by a small cavity (or hole) of arbitrary shape is proposed here. The method is based on the velocity method of shape optimisation. The speed vector field is chosen as a linear function in the space variable. This method is applied for confirming the Eshelby-Mazja formula by a new manner. Moreover, a new exterior topological derivative is introduced, thus making the evolutionary optimisation algorithm reversible with respect to the usual process of removing the material from the feasible domain.

Nash Equilibrium in Bicriteria Structural Optimization

SM24S_10621
Tue • 14:40 • 123

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Nash equilibrium, a game theoretic concept, has lately been introduced in multicriteria optimization of structures as a computationally cheap alternative to Pareto optima. In this paper we consider the Nash equilibrium as a solution to a bicriteria structural optimization problem. We give a Nash game formulation for a bicriteria optimization problem. This formulation can be done in different ways, giving as many different games, depending on the dimension of the feasible set. It is well known that the Nash equilibrium need not exist even for in well posed problems with smooth criteria. Moreover, the Nash equilibrium tends to be Pareto inefficient. However, if the criteria are in a certain way strictly monotonous and if the mapping they form is a bijection, then there exist a Pareto optimal Nash equilibrium point as we state in 2D-rectangle case of feasible set. We illustrate the theory by a simple static truss optimization example.

Efficient Optimization of Transient Dynamic Problems for a Micro Accelerometer Using Model Order Reduction

SM24S_11316
Tue • 14:45 • 123

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One of the main obstacles to including transient dynamic effects into the performance functions of a structural optimization is the high computational cost of each time-dependent simulation. The focus of this paper is on the application of model order reduction techniques to reduce the transient analysis time for the attainable optimization process. The software mor4ansys developed at IMTEK performs model reduction via the Arnoldi algorithm directly to ANSYS finite element models. We adopt a micro accelerometer as an example to demonstrate the advantages of this approach. The harmonic and transient results of a reduced model of the accelerometer yield very good agreement with those from the original high di-

mensional ANSYS model. The use of model reduction within the optimization iterations produces almost the same results as without order reduction and speeds up the total computation by about an order of magnitude.

Topological Optimization for Contact Problems

SM24S_11486
Tue • 14:50 • 123

Jan Sokolowski, **Antoni Zochowski**
Systems Research Institute of the Polish Academy of Sciences

The new approach is proposed for the topological optimization of contact problems. Contact problems are described in the framework of linear elasticity with unilateral constraints, so the model takes on the form of variational inequality. We derive the first order exterior asymptotic approximation of solutions with respect to small parameter. The small parameter measures the size of a small hole or inclusion in the geometrical domain. The approach is based on parametrization of energy functionals using the regular perturbations. By means of this method the exterior expansion of solutions is obtained, with the first term given by the solution of an auxiliary variational inequality. Such an expansion enables us to derive the form of topological derivatives of shape functionals including, among others, the compliance. Numerical results are provided which confirm the theoretical error estimates derived for model problems.

Coupled Sensitivity and Design Optimization for Thermo-Structural Systems

SM24S_11532
Tue • 14:55 • 123

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Thermo-structural systems coupled with heat conduction and structural mechanics exist in many industrial engineering. The thermal responses of such systems, e.g. thermal deformation, stresses, and buckling are commonly the predominant factors in the system design. Hence it is imperative to incorporate the heat conduction and structural mechanics in the design phase. This paper presented a systematical methodology for the design optimization of thermo-structural systems using the coupled sensitivity analysis and mathematical programming techniques which takes the heat conduction and structural mechanics into account simultaneously. Detailed attentions are paid to the coupled sensitivity effects of the two disciplines by employing the direct and the adjoint methods for the static thermal stress, the qusi-static thermal stresses and the thermal buckling problems. The design optimization is solved with the sensitivity information. Numerical examples reveal the necessity of the coupled sensitivity analysis and effectiveness of design optimization. The implemented software system includes the size and the shape design variables, and then can be applied to the design optimization for the plane, axi-symmetric, and thin-walled shell elements for complex structures.

Optimal Structures for Buckling Forces and Buckling Displacements

SM24S_11634
Tue • 15:00 • 123

Jacek Kruzelecki, **Pawel Smas**
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The classical problem of optimal design of structures under stability constraints concerns mainly loadings controlled by a system of forces. However, in some practical engineering applications the loadings controlled by displacements can also occur. This type of problems is, for example, connected with structures under thermal loadings or in the case of assembly loadings. Then, the compressive forces depend on geometry of the structure,whereas in the classical optimization problem the forces are independent of the structure. Hence, the results of shape optimization can be qualitatively and quantitatively different for both types of loading control. In the paper optimal design of elastic structures under two types of loading control is considered and compared. Uni- and multimodal optimization of columns is considered as one-dimensional problem. The two-dimensional problem is represented by uni- and multimodal optimization of annular plates. Solutions were obtained by the Method of Moving Asymptotes and/or Simulated Annealing Method.

Optimal Design of Unconstrained Damping Layer on Beams

SM24S_11858
Tue • 15:05 • 123

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The optimum layout of unconstrained damping layer on beams is obtained using an equivalent stiffness approach and finite element formulation. The Ross, Ungar and Kerwin's (RUK) formula is introduced to represent the equivalent complex

modulus of the damping layer and beam. The fractional derivative model describes the dynamic characteristics of viscoelastic materials in order to include the non-linearities of real materials with respect to frequency and temperature. Using the equivalent stiffness, a finite beam element is developed and a nonlinear eigenvalue problem is solved for a beam with the unconstrained damping layer on it. The objective of optimization problem is to maximize the product of loss factor and eigenfrequency of a specified mode. Optimum coverage is obtained by combining an analytic design sensitivity analysis and a gradient-based numerical search algorithm.

Topology Design Optimization for Structures by Adaptive Growth Method

SM24S_11997
Tue • 15:10 • 123

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The paper suggests an innovative design methodology of structural topology optimization by utilizing the optimality of branch systems in nature – so called as the adaptive growth method. The method bases on such essential characteristics of branch systems in nature that branches can grow by adapting themselves automatically to the growth environments in order to achieve better global performances, such as the maximal absorbance of nutrition or sunlight in plants and intelligent blood distribution of a vascular system in animal body. Thus, it can be expected that optimal topologies of engineering structures and systems can be generated by utilizing the generation method based on the growth mechanism of branch systems in nature. The layout design of cooling channel in a heat transfer system is studied as an application. If the so-called nutrient density in the generation process of branch system is referred to the temperature in a heat transfer system, the distribution of branches is responsible to the distribution of cooling channels. Because branch system can grow adaptively corresponding to the nutrition distribution in order to absorb the nutrition to the maximal extent, the cooling channel can be constructed adaptively by the control of the temperature so as to make it possible to achieve comparative uniform temperature distribution of the whole heat transfer system. Having the similar optimality of branch systems in nature, the constructed cooling channel can be designed flexibly under any complex thermal boundary conditions within any shapes of perfusion volumes to be cooled and can achieve good cooling performance. The design problems of both the conductive cooling channel and the convective cooling channel are studied, and the layouts of two-dimensional and three-dimensional cooling channels are illustrated.

Density Gradient Based Regularization of Topology Optimization Problems

SM24S_12074
Tue • 15:15 • 123

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University of Bochum, Institute of Mechanics, Germany

The discretization of topology design problems on the basis of the finite-element-method results in general in large-scale combinatorial optimization problems, which are usually relaxed by the introduction of a continuous material density function as design variable. In this context special penalty methods such as the SIMP-approach are used to reduce the set of admissible solutions to so-called black&white designs free of gray regions characterized by intermediate density values. Nevertheless the penalization of intermediate densities results in discontinuities in the global density distribution and often leads to unfavourable microstructures such as the well-known checkerboard patterns. To obtain black&white designs free of microstructures we regularize the optimization problem by introducing a global penalty functional based on the gradient of the density function. Furthermore we discuss numerical aspects of the proposed regularization such as the implementation of the penalty functional into the SIMP-model, the formulation of the corresponding stiffness-matrix, the sensitivity analysis and the numerical solution of the regularized problem.

New Results of Structural Optimization for Post-Buckling Behaviour

SM24S_12075
Thu • 14:30 • 123

Bogdan Bochenek, **Michał Życzkowski**
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Some structures optimized for maximal instability load under prescribed volume show unstable post-buckling path. Such cases, if possible, should be avoided from engineering point of view. Hence the concept of so-called modified optimization including constraints imposed on stability of post-buckling behaviour has been proposed. The present paper gives both numerical and analytical treatment of such the modified optimization presenting general approach and showing new results. The problem of modified optimization against instability in the large is formulated and numerically solved for a compressed and transversally loaded beam placed on the rigid foundation. Analytical approach to optimization of columns for post-buckling behaviour is presented. The general behaviour of loading after buckling is allowed for. Influence of geometry changes in pre-buckling state on modified optimal designs is considered. Analytical optimization of a column loaded by an attached vessel containing liquid and numerical optimization of helical springs are given as illustrative examples.

Compliant Mechanism Design for Adaptive Trailing Edge Flaps

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SM24S_12079
Thu • 14:35 • 123

This research is part of a bigger project where the aim is to reduce fluctuating loads on a wind turbine by using trailing edge flaps. The potential of this technique is analyzed in an aeroelastic code and the desired shape and speed of the flap is analyzed with aerodynamic codes. This part of the project aims at finding the optimal compliant mechanism using topology optimization which will actuate the flap in the desired shape. Since the desired flap must move plus/minus 10 degrees the displacements and rotations become large and a geometrically nonlinear formulation is used. The optimization problem is formulated as an error function where the desired point are given from the aerodynamic calculations. The sum of the squared error between the desired point and the obtained point are minimized. Example shows that the desired shape of a flap can be obtained.

Transition Waves in Controllable Cellular Structures with High Structural Resistance

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SM24S_12170
Thu • 14:40 • 123

The paper suggests an approach for optimization of morphology of mechanical structures subjected to an impact. We consider chains or lattices with breakable bistable links. A nonmonotonic constitutive relation for each link consists of two stable branches separated by an unstable branch. Mechanically, this model can be envisioned as a twin-element structure which consists of two elastic-brittle or elastic-plastic links (rods or strands) of different lengths joined by the ends. The longer link does not resist to the loading until the shorter rod breaks or develops a neck. When a chain or lattice of these elements is elongated they excite waves of damage that carry the energy away. We analytically describe and simulate transition waves of damage in bistable structures. We show that strength against an impact of the chain or lattice with nonmonotonic links increases several times; such structure can absorb much more energy before breakage than a conventional structure.

Why Parameterizing Element Connectivity for Topology Optimization?

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SM24S_12185
Thu • 14:45 • 123

Recently, a new topology optimization formulation, called the element connectivity parameterization (ECP), has been proposed. The objective of this work is to present the motivation for the development of ECP, the idea behind it and its applications to some topology optimization problems which are otherwise difficult to solve. We begin with the issue of unstable elements for topology design problems involving nonlinear analysis and ascribe the source of the numerical problem to the intermediate density element of the conventional topology optimization formulation. To overcome the numerical problem, the degree of element connectivity is used to describe structural layouts while finite elements remain solid during whole topology optimization iterations. A few numerical exmaples are considered to show the usefulness of ECP.

Topology Optimization of the Geometrically Nonlinear Structures Made of Rubber-Like Material

Sami Holopainen
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SM24S_12200
Thu • 14:50 • 123

This paper presents a brief review of the topology optimization of the geometrically nonlinear plate made of a highly nonlinear elastic rubber-like material. So the material is assumed to be incompressible hyperelastic subjected to the plane stress. Typically most structural topology optimization cases are based on the linear elastic assumption. But investigating initially linear structures the optimized final structure may be nonlinear as well the structures subjected to the large deformations. So the topics of the nonlinear computational mechanics, FEM discretization and the solving procedure of the topology optimization in this type of problem are presented. The topology problem is solved iteratively by a sequential convex approximation method and the structural response using the nonlinear quasi-static FEM based on N-R iteration. The mean compliance is chosen as objective and the sensitivity analysis is derived using the adjoint method which is rather straightforward despite specially the material nonlinearity.

Simulation of Trabecular Bone Adaptation – Creating the Optimal Structure

SM24S_12413
Thu • 14:55 • 123

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In the paper the simulation of trabecular bone adaptation based on the micro-structure of the trabecular net is discussed. The assumption to the algorithm of bone remodeling stimulated by mechanical loading is presented. The basics of the own adaptive mesh generator are described. The results of computations, using special prepared software, including parallel Finite Element Analysis are presented.

Optimal Design of Elasto-Plastic Structures Subjected to Normal Loads and Earthquake

SM24S_12573
Thu • 15:00 • 123

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The optimal design of elasto-plastic structures subjected to multiparameter (normal) loads and earthquake is presented. It is assumed that under normal loads the structure must be in elastic stage. In case of earthquake different approximate methods are used in which the plastic reserve of the structure and viscous effects are also taken into account. Introducing bounds for the elastic and permanent deflections a unified optimal design method is elaborated in which both the normal loads and the earthquake are simultaneously taken into consideration. The proposed method is based on the finite element method and on the concept of porous material where the material distribution is described by the densities of the finite elements, which are considered design variables. Numerical test examples are presented.

Optimal Force Action and Reaction in Structural Design and Identification

SM24S_12628
Thu • 15:05 • 123

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Two main classes of optimization problems are discussed in the paper: optimal loading distribution providing maximal or minimal structural response and optimal loading for structural identification providing maximum of the distance measure between the computed response of a model and the response of the actual structure measured in an experiment. Various measures of structural response are discussed, namely the total potential energy as a measure of the global stiffness, quadratic norm of displacement vector or arbitrary functional expressed in displacements. Derived optimality conditions for the optimal force action have the form of the solution of respective eigenvalue problems and result in coaxiality of loads with displacements (or adjoint displacements). Optimal identification problems are formulated and solved as min-max problems. Various distance measures I are discussed. The functionals I are maximized with respect to load coordinates and minimized with respect to model parameters in a step-wise procedure.

Sensitivity Analysis and Optimal Design of Geometrically Nonlinear 3D Frames with Account for Stable Postbuckling Behaviour

SM24S_12645
Thu • 15:10 • 123

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The postbuckling behaviour of optimal geometrically nonlinear 3D frames is usually not analyzed since the critical load constraints are included in the optimization problem. Therefore it is not clear whether behaviour of the optimal frame after buckling is stable or unstable. In order to overcome that it is possible to implement postbuckling constraints into the formulation of optimization problem that take care of the form of nonlinear equilibrium path and modify the design in order to obtain stable behaviour after buckling. To guarantee the stable postbuckling behaviour of the optimal frame we adopt the expression for the change of total potential energy which will allow us to investigate the stability of singular points. Implementation of postbuckling constraints into the problem of determination of the optimal joint positions and

cross-sectional parameters of geometrically nonlinear space frames results in minimization of the global mass of the frame subject to elimination of snap-through. The sensitivity analysis of the small change of total potential energy is performed through analytic differentiation with respect to design parameters.

DSA for Elastic-Plastic Finite Rotation Shells under Dynamic Loads

SM24S_12679
Thu • 15:15 • 123

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The paper describes a constitutive algorithm for elastic-plastic finite rotation shells and explicit dynamics with design derivatives calculated w.r.t. material parameters. Despite a great complexity of the solution algorithm for the finite rotation elastic-plastic shells, we show that it is feasible to compute analytical design derivatives of this algorithm, including in particular the very complicated design derivative of the internal force vector. We show on several computational examples that the yielded sensitivities are of very good accuracy.

Computational Tricks for Efficient Design Sensitivity Analysis

SM24S_12916
Thu • 15:20 • 123

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Efficient design sensitivity analysis is of vital importance when applying gradient based optimization tools on complex coupled nonlinear problems. However, in the analysis of coupled problems the exact Jacobian is often not available and one is faced with the problem of solving a linear system with an unknown coefficient matrix. In the paper we present two iterative methods to accomplish this task efficiently. The key advantages of the two methods compared to an overall finite difference approach are better efficiency because information obtained during analysis can be reused, and a better or at least a known accuracy, because the sensitivity equations are solved to a specified tolerance. These key points are illustrated with a stationary example from nonlinear fluid-structure interaction. Application of the methods to different discretizations shows that the iterative sensitivity analysis scales more favorable than the analysis in terms of number of unknowns in the problem.

Application of Metropolis Genetic Algorithm for the Structural Design Optimization

SM24S_10507
Thu • 15:25 • 123

Yeon-Sun Ryu, Kyun-Bin Park, Hyun-Man Cho, Jeong-Tae Kim
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A Metropolis genetic algorithm (MGA) is developed and applied for the structural design optimization. In MGA, favorable features of Metropolis criterion in simulated annealing (SA) are incorporated in the reproduction operations of simple genetic algorithm (SGA). This way, the MGA maintains the wide varieties of individuals and preserves the genetic information of early generations. Consequently, the proposed MGA alleviates the disadvantages of finding imprecise solution in SGA and time-consuming computation in SA. Performances of MGA are compared with those of conventional algorithms such as Holland's SGA, Krishnakumar's micro genetic algorithm (μGA), and Kirkpatrick's SA. Typical numerical examples are used to evaluate the favorable features and applicability of MGA. The effects of population sizes and maximum generations are also evaluated for the performance reliability of MGA. From the theoretical evaluation and numerical experience, it is concluded that the proposed MGA is a reliable and efficient tool for structural design optimization.

SM25

Structural vibrations

Chairpersons: I. Blekhman (Russia), K. Popp (Germany)

Experimental Study of Nonlinear Energy Pumping

SM25L_10408

Wed • 08:30 • 226

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Experimental verification of passive nonlinear energy pumping in a system of coupled oscillators with an essentially nonlinear end attachment is carried out. It is shown that passive transfer of energy (energy pumping) from the linear oscillators to the nonlinear attachment can take place. Agreement between simulated and experimental results was observed, in spite of the strongly nonlinear and transient dynamics of the system considered. The experiments bear out earlier predictions that a significant fraction of the energy introduced directly to a linear structure by an external impulsive (broadband) load can be transferred (pumped) to an essentially nonlinear attachment, and dissipated there locally without spreading back to the system. In addition, the reported experimental results confirm that (a) nonlinear energy pumping occurs above a threshold of the input energy, and (b) resonance capture cascades occur where the nonlinear attachment resonates in sequence with a number of linear modes.

Nonlinear Vibrations of Jeffcott Rotor with Preloaded Snubber Ring

SM25L_10470

Wed • 08:50 • 226

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Nonlinear vibrations of a Jeffcott rotor system with a preloaded snubber ring subjected to out of balance excitation are investigated theoretically and experimentally. The details of the design, experimental set-up and mathematical modelling of the system will be presented. The rotor makes intermittent contacts with the preloaded snubber ring and it can produce five different contact regimes which are determined using the principle of the minimum elastic energy in the springs supporting the snubber ring. As a result this rotor system is modelled as a nonlinear piecewise smooth dynamical system, for which a suite of approximate methods has been devised. Full details on these methods and their accuracy will be given during the lecture. Chaotic behaviour and co-existence of attractors have been found. A comparison between the theoretical and experimental results made by using bifurcation diagrams, phase portraits and Poincaré maps shows a good correlation between theory and experiments.

Equivalent Stochastic Linearization as an Alternative to Solving the Fokker–Planck Equation

SM25L_10863

Wed • 09:10 • 226

Stephen H. Crandall
Massachusetts Institute of Technology, USA

The popular procedure of equivalent stochastic linearization is widely used to estimate the mean and variance of the stationary response of nonlinear structural vibration systems. The procedure was independently proposed by three pioneers about fifty years ago. The primary reason for errors in the estimated statistics is the adoption of Gaussian probability distributions as substitutes for the true distributions of the nonlinear response processes. For the special case of Gaussian white-noise excitation it is known that the true stationary response distribution can be found by solving the Fokker-Planck equation associated with the Maxwell–Boltzmann equation. In the present paper it is shown that an alternative procedure for arriving at the same true distribution is to apply equivalent stochastic linearization to the Maxwell-Boltzmann equation. The procedure is illustrated for an array of particular examples, including power-law oscillators, Duffing's system, the double-well oscillator, and oscillators with trancendental restoring forces.

Effect of Root Flexibility on the Aeroelastic Analysis of a Composite Wing Box

SM25L_11082
Wed • 09:30 • 226

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This paper discusses the effect of fibre orientations, skin lay-up, bending-torsion material coupling, and the root flexibility or stiffness of the rectangular composite wing box model on the free vibration and aeroelastic characteristics for the Circumferentially Uniform stiffness and Circumferentially Asymmetric stiffness configurations. The dynamic characteristics are in the form of natural frequency and associated mode shapes, where as for the aeroelastic is in the form of flutter and divergence speeds. All this work is conducted using the finite element codes FEMAP 8 and MSC/NASTRAN 70.5. An attempt is made to cover as extensive a field as possible and identify interesting areas. Interesting relations are obtained for both configurations, which could be helpful for aeroelastic analysis. These relations are in the form of stiffness ratio, EI/GJ, material coupling stiffness, K and frequency ratio, wb/wt versus fibre orientations for two skin laminates. The research showed that the root stiffness has a significant influence on the dynamic characteristics and on the flutter and divergence speeds of the composite wing models especially at root stiffness lower than thousand.

Nonlinear Effects, Observed in the Process of the Liquid Flowing Out of the Vibrating Vessels: Theory, Experiment and Applications

SM25L_11090
Wed • 09:50 • 226

I.I. Blekhman, **L.I. Blekhman**, L.A. Vaisberg, V.B. Vasilkov, K.S. Yakimova
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A general physical explanation and theoretical description of two nonlinear phenomena are proposed. The first of them, called vibro-jet effect consists in the fact that when a plate with conic holes vibrates in a fluid, slow flows of fluid appear in the direction of the narrowing of the holes. The second phenomenon – the vibrational injection of gas into the fluid, discovered quite recently, consists in the fact that gas is being sucked into the vessel with the fluid through the hole in its lower part of the vessel, vibrating in the gas. It contains the results of the experimental investigations and of possible applications to the processes of screening and flotation. The phenomenon of the vibrational injection is illustrated by a short movie

Reanalysis of an SEA High-Frequency Vibration Calculation Based on the VTCR

SM25L_11246
Wed • 10:10 • 226

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LMT Cachan, France

A new calculation method is presented for the vibrations of slightly damped elastic structures in the high-frequency range, based on the reanalysis of global information to derive more local information. The global information is obtained by using Statistical Energy Analysis (SEA). The local information results from the reanalysis of the SEA data using the Variational Theory of Complex Rays (VTCR). This method can be viewed as a refined calculation (VTCR analysis) following a large-scale resolution (SEA). It is based on a proven 'Saint Venant' high-frequency energy principle which states that the distribution of the energy density does not depend on the way power is injected. This approach enables one to calculate the spatial distribution of the energy density at high frequencies, thus yielding an approximation of the system's behavior which is more accurate than the average constant value given by SEA.

Active Control of Disk Brake Sqeal

SM25L_11261
Wed • 11:00 • 226

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Considerable effort is spent in the design and testing of disk brakes of modern passenger cars. This effort can be reduced if refined mathematical-mechanical models are used for studying the dynamics of these brakes before prototypes are available. The present paper is devoted to the modeling of a floating caliper disk brake, special regard being given to the suppression of squeal. The model developed includes the brake rotor, modeled as a flexible rotating plate, housing, piston, yoke, and friction pads. In this nonlinear model all the prominent features of squeal are reproduced, such as e.g. independence of the frequency on the speed, etc. In a test rig built in Darmstadt, the model is validated. In addition, the set-up also permits active

control by using “smart pads”. Those pads, which include piezoceramic actuators are successfully used for the suppression of squeal.

Experimental and Theoretical Modal Analysis of Three Support Rotor Test Rig Using LMS CADA-X and ABAQUS

SM25L_11273
Wed • 11:20 • 226

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In the paper presented are results of experimental and theoretical investigations of dynamic properties of test rig support structure incorporating a three-support rotor, bearings and foundation. Experimental modal analysis of the object was performed by means of the impact test with use of SCADAS III frontend and CADA-X software. Theoretical modal analysis of the object was performed by means of numerical analysis with use of ABAQUS system. In the paper presented have been preliminary activities for the test, its course, the results of conducted investigations. The comparison of results obtained by two methods and expected further scope of research have been presented.

Passive Vibration Control of a Piecewise Linear Beam System

SM25L_11783
Wed • 11:40 • 226

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A linear Dynamic Vibration Absorber (DVA) is applied to suppress the vibrations in a harmonically excited piecewise linear beam system. Both experimental and numerical results are obtained and compared. The linear part of the beam system is modelled using the Finite Element Method. The number of degrees of freedom (dof) of this linear system is reduced using a dynamic reduction technique. Subsequently, a spring which only can take pressure forces is added to the model making it piecewise linear. A rotating mass unbalance realizes harmonic excitation. Finally, the linear DVA, modelled as a single dof mass-spring(-damper) system, is added to complete the system model. The undamped DVA is able to suppress the first harmonic resonance peak. The damped DVA guarantees vibration reduction over a wider frequency range. Next to the harmonic resonance also related subharmonic and superharmonic resonances are suppressed. Results of experiments and simulations show good resemblance.

The Running Behaviour of an Elastic Wheelset

SM25L_12322
Wed • 12:00 • 226

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The wheelset is the central element of a railway vehicle, responsible for support and guidance. For simulations of the low-frequent behaviour, the wheelsets are usually considered as rigid bodies. However, the wheel-rail contact is a strong nonlinear element which can be very sensitive even to small relative motions of wheel and rail. Therefore, the wheelsets and the rails are modelled as elastic bodies by using a modal synthesis. The required shape functions are obtained by Finite Element calculations. To investigate the influence of the structural flexibility, the simulation is performed with and without taking into account the elasticity of the wheelsets and the rails. The comparison of the results shows, that the so called critical speed drastically drops to lower travelling speeds, if the structural flexibility is taken into account. Beyond this critical speed, a dangerous limit cycle occurs. Furthermore, the structural flexibility leads to larger amplitudes of the motions.

Self-Excited Stick–Slip Oscillations of Drag Bits

SM25L_12535
Wed • 12:20 • 226

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This note studies the self-excited stick-slip oscillations of a rotary drilling system with a drag bit, using a discrete model which takes into consideration the axial and torsional vibration modes of the bit. Coupling between these two vibration modes takes place through a bit-rock interaction law which accounts for both frictional contact and cutting processes at the

bit-rock interface. The cutting process introduces a delay in the equations of motion which is ultimately responsible for the existence of self-excited vibrations, exhibiting stick-slip oscillations under certain conditions.

Vibration Characteristics of the Main Tower, the Byaon Temple

SM25L_12593
Wed • 12:40 • 226

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Since collapse and degradation are advancing at the Bayon temple, one of the main historical monuments in Angkor remains, it is anxious for the elucidation of collapse mechanism for the purpose of preservation and restoration. We conducted micro-tremor measurement in order to provide structural characteristics of the Main tower for reference of the future study of collapse mechanism. Soil-coupled natural frequencies of the structure are evaluated by power spectrum density of micro-tremor at the top of the structure and damping ratios are deduced by the random decrement method. Base fixed natural frequencies of the structure are deduced from the transfer function of the top to the base. We have acquired indispensable parameters for the future analysis and found that the additional stiffness provided by thick walls and surrounding sub towers must be included along with detailed material properties.

Discontinuous Transformations and Averaging for Vibro-Impact Analysis

SM25L_12694
Thu • 11:00 • 226

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Certain vibro-impact problems can be conveniently solved by discontinuous transformations combined with averaging. We briefly outline the background for this, and then focus on illustrating the procedure for specific examples: A self-excited friction oscillator with one- or two-sided stops, and a particle on a vibrating plane. Vibro-impact systems are characterized by repeated collisions. Applications include devices to crush, grind, forge, drill, punch, tamp, pile, cut, and surface treat a variety of objects, and vibrating machinery or structures with slips and stops. Compared to the classical method of stitching (together non-impacting solution parts), the suggested procedure works even in the presence of additional nonlinearities, and provides analytical solutions without switching conditions. By contrast to the method of equivalent linearisation, it assumes a kinematic rather than kinetic impact formulation. Approximate methods in this area are necessary, and averaging with discontinuous transformations is believed to be a useful supplement.

Mode Switching of Rain–Wind Induced Vibrations

SM25L_12785
Thu • 11:20 • 226

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Rain-wind induced vibrations are a vibration phenomena that occurs when rain and wind act simultaneously on cables, hangars and ropes. The vibration phenomena may induce oscillations with large amplitudes, thus the fatigue of construction elements is possible. In the literature rain-wind induced vibrations are generally investigated in the range of low wind speeds. Continuative experiments in the wind tunnel show that rain-wind induced vibrations exist in the range of higher wind speeds, too. Significant for rain-wind induced vibrations is the mode switching between vibrations in the range of low wind speeds and vibrations in the range of higher wind speeds. A possible mechanism of excitation of rain-wind induced vibrations is described by the phenomena of the Prandtl tripwire and in consideration of rivulets as a movable disturbance. It is shown that the excitation mechanism in the range of low wind speeds is different from the mechanism in the range of higher wind speeds.

Optimum Selection of Design Features of Electromechanical Drive Systems Incorporating a Control Unit

SM25L_12770
Thu • 11:40 • 226

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Problems relating to modelling, sensitivity analysis and optimization of a high-power electromechanical drive system composed of an induction motor and toothed gear, in which a vector control unit is used, have been dealt with in the paper. The spatial model in which couplings between particular subsystems have been taken into consideration was employed here. Direct differentiation method was used to investigate the sensitivity of dynamic forces in kinematic pairs of the drive

system with regard to electromagnetic parameters of the motor. Numerical simulations were carried out for a model of transverse torsional vibrations coupled with a polyharmonic model of the induction motor with a vector control unit. The optimization-oriented objective was to reduce maximal values of the electromagnetic moment of a driving motor. The set of design variables contained design features of gear shafts and settings of control units. Numerical simulations have proved that when all subsystems are tuned one to another the best results can be obtained in respect of lowering of the vibration level, reducing of energy consumption and enhancing of durability.

Extreme Value Distribution and Dynamic Reliability of Stochastic Structures

SM25L_10166
Thu • 12:00 • 226

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A probability density evolution method to compute the extreme value distribution and dynamic reliability of stochastic structures is presented. In the past few years, an original method, by which the instantaneous probability density function (PDF) of the dynamic responses of stochastic structures can be computed, has been developed. In the method, if the PDF of any response quantity is needed, a related joint probability density evolution equation is deduced and numerically solved to give the instantaneous PDF. In the present paper, a virtual stochastic process, related to the extreme value of the considered response, is firstly constructed and then a probability density evolution equation can be deduced and numerically solved in an analogous way. The dynamic reliability of the stochastic structural system is then assessed by a simple integration. The comparison with the Monte Carlo simulation shows that the proposed method is of accuracy and efficiency.

Thermoelastic Relaxation in Thin Plates with Applications to MEMS and NEMS Oscillators

SM25L_12404
Thu • 12:20 • 226

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Equations governing thermoelastic loss in vibrating thin plates are derived. For flexural vibration a critical plate thickness exists, defining two distinct types of response, thermally thick and thin. Thermal diffusion is restricted to a 1-dimensional heat flux across the plate thickness in thick plates. Otherwise in-plane thermal diffusion cannot be ignored, and may in fact dominate. Among results obtained for thermally thick plates, it is shown that the local thermal relaxation loss depends upon the local state of vibrating flexure, e.g. thermal loss vanishes at points where the principal curvatures are equal and opposite, i.e. saddle shaped deformation. An effective plate equation is derived that incorporates the thermoelastic loss as a damping term. The general form of the effective damping can be generalized to arbitrary thickness, in particular the case of thermally thin plates can be considered. These results are useful in predicting mode widths in MEMS and NEMS oscillators.

Experimental Analysis of Modal Interactions in the Non-Linear Vibrations of a Plate

SM25L_12759
Thu • 12:40 • 226

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The geometrically non-linear vibrations of an aluminium fully clamped plate are experimentally investigated. The plate is excited transversely with harmonic excitations of constant amplitude and the frequency of the excitation is varied slowly from values below the first linear natural frequency to values above and vice-versa. The amplitudes of the first and higher harmonics of the response are analysed at different points of the plate, in order to detect the modes involved in the motions. It is demonstrated that internal resonances occur between the first and higher order modes, that is, that due to the non-linearity of the system, energy is transferred from the first to higher order modes, when the non-linear natural frequencies become related by integer numbers. The data obtained is compared with results from a finite element code.

Vibration of the Train/Track System with Two Types of Sleepers

SM25S_12890
Tue • 14:30 • 219

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The conventional and reinforced railway track is composed of two infinite rails separated from the sleepers by visco-elastic pads. There are numerous assumptions leading to different simplifications in railway track modelling. Two-dimensional

periodic model of the track consists of two parallel infinite Timoshenko beams (rails) coupled with the visco-elastic foundation (or equally spaced sleepers). Nowadays the interest of engineers is focused on the Y-shaped sleepers. The fundamental qualitative difference between the track with classic or Y sleepers is related to local longitudinal symmetric or antymetric features of railway track. The sleeper spacing influences the periodicity of elastic foundation coefficient, mass density (rotational inertia) and shear effective rigidity. The track with classical concrete sleepers is influenced stronger by rotational inertia and shear deflections than the track with Y sleepers. The increase of elastic wave velocity in track with Y sleepers and more uniform load distribution will be proved by the analysis and simulations. The analytical and numerical analysis allows us to evaluate the track properties in a range of moderate and high train speed. However, the correct approach is not simple, since the structure of the track interacts with wheels, wheelsets and vehicles, depending on the complexity of the analysis. We can notice the amplitude growth in selected velocity ranges.

Dynamics of Beck's Column via Nonlinear Normal Modes

SM25S_10221
Tue • 14:35 • 219

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The present work deals with the nonlinear dynamics of the column of Beck under a partial follower loading at its tip, characterised by a non-conservativeness parameter η. In the context of Elastica and assuming inextensionality, the beam's motion is governed by a strongly nonlinear integro-differential equation with respect to the cross-sectional rotation $\theta(x,t)$. In order to capture all nonlinear phenomena associated with the motion in both divergence and flutter regimes, this equation is discretized using a two-mode generalized Galerkin approach, in which the spatial functions are nonlinear normal modes satisfying all the boundary conditions. In doing this and after numerous symbolic manipulations the equation of motion is reduced to a set of two second order differential equations with respect to the time functions. These are solved numerically and the corresponding behaviour in both regions of existence and non-existence of adjacent equilibria, i.e. divergent motion or limit cycles (flutter) are assessed.

Non-Linear Stochastic Vibration Problems for the Plates with Time-Dependent Parameters

SM25S_10656
Tue • 14:40 • 219

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This paper deals with the new hybrid asymptotic technique which combines the perturbation, WKBJ method and Hamilton variational principle. Given approach is applied to some geometrically non-linear vibration problem for the plates with time-depended parameters. Generally, the technique means the using on the first steps the perturbation and the phase integrals method to determine an approximate asymptotic solution of mechanical problem. The unknown coefficients of the respective general solution could be found with the Hamilton variational principle for some finite interval of time. The solution of stochastic problem for non-linear vibrations of the plate under casual load with known correlation function is presented. The analytical closed-form formula for the correlation function of displacements of plate is obtained as well. It is shown, that hybrid results are more accurate than the classical asymptotic perturbation-WKBJ-solution.

A Multi-Step Transversal Linearization Method in Nonlinear Dynamics

SM25S_10750
Tue • 14:45 • 219

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An implicit, multi-step transversal linearization (MTL) family of methods is proposed for accurate, efficient and numerically stable integration of non-linear oscillators of interest in structural dynamics. The presently developed method is a multi-step extension of the locally transversal linearization (LTL) method proposed earlier by Roy (2001). The MTL-based linearization is achieved through a non-unique replacement of the nonlinear part of the vector field by a conditionally linear interpolating expansion of known accuracy, whose coefficients contain the discretized state variables defined at a set of discretization points. Any available interpolating expansion (such as the ones based on polynomials, wavelets or distributed approximating functionals) may be used to achieve linearization and, indeed, an appropriate choice may be based on the kind of system trajectories being simulated. It is shown that the tangent spaces of the non-linear and linearized systems are transversal almost everywhere in the associated phase space, and, in particular, at the points of discretization. The unknown state vectors are thus determined by constructing a set of algebraic constraint equations, which ensure transversal

intersections of the linearized and non-linear solution manifolds. Since an exact solution of the linearized dynamical system can be constructed, the formal accuracy of the MTL method as a function of the time step-size depends only on that of the interpolating expansion, used to replace the nonlinear terms. Moreover, if the original system is Hamiltonian, then so is its MTL-based linearized form. Finally, a limited numerical illustration of the method is provided for a few low dimensional nonlinear oscillators in their periodic and chaotic regimes.

Interaction of Primary and Internal 1:1 Resonances in Nonlinear Symmetric 2DOF Systems with Cubic Nonlinearities

SM25S_10871
Tue • 14:50 • 219

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The primary resonance at forced oscillations in symmetric cubic two-degree-of-freedom systems with close eigenfrequencies under harmonic excitation is studied. Equations of motion(which are written for the case when generalized displacements are the principal coordinates) are solved by the multiple scales method. The interaction of the internal resonance and the primary external resonance gives rise to one or two additional resonances due to appearance of coupled stationary (steady-state) modes (CSM). A complete analysis of the number of CSM's, their stability and confi guration of the CSM's paths in phase spaces is carried out. It is shown, in particular, that in damped systems the CSM's are not exact normal or elliptic modes but they asymptotically approach NM or EM when the energy of oscillations increases (if they exist at large amplitudes).

Vibrorheology: Main Results, New Problems

SM25S_11055
Tue • 14:55 • 219

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Vibrorheology was defi ned by the author as part of rheology and nonlinear mechanics in which one studies the change of the rheological properties with respect to slow forces as well as the corresponding slow motions of bodies under the action of vibration (i.e. “fast” actions). One can also say that vibrorheology is a rheology for the observer who does not notice the fast forcers or fast motions, i.e. that it is part of vibrational mechanics. A brief review of the results in this fi eld developing very intensively is presented in the paper. A particular attention has been given to the latest results. Some problems unsolved as yet are also enumerated.

Propagation Analysis of Flexural Waves by Wavelet Transform

SM25S_11066
Tue • 15:00 • 219

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The purpose of this study is to investigate the possibility of structural health monitoring by using the flexural waves propagation. We investigate the velocity of the propagation of flexural waves. In this paper, the rectangular aluminum thin plate is used in the experiment, which is basic element of structures. The specimen is excited at one point by the exciter, and, the displacement of vibration is measured by using two non-contact displacement sensors. The velocities of the flexural waves are calculated by wavelet transform analysis. As a result, the velocities of the flexural waves could be measured exactly by wavelet transform. Therefore, it is found that the structural health monitoring by the flexural waves is possible.

Bifurcations of Damped Nonlinear Normal Modes: Linear Oscillator with Strongly Nonlinead Attachment

SM25S_11079
Tue • 15:05 • 219

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Linear oscillator coupled to damped strongly nonlinear attachment with small mass is considered as model design for nonlinear energy sink (NES). The coupling and damping terms are adopted to be symmetric and to depend only on relative displacement of the oscillator and the attachment. Damped nonlinear normal modes of the system are considered for the case of 1:1 resonance by combining the invariant manifold approach and multiple scales expansion. Special asymptotical structure of the model allows clear distinction between three time scales. These time scales correspond to fast vibrations, evolution of the system towards the nonlinear normal mode and time evolution of the invariant manifold respectively. Cusp catastrophe scenario is proved to be the only possible for the invariant manifold in time–amplitude–damping coeffi cient

domain. Passage of the invariant manifold through saddle-node bifurcation may bring about destruction of the resonance regime and essential increase of the energy dissipation rate.

Stability of a Rotor with Periodically Varying Angular Velocity

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SM25S_11338
Tue • 15:10 • 219

The stability of a rotor with periodically varying angular velocity is investigated. The rotor consists of a massless simply supported shaft with equal bending stiffness in all directions and with a disk in its centre. The shaft is rotated at a rate that is a prescribed function of time. The stability region in the parameter space is determined for the cases in which the rotation rate is piecewise constant or harmonically varying; this region appears to be large. Parametric resonances are not found. Viscoelastic material behaviour for the shaft gives a larger stability region. Small differences in the bending stiffness in two directions have a small influence.

Paradoxical Behaviour of Vibrating Systems Challenging Rayleigh's Theorem

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SM25S_11384
Tue • 15:15 • 219

Rayleigh has proved a theorem that an additional constraint cannot reduce any of the natural frequencies of an elastic conservative vibration system. Since linear free vibration and linear stability problems are analogous to each other mathematically, the question arises, whether there exist a counterexample to Rayleigh's theorem, because to a similar theorem on critical loads, there are counterexamples. In this paper, examples of vibrating systems will be shown that contradict Rayleigh's theorem. So the known form of Rayleigh's theorem might need correction. From the results presented here it follows that Rayleigh's theorem is valid if additional restraints have no effect on pre-vibration displacements, or there are no pre-vibration displacements, but additional restraints on pre-vibration displacements can decrease the natural frequencies. The latter case can happen if external static forces are in the system.

Short Wave-Length Dynamics of a String on Asymmetric Nonlinear Supports

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SM25S_11402
Tue • 15:20 • 219

Contrary to conventional approach to nonlinear dynamics of the string on symmetric nonlinear elastic foundation dealing with long wave-length vibrations, we present a study of short wave-length dynamics taking into account discreteness of elastic supports and asymmetry of their nonlinear characteristics. The approach is based on the transition to complex representation of dynamical equations and use of multiple scale expansions. In our calculations the infinite weightless string with uniformly distributed concentrated masses is supposed to be supported by asymmetric nonlinear anchor springs, spatial distribution of masses being coincided with that for the springs. Potential energy of the springs is described by a fourth power polynomial. In main asymptotic approximation we obtain two continuous equations of motion with respect to complex combinations of the envelopes of displacements and velocities. In important particular cases these equations coincide with the system of coupled Nonlinear Schrodinger Equations and have localized soliton-like solutions. The comparison with numerical results is also made.

Imperfection Sensitivity of Circular Arch's Non-Linear Modes

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SM25S_11494
Tue • 15:25 • 219

The paper addresses the imperfection sensitivity of non-linear vibration modes of moderately low and slender circular arches. Such structures may undergo unstable symmetric bifurcation prior to snap-through, under static uniform radial loading. Such instability corresponds to a buckling load that happens to be imperfection sensitive. A small imperfection may drastically cause the reduction of the arch's critical load and, consequently, of its stiffness and vibration properties. Two finite-element procedures developed by the authors were employed, based on the invariant manifold and the multiple-scale techniques. A range of geometric, static loading and imperfection parameters are considered in the numerical simulations, so as to allow for comparison among different levels of description of the free-vibration properties of these structures, such as the linear modes, the non-linear modes about the undeformed configuration, and the non-linear modes about the equilibrium configuration of both perfect and imperfect systems.

Optimal Shapes of Parametrically Excited Beams

SM25S_11536
Tue • 15:30 • 219

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Straight elastically supported beams of variable width under the action of a periodic axial force are considered. Two shape optimization problems for reducing parametric resonance zones are studied. In the first problem, the range of resonant frequencies is minimized for a given parametric resonance zone and a fixed amplitude of excitation. In the second problem, the minimal (critical) amplitude of the excitation force is maximized. These two optimization problems are proved to be equivalent in case of small external damping and small excitation force amplitude. It is shown that optimal designs have strong universal character, i.e., they depend only on the natural modes involved in the parametric resonance and boundary conditions. Efficient numerical method of optimization is developed. Optimal beam shapes are found for different boundary conditions and resonant modes. Experiments for uniform and optimal simply supported beams are conducted, which show a very good agreement with theoretical prediction.

Frictional Auto-Oscillations under the Action of Almost Periodic and Periodic Excitations

SM25S_12989
Tue • 15:35 • 219

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The mechanical systems with frictional interaction under the action of both almost periodical and periodical forces are considered in this paper. The systems under the action of almost periodic forces are considered with two independent small parameters. The multiple scales method is used to study bifurcations and chaotic oscillations of these systems. The obtained system of modulation equations contains one small parameter. The Van der Pol method is used to study the bifurcations of modulation equations periodic solutions. The homoclinic Melnikov function is derived to study chaotic solutions of the modulation equations. In the case of the periodical force action and small dissipation a new approach for a construction of homoclinic trajectory of mechanical system is utilized. Also an approach to determine the onset of chaos based on some consequence from the Lyapunov stability definition is suggested for the case when the dissipation is not small.

Non Trivial Effect of Strong High-Frequency Excitation on a Nonlinear Controlled System

SM25S_11679
Tue • 15:40 • 219

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Nontrivial effects of high-frequency excitation on mechanical uncontrolled systems have been investigated intensively in the last decade. Some of these effects are usually used in controlled systems in form of dither to smoothen out undesired friction and hysteresis. However the level of damping due to control is usually high compared to uncontrolled systems. A standard optimal controller for a standard nonlinear system (a movable cart used to balance a pendulum vertically) is shown to exhibit pronounced bias error in presence of HF-excitation. The bias increases with increased excitation intensity, but it also increases with the increased control power. Analytic prediction for the bias shows, the interaction between fast excitation and strong damping terms in the control system to be the cause of the permanent control error. A “slow observer” ignoring fast motions is shown to be the simplest way to avoid the undesired bias in the considered particular system.

An Aproach to Worm-Like Motion

SM25S_11699
Tue • 15:45 • 219

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Observing the locomotion of worms one recognizes a conversion of (mostly periodic) internally driven motions into change of external position (undulatory locomotion). In this paper motion of a system of two material points x_1 and x_2 with the masses *m*, connected by a spring of stiffness *c* along an axis *x* is considered. It is supposed that the points are under the action of a small non-symmetric Coulomb dry frictional force $\varepsilon m F(\dot{x})$, $\varepsilon \ll 1$, depending on velocities $\dot{x} = \dot{x}_i$ $(i = 1,2)$, where $F(\dot{x}) = F_+$ if $\dot{x} > 0$, $F(\dot{x}) = F_-$ if $\dot{x} < 0$; $-F_- \geq F_+ \geq 0$. Excitation is carried out by the action of small internal periodic force. Investigations show: at presence of excitation and non-symmetric Coulomb dry friction a motion of the system with a constant on the average velocity $V > 0$ is possible and this motion is stable. The expression for V is obtained. A worm prototype applying the principles outlined above has been constructed.

Dynamics of a Rotor Rolling Along a Circular Surface

SM25S_11712
Tue • 15:50 • 219

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The work is devoted to investigation of the dynamics of centrifugal-vibrational concentrator (CVC) – recently invented device for separating particles of granular materials according to their densities. Dynamical scheme of the CVC is an axially symmetric rigid body rolling along a circular surface. Experience shows that optimal motion of the CVC is a regular precession of the body along an inner surface of the hub without sliding. In presented work parameters of such motion and conditions of its stability are determined. Transient motions at different types of friction are also considered. It is shown that together with cumbersome conditions of stability the simple condition suffi cient for stability could be obtained. Considered motion exists in the system in conservative case and in the case when forces of dry and viscous friction are taken into account. It is shown that stability has not gyroscopic character and forces of friction could not break stability.

The New Statement of Problem of Unbalance Identification

SM25S_11716
Tue • 15:55 • 219

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The algorithms of inverse problem solution of rotor unbalance identifi cation in new statement is offered. This statement of problem permits to obtain the most probable solution. The vibrations of rotor supports in two mutually perpendicular directions during the work for a few rotor rotations as the initial information are used. Tikhonov regularization method is applied for solution of this ill-posed problem taking into consideration the error of mathematical model. The numerical calculations of examples are given to illustrate these algorithms. The suggested method permits to evaluate all characteristics of unbalance on working machinery in real time. It can be used for technical diagnostics of unbalance and for balancing of rotors in their own bearings. The following might be considered as the main advantages of such approach: i) there is no need to use the testing signals; ii) the stability of diagnostic results.

Nonlinear Vibrations of Gear Drives

SM25S_11759
Thu • 14:30 • 219

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The contribution presents the original method of the mathematical modelling of the gear drive vibrations caused by internal excitation generated in gear meshings. Especially undesirable vibrations characterized by discontinuity of mesh gear can be caussed by kinematic transmission errors and time dependent meshing stiffnesses in the case of small static loading. The modal synthesis method is used for creation of the condensed nonlinear mathematical model of the whole complex system. This condensed model with smaller number DOF is constituted by means of the lower undamped vibration mode shapes of the uncoupled subsystems. The maximum and minimum meshing deformations in time and the regions of the constant mesh gear are investigated in dependence on the gear drive revolutions and static load. The condensed model is used for numerical simulation of nonlinear vibrations in phases of the mesh gear interruption. The impact motions of the gears are explained using time series, phase trajectories and Poincaré maps. The theory is applied to a simple test-gearbox.

A power Flow Mode Theory Based on Inherent Characteristics of Damping Distributions in Systems and Its Applications

SM25S_11834
Thu • 14:35 • 219

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A generalized power flow mode theory is developed to describe the power-flow behaviour of a dynamical system based on the inherent characteristics of the system's damping distribution. The eigenvalues and eigenvectors of the damping matrix are defined as the characteristic damping factor and the power flow mode vectors of the system, respectively. These power flow mode vectors are chosen as a set of base-vectors spanning the power flow space and completely describe the power flow of the system. The generalized coordinate of the velocity vector decomposed in the power flow space is defined as the characteristic velocity. The time-averaged power flow is determined from the characteristic damping factor and the characteristic velocity. This demonstrates that for any system with prescribed damping, the power flow of the system is determined if the velocity is derived analytically, numerically or experimentally without requiring force information. Two distinct examples are provided to demonstrate applicability and generality of the theory. This power flow mathematical model allows development of guidelines for the design of dynamic systems based on knowledge of the damping distribution in the system.

Stability of a Spinning Disk Under a Stationary Oscillating Unit

SM25S_11867
Thu • 14:40 • 219

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This paper studies the free vibration and stability of a spinning annular plate transversely in contact with a stationary oscillating unit. The oscillating unit consists of two parallel combinations of springs and dampers attached above and under a mass. Therefore, the displacement of the mass is not the same as that of the disk at the contact point. First the equations of motion of the spinning disk and the oscillating unit are given in an inertial coordinate system. The Galerkin method is then applied to obtain the discretized system equations for the disk. Finally the stability analysis is conducted by investigating the eigenvalue problem of the combined system. Numerical results show that extra flutter-type instability is generated between the oscillating unit and the reflected modes of the disk, and these unstable regions are much larger than those of the flutter-type instability between the reflected and backward modes of the disk.

High Revolving Speed Spindles Definition Due to Transient Vibration Conditions

SM25S_11904
Thu • 14:45 • 219

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Spindle is the main part of Machine tool that its products face finishes are influenced strongly by vibrations through cutting process. With consideration a conventional turret spindle and new production conditions that require striker tolerance criteria, through a Finite Element Transient Analysis (FEA), terms of new spindles, their bearing types and arrangement was defined. The bearing sets number must restricted to two sets (number of bearings has to minimized to avoid imbalanced masses). Angular trust bearing for spindle front (where the chuck or other are installed) and Taper roller bearings for other side must be used. High revolving speeds lead us to use stiffer material to reduce spindle's weight. It was confirmed by Finite Element Analysis that new spindles had smaller vibration amplitude, so more accurate tolerances can be achieved more easily. Other advantages are lesser energy consumption and more economic machine tools.

Suppressing Self-Excited Vibrations in a Coupled Pendulum System

SM25S_12026
Thu • 14:50 • 219

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The main objective of this contribution is to show the phenomenon of full vibration suppression of a simple two degree of freedom model by interaction between self-excitation and parametric excitation. We investigate a mechanical system consisting of two pendulums in a gravity field. Both pendulums are coupled by a linear spring-element. Self-exciting forces are acting on one pendulum while the pivot of the second pendulum is periodically excited (parametric excitation). Using the averaging method general conditions for full vibration suppression are derived for the linearized system with harmonic

stiffness variation. These analytical results are compared with results obtained from numerical time integration of the linearized and the original non-linear system.

Estimation of the Vibration Energy Characteristics for Joints of Constructional Elements

SM25S_12498
Thu • 14:55 • 219

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Detailed estimation of energy characteristics in vibration structures such as loss factors, potential and kinetic energy, mechanical power flow is important for modeling in many fields of structural acoustics. The paper presents the approach to energy characteristics evaluation for wide range of constructional element joints based on structural intensity analysis. As the result is obtained the precise information on vibration energy flow. The analysis of spatial distribution of structural intensity vector fields enables determination and location of paths, sources and sinks of energy of vibrations in application to the mechanical systems. Gives the particular information on the streams of energy flow. The method is theoretically based and validated in computer simulations. Some selected results of calculations are discussed in particular.

Sound Radiation by the White Noise Excited Viscoelastic Shallow Shells

SM25S_12511
Thu • 15:00 • 219

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The results of estimation of the sound pressure radiated by structurally vibrating viscoelastic shallow shell are discussed. The shells, whose shapes are based on the square-type projection, have different radii of curvatures of the middle surfaces. The shells are loaded by the continuous-type forces, distributed over the whole middle surface, and randomly varying in time. Their form is a multiplication of the constant value (amplitude) and the white noise type function. The sound pressure dispersion level calculated in chosen control point in the surrounding acoustic medium, are estimated based on the knowledge of dispersion of displacements for structural vibrations. The method applied to their estimation is based on the acoustic power radiated by the shell and are valid for the far-field acoustic analysis. The results show the importance of the shell deflection on the levels of sound pressure dispersion.

Application of Extended Phase Trajectories to Investigation of Forced Biharmonic Oscillations

SM25S_12632
Thu • 15:05 • 219

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The results of investigation of dynamic behaviour of mechanical systems which oscillations are described by a non-linear Duffing-type equation are presented in the paper. The outer periodic biharmonic excitation is applied to the mechanical system. The system state at each moment of time is defined by values of three phase co-ordinates. The sequence of points conforming to different system states forms phase trajectories in the extended phase space “displacement–velocity–acceleration”. Fundamentals of qualitative methods of dynamic systems investigation were developed by Poincaré. These methods have shown their efficiency in studies of autonomous oscillations of systems having one degree of freedom. The authors of this paper suggested application of projections of phase trajectories on a plane “displacement–acceleration” and “velocity–acceleration”. The application of these projections of phase trajectories allows to expand essentially the possibilities of qualitative methods of dynamic systems investigation. In particular, they can be used in procedures of structural identification.

Non-Linear Modelling of Earthquake Induced Pounding of Buildings

SM25S_12659
Thu • 15:10 • 219

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The aim of the present paper is to analyse earthquake induced pounding between two insufficiently separated buildings with different dynamic characteristics. In the analysis, elastoplastic multi-degree-of-freedom lumped mass models are used to simulate the structural behaviour. In order to model pounding, non-linear viscoelastic impact elements, which become active when contact is detected, are used. The parametric study on structural behaviour is conducted for different values

of gap size between structures as well as values of mass, elastic stiffness and damping coefficients of a storey of one of the buildings. The results of the study prove that pounding has a significant influence on behaviour of a more flexible and lighter structure amplifying its response. On the other hand, the behaviour of the heavier and stiffer structure is influenced negligibly. Furthermore, the results confirm the effectiveness of the non-linear, viscoelastic model of collisions, which allows to simulate the pounding phenomenon more precisely.

Regenerative Tool Chatter Near a Codimension-2 Hopf Point

SM25S_12814
Thu • 15:15 • 219

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Regenerative tool chatter can cause undesirable vibrations during machining. The corresponding mathematical model is a delay differential equation (DDE). These DDE models have potential codimension-2 (or double) Hopf bifurcation points where two pairs of pure imaginary roots coexist. We analyze such a model near a codimension-2 Hopf bifurcation point. The method of multiple scales (MMS) is used directly, bypassing a center-manifold reduction. Our choice of the associated small parameter for the analysis allows us to *not* treat the vibration amplitude as small. Damping is assumed to be small. Both sub- and supercritical Hopf bifurcations are observed, depending on how two key parameters vary near the double Hopf point. A reverse subcritical pitchfork bifurcation also occurs as parameters are varied. The analytical observations are also verified via direct numerics. The supercritical bifurcations observed here are important in the context of *control*: a minor excursion into the unstable region causes small amplitudes of vibration, leaving scope for returning to stable operation. In contrast, in the subcritical regime, any excursion into instability leads immediately to large amplitudes from which return to stable operation is problematic.

Axial Decay of Time Harmonic End Perturbation in Prestretched Hyperelastic Plates

SM25S_12842
Thu • 15:20 • 219

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A detailed spectral analysis is presented for dynamic eigenfields generated by time harmonic end perturbations applied to a semi-infinite prestrained plate. Formulation is exact within continuum elasticity theory and frequency maps are provided over a range of prestretch, material (hyperelastic) properties, boundary constraints and frequency of applied disturbance. We concentrate on axially decaying eigenmodes and show that at each frequency there is a finite limited number of propagating modes. It is suggested that the infinite number of axially decaying modes defines a restricted validity of Saint-Venant's principle in finite elastodynamics. The influence of field parameters on frequency maps and axial decay rates is numerically exposed and supported by asymptotic expansions. Among the main findings are the sensitivities of dynamic response near points of instability, the effect of finite strain compressibility and importance of boundary data. All illustrations are for laboratory tested hyperelastic solids, with possible application to laminated composite structures.

Drilling under Percussive Vibro-Impact with Dry Friction

SM25S_12861
Thu • 15:25 • 219

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New drilling techniques have been studied to increase the penetration rate in hard rock formations. One approach, that appears suitable for off shore drilling in deep seas, uses harmonic loads and, in some cases, impacts. Hard rocks present a resistance to drilling that can be modeled as a dry friction on the drill bit, which is rotating under static loading. The drilling is therefore a percussive penetration phenomenon, allowing the forward motion (with a drift) but in stick-slip condition due to the rock resistance and may be considered with and without impact. This paper focuses on numerical investigations and presents results using a novel way to change between the several phases that are possible in this non-smooth problem with two discontinuities. It is also shown that the behavior may vary from periodic to chaotic motion. Some engineering aspects are also analyzed.

Characteristics of Vibroacoustic Signals in Diagnosing Early Stages of Defects

SM25S_12977
Thu • 15:30 • 219

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We are considering certain properties of transformation of time series that register the actual physical process. Our goal is to defi ne these basic features of the data analysis itself that ensure that the processing applies to the properties of a phenomenon which generates the signal independently of its numerical representation and could be used for early recognition of new type factors and components of the source. It turns out that the information concerning that physical process may be fi nd in some distribution of vector values determined by the time series. This characteristics of a vibroacoustic signal, could be used in diagnosing early stages of defects. As we observe in many experiments the structure of histograms approximating the distribution functions of disturbed signal are in many cases more susceptible to changes than Fourier spectrum. Especially the low energy disturbances, poorly visible in Fourier spectrum may be detected as the evolution of the described here random variable and its moments.

Entering the Excitation into a Mechanical System with Dynamic Eliminators of Vibration

SM25S_12984
Thu • 15:35 • 219

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System consists of many objects connected by visco-elastic elements. The objects are equipped with freely rotating vibrators (pendulums) that can eliminate or increase the object's vibration. As the result of object's vibration there are vibration forces that move the vibrators to a new positions. The forces generated by freely rotating vibrators can compensate the excitation. If the excitation is too large and the vibrators are not able to compensate the ijth object's excitation then the vibrators occupied the position opposed to the excitation. They only compensate a part of the excitation and the vibration does not vanish. The rest of the excitation goes to the adjacent objects. If the force transmitted to the next objects is also too large then again a part of it goes to the adjacent objects, etc. In this way the excitation spreads in the system in the decreasing way. To prove this hypothesis the detailed analysis should be done. The results of the simulation show that the vibrators behave in the way as it was expected. The vibrators will compensate the excitation if its frequency is greater than the natural frequency of the objects. In opposite situation the vibrators will increase the vibrations.

SM26

Vehicle dynamics

Chairpersons: S. Iwnicki (UK), R. Sharp (UK)

Experimental and Theoretical Aanalysis of Freight Wagon Link Suspension

SM26L_11795

Fri • 11:00 • 206

Per-Anders Jönsson, Sebastian Stichel
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In an ongoing project at KTH the running behaviour of freight wagons is studied. The background to the project includes plans to increase axle load, loading gauge and speed of freight trains in Sweden to make freight traffic more competitive. Prediction of running behaviour for wagons with link suspension is found to bee very difficult. One cause for that is the strongly non-linear characteristic of the link suspension and the fact that the vehicle behaviour is very sensitive to the horizontal suspension characteristics. Another reason is that the characteristics vary with maintenance status of the link suspension and climate conditions. The present paper covers laboratory measurements and mathematical modelling of a pendulum link. First the laboratory measurement rig is described. Then the influence of normal load, amplitude and frequency of excitation are discussed. Finally a model based on contact mechanics is proposed to describe the observed behaviour.

Mathematical Models and Simulation of Stick–Slip Processes in a Car Steering System

SM26L_11832

Fri • 11:20 • 206

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Problems of “stick–slip” phenomenon in car-steering systems are still important but rarely taken into account in the literature. Original luz(...) and tar(...) projections are useful for modeling and simulation of stick-slip. The model: A multi-body car dynamics model has been treated as a coupling of two partial models – steering system model and vehicle motion model. The model of steering system mechanism includes dry (kinetic and static) and viscous friction, elasticity of elements, and also the gear freeplay. It bases on the luz(...) and tar(...) projections. The vehicle model takes into account tire, independent suspension, drive, rolling resistance and aerodynamic drag. Simulation: Elaborated models were used for digital simulation studies (as well as sensitivity and bifurcation analyses) concerning open-loop tests of a passenger car. The paper presents results of simulation of three manoeuvres taken in series: step input on the steering wheel, steady state cornering and sudden release of steering wheel.

A Modelling Technique for Fast Computer Simulations of Configurable Vehicle Systems

SM26L_11672

Fri • 11:40 • 206

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Computer simulations have become very popular in the automotive industry. To develop and enhance control systems and to optimize model parameters, easily configurable vehicle models with a good run-time performance are needed. To minimize the computational effort the vehicle is modelled by a non-perfect multi body system where the specific vehicle structure is taken into account. The vehicle model is separated into subsystems having a functional skeleton and consisting of several configurable modules. The numerical solution is done by a modified implicit Euler-Algorithm which guarantees sufficient accuracy and numerical stability. The generic model architecture makes it possible to describe nearly all kind of road vehicles, passenger cars, trucks and busses, as well as tractor semitrailer and tractor trailer combinations. The pre-

sented modelling concept is realized in the product ve-DYNA applied world wide by automotive companies and suppliers. A computer application shows the efficiency of this modelling concept.

Railway Vehicle Simulation Using Non-Elliptical Wheel–Rail Contact Model

SM26L_11589
Fri • 12:00 • 206

Vladislav Yazykov, Dmitry Pogorelov, Georgy Mikhalchenko
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An approximate model of wheel-rail contact, which does not lead to stiff equations of motion and can be used for non-elliptical contact area, is considered. The elastic Winkler foundation model is employed to find the contact patch configuration and the distribution of the normal pressure. The foundation modulus is determined with the help of the half space method. The FASTSIM algorithm, which was adapted for non-elliptical contact area, is applied for solving the tangential contact problem. An analytical solution of the tangential problem for a slice of the contact patch in the formulation of Kalker's simplified theory is used in the model. Results of contact problem solution and wheel wear prediction for a locomotive equipped with radial steering bogies using an algorithm based on the model are given.

Optimal Path Following Road Vehicle Steering Control

SM26L_10701
Fri • 12:20 • 206

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The theory of the discrete-time Linear Quadratic Regulator with road preview has been applied previously to minimum error path following control of an automobile. The results have shown how an optimal "driver" of a linear car can convert the path preview sample values into steering wheel displacement commands to cause the car to follow the previewed path with precision. Using the same theoretical basis, new results are generated to show optimal preview controls for cars and drivers with different layouts and priorities. A new performance criterion is set up, involving the minimisation of the preview distance required, and the sensitivities of this distance to variations in the car design parameters are calculated. The influence of additional rear steering is shown. The results yield new insights into driver steering control behaviour and vehicle design optimisation. They lead to some important conclusions about the way ahead for driver modelling from a steering control viewpoint.

Simulation and Testing of a Wheelset with Induction Motor Driven Independent Wheels

SM26L_10909
Fri • 12:40 • 206

B. Liang, **S.D. Iwnicki**, F.J. Swift
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Independently rotating wheels (IRW) for railway vehicles have been under serious consideration at a theoretical and experimental level for many years. This paper presents dynamic and control simulations of a rail vehicle wheelset with induction motors for independently rotating wheels. Simulation models have been developed for both the mechanical and electrical aspects of the system. The simulation and experimental results have demonstrated that the proposed control strategy has good dynamic performance in term of response time and controllability. A test implementation on a 1/5 scale roller rig has validated the simulation results and shown that good stabilization can be achieved by the proposed wheel motor driven configuration.

SM27

Viscoelasticity and creep

Chairpersons: A. Cocks (UK), N. Ohno (Japan)

Sintering Simulation of Stainless Steel Powder Compacts

SM27L_10906
Fri • 11:00 • 231

Rui Zhang, **Renata S. Engel**
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Die compaction of powder metals is a classic discrete component fabrication process that relies on the rearrangement, distortion, and flow of metal particles in a die cavity, where the powders are compressed into a preform that is subsequently sintered. The sintered material has competitive properties, but without the cost associated with additional machining. One of the technological challenges when fabricating parts via powder processing methods is the ability to achieve undistorted, full density parts. For example, density gradients induced from the press motions lead to nonuniform shrinkage during the thermal processing. This research presents a model that predicts the shrinkage during high temperature sintering for powder compacts that have density gradients. The one-dimensional diffusional flow model for pressureless sintering includes an Arrhenius-type viscosity model and allows for the inclusion of grain growth and thermal expansion as functions of temperature.

Characterisation of the Cyclic Behaviour of Elastic-Plastic-Creeping Bodies

SM27L_11201
Fri • 11:20 • 231

Alan R.S. Ponter
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The paper describes a systematic theoretical approach to the characterization of the cyclic behaviour of a body that exhibits creep and plasticity. The cyclic state for a particular constitutive equation may be characterized as a minimum theorem in terms of a class of kinematically admissible inelastic strain rate history. The minimum for some particular class of approximating strain rate histories my be determined by means of a new mathematical programming method, the Linear Matching Method, that sequentially reduces the functional through the solution of linear problems. The theory is developed for the standard Mandel thermodynamic model of constitutive behaviour allowing for both plasticity and creep behaviour. Examples are given of applications typical of those occurring in the life assessment of high temperature structures where the load corresponding to a particular failure condition is required.

A Creep Continuum Damage Theory for Beams, Plates and Shells

SM27L_11368
Fri • 11:40 • 231

Holm Altenbach, Konstantin Naumenko
Martin-Luther-University Halle-Wittenberg, Department of Engineering Sciences, Halle, Germany

The widely used approach in modelling the creep-damage behavior of structures is the continuum damage mechanics, which is based on constitutive equations for the creep strain rate tensor, and evolution equations for internal state variables. This approach is usually not compatible with those theories of beams, plates and shells which are based on cross-section approximations of displacement and/or stress fields. In this case there is no unique possibility to transform three-dimensional constitutive and evolution equations to the averaged equations for tensors of forces and moments and the corresponding strain or strain rate measures. We discuss an extension of the theory of simple shells recently proposed for problems of finite elasticity to the creep-damage analysis. The balance equations are formulated directly without any cross-section approximation. A general structure of creep-damage constitutive equations is discussed considering the symmetries of a shell and within the framework of continuum thermodynamics. Based on simplified examples of rods and plates we compare our approach with the three-dimensional analysis by the finite element method.

Constitutive Modeling of Rubber Components Under Small Vibration Superimposed on Large Static Deformation Considering Strain-Dependent Properties

SM27L_11827

Fri • 12:00 • 231

Ji-Hyun Cho[(1)], Sung-Kie Youn[(1)], Wan-Sul Lee[(1)], Bong-Kyu Kim[(2)]
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A steady-state viscoelastic constitutive equation of filled rubber considering the effects of large static pre-strain and dynamic strain amplitude is proposed. The proposed model is based on the linearization of Simo's finite viscoelastic model and is modified to consider the influence of static pre-deformation and the dynamic strain dependent properties. Static deformation influence factor is introduced to consider the influence of static pre-deformation on the relaxation function. And the relaxation function is modified by a function of frequency and dynamic strain amplitude in order to consider the influence of frequency and strain-dependent properties, which is called by Payne's effect. Various dynamic tests are executed in order to get the model parameters and verify the proposed model. The FEA results using the proposed model are compared with the test results to estimate the performance of the model.

A Model of Cyclic Viscoplasticity with Special Reference to Yield-Point Phenomena

SM27L_12450

Fri • 12:20 • 231

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A constitutive model of viscoplasticity that describes the yield-point phenomena is presented on the premise that the sharp yield point and the subsequent abrupt yield drop result from rapid dislocation multiplication and the stress dependence of dislocation velocity. This model can well simulate rate-dependent stress-strain responses with respect to flow stress and Luders elongation. This paper describes its modeling, some strong features of this model by comparing the numerical simulations and the corresponding experimental data on fundamental cyclic plasticity such as cyclic straining and rate-dependent ratcheting. Furthermore, as an example of industrial application of this model, a result of finite element numerical simulation on skin-pass rolling in a sheet metal producing process is presented.

Multiscale Modeling Schemes Spanning a Large Range of Scales

SM27L_11506

Fri • 12:40 • 231

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This paper presents effective multiscale modeling schemes to carry out analyses spanning a large range of scales. The proposed concepts in the continuum realms is to use the medium of the intermediate scale as a means to connect variables at the lower scale with those at the upper scale through developing equivalent constitutive equations. These equations are developed based on microstructures of the lower scale through making the variables satisfy corresponding mechanics principles. In the realm of joint atomistic and continuum scales, a mixed particle and molecular dynamics (MD) method will be coupled with quantum methods. The particle method is used to lump many atoms together as a molecular particle to reduce degrees of freedom in the low-stress gradient region. This lumped molecular particle can further connect to structure particles that are used in mesh-free finite element analysis to make the transition from the atomic scale to the continuum possible.

Nonlinear Overall Viscoelastic Properties of the Random Multicomponent Media

SM27S_10018

Tue • 14:30 • 244A

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Theoretical determination of the overall properties of inhomogeneous media is a problem of a great importance. This work is concerned with the prediction of the effective or overall response of a random multi-component media with nonlinear visco-elastic constituents. The elastic properties of inhomogeneous structures have been studied intensively during last decades. But there are a lot of questions arising in the case when visco-elastic response is a subject of investigation, nonlinear especially. The continuum considered here is suggested to be subjected to finite deformation. Kirchhoff stress tensor and

deformation gradients are used as field variables in a fixed reference state. Nonlinear problem is investigated in second order approximation theory when the gradient deformation terms higher than second order are neglected. Five constant elastic potential in elastic problem and five time functionals in visco-elastic one are used to build overall constitutive relations.

Inverse of Constitutive Equations of Anisotropic Hereditary Elastic Continua

SM27S_10254
Tue • 14:35 • 244A

Alexander M. Dumansky
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Inverse of constitutive equations of anisotropic hereditary elastic continua. The inverse of Boltzmann-Volterra constitutive equations is based on defining the resolvent of the matrix Neumann series with the aid of algebraic properties of the resolvent operators. In practical realization the procedure of the inverse does not depend on the kind of the operator and is reduced to some matrix calculations. A kernel of the resolvent operator may be chosen either exponential, power (Abel's), fraction-exponential (Rabotnov's) functions or their linear combinations. The examples of the constitutive equations inverse for orthotropic glass fiber-reinforced epoxy laminates are given. The verification of the procedure correctness is carried out.

Creep Damage Anisotropy of Thinwalled Elements Structures

SM27S_11786
Tue • 14:40 • 244A

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The paper is devoted to damage-induced due to a creep anisotropy (transversally-isotropic) of metallic materials under thermo-mechanical loading. Both types of an initially isotropic and anisotropic material were considered. For the description of ini-tial anisotropy and damage-induced anisotropy the second-order damage tensor has been used. Constitutive equations are based on irreversible thermodynamics, namely the Helmholtz free energy. Theoretical results were compared with experimental data; the results of comparison were satisfactory. The proposed model was generalized to describe damage anisotropy and lifetime prediction in thin-walled elements of structures, using the engineering models of plates and shallow shells. The method of numerical simulation of an anisotropic creep damage analysis on the basis of finite element scheme was elaborated. Various creep properties of damage-induced anisotropy plates depending on the orientation of anisotropy axes of a material concerning to a direction of loading and from a degree initial anisotropy have been established.

An Influence of Cold Work on Creep of Engineering Materials

SM27S_11957
Tue • 14:45 • 244A

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An influence of prior tensile plastic deformation on the basic creep parameters such as minimum creep rate, time to rupture, duration of creep stages and elongation is studied for copper and aluminium alloy. The materials were tested at two different temperatures, copper at 523 K and 573 K, aluminium alloy at 423 K and 473 K. It is shown for both materials that the minimum creep rate, and elongation decreases as the amount of the plastic prestrain increases. However, this relation was proportional to the plastic predeformation only up to 5% in the case of copper, and up to 6% for aluminium alloy. For copper, a little increase of time to rupture with the increase of plastic predeformation has been observed for specimens tested at higher temperature (573 K) in comparison to the nonprestrained material. In the case of lower temperature (523 K) the lifetime decreases significantly with the increase of plastic predeformation. The creep data for aluminium alloy exhibit the same tendency of lifetime variation due to prestraining programme in both temperatures under the question, namely, an extension of lifetime proportional to the magnitude of plastic prestrain. It has to be noted however, that plastic prestrain magnitudes greater than 6% led to the opposite effect, i.e. lifetime reduction.

Multi-Scale Model for Low-Temperature Creep of Asphalt

SM27S_11981
Tue • 14:50 • 244A

Roman Lackner, Andreas Jäger, Karl Kappl, Markus Spiegl, Ronald Blab, Josef Eberhardsteiner
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The increase of service time of flexible pavements requires to optimization of the complex thermo-rheological behavior of asphalt, consisting of bitumen, aggregate, and air voids. Basically, three different modes of optimization are distinguished:

(i) variation of mixture characteristics, (ii) change of constituents used, and (iii) allowance of additives. In order to account for the wide range of asphalt mixtures, resulting from the variations of the different constituents, a multiscale model is proposed by introducing five observation scales, reaching from the bitumen-scale to the macro-scale. This model is used to predict low-temperature creep properties of asphalt by assigning the temperature dependence of creep to the bitumen phase only, and using homogenization schemes to incorporate the effect of the filler. The good agreement between the material properties obtained via homogenization and the respective experimental results suggests that only the volume content of the filler affects the creep properties of asphalt, explaining phenomena and problems recently encountered in asphalt pavement engineering.

Viscoelastic Composites with Unbounded Overall Stiffness and Damping

SM27S_12152

Tue • 14:55 • 244A

Yun-Che Wang, Roderic S. Lakes

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Searching for high stiffness and high damping materials is of scientific and engineering interest. The recent development of using negative stiffness inclusions to achieve extreme overall stiffness and mechanical damping reveals a new avenue for constructing high performance materials. Negative stiffness induced extreme effective properties is a natural consequence of the composite homogenization theory based on the theory of elasticity and viscoelasticity. However, the applicability and observability of this idea highly relies on the stability of the corresponding dynamical systems. In this paper, I will first introduce some theoretical results of systems with negative stiffness inclusions through composite models, such as the Voigt, Reuss, and Hashin-Shtrikman model. Then, investigations on the stability of systems of this sort will be presented through analyzing discrete rheological models with Lyapunov's indirect theorem as the fundamental stability criterion.

TOPICS INVOLVING BOTH FLUID MECHANICS AND SOLID MECHANICS

FSM1

Acoustics

Chairpersons: T. Geers (USA), N. Peake (UK)

An Empirical ‘lower bound’ on Free-Shear-Flow Noise

FSM1L_10907
Tue • 17:00 • 123

Jonathan B. Freund, Mingjun Wei
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The adjoint of the linearized compressible flow equations is formulated in such a way that it can be used to optimize local control actuation to reduce the noise radiated by a free shear flow. Both the flow and the adjoint are solved numerically and without modeling approximations. Jet noise is the technological application of interest, and a two-dimensional mixing layer is studied as a model of the near-nozzle region of a jet. It is found that the correct small perturbations near the inflow can dramatically reduce the radiated noise. This approach allows us to establish an empirical lower bound on the noise radiation by a this flow subject to our constraints. More importantly, it gives us an opportunity to study its mechanisms by providing noisy and quieted versions of the same flow. Superficially, the unsteady flow dynamics are remarkably unchanged despite a 10dB reduction in the noise.

Special Short Wave Finite Elements for Flow Acoustics

FSM1L_11249
Tue • 17:20 • 123

Jeremy Astley, Pablo Gamallo
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It is well known that the standard Finite Element Methods are not well suited to solving 3D harmonic wave propagation problems in which the wavelengths involved are much smaller than the typical dimensions of the problem domain. A special finite element method is proposed here to tackle this type of problem in a more computationally efficient manner using fewer degrees of freedom. The present study focuses on flow acoustic problems but the method proposed is applicable to other wave propagation problems which include inhomogeneous convective effects. The method is based on the Partition of Unity Finite Element Method in which a suitable local basis is included in the approximation space to take account the known local characteristics of the solution, i.e. highly oscillatory behaviour modified by the anisotropic and inhomogeneous effects of the mean flow. Two-dimensional and axisymmetric numerical experiments are carried out to prove the feasibility of the method.

3-D Structural Acoustics Modeling with HP-Adaptive Finite Elements

FSM1L_11373
Tue • 17:40 • 123

David S. Burnett, Mario Zampolli
NATO Undersea Research Centre, Italy

The Centre has developed a 3-D hp-adaptive finite-element structural acoustics code for modeling acoustic scattering from underwater elastic structures. The entire fluid-structure domain is treated as a single continuum, which is modeled using only one type of finite element: a fluid-solid element. The wave equations for both media are derived from the same underlying equations of continuum mechanics, and then combined into a single wave equation, from which the fluid-solid finite element is derived. 3-D continuum mechanics is used throughout the computational domain; thin structural components, such as plates and shells, are modeled with 3-D physics rather than plate or shell theories. The formulation is therefore fully 3-D, i.e., in both physics and geometry. The paper describes an unusual approach to code development, explains the underlying physics and mathematics, and presents several scattering and propagation models.

Shock Leakage Through a Vortex-Laden Mixing Layer Causing Jet Screech

FSM1L_11561
Tue • 18:00 • 123

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(2) *Stanford University, USA*

The unsteady interaction between shock-cells and vortices in a mixing layer of a supersonic jet generates intense shock noise causing jet screech. We develop a linear geometrical theory for weak shock motion consisting of the eikonal equation and the Blokhintzev invariant for unsteady flows and study this shock noise phenomenon. The equation for the shock-front normal shows that the local vorticity in the mixing layer behaves as a barrier; hence, the standing shock periodically leaks near the saddle points between convective vortices and radiates as intense tonal sound in the far field. We perform direct numerical simulation of a two-dimensional supersonic mixing layer and validate the model of shock leakage by exhibiting good agreement between the geometrical theory and the full simulation in terms of shock-front as well as shock noise amplitude.

A Theoretical Model for Resonances in Flow Past a Cavity

FSM1L_12477
Tue • 18:20 • 123

E.J. Kerschen, J.O. Alvarez, A. Tumin
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Acoustic resonances leading to high unsteady pressure levels may occur in flow past cavities. The resonance involves a coupling between the downstream-propagating instability wave on the shear layer spanning the open face of the cavity, and acoustic waves propagating inside and outside the cavity. The elements of the disturbance field are coupled by the scattering processes at the upstream and downstream ends of the cavity. We develop a theoretical prediction method that combines propagation models in the central region of the cavity with scattering models for the end regions. The scattering processes are calculated using the Wiener-Hopf technique. The global analysis leads to a prediction for the resonant frequencies which has much in common with the Rossiter formula, but contains no empirical constants. The analysis also determines the temporal growth (or decay) rate of each mode, thereby providing the stability boundaries in parameter space.

Structure of Sonic Booms in a Medium with Multiple Relaxation Modes

FSM1L_12497
Tue • 18:40 • 123

Paul W. Hammerton, M.E. Johnson
University of East Anglia, UK

The shock structure of a sonic boom is controlled by the balance between nonlinearity and dissipation/dispersion mechanisms. In the atmosphere relaxation modes associated with nitrogen and oxygen molecules are important as well as viscosity. For realistic parameter values, these effects occur on different scales making asymptotic analysis possible. In this paper, numerical and asymptotic results are presented first for travelling wave solutions and then for disturbances evolving from an initial N-wave form. It is found that structure of the shock can be particular intricate with the possibilty of two sub-shocks embedded within the main shock. This change in shock struture leads to the appearance of different length scales, important when assessing the annoyance of a sonic boom. It is shown that numerics alone prove impractical due to the need to resolve three different lengthscales within the shock, while in some cases the asymptotic analysis must be supplemented by numeric solutions of the disturbance outside the shock region.

Dissipative Effects on Propagation of the Acoustic Solitary Waves

FSM1S_10294
Tue • 14:30 • 000A

N. Sugimoto, M. Masuda, K. Yamashita, H. Horimoto
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This paper examines dissipative effects on the acoustic solitary waves propagating in an air-filled tube with a periodic array of Helmholtz resonators connected axially. The dissipation is brought about by wall friction through boundary layers and by jet loss in resonators' throat, but the dissipation due to the diffusivity of sound is negligible. For pressure profiles measured experimentally, numerical simulations are carried out to identify the respective dissipative effects. It is revealed that the boundary layers give rise to a long tail while the jet loss yields a hump behind the peak. Although both effects decay commonly the peak pressure, they emerge prominently in the trailing behaviour of the pulse. The leading behaviour is well described locally by the solitary waves in lossless limit. Discussions are included on how the dissipative effects may be reduced to realize a pulse as closely as possible to the solitary waves.

Bifurcation of the P2 Wave and its Influence on Fluid-Induced Micro Earthquakes in Porous Rocks: Long Wave Asymptotics of the Biot Model

FSM1S_11044
Tue • 14:35 • 000A

Inna Edelman
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The behavior of the Biot wave in a fluid-saturated porous medium is investigated by asymptotic methods. It is proven that the P2 wave possesses a bifurcation: it is fully attenuated if its wave number is smaller than critical value and it becomes propagatory with wave numbers bigger than critical one. Although the long wavelength P2 modes are not propagatory and have a diffusive behavior, they influence significantly the pore pressure distribution in a medium. One knows that an injection of the borehole fluids into surrounding rocks often results in micro earthquakes if the value of the pore pressure exceeds some threshold. The solution of the Biot system with relevant boundary conditions at the borehole is constructed and applied to the description of the seismic cloud and to the evaluation of the critical values of the pore pressure. Moreover, this approach allows one to estimate a permeability of natural rocks.

Wave Propagation in and Sound Emission from a Sandwich Plate Under Heavy Fluid Loading

FSM1S_11337
Tue • 14:40 • 000A

Sergey Sorokin
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Stationary wave motion in an unbounded fluid-loaded elastic sandwich plate of symmetric composition is considered in a three-dimensional problem formulation. Several alternative theories are suggested, including a formulation in the framework of a theory of elasticity applied for the core ply. In the first instance, a fluid loading at the both sides of a plate is considered and "in-phase" and "anti-phase" wave motions (with respect to transverse deflections of skins) are analysed independently upon each other. It is shown that the simplified models are capable to give a complete and accurate description of all propagating waves in not too high frequency range. Furthermore the analysis is extended to take into account for the "symmetry-breaking" effects, e.g., a static pre-stress of one of skin plies and a fluid loading at one side of the sandwich plate. The standard perturbation technique is applied to analyse an interaction between dispersion curves.

The Low-Temperature Acoustical and Thermal Properties of Materials due to the Dynamics of Linear Topological Defects

FSM1S_11508
Tue • 14:45 • 000A

Dmitry V. Churochkin, Vladimir Osipov
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A contribution to the specific heat and the frequency-dependent loss due to pinned twist disclinations is calculated within the vibrating heterogeneous string model. The specific heat is found to be the linear function of the temperature and the defect density. The internal friction is proportional to the fourth power of the disclination length.The low-temperature internal friction of plastically deformed high-purity superconducting metals (aluminium, niobium, tantalum) increases over two orders in comparison with that observed in annealed samples and becomes comparable to that of amorphous solids. The thermal conductivity also has a similar value as that in amorphous state. We have investigated these anomalies within the string-like model for dipoles of edge dislocations. It is found that the presence of dipoles leads to the remarkable increase of the resonance frequency thus allowing us to obtain a good agreement with experiments.

Fourier Spectrum Representation of Vector Multipole Field and its Application in Wave Scattering in Elastic Half-Space

FSM1S_11881
Tue • 14:50 • 000A

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This paper presents the stress concentration of a cavity embedded in elastic half space and impinged by two-sets of standing Goodier-Bishop incident waves which can simulate a uniform tension surrounding. The scattering field is expressed as Fourier spectrum representation. This representation by Cartesian coordinates can make the construction of the reflective waves easily. Applying Betti's third identity develops the transition matrix for elastic half-space. This matrix presents the salient features of the interaction between the flat surface and the scatter, and then is applied for the problem undertaken. The numerical results are presented and discussed.

Transmission of Elastic Waves and Localised Modes in Composite Structures

FSM1S_11896
Tue • 14:55 • 000A

Natasha V. Movchan, Alexander B. Movchan
University of Liverpool, Liverpool, UK

This work addresses the spectral analysis of elasticity problems in doubly periodic composite structures presented either by arrays of inclusions embedded into an elastic matrix or discrete lattice structures. Particular attention is paid to filtering properties, i.e. the presence of stop bands within the spectrum, and localised modes for composite structures containing defects. First, we consider a problem of propagation of elastic waves through an elastic medium containing an array of coated inclusions and show that the parameters of the coating can be tuned in such a way that, in the long-wave approximation, the elastic system responds as a homogeneous medium without inclusions. Further, we note that it is efficient to model localised eigen-modes using approximations involving lattice structures and show how to approximate accurately high-contrast densely packed composite structures by discrete lattices.

Arbitrarily Wide-Angle Wave Equations and their Applications to Unbounded Domain Modeling and Subsurface Imaging

FSM1S_11973
Tue • 15:00 • 000A

Murthy N. Guddati, A. Homayoun Heidari, Keng-Wit Lim
North Carolina State University, USA

One-way wave equations (OWWEs) are special mathematical constructs that allow propagation of waves in a 180-degree range of angles (as opposed to normal 360-degree range for regular wave equations). Due to this property, OWWEs found applicability in modeling wave propagation in unbounded domains and in imaging. Exact OWWEs are often not amenable for computation and must be approximated. This paper presents new approximations of OWWEs: Arbitrarily Wide-angle Wave Equations (AWWEs). Unlike the existing approximations, AWWEs are applicable and accurate for one-way propagation of complex waves in heterogeneous, anisotropic, porous visco-elastic media. This presentation briefly describes the underlying ideas of AWWEs and illustrates AWWEs' accuracy in modeling propagating as well as evanescent waves. In addition, AWWE-based procedures are developed for imaging of defects in solids and for modeling wave propagation in unbounded domains. Results from these procedures will be compared with those from existing methods to illustrate the effectiveness of AWWE.

Ultrasonic Travel-Time Technique for Diagnostic of Grid-Generated Turbulence

FSM1S_12149
Tue • 15:05 • 000A

Tatiana A. Andreeva, William W. Durgin
Worcester Polytechnic Institute, Worcester, USA

The paper presents a summary of experimental and theoretical work conducted by authors in the area of acoustical wave propagation through turbulent media. The statistics of the travel-time variations of ultrasonic wave propagation along a path are used to determine some metrics of the turbulence. It is shown that the technique can be used to study the effect of turbulence on acoustic waves in terms of the travel time for various mean velocities and for different angular orientations of the acoustic waves with respect to the mean flow. The influence of temperature inhomogeneities on ultrasonic wave propagation is investigated using a set of experiments with a heated grid. Ultrasonic time-of-flight method is utilized to develop a semi-analytical methodology for determination of the correlation functions of turbulent velocity and sound speed fluctuations. Experimental data confirms numerical and theoretical predictions of nonlinear increase of the travel time variance with propagation distance (caustics).

The Acoustics of Two-Dimensional Leapfrogging Vortex Interactions

FSM1S_12180
Tue • 15:10 • 000A

Jeff D. Eldredge
Mechanical and Aerospace Engineering Department, University of California, Los Angeles, USA

We investigate the acoustics produced by coupled pairs of counter-rotating vortices. The DNS of the compressible near field is performed with the dilating vortex particle method, wherein mass-preserving computational elements convect with the velocity and carry vorticity, dilatation, enthalpy and entropy strengths, which vary in accordance with the Navier–Stokes equations. The acoustic far-field is extrapolated from the near-field results by a Kirchhoff method. We explore the effects of relative vortex strengths and spacing, core sizes, Mach number, and Reynolds number. The acoustics of the leapfrogging process are dominated by the event of one pair passing through the other, which produces a four-lobed pressure wave, followed by a second of opposite sign. In the intervening periods are small, higher-frequency oscillations due to vortex

nutation. The eventual merger generates a large acoustic pulse, followed by smaller oscillations from the resulting pair of counter-rotating elliptical vortices.

Gas Oscillations in a Closed Tube at Resonance

FSM1S_12516
Thu • 14:30 • 000A

Alexander Alexeev, Chaim Gutfinger
Faculty of Mechanical Engineering, Technion, Haifa, Israel

Periodic gas oscillations in a closed tube are investigated experimentally and numerically. At resonance, these oscillations are accompanied by shock waves traveling back and forth along the tube. Gas temperature and pressure measurements are reported. It is found that the gas temperature changes substantially along the tube. A two-dimensional numerical model of turbulent gas oscillations is formulated and verified by comparison with experiments. It is found that the experimental data of temperature and pressure inside the resonance tube are well correlated by this model. Using the numerical model, turbulence and acoustic streaming at resonance are investigated. It is shown that the normalized pressure amplitude, as well as other flow characteristics, are functions of a single parameter, which is a combination of the acoustic Reynolds number and dimensionless tube length.

The Effect of Viscosity on the Propagation of Acoustic Waves Through Fine Cylindrical Meshes

FSM1S_12527
Thu • 14:35 • 000A

Iain D.J. Dupere, Ann P. Dowling, Tian J. Lu
Cambridge University Engineering Department, UK

The generic problem of the viscous drag associated with the propagation of acous tical waves through cylindrical mesh structures is solved. At low acoustic Reyn olds numbers based upon the cylinder diameter and the acoustical velocity, the t otal drag results from the combination of the drag associated with propagation a long the axis of the cylinder and the drag associated with propagation normal to the axis of the cylinder. For the former, rather than considering waves propag ating over isolated cylinders, as considered by previous authors, we consider th e case of propagation within a channel bounded by polygonal periodic boundaries with a cylinder at the centre. This is a more realistic description of the real situation and the effects of the high order circumferential modes impli ed by this are shown to be second order but noticeable at low frequencies. Each of these is linear and thus arbitrary geometries can be considered. In this pa per we develop a theory which is valid in the limit of unsteady low Reynolds num ber acoustical flow and use this to consider the effect of geometry on the acous tical drag, and hence the acoustical absorption.

Modelling of Hydrophone Based on a DFB Fiber Laser

FSM1S_12533
Thu • 14:40 • 000A

Lars V. Hansen[(1)], F. Kullander[(2)]
(1) *Technical University of Denmark, Department of Mechanical Enineering, Denmark*
(2) *FOI, Swedish Defence Research Agency, Department of Laser Systems, Sweden*

This paper deals with modeling of a DFB fiber laser based hydrophone. Both an analytical and a finite element model are developed to describe the acoustic response of the hydrophone. Results from the finite element model are compared to the analytical results. The small dimensions (length 3–6 cm) and low frequency noise properties of DFB fiber lasers make them useful as hydrophones. Generally, for underwater surveillance applications or similar tasks the acoustic pressure sensitivity of the fiber laser needs to be enhanced by more than two orders of magnitude. Our models predict that this can be achieved by an intermediating amplifying mechanical mounting.

Numerical Analysis of the Texture and Acousto-Elastic Properties of Prestressed Polycrytalline Aggregate

FSM1S_12555
Thu • 14:45 • 000A

Józef Lewandowski
Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland

The propagation of ultrasonic waves is considered in a polycrystalline aggregate (e. g., steel) made of crystallites of the highest cubic symmetry, the waves being plane and linearly polarized. The crystallite orientation distribution is assumed to imply the orthorhombic symmetry of the macroscopic (effective) acoustoelastic properties of the body. Moreover, the sample is assumed to be subjected to plane increasing stress (up to 750 MPa), the principal directions of the stress as well as the directions of wave propagation and polarization are assumed to be coincident with the orthorhombic symmetry axes.

The Voigt's averaging procedure and Jaynes' principle of maximum Shannon entropy of the probability density functions of the single crystallite orientation and the equations governing the wave propagation in prestressed polycrystal are accepted as a reliable basis for the evaluation of the influence of the changes in stress on both the effective acoustoelastic properties of the polycrystalline aggregate and the probability density function of the crystallite orientations (texture). In this way an algorithm is prepared which allowed us to evaluate numerically these effects.

Measurements and Calculations Related to Curve Squealing in the Railway System

FSM1S_12586
Thu • 14:50 • 000A

Rossano Stefanelli, Juerg Dual, Eric Cataldi-Spinola, Mathias Götsch
Swiss Federal Institute of Technology, Zurich, Switzerland

Within a collaboration between the Swiss Federal Institute of Technology (ETH) and the Swiss Federal Railways (SBB), the phenomenon of curve squealing is studied. The aim is to understand the phenomenon causing the noise. Therefore various measurements and studies have been done. These include long-term-measurements on regular railway traffic, test runs with a test train, lab tests and simulations. Long-term-measurements gave first inputs of the critical weather conditions and critical vehicles. Test runs with the test train gave information about running behaviour depending on train speed and moisture on rail and the resulting wheel displacement and striking angle between wheel and rail. In the same time acoustic measurements allowed to establish which wheel squealed while passing by the microphones. Lab tests and simulations were used to characterize the behaviour of the train wheel depending on its decreasing diameter due to wear. Results are presented in the paper.

Acoustic Wave Propagation Through a Random Array of Dislocations

FSM1S_12643
Thu • 14:55 • 000A

Agnes Maurel(1), Jean F. Mercier(2), **Fernando Lund**(3)
(1) *LOA-ESPCI, Paris, France*
(2) *LSMPP-ENSTA, Paris, France*
(3) *CIMAT, Santiago, Chile*

We compute the scattering amplitude for the scattering of anti-plane shear waves by screw dislocations, and of in-plane shear and acoustic waves by edge dislocations, within the framework of elasticity theory. The former case reproduces well known results obtained on the basis of an electromagnetic analogy. The latter case involves four scattering amplitudes in order to fully take into account mode conversion. These results are then used to compute the coherent wave number of an elastic wave propagating through an elastic medium filled with randomly placed dislocations. The calculation is perturbative, with a wave equation whose right-hand-side takes into account the wave-dislocation interaction The effective velocity of the coherent wave appears at first order in perturbation theory, while the attenuation length appears at second order. The possibility of utilizing these results in the design of non intrusive probes of dislocation mediated phenomena, such as the brittle-to-ductile transition, is discussed.

Distributed Parameter Control of a 2D Acoustic Helmholtz Problem on a Halfspace

FSM1S_12691
Thu • 15:00 • 000A

George Biros(1), Seong-Won Na(2), Loukas F. Kallivokas(2)
(1) *Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, USA*
(2) *Department of Civil Engineering, The University of Texas at Austin, Austin, USA*

In this work we present the formulation and numerical solution of a distributed parameter control problem for the acoustic equation in a halfspace with potential applications to the seismic insulation of surficial structures. We consider the case of SH-waves in a two-dimensional materially inhomogeneous halfspace. The goal is to invert for the necessary material injections in a pre-selected region near the free surface so that, for a range of excitation frequencies of an incoming disturbance, the displacement response on the free surface is constrained below a threshold value. We use an infinite-dimensional constrained optimization formulation, in which the constraints are given by a set of (uncoupled) Helmholtz problems corresponding to a range of excitation frequencies. The Helmholtz problems are discretized using a finite element formulation on a half disk with absorbing boundary conditions prescribed over the truncation boundary. We use a Lagrange-Newton-Krylov-Schur algorithm (LNKS) to solve the system of nonlinear PDEs that correspond to the first-order necessary optimality conditions. We present the formulation and numerical results.

Frequency- and Directionality- Continuation Schemes for Scatterer Shape Detection in Acoustics

FSM1S_12717

Thu • 15:05 • 000A

Seong-Won Na, **Loukas F. Kallivokas**

Department of Civil Engineering, The University of Texas at Austin, Austin, USA

In this paper we discuss continuation schemes for detecting the location and shape of rigid scatterers embedded in a host acoustic medium when considering scant measurements of the scattered acoustic pressure in the region exterior to the scatterer (near- or far-field). Underlying the inversion process are frequency- and directionality-continuation iterative schemes that allow robust determination of the unknown shape using a small number of frequencies and directions of the probing insonifying waves. The methodology is based on boundary integral equation for the solution of the forward problem. The scattered pressure is measured only in the backscatter region and at receiver locations that do not circumscribe the sought scatterer. Several numerical results are presented, both for parametrically defined shapes (e.g. circle, ellipse, etc), as well as for penny-shaped scatterers and completely arbitrary geometries. For the latter cases, conditions for non-self-intersecting shapes complement the numerical implementation to allow for the recovery of the nodal coordinates of the meshed scatterer boundary.

FSM2

Chaos in fluid and solid mechanics

Chairpersons: I. Mezic (USA), G. Rega (Italy)

The Effect of Smoothing on Bifurcation and Chaos Computations in Non-Smooth Mechanics

FSM2L_10499
Tue • 17:00 • 144

John S. Hogan
University of Bristol, Bristol, UK

In rigid body mechanics involving impacts, backlash or friction, mathematical models of these phenomena involve functions that are discontinuous. Yet when numerical computations of the governing equations are carried out, especially when detection of bifurcation or chaos is important, a smoothed version of the dynamics is often used. In this paper we consider the effect of smoothing on the detection of border-collision or C-bifurcations, which occur when the system steady state intersects a boundary under parameter variation. Using a simple generic example, we show how smoothing always introduces spurious solutions into some part of parameter space. We also show how the location of the bifurcation point itself varies according the way in which the smoothing is carried out. In particular we show how to correct for this variation. We conclude by showing how different border-collision or C-bifurcations are different limits of smooth bifurcations.

A Set-Valued Force Law For Spatial Coulomb–Contensou Friction

FSM2L_11183
Tue • 17:20 • 144

Remco I. Leine, Christoph Glocker
Institute of Mechanical Systems, ETH Zentrum, Zurich, Switzerland

The aim of this paper is to develop a contact law for combined spatial Coulomb friction and normal friction torque (drilling friction) as a function of sliding velocity and spin. We will call this extended contact law the Coulomb-Contensou friction law. The Contensou phenomenon occurs for instance in an electric polishing machine with turning brushes used to clean floors. The machine is hard to move when the brushes are non-rotating (Coulomb friction) but the machine can easily be pushed over the floor with rotating brushes (Contensou phenomenon). The Coulomb-Contensou friction law shows a continuous behaviour for non-zero sliding velocity and spin and a set-valued behaviour for zero sliding velocity and spin (stick). The theory and numerical methods are applied to the Tippe-Top. The analysis and numerical results on the Tippe-Top illustrate the importance of Coulomb-Contensou friction for the dynamics of systems with friction.

Numerical Detection and Continuation of Sliding Bifurcations in a Dry-Friction Oscillator

FSM2L_11363
Tue • 17:40 • 144

M. di Bernardo, Piotr Kowalczyk, **P. Piiroinen**
Department of Engineering Mathematics, University of Bristol, Bristol, UK

Numerical techniques allowing for the detection and continuation of codimension-1 sliding bifurcations of limit cycles is discussed. Using these methods codimension-2 degenerate sliding bifurcations can also be detected. A dry-friction oscillator model is investigated for which a crossing sliding bifurcation scenario is found. A branch of crossing-sliding bifurcations is continued in two parameter space. While following the crossing-sliding branch a degenerate codimension-2 sliding bifurcation is detected. At this point three branches of codimension-1 sliding bifurcations merge. Our numerical techniques allow to further continue any of the other two branches. In the paper we present continuation of the grazing-sliding branch. Another important feature of the continuation techniques is the fact that the stability of bifurcating orbits can be determined. This feature is used to show that a limit cycle around the codimension-2 node, while crossing any of the three distinct codimension-1 sliding bifurcation curves, remains its stability properties.

Low-Dimensional Chaotic Dynamics in Dripping Faucets

FSM2L_11535

Tue • 18:00 • 144

Ken Kiyono[1], Tomoo Katsuyama[2]
(1) *Graduate School of Education, University of Tokyo, Tokyo, Japan*
(2) *Division of Liberal Arts, Numazu College of Technology, Japan*

Dynamical characteristics of low-dimensional chaos have been observed in dripping faucet experiments. The fluid is an infinite dimensional system, so how can low-dimensional dynamics be extracted from the fluid system? To try to answer this question, we studied potential structure of the dripping faucet system. Through numerical computations, it was shown that the dripping faucet dynamics can be basically described using an approximate potential function with only two variables, the mass of the pendant drop and the position of the center of mass. The potential function corresponds to a set of solutions of Young-Laplace equation which describes the static equilibrium shape of drops. The potential landscape based on a quasi-static approximation illustrates how the drop formation dynamics can exhibit low-dimensional chaos. The numerical results have been supported by experimental observations using a high-speed camera.

A Dynamical Systems Analysis of the Overturning of Rigid Blocks

FSM2L_12129

Tue • 18:20 • 144

Stefano Lenci[1], **Giuseppe Rega**[2]
(1) *ISTC, Polytechnic University of Marche, Ancona, Italy*
(2) *DISG, University of Rome, Rome, Italy*

This work deals with the overturning of a rocking rigid block on an oscillating base. This old and fascinating topic is reconsidered by modern techniques of dynamical systems theory. In particular, it is investigated how the invariant manifolds of hilltop saddles are involved in the toppling. The work is divided in two parts: The first is theoretical and concerns the amplitude threshold for contact between stable manifolds and rest position, while the second is numerical and leads to the definition of the "true" safe basin of attraction and its erosion, which in turn triggers the toppling. One element of novelty is that dynamical systems theory is applied to a single initial condition (the rest position) instead of to the whole dynamics, as customary done. To the authors knowledge, this work is one of the first attempts to make explicit the role played by the invariant manifolds on the overturning, and to provide a theoretical interpretative framework for this important practical phenomenon.

Nonlinear Dynamics of Axially Moving Viscoelastic Strings Based on Translating Eigenfunctions

FSM2L_12674

Tue • 18:40 • 144

Li-Qun Chen, Neng-Hui Zhang
Department of Mechanics, Shanghai University, Shanghai, China

Nonlinear dynamics is investigated for transverse vibration of axially moving strings. The Kelvin viscoelastic model is chosen to describe the viscoelastic property of the string material. The tension is characterized as a small periodic perturbation on a constant mean value. The translating string eigenfunctions are employed to discretize the governing equation, a nonlinear partial differential equation. By use of the Poincaré maps, the dynamical behaviors are identified based on the numerical solutions of the ordinary differential equations that define respectively the 1, 2, 3 and 4-term truncated systems. The bifurcation diagrams are calculated in the case the dynamic viscosity is varied while other parameters are fixed. The bifurcation diagrams of 1, 2, 3 and 4-term truncated systems are qualitatively same. The numerical results indicate that chaos occurs for the small dynamic viscosity, and regular and chaotic motions alternately appear for the increasing dynamic viscosity.

Nonlinear Oscillators with Time Delays

FSM2L_12927

Fri • 09:30 • 144

Zbigniew Peradzyński[1,2], Jacek Kurzyna[2]
(1) *Warsaw University, Department of Mathematics, Warsaw, Poland*
(2) *Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland*

Because of its importance for various fields (technology, physics, electronics, biology, medicine) and also for controlling the chaos, the theory of delay differential equations has been violently developed during the last 25 years. Here we present the theoretical as well as numerical results for a nonlinear damped oscillator, with a small part of the restoring force retarded in time. It appears that the dynamics of such a system is quite complex. Depending on the retardation time t a number of Hopf bifurcations as well as a number of various chaotic regimes appears. Also different roots to chaos are observed. For several cases we reconstructed strange attractors and estimated their correlation dimentions as well as Lapunow exponents.

For a small damping, the time of the first Hopf bifurcation is proportional to the damping in the system. This demonstrates that hamiltonian systems can be unstable with respect to perturbations containing terms with time delay. The equation considered here was proposed as a simplest possible model of keyhole instabilities observed during the laser welding. That is to say, the thin channel formed by metallic vapours in the molten material is performing irregular chaotic oscillations.

Non-Linear Oscillator Under Random Renewal-Driven Trains of Impulses

FSM2L_12972
Fri • 09:50 • 144

Radoslaw Iwankiewicz, Matilde R. Sotera
University of the Witwatersrand, Johannesburg, South Africa

A non-linear, non-hysteretic oscillator under a stochastic excitation in form of a random train of impulses driven by a renewal process is considered. The state vector of the oscillator is a non-Markov stochastic process. The class of renewal impulse processes considered is obtained by multiplying an Erlang renewal impulse process by an intermittent, zero-one auxiliary stochastic variable. This variable is governed by a stochastic differential equation driven by two independent Erlang renewal processes, each of which is exactly expressed, with the aid of a set of auxiliary variables, in terms of a Poisson process. Thus the augmented state vector, consisting of the original state vector and of auxiliary variables, is driven by two independent Poisson process, and becomes a Markov process. The Ito's differential rule is used to derive the differential equations governing the response statistical moments. The special cumulant-neglect closure technique is devised to truncate the hierarchy of moments equations. The mean value and variance of the response are obtained by numerical integration of moment equations and verified against Monte Carlo simulations.

Nonlinear Dynamics of High-Speed Milling

FSM2L_10252
Fri • 10:10 • 144

Gabor Stepan, Tamas Insperger, Robert Szalai
Department of Applied Mechanics, Budapest University of Technology and Economics, Budapest, Hungary

In case of highly interrupted machining, the ratio of time spent cutting to not cutting is considered as a small parameter, and the classical regenerative vibration model breaks down to a simplified discrete mathematical model. The linear analysis of this discrete model leads to the recognition of the doubling of instability lobes in the stability charts of machining parameters. This kind of lobe doubling is related to the appearance of period doubling bifurcations occurring primarily in low-immersion high-speed milling along with the classical self-excited vibrations (or secondary Hopf bifurcations). The present work investigates the nonlinear vibrations in case of period doubling and compares this to the well-known subcritical nature of the Hopf bifurcations in turning processes. Our experimental results draw the attention to the limitations on the highly interrupted cutting condition. The analysis of the general milling model requires the use of the stability chart of the delayed Mathieu equation.

Nonlinear Dynamics of Parametrical Excited Two-Degrees-of-Freedom Flexible Pendulum

FSM2S_10070
Tue • 14:30 • 000B

Amir A. Zadpoor
Department of Mechanical Engineering, Iran University of Sciences and Technology, Iran

The motion of a flexible pendulum subjected to a harmonic vertical motion of pivot is studied in this paper. Rotational displacement of mass is associated with radial displacement due to existence of a linear, weakly nonlinear or strongly nonlinear spring. These two degrees of freedom, rotational and longitudinal, are coupled nonlinearly and parametrical excitation of the system makes it a non-autonomous nonlinear system. Bifurcation theory is used to study dynamics of the system. It has been shown that it is possible for system to become chaotic. Routes to chaos are studied through construction of the phase portraits and Poincaré maps and computation of Lyapunov exponents. The linear, weakly nonlinear and strongly nonlinear springs are studied respectively and dynamical alternation of system in each case is studied separately. Amplitude of pivot vertical harmonic displacement is chosen as control parameter.

Attractor and Pattern Control in Nonlinear Media by Localized Defects

FSM2S_10823
Tue • 14:35 • 000B

Sergey Vakulenko[1], **Bogdan Kazmierczak**[2]

(1) *Institute for Mechanical Engineering Problems, Russian Academy of Sciences, Saint-Petersburg, Russia*
(2) *Institute of Fundamental Technological Research, Polish Academy of Science, Warsaw, Poland*

We consider pattern and attractor control in nonlinear dissipative systems. We develop an analytic approach to attractor control for neural, genetic networks systems of coupled oscillators and spatially extended systems. In particular, we apply this method for some systems of Ginzburg-Landau's type and others.

Chaotic Attractors with Long Regular Sequences

FSM2S_11241
Tue • 14:40 • 000B

Ugo Galvanetto
Department of Aeronautics, Imperial College London, London, UK

Dissipative dynamical systems are characterised by chaotic attractors, which exhibit sensitive dependence on initial conditions. The chaotic nature of an attractor can be established by examining the divergence of neighbouring orbits, usually quantifi ed by the computation of Lyapunov exponents. The Lyapunov exponents, li, of an orbit measure the average long-term rate of divergence of all adjacent trajectories and are defi ned as the limit, as time goes to infi nity, of li =(1/t)ln(dt/d0), where t is time, dt the separation between the orbits at time t and d0 the initial separation. The trajectory will visit all regions of the chaotic attractor and different regions will in general be characterised by different rates of divergence. This paper will present examples of chaotic motions in non-smooth mechanical systems affected by dry friction, in which the existence of zones of the attractor with different rates of divergence assumes unusually extreme characteristics. The mechanical system generates one-dimensional maps the orbits of which exhibit sensitive dependence on initial conditions only in an extremely small set of their fi eld of defi nition. The Lyapunov exponent of the map will be computed to characterise the nature of the steady state motions.

Reduction of Multidimensional Flow to Low Dimensional Map for Piecewise Smooth System Experiencing Chaos

FSM2S_11302
Tue • 14:45 • 000B

Ekaterina E. Pavlovskaia, Marian Wiercigroch
Centre for Applied Dynamics Research School of Engineering and Physical Sciences, University of Aberdeen, Aberdeen, UK

We consider dynamics of the piecewise smooth nonlinear systems for which general methodology of reducing multidimensional fbws to low dimensional maps is proposed. This includes creation of the global map by stitching together local maps, which are constructed in the smooth sub-regions of phase space. Full details are given for a case study of drifting impact oscillator where fi ve-dimensional fbw is reduced to one dimensional (1D) approximate map. An appropriate co-ordinate transformation allowed the drift to be de-coupled from the bounded system oscillations. For these oscillations an exact two-dimensional map has been formulated and analysed. A further reduction to 1D approximate map is possible and will be discussed in the lecture. A standard nonlinear dynamic analysis reveals a complex behaviour ranging from periodic oscillations to chaos, and co-existence of multiple attractors. Accuracy of the constructed maps by comparing the dynamics responses with the exact solutions for a wide range of system parameters will be examined.

A New Road to Chaos in Dynamical Systems with Impact Interactions

FSM2S_11355
Tue • 14:50 • 000B

Sergey P. Gorbikov, **Alevtina V. Menshenina**
Nizhny Novgorod State University of Architecture and Civil Engineering, Department of Higher Mathematics, Nizhny Novgorod, Russia

In this report a new road to chaos in dynamical systems with impact interactions is investigated. This road to chaos is connected with the bifurcation of the periodic motion. The bifurcation occurs when the periodic motion comes to the boundary of the region of infi nite-impact motions existence (i.e. motions with infi nitely many impact interactions in a fi nite time interval). It is shown how Smale's horseshoes can emerge in dynamical systems with impact interactions as a consequence of the bifurcation. Existence of Smale's horseshoe generates motions which are described by symbolic sequences of two characters. It results in chaotic behavior of the motions. A model of vibroimpact device is considered as an example. Different

Smale's horseshoes and chaotic motions are numerically observed after the bifurcation. There are determined parameters values when stationary motions of the system are chaotic and have unusual limiting sets.

On Generating Chaotic Dynamics in Nonlinear Vibrating Systems

FSM2S_11416
Tue • 14:55 • 000B

Elżbieta Tyrkiel
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The paper is aimed at demonstrating the mechanism triggering chaotic phenomena in dissipative nonlinear vibrating systems. The common dynamical element underlying the build-up of chaotic responses, i.e. the formation of nonattracting invariant sets (chaotic saddles), is highlighted. Characteristic examples of the practical consequences, such as chaotic transient motions, fractal basin boundaries and an unpredictability of the final outcome, are shown and discussed for two representative models of oscillators driven externally by periodic force. The results are presented and interpreted with the use of concepts and numerical techniques of nonlinear dynamics and chaos. It is shown that the presence of a chaotic saddle triggers chaotic transient motions apart from either single or multiple attractors coexist, as well as that transient chaos may appear at the level of control parameters much lower than a steady-state chaos (chaotic attractor). The study of formation of chaotic saddles related to the sequence of global bifurcations allows to establish critical thresholds of forcing parameters that define the domains of the safe (regular) and unsafe (unpredictable) system motion.

Chaos in Wave Front Propagation in Heterogeneous Media

FSM2S_11512
Tue • 15:00 • 000B

Anatoly V. Chigarev(2), Yuri V. Chigarev(1), Aleksander Brostovich(1), Larysa N. Bialiatskaya(2)
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(2) *BNTU, Department of Technical Mechanics, Minsk, Belarus*

Appearing of chaos at an propagation of waves in the determined heterogeneous media to investigation in the general case yet it is not possible. The ray method allows to reduce partial differential equation to the ordinary nonlinear differential equations, to which investigation it is possible to apply methods of nonlinear dynamic of systems. The closed systems of the equations describing geometry of rays, wave front and intensities of waves of jump of stress for volume and surface waves in a heterogeneous elastic medium are obtained. Stochastization of rays causes a chaotization of parameters of interior geometry of wave surfaces and intensities of waves. It is shown, that in a case bivariate of heterogeneous media in an approximation of cubic nonlinearity the equation of a ray is reduced in the Duffing's equation.

Influence of Remaining Chaos on Convergence of Solutions in Time Delayed Feedback Controlled Duffing System

FSM2S_12014
Tue • 15:05 • 000B

Kohei Yamasue, Takashi Hikihara
Department of Electrical Engineering, Kyoto University, Kyoto, Japan

Time delayed feedback control is well-known as a practical method for stabilizing unstable periodic orbits embedded in chaotic attractors. The systems under the control method are described by delay differential equations and then become infinite dimensional system whose phase space is function space. However, no intrinsic discussion has been obtained for the control performance associated with global dynamics in function space. In this paper, we numerically discuss the influence of a remaining chaotic invariant set on control of chaos in Two-well Duffing system. The discussion is based on the existence of the global unstable manifold of the directly unstable periodic orbit which can not be stabilized by the control method. We reveal that it causes highly complicated domain of attraction for target orbits and long chaotic transient before the convergence.

On the Nonlinear Dynamics of Multicomponent Dynamical Systems

FSM2S_12468
Tue • 15:10 • 000B

Igor Mezic
Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, USA

We propose a framework for analysis of dynamical systems with a large number of heterogeneous coupled components. This framework is used to propose a graph-theoretic decomposition that exhibits a chain of vertically unidirectionaly coupled

levels and horizontally decoupled components within each vertical level. The decomposition is used to prove a number of results on asymptotic dynamics of coupled dynamical systems.

Short-Time Dynamical Behavior of Fluids at the Atomic Scale

FSM2S_12482
Tue • 15:15 • 000B

Theodoros E. Karakasidis, Antonios B. Liakopoulos
Hydromechanics Laboratory, Department of Civil Engineering, School of Engineering, University of Thessaly, Volos, Greece

In this paper we discuss fundamental aspects of the dynamical behaviour of fluids at the atomic scale using Molecular Dynamics simulation. We present time-series analyses of instantaneous temperature and pressure using linear and non-linear methods. Within the framework of the linear analysis methods, power spectra show evidence of a two-regime power-law (1/fa) behaviour with a large exponent at the high frequency region and a smaller exponent at low frequencies. The dependence of exponent a on system density and temperature is discussed. All time-series exhibit essentially the same characteristics for short times (high frequencies). In contrast, at low frequencies, pressure shows a faster loss of memory. Extracted characteristic times are consistent with results obtained from mean square displacements calculations. Rescaled range analysis reveals also a two-regime behavior. In the framework of nonlinear time series analysis, mutual information is employed for the determination of the optimal embedding delay leading to phase space reconstruction.

Parametric Instability and Chaos in the Simple Portal Under Ground Motion

FSM2S_12734
Tue • 15:20 • 000B

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The responses of an elastic frame, with inertial nonlinearities (single degree of freedom) due to vertical and horizontal ground motion, are investigated. The horizontal component of ground motion acts as an ordinary lateral forcing efect on the structure. The vertical component of ground motion acts in a parametric manner on lateral displacement. If only the vertical ground motion acts (and if the ground motion is periodic in time), the well known dynamic instability in Bolotin's sense can occure. If interactions between horizontal and vertical forces are considered, the instability regions must be analysed in the diferent manner. The results of the numerical analysis reveal periodic, quasy-periodic and chaotic motions, as shown in Poincaré's maps.

FSM3

Continuum mechanics

Chairpersons: K. Rajagopal (USA), G. Saccomandi (Italy)

Weakly Nonhomogeneous Viscous and Viscoplastic Flows: Stability and Mixing

FSM3L_11171

Fri • 11:00 • 124

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A stability and beginning of mixing in weakly nonhomogeneous viscous and viscoplastic (Bingham) media with respect to low perturbations are investigated. Both the main fbw and imposed perturbations are supposed to be three-dimensional. The suffi cient estimates based on variational inequalities in various functional spaces (the energetic estimates) are derived to analyse an increase or decay of initial perturbations. A choice of the functional space determines the measures for parameters deviation. Moreover, these measures may differ for the initial parameters and current ones. An arbitrarily general insteady motion of a homogeneous incompressible viscous or viscoplastic medium in 3D domain of the Eulerian space is taken in the capasity of the non-perturbed process. It is shown that an increase or decay of kinematic perturbations linearly depend on the initial variations of density and viscosity. An unlimited growth of these variations is interpreted as mixing beginning on macrolevel.

Nonlinear Response of Magnetoelastic Solids

FSM3L_11227

Fri • 11:20 • 124

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A magnetoelastic solid consists of an elastomeric matrix and a distribution of micron-sized ferrous particles. The composite is treated as a solid with combined elastic and magnetic properties. Recently, growing interest in these materials for industrial applications has motivated a renewed interest in electromagnetic continua with particular reference to large magnetoelastic deformations. We fi rst derive governing equations of equilibrium and constitutive laws by introducing an amended free energy formulation. The resulting equations, based on use of the referential magnetic fi eld vector as an independent variable, provide a compact formulation that may be expressed in either Lagrangian or Eulerian form. The equations are then applied to the solution of a prototype boundary-value problem in which a rectangular block is bent into a sector of a circular cylindrical tube with a referential magnetic fi eld normal to one of the faces of the block. A closed-form solution for this problem is obtained for a particular choice of energy function. The magnetic fi eld in the deformed confi guration becomes radial in the deformed confi guration and the stress/strain response stiffens with increasing magnetic fi eld strength.

Generalized Continuum Mechanics: Three Paths

FSM3L_11347

Fri • 11:40 • 124

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The material framework is considered to place in evidence three essential ways of generalizing stanard continuum mechanics, the latter being here the theory of one-component simple materials(after W.Noll) with symmetric Cauchy stress. the three possible paths to generalization are (i) the loss of the Euclidean nature of the backgrounbd material manifold, (ii) the loss of validity of Cauchy's construct of the notion of stress and (iii) the loss of symmetry of the latter. Special attention is paid to the consequences of these different losses on the canonical balance of momentum and its moment, whose ontological status is the same as that of the balance of energy, i.e., they concern the whole physical system under consideration (in particular, all degrees of freedom simultaneously). Because of (i), these cosniderations of necessaity are in that material framework which is the realm of confi gurational forces and forces driving structural defects.

Deformation of Solder Joints Under Current Stressing: Experimental Measurement and Numerical Simulation

FSM3L_11515
Fri • 12:00 • 124

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In this paper, the in-situ displacements evolutions of lead-free solder joints under electric current stressing are measured with Moire Interferometry technique. Large deformation was observed in solder joint under high density current stressing. The deformations are due to electromigration in the solder joints. An electromigration constitutive model is applied to simulate deformations of the lead-free solder joints under current stressing. The simulations predict reasonably close displacement results to Moire Interferometry experimental results in both spatial distributions and time history evolutions. This indicates that this electromigration model is reasonably good at predicting the mechanical behavior of lead-free solder alloy under electric current stressing. Both the experimental observations and finite element simulation results indicate that, in addition to the current density level, the current density distribution within the solder joint has a great effect on the displacement development in the solder joint under current stressing.

Extended Polar Decompositions for Finite Plane Strain

FSM3L_11818
Fri • 12:20 • 124

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The concept of unsheared triads of material line elements in a body was introduced by Boulanger & Hayes (2001) who showed that there is a link between these triads and new decompositions of the deformation gradient, generalizing the classical polar decomposition. Associated with any unsheared (oblique) triad of material line elements is a new decomposition. Because there is an infinity of unsheared triads, there is an infinity of such decompositions, called "extended polar decompositions". In the present paper attention is confined to finite plane strain so that the deformation gradient is essentially two-dimensional. The typical unsheared triad consists of a pair of unsheared material line elements in the strain plane and an element normal to that plane. As such a triad is varied it is seen how the decomposition also changes. In particular, for simple shear, the whole range of extended polar decompositions is presented.

Explicit Secular Equations for Surface and Interface Waves in Anisotropic Solids

FSM3L_11950
Fri • 12:40 • 124

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Many problems of anisotropic elasticity have been beautifully addressed by the now-called Stroh-Barnett-Lothe formalism; in particular, the questions of existence and uniqueness were solved for surface and interface waves in crystals, and numerical schemes were elaborated for the determination of the speeds of propagation. However, explicit secular equations remain rare outside certain high symmetry/special boundary conditions contexts. Here a novel and efficient method is proposed, which permits the derivation of such secular equations for a great variety of surface and interface wave problems. It does not rely on the above formalism and requires only elementary algebraic manipulations. It is applicable, among other possibilities, to: linear anisotropic elasticity; small motions superposed on large static homogeneous deformations; rotating bodies; solid/vacuum, solid/solid, solid/fluid interfaces; or several combinations of these contexts.

On the Volumetric Growth of Binary Solid-Fluid Mixtures

FSM3S_10633
Tue • 14:30 • 000C

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This work aims at investigating the possibility of modelling the volumetric growth of a binary solid-fluid mixture within the context of biomechanical perspectives in rational mixture theories. A solid-fluid mixture may be regarded as a couple of body manifolds, embedded into the three-dimensional Euclidean space, so as to share a smooth region of the physical environment while undertaking independent motions (see e.g. Atkin and Craine (1976), Bowen (1976), Rajagopal and Tao (1995), Truesdell (1957)). Extending the pioneering proposal put forward by Rodriguez, Hoger and McCulloch (1994) to binary solid-fluid mixtures, the bulk growth of a soft tissue is regarded as the time evolution of its stress-free configuration

(Di Carlo and Quiligotti (2003), Epstein and Maugin (2000)), described by a smooth (but geometrically noncompatible) tensor field on the reference configuration.

Pseudo-Rigid Bodies Viewed as Globally Constrained Continua

FSM3S_11096
Tue • 14:35 • 000C

James Casey
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Pseudo-rigid bodies (or Cosserat points) are continua whose deformation gradient fields are restricted to be spatially homogeneous. The theory, initiated by Slawianowski, was elaborated upon by Cohen, Muncaster, MacSithigh, Rubin, and others, and has been successfully applied to a wide variety of problems. The purpose of the present paper is to show theoretically how such continua can maintain the assumed homogeneity of their deformation fields in the presence of arbitrarily applied loads. Pursuing ideas introduced by Antman, Marlow, and Podio-Guidugli, pseudo-rigid bodies are regarded here from the novel viewpoint of globally constrained continua. Roughly speaking, the pseudo-rigid continuum is an idealized reinforced body in which the Cauchy stress tensor at each point is the sum of an active stress, which is specified by a constitutive equation, and an indeterminate reactive stress, which takes on whatever values are necessary to maintain the homogeneity of the deformation field. Remarkably, the active stresses form an equilibrated system, while the reactive stresses satisfy the same equations as for rigid continua.

Constitutive Equations of Mesoelastic Deformation

FSM3S_11140
Tue • 14:40 • 000C

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We study deformations of mesoelastic materials that display different types of imperfections with a typical size of 1μm. Stress-strain relationships of these materials depend on the processing history and exhibit common behaviour, including non-linearity, hysteresis, etc. We focus our study on the continuous distribution of singularities in the deformation field, which are described in terms of dislocation densities and fluxes. We define the mass mesodensity tensor and deduce the constitutive relationship between the dislocation current and the linear mesomomentum. Based on the modification of Peach-Koehler formula we propose the constitutive relationship between the line mesostress tensor and the dislocation density. These constitutive relationships allow us to model stresses in mesoelastic materials.

Application of Continuum Mechanics in the Textile Fabrics

FSM3S_11247
Tue • 14:45 • 000C

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Textile fabrics represent complicated structures. The mechanical properties of these formations are possible to describe on the basis of theirs specific idealization. One of the methods of problem solving of the mechanics textiles is substitute of the textile formation by continuous environment – continuum. The substitute continuum has identical mechanical properties like testing textile fabric. Geometrically and physically for the non-linear properties of the substitute continuum is necessary to apply an apposite descriptions of states of stress as well as deformation. In that case these descriptions have to be conjugated couple of tenzors of tension as well as deformation. Unlike the solid bodies, the uniaxial stress of fabric textile does not capture its mechanical properties. That is why the strength hypotheses are no use for them.

Viscoelastic Fluid Flows in a Falling Cylinder Viscometer and the Evaluation of Shear Viscosity

FSM3S_11638
Tue • 14:50 • 000C

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In this paper we consider the problem of a falling cylinder viscometer filled with a viscoelastic fluid (second grade fluid, third grade fluid and a class of second order fluid respectively). If the problem for a second grade fluid is similar to the problem for a linear viscous fluid, largely discussed in Cristescu and all [1], the coresponding boundary value problems for a third grade fluid and for a second order fluid are different. We prove the existence and uniqueness of the solutions (which are numerically computed) and we graphically compare the obtained results. The differences concerning the velocity field as well as the shear stress are put into evidence. In particular, we remark that the formula obtained for shear viscosity of

a third grade fluid can be interpreted as a relation for the determination of the sum $\beta_2 + \beta_3$, of constitutive moduli, once the shear and plateau viscosities are known.

Fundamental Inequalities for the Bounds on the Effective Transport Coefficients of Two-Phase Media

FSM3S_11642
Tue • 14:55 • 000C

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(2) *Centre de Physique Théorique, CNRS, Marseille, France*

By using a special multipoint continued fraction technique we derive, starting from the truncated power expansions given at a number of discrete real points, the general inequalities for the effective transport coefficients Q of macroscopically isotropic two phase media. The inequalities obtained provide new upper and lower bounds on Q, the best ones with respect to rational functions and the available power series coefficients. In particular cases these new bounds reduce to the classical ones of Wienner and Hashin-Shtrikman. They also coincide with the estimations due to Milton and Bergman obtained for the fitting problem. Many illustrative examples clearly show the usefulness of the new bounds derived.

On the Source of Singularities in Mechanics

FSM3S_11704
Tue • 15:00 • 000C

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Stress singularities occur at discontinuities, such as sharp corners, in both fluid and solid mechanics. While such singular stresses are often qualitatively physically appropriate, they are never quantitatively physically appropriate. To begin to improve the modeling so that more physically-sensible stresses are produced, the source of these singularities need to be identified. Here this is demonstrated to be infinite stiffnesses in underlying intermolecular laws that enter implicitly with some traditional boundary conditions. When finite stiffnesses are introduced instead, local asymptotic analysis shows that finite stresses result (confirmed in some instances with global numerical analysis). This is so even with the originating discontinuity still present, thus indicating that it is the infinite stiffnesses involved that are the sources of singularities rather than the associated discontinuities themselves. Removal of singularities via the introduction of finite stiffnesses is illustrated for a range of otherwise singular problems in both fluid and solid mechanics.

Nonlinear Waves in Elastic Solids

FSM3S_11840
Tue • 15:05 • 000C

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Institute of Fundamental Technological Research Polish Academy of Sciences, Warsaw, Poland

Using a weakly nonlinear perturbation method we derive evolution equations for the amplitudes of nonlinear elastic waves. We obtain some new asymptotic models like e.g. the complex Burgers equation describing the propagation of amplitudes of quasi-shear waves along the diagonal of a cube in a cubic crystal. We also study wave interactions by deriving new formulas for the interaction coefficients, calculating the coefficients explicitly and analyzing them. These new formulas are used in the formulation of a condition which assures global existence of a classical solution to the initial-value problem of nonlinear elastodynamics equations.

Views on Material Forces in Multiplicative Elastoplasticity

FSM3S_12392
Tue • 15:10 • 000C

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Chair of Applied Mechanics, Faculty of Mechanical and Process Engineering, University of Kaiserslautern, Kaiserslautern, Germany

The main goal of this contribution is the examination of a general framework for finite hyper-elastoplasticity that reflects the nature of material forces. In particular, we thereby address representations of Eshelbian stress tensors and Eshelbian volume forces with respect to different configurations, namely the spatial, the material and – what we call – the intermediate setting which allows alternative interpretation as being referred to a local rearrangement. Deriving these relations, one naturally incorporates connections which are determined by either the irreversible or the reversible portion of the deformation gradient. The physical interpretation of these contributions consists in the fact that their skew part can be related to the, say,

dislocation density. With these Eshelbian stress tensors and volume forces at hand, we finally come up with different representations of balances of linear momentum which are carried out with respect to the spatial or material setting, referring either to the spatial or to the material motion problem. The developed framework serves as the fundamental outset for the application of the material force method.

Affine Symmetry in Mechanics of Discrete and Continuous Systems

FSM3S_12406

Tue • 15:15 • 000C

Jan J. Slawianowski
Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland

Discussed are the theory and applications of affine invariance in dynamics of multiparticle systems and continuous media. Traditional invariance and objectivity principles are based on Euclidean geometry of the physical space and its isometry groups (translations and rotations). Among all constrained mechanical systems rigid bodies play a distinguished role both in macroscopic mechanics and in theory of microstructured bodies like, e.g., Cosserat continua. Similarly, in fundamental physics elementary particles and fields are classified in terms of representations of isometry groups (Euclidean and Lorentz groups). Models of collective and internal degrees of freedom based on affine geometry (rigid rotations and homogeneous deformations)are also used in various mechanical and physical problems, e.g., in macroscopic elasticity, mechanics of micromorphic continua (Eringen), molecular and nuclear dynamics and astrophysics. However, it is only kinematics, but not dynamics that is affinely invariant. Unlike this, we develop mathematical models of affine degrees of freedom the dynamics of which is ruled by affine group. In a sense, this may be considered as a discretization of the Arnold, Marsden and others model of the ideal fluid as a Hamiltonian system on the diffeomorphism group. In particular, we discuss geodetic models, where the dynamics of elastic vibrations is encoded in an appropriately chosen kinetic energy form invariant under the affine group. Independently of the mathematical beauty of such models and in spite of their apparently academic character, they seem to be applicable in certain problems of microstructured media, the dynamics of defects in solids, nanomechanics and in fundamental physics like, e.g., the droplet model of nuclei. Certain aspects of our results are relevant for the theory of completely integrable mechanical systems.

FSM4

Fluid-structure interaction

Chairpersons: J. Grue (Norway), M. Paidoussis (Canada)

The Hydroelastic Destabilisation of Finite Compliant Panels

FSM4L_11736
Thu • 09:30 • 124

Anthony D. Lucey
Curtin University of Technology

The destabilisation of finite compliant panels by a uniform mean flow is studied using numerical simulation. Both a generic plate-spring type of wall and a viscoleastic continuum are investigated, respectively modelled using finite-difference and finite-element methods while the flow is modelled using a boundary-element method. The investigation addresses the means by which instability of the whole panel develops from a highly localised applied excitation at flow speeds above that of divergence-onset. A general result emerges. For finite panels two types of convectively unstable divergence waves exist with opposite directions of wall-energy-density propagation. The co-existence of these waves, and their repeated interactions with the panel ends, permits the spread of wall-energy increase to all spatial locations. This globally unstable behaviour and sustained growth with time occurs without the formal existence of absolute instability that is theoretically predicted for much higher flow speeds.

Nonlinear Dynamics of Pinned-Pinned Cylinders in Axial Flow

FSM4L_11078
Thu • 09:50 • 124

Michael P. Paidoussis, Yahya Modarres-Sadeghi, Christian Semler
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It is known that cylinders with supported ends subjected to high enough axial flow develop divergence and at higher flow coupled-mode flutter, as shown experimentally and confirmed by linear theory. Also, the same dynamics is predicted by linear theory for the closely related problem of a pipe conveying fluid, but in this case post-divergence flutter has never been observed; its nonexistence was confirmed by nonlinear theory. The problem of the cylinder in flow is re-examined in this paper by means of weakly nonlinear theory. It is shown that post-divergence flutter does exist, but not as an instability of the trivial equilibrium, but as a Hopf bifurcation emanating from the divergence solution. For high enough flow, interesting dynamics follow, including quasiperiodicity and chaos. Reasons for the different dynamics with internal and external flow are explored.

Incompressible Flow with Elastic Filaments Using Moving Overset Grids

FSM4L_12896
Thu • 10:10 • 124

Petri Fast
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We consider elastic filaments with mass that are coupled to a viscous incompressible flow using a new pressure velocity formulation. The key idea is to use thin, body-fitted grids that move and deform with moving boundaries, while using fixed Cartesian grids to cover most of the computational domain. Since the elastic boundary is always aligned with a grid line we can guarantee there is no leakage across immersed elastic boundaries: This is a major improvement over the immersed boundary and immersed interface methods. Our approach combines the strengths of earlier moving overset grid methods for rigid body motion, and unstructured grid methods for flow-structure interactions. Large scale deformation of the flow boundaries can be handled with only locally regenerated grids that adapt to moving boundaries in a computationally efficient way. Numerical experiments are used to demonstrate the improved accuracy of the method over prior work.

Water-Surface Dynamics Among a Periodic Array of Floating Bodies Subject to Regular Incident Waves

FSM4L_11758
Thu • 11:00 • 124

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(2) *Yokohama National University, Yokohama, Japan*

Theoretical and experimental investigation on the water-surface dynamics among a periodic array of floating bodies placed in an incident regular wave train is conducted. The structures in mind are such offshore structures as a column-supported semi-submersible oil rig or a column-supported floating airport now projected in Japan. The focus is placed on the possible wave trapping among a periodic array and the resultant water-surface movements. It is demonstrated that viscous forces play a dominant role in determining the water-surface dynamics among the array in trapped waves. Another interesting fact found in the experimental work is also shown in which noticeable non-linear double-frequency oscillations of water-surface were induced among a periodic array in some particular waves. Finally, as a possible exploitation of wave trapping, the results of experimental investigation on the transmission and reflection characteristics of waves due to a floating wave-breaker composed of a periodic array of bodies are presented.

Fast Multipole Algorithm for Wave Response Analysis of Floating Structures

FSM4L_12175
Thu • 11:20 • 124

Tomoaki Utsunomiya, **Eiichi Watanabe**
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The conventional Boundary Element Method (BEM) employing free-surface Green's function is practically impossible to be applied for large-scale analysis such as wave diffraction/radiation analysis for Very Large Floating Structures (VLFS) in general sea-bed topography. This is mainly due to $O(N^2)$ requirement for storage and $O(N^3)$ characteristics for CPU time, where N is the number of unknowns for the BEM. The Fast Multipole Algorithm (FMA) has thus been applied to the BEM utilizing the Green's function by the present authors. The method has $O(N)$ characteristics both for storage requirement and CPU time. The method has been applied to large-scale analysis such as wave response analysis of pontoon type VLFS in general sea-bed topography, and hybrid-type VLFS having complicated shape, where N is the order of 10^4-10^5.

A New Model for the Study of Rain–Wind Induced Vibration

FSM4L_11319
Thu • 11:40 • 124

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Inclined stay cables of bridges are fixed on one end to a pylon and on the other end to the bridge-deck. Usually the stay cables have a polyurethane mantle and a cross section which is nearly circular. With low structural damping of the bridge, a wind-field containing raindrops may induce vibrations of the cables.In this paper model equations are presented for the study of rain-wind induced vibrations of a simple oscillator and a rod of circular crosssection. As will be shown the presence of raindrops in the wind-field may have an essential influence on the dynamic stability of the cable. In this model equation the influence of the variation of the mass of the cable due to an incoming flow of raindrops hitting the structure and a mass flow which is blown and shaken off, is investigated.The time-varying mass is modeled by a time harmonic function whereas simultaneously also time-varying lift and drag forces are considered.From a practical point of view one may conclude that in order to avoid instabilities one should design the oscillator in such a way that rain water accumulation and variation should not be possible.

Disturbed-Laminar Flow Over an Oscillating Cylinder

FSM4L_12557
Thu • 12:00 • 124

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The flow around a cylinder oscillating at small amplitude in fluid otherwise at rest is subject to instabilities that trigger first a regime of three-dimensional disturbed-laminar flow, and with increasing amplitudes of motion, turbulence. In the literature there are several accounts of both experimental and theoretical studies of this problem, which has relevance to the hydrodynamic damping of large floating offshore structures. However, there appears to be a conflict between analytical predictions and laboratory measurements relating to the onset of three-dimensional flow. Several researchers have reported damping levels to be about twice that predicted by Stokes' theory in conditions where no disturbances in the laminar flow are expected. This paper describes experiments aimed at resolving this difference, and describes measurements of

hydrodynamic damping and visualisations of the flow. Attention is directed at the range $1,000 < \beta < 20,000$ where β is the Stokes parameter based on the cylinder's diameter.

The Mixing Layer Instability of Wind Over a Flexible Crop Canopy

FSM4L_11801
Thu • 12:20 • 124

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(2) *UEPF, INRA, Lusignan, France*

Wind flow over vegetal canopies is characterized by large scale coherent stuctures propagating over the crop surface. Those structures result from an instability mechanism similar to a mixing layer. It leads to oscillatory wind induced plant motions. A coupled fluid-stucture model is proposed to study the dynamics of a flexible crop canopy exposed to wind. The canopy is represented by an elastic continuous medium and coupled to the wind mixing layer through a drag load. The mixing layer instability is shown to remain the principle instability mechanism but its characteristics are modified when taking into account the flexible canopy. The size of the coherent structures is decreased as well as the instability growth rate.

PIV Experiments on Vortex Induced Vibrating Cylinders at High Reynolds Numbers

FSM4L_12956
Thu • 12:40 • 124

John Grue, Odin Gramstad, Arnaud Sanchis
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PIV measurements of the flow at rigid (horizontal) smooth or roughened cylinders of diameter 0.08 m, mounted to springs, moving with constant speed in a water tank of dimensions (25 m, 0.5 m, 1 m) (length, width, depth) are carried out at Reynolds number 100.000. The cylinder is allowed to vibrate in the cross-flow and in-line directions. The local turbulence distribution, the turbulent production, the Reynolds stresses, the eddy dissipation rate, and the various terms contributing to the turbulent kinetic energy budget (TKEB) are extracted from the PIV analysis. Detailed study of the flow separation and movement of the separation point at the shoulders of the cylinder is performed as well as recording the forces.

On a Fluid-Elastic Isotropic Cusped Plate Interaction Problem

FSM4S_10215
Thu • 14:30 • 000B

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For the last decades the direct and inverse problems connected with the interaction between difference vector fields have received much attention in the mathematical and engineering scientific literature and have been intensively investigated. They arise in many physical and mechanical models describing the interaction of two different media. A lot of authors have considered and studied in details the direct problems of interaction between an elastic isotropic body occupying a bounded region $\overline{\Omega}$ with a smooth boundary and some isotropic medium occupying the unbounded exterior region, namely the compliment of Ω with respect to the whole space. Our aim is to determine transmission conditions for thin elastic cusped plate-incompressible fluid interaction problems and to investigate the corresponding problem of vibration of a plate caused by the flow of the fluid.

Influence of the Circular Cylinder Cross-Sectrion Variation on the Near Wake Behaviour

FSM4S_10379
Thu • 14:35 • 000B

Oualli Hamid(1), Hanchi Samir(2), Boubdallah Ahcene(1), Radomir Askovic(3)
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(3) *LME UHVC, Valenciennes, France*

Flow past a circular cylinder started impulsively into radial vibration is investigated by visualizing the flow patterns by smoke release and by analyzing qualitatively (flow topology) and quantitatively (PIV and anemometry measurements) the corresponding images. The considered Reynolds numbers range corresponds to the subcritical regime (10 000<Re<70 000). The details of the mechanisms of the near wake shedding are particularly considered and the actuation influence on the flow behaviour are pointed out. The drag coefficient decreasing to reach negative values propelling thus the cylinder is confirmed by the numerical results obtained by solving the Navier–Stokes equations. Furthermore, the new phenomenon of radial flow creation by diameter increasing-decreasing motion and primary vortices coalescence and dislocation have been identified in the near wake region. The analysis of flow properties such as drag and vorticity provide important information on the validity of a new cylinder wake control technique proposed herein and which can be extended to unsteady separated flows around bluff bodies.

Coupled Frequancies of a Fluid-Structure Interaction Cylindrical System

FSM4S_10520
Thu • 14:40 • 000B

Elena Gavrilova
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An upright fixed circular cylindrical tank with rigid bottom and side wall, where as a part of the side wall is an axial-symmetrical vibrating thin shell with clamped edges, is partly filled with an incompressible and inviscid fluid. The fluid motion in the tank is supposed to be axisymmetrical and potential. Using the Bubnov-Galerkin method, the analytical solution of the problem about the determination of the free coupling vibrations of the obtained fluid–structure interaction system is found. The performed numerical calculations show that the elastic part of the tank side wall lowers the natural frequency in comparison with the case of the rigid tank as the coupled frequency increases with the increase of the shell thickness and decreases with the increase of the fluid depth.

Fluid Structure Interaction in Multiphase Mixing Vessel

FSM4S_10826
Thu • 14:45 • 000B

Matej Vesenjak, Zoran Ren, Matjaz Hribersek
University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia

In this paper a problem of fluid-structure interaction in a mixing vessel is solved with weakly coupled fluid-structure interaction computational analysis. The computational fluid dynamics code CFX, based on the finite volume method, is used for determination of the multiphase flow field (water and air) in the mixing vessel. The results in form of pressure distribution are then applied to the blade model, which is then analysed with the finite element structural analysis system MSC.visualNastran for Windows. The resulting deformations and stresses are evaluated. The proposed procedure can be effectively used for optimization of structures with significant fluid flow influences.

Piston Impact Onto the Boundary of Two-Layer Fluid

FSM4S_10911
Thu • 14:50 • 000B

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The plane unsteady problem of fluid flow caused by impact onto its boundary is considered. Initially fluid is at rest and occupies a lower half-plane. The fluid consists of two horizontal layers with different densities and sound velocities. Displacements of the upper boundary are prescribed. The fluid flow is described within the acoustic approxima-tion. This approximation is valid for impact speeds well below the me-dium's sound velocity and for times, when displacements of the rigid boundary are small compared to the thickness of the upper layer. For the special case of practical importance, when impact velocity is a step function, both the velocity potential and the distribution of hydro-dynamic pressure along the upper boundary of the fluid are obtained in the forms of series at any time instant. This allow us to study peculiari-ties of the impact process for different parameters of the liquid layers.

The Cross-Flow Over a Pair of Staggered Cylinders

FSM4S_11263
Thu • 14:55 • 000B

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An experimental investigation of the cross-flow past a pair of staggered circular cylinders, with the upstream cylinder subject to forced harmonic oscillation transverse to the flow direction, is presented. Flow-visualization and hot-film wake spectra are reported for Reynolds numbers, based on upstream velocity and cylinder diameter in the range $1440 < Re < 1680$. The longitudinal separation between cylinder centres is $L/D = 2.0$, with a transverse separation (for the mean position of the upstream cylinder) of $T/D = 1.0$. The oscillation of the upstream cylinder causes considerable modification of the flow patterns compared to what is obtained when the cylinder is fixed; depending on the frequency of oscillation, lock-in between the wake periodicity and the cylinder motion occurs. Indeed, two distinct types of wake synchronization are identified, where either the shear-layer shedding frequency or the frequency of the combined wake synchronize with the oscillation frequency.

Interaction of Oscillating Flow with a Pair of Side-By-Side Square Cylinders

FSM4S_11668
Thu • 15:00 • 000B

Ming-Jyh Chern, Ji-Zen Lu
Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan

The main purpose of this study is to investigate the interaction of vortices induced by two square cylinders in an oscillatory flow. Unsteady variation of vortices are obtained using the numerical calculation and the experimental approach. Flow fields are visualized using numerical and experimental results. The variation in vortices depends on the gap ratio, Keulegan-Carpenter number and Reynolds number. Several modes in flow fields are found due to variation of these parameters. Strong interaction between two vortex system induced by two square cylinders are observed in small gap ratios and high Keulegan-Carpenter numbers. The flow in the gap plays a very important role in the interaction.

An Updated Arbitrary-Lagrangian-Eulerian Description in Continuum Mechanics and Its Application to Nonlinear Fluid-Structure Interaction Dynamics

FSM4S_11833
Thu • 15:05 • 000B

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An updated Arbitrary-Lagrangian-Eulerian (UALE) coordinate system is proposed to solve problems in continuum mechanics. It is compared to and distinguished from an ALE system. The governing equations in differential and integral forms in an UALE system are derived. A key feature of the UALE system is that the current position coordinates defined in a Cartesian Eulerian Spatial System (CESS) are chosen as the reference coordinates to investigate the motion of the continuum. When the reference point moves to a new position, the reference coordinates are updated to the new position coordinates in CESS. This UALE system and the updated Lagrangian (UL) system have the same base vectors as the CESS at each point in space, which provides a convenient way to overcome fundamental difficulties occurring in a nonlinear fluid-structure analysis. In the fluid's UALE system and the solid's UL system in solids, variational principles and a mixed finite element − finite volume approach for nonlinear fluid-structure interaction dynamics are developed and formulated.

Slender Body Theory Approach to Nonlinear Ship Motions

FSM4S_11912
Thu • 15:10 • 000B

Edwin J. Kreuzer, **Wolfgang M. Sichermann**
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The accurate prediction of large amplitude ship motions poses still a delicate problem in the field of fluid-structure interaction. While three-dimensional panel methods have reached the state of maturity in linear seakeeping analysis, the original problem, governed by strongly nonlinear boundary conditions, is far from being solved efficiently. This paper presents a solution method for the time-domain investigation of nonlinear heave and pitch motions of ships in head seas. It is implied that the wave patterns around the ship are described sufficiently by potential flow. Further, the slender body assumption for ships is employed in order to decompose the three-dimensional flow problem into a series of consecutive two-dimensional problems where the nonlinear character is retained. The numerical integration of the ship motions is complicated by the impulsive character of the hydrodynamic forces so that special care has to be taken with respect to efficiency and stability of the integration scheme.

Inverse Magnus Force in Free Molecular Flow

FSM4S_11986
Thu • 15:15 • 000B

Andrzej Herczynski[(1)], Patrick Weidman[(2)]
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A particle interaction model is introduced for calculating the sidewise force on spinning projectiles in a rarefied gas. The simple method reproduces the result obtained recently by Borg, Söderholm and Essén for a sphere using probabilistic calculation, and can be extended to other shapes and also to flows with shear. For high Knudsen number uniform flows, the sidewise force on spinning and translating objects is in the opposite direction to the classical Magnus force in continuum flows. This inverse Magnus force is calculated for cylinders and right parallelepipeds of various section. For a sphere, a cylinder, and parallelepipeds of regular polygon section with even number of sides, the force is steady and proportional to one-half of the mass of gas displaced by the body. We hypothesize that this is a universal property of a class of planar objects having convex section with two perpendicular axes of reflectional symmetry.

Effect of an Oscillating Cylinder on a Neighbouring Cylinder Wake

FSM4S_12521

Thu • 15:20 • 000B

Y. Yang[(1)], **Y. Zhou**[(2)], Z. Guo[(3)]

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This work aims to investiagte numerically how an oscillating fluid-structure system influences vortex shedding from a neighbouring stationary cylinder. The numerical technique employed is a newly developed lattice Boltzmann method. The calculation was carried out at Re = 150 for a two-dimensional fbw around two side-by-side circular cylinders, one oscillating laterally at an amplitude A/d = 0   1 and frequency fe/fo = 0.4   1.6. The cylinder centre-to-centre spacing T/d varied from 1.8 to 3.5. The numerical data reconfi rm previous experimental fi nding that the oscillation of one cylinder can lock in vortex shedding from a neighbouring stationary cylinder as well as from the oscillating one. It is further found that the fe/fo range over which the locked-in response is observed grows as A/d increases. As T/d increases, this range shrinks at a fi xed A/d because of the fading oscillating influence. Furthermore, the dependence of typical fbw structures, drag and lift on A/d, fe/fo and T/d are also examined.

FSM5

Mechanics of foams and cellular materials

Chairpersons: S. Hilgenfeldt (Netherlands), D. Weaire (Ireland)

Bubble Shapes in Foams: The Importance of Being Isotropic

FSM5L_10597
Wed • 11:00 • 144

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Foams, and by extension a whole class of random cellular materials are characterized by minimizing total interfacial area between the cells. Both structure and evolution of such materials by aging (coarsening) are ill-understood because of our lack of knowledge of the cell geometry. Combining Plateau's rules and certain symmetry requirements, we analytically determine the geometry of generic polyhedral cells we call Isotropic Plateau Polyhedra (IPPs). Their properties, such as surface area, edge length, or coarsening rate, are exactly known and very close approximations to the corresponding properties of average, random foam bubbles. Certain IPPs can also be found experimentally in soap foam. We show that measuring the coarsening rate of these bubbles allows for the simple computation of the soap film thickness, which is found to vary with foam age.

Mechanics of Bidimensional Liquid Foams

FSM5L_11095
Wed • 11:20 • 144

Benjamin Dollet[(1)], François Graner[(1)], Catherine Quilliet[(1)], Miguel Aubouy[(2)], Florence Elias[(3)]

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(3) *Laboratoire des Milieux Désordonnés et Hétérogènes, Université Paris, France*

An experimental study of foam flow is presented. A 2D foam is confined between a soap solution and a glass plate. It flows through a channel around an obstacle. This device enables to perform simultaneously external sollicitation, measurement of the response force and image analysis. We perform a systematic study of the drag exerted by the foam on the obstacle, *versus* the experimental control parameters: flow rate, bubble size and fluid fraction. Simultaneously, local velocity and stress fields are measured; we also measure a statistical strain field. The comparison of both types of measurements enables to study the link between local events and the global mechanical behaviour of the foam.

Average N-hedra as Descriptors of 3D Network Cells

FSM5L_11240
Wed • 11:40 • 144

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Space filling in 3-d networks is both basic and of long-standing interest. Network cells represent physical entities, such as grains in polycrystals or bubbles in foam. Topology and integral geometry impose requirements that the total spherical image for network cells is conserved. The theory represents cells with N neighbors by proxies called average N-hedra, satisfying space filling and equilibrium. Average N-hedra are symmetric topological equivalents of network cells. Analysis yields estimates of the metrical, energetic, and kinetic properties for isotropic foams and polycrystals as functions of the number of neighbors, N. Kinetics for area rates of change in 2-d networks (von Neumann-Mullins) has an exact analog in 3-d: $\frac{dA}{dt} = -\gamma M \oint_{faces} K dA$, where γM is the reduced boundary mobility, and K is the Gaussian curvature. Similar analogs exist in 3-d for the total network free energy. Additional expressions for the volumetric rates of change are found and checked accurately against simulation data.

Foam Drainage on the Microscale

FSM5L_11497
Wed • 12:00 • 144

Stephan A. Koehler
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Although foam drainage occurs on the microscale, i.e. the level of individual channels and nodes, most experiments have been performed on the macroscopic scale at the level of many bubbles. Various different mean-field models have been developed which differ in their assumptions of the fluid flow on the microscale, which until recently could not be verified. Novel foam drainage experiments on the scale of individual channels are presented, which confirm the model of Leonard and Lemlich, that the surface viscosity sets the interfacial mobility. Analytical solutions for the flow rates through the channels are given, which are a key ingredient for developing a complete macroscopic description of foam drainage.

On the Crushing Response of Open Cell Foams

FSM5L_11605
Wed • 12:20 • 144

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Center for Mechanics of Solids, Structures & Materials, University of Texas, USA

The compressive stress-displacement response of foams exhibits a characteristic three regime shape. Initially the response is stiff and linear; this terminates into a limit load followed by an extensive load plateau which governs the foam's energy absorption capacity. Through a combination of experiment and analysis on open cell polymeric foams, it was established that elastic buckling involving interaction of global modes and modes at the cell level are responsible for the stress plateau. The foam is idealized to be periodic using Kelvin cells which are elongated in the rise direction. The ligaments are straight with variable Plateau border cross sections. The initial response, the onset of instability and the initial postbuckling response have been established through characteristic cell type-models discretized with FEs. The localization of deformation, its spreading and the associated stress plateau are reproduced using large scale finite size type models involving a large number of cells.

Dissipation in 2D Foam Flow

FSM5L_12052
Wed • 12:40 • 144

Isabelle Cantat, Renaud Delannay
Rennes University, France

We study the dynamical behavior of large bubbles embedded in the plug flow of a 2D foam made of smallest bubbles. At a critical velocity the foam structure becomes instable and the largest bubbles migrate through the foam faster than the mean flow. This size segregation is due to viscous effects and happens only for flow velocities larger than a given threshold. We compare our theoretical predictions (Cantat, Delannay, Phys. Rev. E. 2003) to experimental and numerical recent results and thus we give a extended description of this original instability involving the full visco-elastic properties of the foam. We show that the phenomenon can induce flow destabilization with dramatic effects on foam transport, like avalanches of film ruptures and flow intermittency.

Surfactant and Protein Foams: Differences in Drainage and Rheology

FSM5L_12212
Thu • 09:30 • 144

Arnaud Saint-Jalmes, Sebastien Marze, Dominique Langevin
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We report results on drainage and rheology of aqueous foams made either with small classical surfactants, or large protein molecules, or the mixture of these 2 compounds. These chemicals provide different mechanical conditions at the surfaces of the bubbles, as well as different thin film structures. We have evidenced differences in foam drainage and mechanical properties. Bulk and surface rheology, multiple light scattering techniques (static and dynamic modes), thin film microscopy have been used to extract information at all the length scales within the foam, allowing us to eventually find the origins of the different macroscopic behaviors. Different drainage regimes have been found, illustrating the important role of the interfacial mobility within the foam skeleton (channels and nodes). For rheology, the thin film structure is important: thick gelified protein films provide complementary storage and loss contributions, resulting in more brittle foams. The case of the mixture illustrates complex interfacial adsorption competition between small and large molecules.

Determining Stress During Finger Propagation in 2D Foams

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FSM5L_12373
Thu • 09:50 • 144

We investigate the formation of fingering patterns in a radial Hele-Shaw cell filled with quasi-two-dimensional polydisperse foam of very small liquid content. Air is used as the low-viscosity driving fluid. Using high speed imaging (up to 2000fps), we directly observe the topological rearrangements on the size scale of single bubbles at the air-foam interface. We find that the growth process of the finger can be discretized as successive elementary T1-type edge exchanges between neighboring bubbles at the interface of the advancing finger. Apart from the rate of T1 events, other statistical quantities can be determined with good spatial resolution using a coordinate system moving with the finger. Measures of local bubble anisotropy (such as the texture tensor) and connectivity are used to determine the deviatoric stress tensor in the material. The data are compared to continuum results in the viscous liquid and elastic solid limits, shedding light on the continuum behavior of foam as a viscoelastic material.

The Dispersion of Particles within Foams

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FSM5L_12851
Thu • 10:10 • 144

Particle motion within foams or froths is of great importance to processes such as mineral flotation. One of the aspects of this motion is the dispersion of unattached particles relative. This paper examines this dispersion. The main focus of this paper is the dispersion in the direction parallel to the net fluid motion. This dispersion is brought about due to the velocity profiles found within individual Plateau borders and is thus referred to as Plateau border dispersion. It was found that, despite the laminar nature of the flows, there was sufficient radial mixing within individual Plateau borders that the dispersion profiles were very much like those found for diffusion, rather than the more angular profile that would be expected for purely convective dispersion. A Peclet number with the radius of curvature of the Plateau borders as characteristic length scale was found to be appropriate for characterising this dispersion. This Peclet number was found to be constant w.r.t. both the bubble size and the Plateau border Renolds number. The Peclet number obtained in this work for both particle and liquid dispersion was found to be about 0.15.

Drainage of Emulsion and Foam Films in Scheludko–Exerowa Cells

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FSM5L_12435
Fri • 09:30 • 219

Thin liquid films are fundamental components in a variety of industrial processes including foam manufacturing and oil exploration. Improved understanding of the drainage is essential for accurate predictions of the stability and lifetime of a film. Numerous fundamental studies of thin films have been conducted in Scheludko–Exerowa cells, in which a biconcave foam or emulsion film is created by suspending a thin liquid film across a gas filled or liquid filled tube. Using optical probes, the film thickness can be measured as a function of time with high precision. In this paper, predictions of drainage times from the lubrication theory of Reynolds and the Manev–Tsekov–Radoev (MTR) theory are compared to experimental measurements obtained from numerous investigators. A semi-empirical equation consistent with MTR theory is described and is shown to be most consistent with a broad range of experimental data.

Shear-Induced Normal Stress Differences in Aqueous Foams

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FSM5L_12578
Fri • 09:50 • 219

Using a special purpose rheometer equipped with a cone-plate geometry, we have studied the first normal stress difference N1 of aqueous foams of different physico-chemical characteristics, subjected to an oscillatory shear strain. We show that for small strains, N1 depends on the rheological history of the foam sample, and that this memory effect can be at least partially suppressed by pre-shearing. Our results are compatible with the relation N1=s g, known to hold for any nonlinear elastic material, where s and g denote the shear stress and strain. This agreement is non trivial since aqueous foams are

viscoelastic. Moreover, we observe that this relationship is approximately valid even in the viscoplastic regime, close to the yield strain. These findings are discussed in the context of recent numerical simulations and constitutive models.

Transient Displacement of Viscoelastic Liquids by Air

FSM5L_12858
Fri • 10:10 • 219

Yiannis Dimakopoulos, **John Tsamopoulos**
Department of Chemical Engineering, University of Patras, Greece

We examine the transient displacement by air of viscoelastic liquids, which occupy axisymmetric tubes either completely or partially, as it arises in the Gas-Assisted Injection Molding (GAIM) Process. For the simulations we combine our recently advanced quasi-elliptic grid generation scheme for computing the highly deforming liquid boundaries, the mixed finite element technique and the Discontinuous Galerkin method for computing the viscoelastic stresses. In our parametric study we examine the effects of the elastic and inertia forces, and the solvent to polymer viscosity ratio. Results using the PTT and Giesekus constitutive models show that the thickness of the remaining film increases as the Deborah number increases and remaining fluid fractions greater than 0.60 (the Newtonian limit) arise, in agreement with experiments. Increasing the viscosity ratio decreases the effects of elasticity. Similar is the effect of the Reynolds number which may also result in variable film thickness and a tip splitting instability.

Modelling the Round-off and the Tensile/Compressive Failure Behaviour of Plant and Vegetable Tissues

FSM5S_11292
Tue • 14:30 • 000D

H.X. Zhu
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Plant and vegetable tissues are treated as a lattice of identical 3D hexagonal cells, which are turgored and glued by a layer of the middle lamella pectin. The cell walls are treated as an anisotropic rubber-like material and the layer of the middle lamella pectin is treated as a set of one-dimensional springs made of a rubber-like material. Based upon the above mechanical model, the following works have been carried out: a) the cell round-off behaviour is modelled by looking at the deformed cell structure upon the continuously increasing turgor pressure; b) for a given turgor pressure, the mechanical response of the cells to the applied tensile/compressive stress has been simulated. All the possible failure mechanisms have been analysed, and the effects of the initial turgor pressure on the results a) and b) are discussed.

A Statistical Mechanics Theory of Random Honeycomb and Open-Cell Foam Structures

FSM5S_11663
Tue • 14:35 • 000D

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Honeycombs and foams are examples of advanced engineering materials with random structures. Because of structural randomness, the internal force distribution in these materials due to external loadings would not be uniform, yet existing failure criteria of these structures are derived from mean-field considerations in which the structural randomness is not explicitly taken into account. In this work, finite element simulations are used to investigate the force distributions in stressed random honeycomb and open-cell foam structures. A statistical-mechanics-based theory is also presented to describe the force distributions. The key in this theory is the use of an entropy functional, analogous to the Shannon entropy in Information Theory, to describe the structural randomness. The theory predicts the internal force distributions to be Gaussian for hydrostatic or pure shear loading, and convolutions of Gaussian functions for other load mixities. Agreement with finite element results is excellent.

Nucleation of Cracks in Two-Dimensional Periodic Cellular Material

FSM5S_11880
Tue • 14:40 • 000D

Michael Ryvkin, Moshe Fuchs, Fabian Lipperman
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The brittle fracture behavior of cellular material modeled as 2D regular beam lattice is examined. The lattice is subjected to remote uniaxial or isotropic tensile loading and flaw development from failure of a single beam element to a macrocrack(s) produced by multiple beam breaks in sequence is observed. Employing the representative cell analysis method based on the discrete Fourier transform enabled to obtain the exact solution for infinite lattices of different topologies without any simplifying assumptions. Lattices with triangular, square and hexagonal cells are considered. The obtained fracture patterns

are in agreement with results on fracture toughnesses which were calculated separately. The revealed influence of the material microstructure on the crack propagation direction show that in cellular materials, in contrast to homogeneous ones, the condition of zero Mode II stress intensity factor can not be employed for predicting the crack propagation path.

Thermal Flow through Brazed Woven Screens

FSM5S_12395
Tue • 14:45 • 000D

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(2) *Materials Science Department, University of Virginia, USA*

The heat transfer performance of a novel type of periodic cellular structures, woven screens made by transient liquid phase bonding, is experimentally characterized under forced air convection. The experimental results for pressure loss and heat transfer are expressed on the basis of channel height, and are compared with other cellular materials. The effects of cellular morphology, porosity, material make (copper and stainless steel) are studied. Friction factor is found to mainly depend on porosity or open area ratio. Characteristics for heat transfer include solid thermal conductivity, porosity and surface area density. Analytical models are subsequently developed to predict the pressure loss (pressure drag model) and heat transfer performance (fin analogy model) for different textile geometries, with good agreement between prediction and measurement obtained. Compared with other heat exchanger media, the periodic copper structures have similar heat transfer performance as that of stochastic metal foams, but the overall performance of the former is superior due to lower pressure loss.

Iinvestigation of Foam Development in Porous Media Using X-Ray Computed Tomography

FSM5S_12986
Tue • 14:50 • 000D

Quoc P. Nguyen, Peter K. Currie, **Pacelli L.J. Zitha**
Delft University of Technology, Faculty of Applied Earth Sciences, The Netherlands

The development of foam when mixtures of gas (N2 or Xenon)-surfactant (sodium dodecyl sulfate) solutions flow in a granular porous media (diameter = 4.5 cm, length = 18 cm) containing a surfactant solution has been investigated with the aid of X-ray computed tomography (CT). The evolution of the fluid distribution is presented. Liquid fractions determined from the CT images are presented. The liquid fraction profiles exhibit essentially a similar trend: (1) a low (less than 55%) upstream liquid saturation, (2) a high (100%) downstream liquid saturation, and finally (3) a transition zone where the liquid saturation increases smooth and rapidly towards the downstream. Within the upstream region the liquid saturation declines gradually from the inlet. For example, at t = 0.61 (dimensionless time) the liquid fraction decreases by almost 10% from the inlet to the position at 7.5 cm. The further decrease of the liquid fraction (secondary desaturation) manifests itself more clearly after the leading edge of the foam displacement front reaches the outlet of the porous medium. At a fixed position, for example at 12.0 cm, the saturation decreases over time, from about 38% to less than 18%. Even at the position 2.0 cm, where the steady state profile indicates that much liquid still remains in the core, the liquid saturation decreases from 55% to 48%. An interpretation of these observations is developed based on novel ideas about foam rheology.

FSM6

Multiscale phenomena in mechanics

Chairpersons: A. Carpinteri (Italy), C. Miehe (Germany)

Multi-Scaling Approach in the Mechanics of Disordered Materials

FSM6L_11224
Wed • 08:30 • 124

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Several theories have been proposed in the last decades, in order to describe the scaling of mechanical properties in solid mechanics, particularly the brittle-ductile transition as the structure size increases. Among them, the only approach that encompasses coherently the size-scale effects not only on strength, but also on fracture energy and on the critical displacement, is the fractal one. It is based on the assumption of a fractal-like damage localization at the mesostructural level. This fractality evidences the size scale effects and permits, by using a renormalization procedure, to define new fractal quantities, which are the true material properties governing the failure mechanism independently of the structural size. These quantities permit to introduce a scale-independent (fractal) cohesive crack model, which overcomes the original cohesive crack model drawbacks. Moreover, the fractal quantities allow, by means of fractional calculus, to write the Principle of Virtual Work for fractal media. Eventually, the fractal model is applied to some experimental data.

A Geometrical Theory of Discrete Dislocations in Lattices, with Applications to Dislocation Dynamics and Crystal Plasticity

FSM6L_11471
Wed • 08:50 • 124

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The mechanics of crystal lattices containing dislocations can be expressed in terms of fields that are supported on the lattice itself, e. g., the displacement field and the energy density; and fields that are defined on certain ancillary lattices, e.g., the eigendeformation fields which describe the dislocations. In the harmonic approximation, the energy is a quadratic form in the displacement field and the eigendeformations. At fixed dislocation density, the displacement field of the crystal lattice follows by energy minimization. We show that the structure of the resulting mechanics of defective lattices can be streamlined and given a compelling interpretation in terms of a discrete version of homology and differential calculus. The resulting differential operators generalize the conventional differential operators of exterior calculus in a manner which reflects and takes full account of the structure of the crystal lattice. Based on this mathematical framework, we generalize to lattices classical constructs and relations from the geometrical theory of continuously distributed dislocations, such as the notion of Burgers circuit and slip system; and Frank's and Kroner's formulae. We also show how the forest-hardening model can be phrased in terms of certain topological invariants. We illustrate the versatility of the theory by means of a number of selected applications, including: core energies of bcc dislocations; the dislocation field of an expanding nanovoid; and the dislocation structures selected by the forest mechanisms and the attendant hardening rates.

Stress-Defect Interactions at Molecular/Continuum Scales

FSM6L_11476
Wed • 09:10 • 124

Mathieu Bouville, **Krishna Garikipati**, Michael Falk
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External stress on a crystal affects the Gibbs free energy of formation and migration of point defects, thereby lowering/raising defect concentrations and mobilities. This effect is determined by the volume change of the crystal-for defect creation it is the formation volume, Vt. Lattice distortion at the defect itself can only be predicted by atomistic simulations, not by continuum elasticity. However, this distortion, represented as a dipole tensor of forces in continuum elasticity, determines the far-field deformation, and hence Vt. For the vacancy in silicon, we have quantified Vt by such studies, using the Stillinger-Weber empirical potential at atomic scales and elasticity at continuum scales. We also have treated issues

related to bridging these scales, obtained consistent interpretations of parameters, identified the limitations of continuum, molecular and ab initio calculations, and found overall agreement with relevant results by Eshelby.

Deterministic Size Effect in the Strength of Cracked Quasi-Brittle Structures

FSM6L_11806
Wed • 09:30 • 124

B.L. Karihaloo, H.M. Abdalla, Q.Z. Xiao
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This paper is concerned with the quantification of the deterministic (as opposed to the statistical) size effect in the strength of cracked quasi-brittle structures. This effect is believed to be a result of stress discontinuities and redistribution introduced by the cracks. Quasi-brittle materials are characterized by the presence of a large fracture process zone (FPZ) ahead of a crack in which the material softens. The FPZ is captured within a nonlinear theory of fracture in the so-called fictitious crack model (FCM) which has its origin in the Barenblatt-Dugdale cohesive zone concept. In the FCM, the FPZ ahead of a real crack is replaced with a fictitious crack in which the material exhibits softening described by a stress-crack opening relationship. As the size of FPZ can be commensurate with that of the structure, it is necessary to consider not only the singular term in the asymptotic field at the real crack tip but also higher order, non-singular terms, in order to describe stress distribution in the FPZ. This necessitates determination of these higher order terms, as well as of the required weight functions for finite size specimens that can be tested in a laboratory. This has been done in present work. The results of this theoretical work have been found to be in excellent agreement with test data in the limited range of sizes tested in the laboratory. The theoretical results have been extended to cover the very large size range of 1:80. Based on these results, a deterministic strength size effect formula that is very simple to use in the size range 1:80 has been proposed. In agreement with experimental observations, this formula predicts that the deterministic strength size effect weakens as the size of the crack reduces relative to the size of the structure but it becomes stronger as the size of the structure increases but never stronger than that predicted by linear elastic fracture theory.

Multi-Scale Second-Order Computational Homogenization of Heterogeneous Materials

FSM6L_11830
Wed • 09:50 • 124

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A novel second-order computational homogenization scheme suitable for the multi-scale modelling of macroscopic localization and size effects is proposed. The second-order scheme is an extension of the classical computational homogenization framework and is based on a proper incorporation of the gradient of the macroscopic deformation gradient tensor into the kinematical macro-micro scale transition. From the microstructural analysis the macroscopic stress and higher-order stress tensors are obtained, thus delivering a microstructurally based constitutive response of the macroscopic second gradient continuum. As an example the approach is applied for the multi-scale analysis of macroscopic localization in a microstructurally perforated plate and simple shear of a constrained heterogeneous strip, where a pronounced boundary size effect appears. The distinct role of the size of a representative volume element, which in the second-order computational homogenization framework is related to the length scale of the macroscopic homogenized continuum, is discussed.

Jumping of a Spinning Spheroid

FSM6L_11862
Wed • 10:10 • 124

Yutaka Shimomura(1), Michal Branicki(2), Keith Moffatt(2)
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As is well known, a hard-boiled egg will rise from the horizontal to the vertical if it is spun sufficiently rapidly on a table with its axis of symmetry initially horizontal. We consider here the problem of a spinning spheroid, and show that in certain circumstances the spheroid may lose contact with the table in the course of this rising motion. Allowing for slip and weak friction at the point of contact, the dynamical equations for a uniform spheroid, are treated by the multiple-scale perturbation method to resolve the two time-scales intrinsic to the dynamics. An approximate solution for the high frequency component of the motion shows a growing oscillation of the normal reaction, and predicts the circumstances in which this can fall to zero (leading to jumping of the body). The exact solution for the free motion after jumping and until contact with the table is reestablished. The analytical results agree well with numerical simulations of the exact equations.

Multiscale Analyses of Granular Media at Finite Strains Based on Micro-Macro Transitions with Different Boundary Constraints

FSM6L_12112

Fri • 09:30 • 124

Joachim Dettmar, Christian Miehe
University of Stuttgart, Institute of Applied Mechanics, Stuttgart, Germany

We consider a homogenized macro–continuum with locally attached discrete microstructure that may be represented by granular particles in soil mechanics or atoms in nanoscale mechanics of metals. Specific micro–macro transitions are derived by a consistent transfer of the discrete micro–variables to macroscopic field variables on a continuous macrostructure. On the microscopic side, the classical boundary conditions of homogenization theory of continuous structures are consistently transferred to their discrete counterparts. We show that those for linear displacements and uniform tractions on the surface yield upper and lower bound characteristics for the periodic boundary constraints with regard to the particle aggregate stiffness. Special attention is paid to the definition of the representative volume element which leads to specific constraints for both the displacements and rotations of the granules on the defined boundary frame. On the macroscopic side, the homogeneous problem is solved by a finite element method where the material model is implemented by directly evaluated micro–macro transitions based on the discrete microstructures for the case of periodic boundary constraints. The two–scale simulations are linked by solving coupled boundary–value problems on both the micro- and macroscales. Numerical examples are finally discussed which clarify the proposed method.

Exploitation of Incremental Energy Minimization Rinciples in Computational Multiscale Analyses of Inelastic Solids

FSM6L_12113

Fri • 09:50 • 124

Christian Miehe
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The lecture provides an overview about recent developments in the formulation and numerical implementation of incremental minimization principles for inelastic solids and their exploitation with regard to multiscale analyses of deformation microstructures. The point of departure is a general internal variable formulation for standard dissipative materials. Consistent with this type of finite inelasticity we outline a distinct incremental variational formulation of the local constitutive response where an incremental stress potential is obtained from a local minimization problem with respect to the internal variables. The existence of the incremental stress potential allows the formulation of IBVPs for standard dissipative solids as a sequence of incremental minimization problems. For this scenario, multiscale microstructure developments in stable and instable dissipative solids can be based on incremental minimization principles of homogenization and energy relaxation. These concepts are applied to conceptual model problems which treat multiscale microstructure evolutions in stable / instable and a priori heterogeneous / homogeneous elastic–plastic solids.

Physical Modeling of Fracture Mechanics in Complex Materials

FSM6L_12334

Fri • 10:10 • 124

Fabrizio Cleri(1), **Luciano Colombo**(2), Pier G. Gabrielli(1), Mariella Ippolito(2), Alessandro Mattioni(2)
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(2) *University of Cagliari, Cagliari, Italy*

The mechanical behaviour of brittle materials is very sensitive to microstructure defects, like point or extended lattice imperfections, elastic inclusions, voids. Since the local stress conditions (i.e. the conditions nearby a defect) may largely differ from their average values, the the prediction of the overall mechanical response to external loads results to the a though theoretical problem. This is, for instance, the case of the stress threshold at which a microcrack starts propagating, or the interaction features bewteen a defect and an incoming crack. In this work, we investigate at the proper nanoscale the interaction between a crack tip and elastic inclusions by combining a hierarchy of different computational tools, namely atomistic simulations (carried out at the molecular dynamics level) and statistical mechanics models (based on replica-symmetry breaking). The investigated material is silicon carbide, i.e. the prototypical example of brittle material with directional and covalent bonding.

Simulations of Micro- and Nano-Channel Flows by a Dissipative Particle Dynamics Method

FSM6S_10399
Thu • 14:30 • 000C

Justyna Czerwinska, Nikolaus A. Adams
Technical University, Dresden, Germany

The numerical modeling of micro- and nano-flows is very important for understanding micro-fluidics phenomena in industrial applications. However the methods, which are widely used, have various limitations. The continuum models cannot provide correct description of near wall behavior of fluids (no-slip boundary conditions is enforced). Molecular Dynamics approach is very expensive computationally. Therefore the industrial application is limited. In this paper we propose to model nano- and micro-flows by Dissipative Particle Dynamics.

Grad-Type Expansion About Nonequilibrium States for the Relaxion-Time Approximation of the Boltzmann–Peierls Equation

FSM6S_11237
Thu • 14:35 • 000C

Zbigniew Banach, **Wiesław Larecki**
Polish Academy of Sciences, IPPT, Warsaw, Poland

A new type of heat transport equations for transient processes under high thermal loads is derived from the microscopic, kinetic-theory description of a phonon gas. The Grad-type expansion of the phonon distribution function about the nonequilibrium anisotropic Planck distribution (called drifting distribution) is applied to the two-relaxation-time approximation of the Boltzmann-Peierls kinetic equation. Substitution of the truncated expansion into the corresponding system of moment equations results in a closed system of the evolution equations for the moments which involves two relaxation times, is nonlinear in the energy and in the heat flux, and depends linearly on the higher-order moments of the distribution function. Thus, the obtained theory conforms to the two time scales of the phonon gas relaxation processes and admits arbitrarily large heat fluxes.

Two-Scale Simulations of Epitaxial Surfaces

FSM6S_11340
Thu • 14:40 • 000C

Heike Emmerich(1), Christof Eck(2)
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(2) *University Erlangen-Nuernberg, Erlangen, Germany*

Spiral surface growth is well understood in the limit where motion of the spiral ridge is controlled by the local supersaturation of adatoms in its surrounding. In liquid epitaxial growth, however, spirals can form governed by both, transport of heat as well as solute. Here we propose a new two-scale model of epitaxial growth which takes into account all of these transport processes. Our model assumes a separation of time scales for the transport of heat compared to that of the solutal field. It allows for the first time for numerical simulations of extended surfaces regions by at the same time taking into account micro-structure evolution and micro-structure interaction. We apply this model successfully to extend the scaling relation for the step spacing given by the BCF theory to micro-structure evolution governed by heat and solutal transport. Applications of the model are illustrated by simulations.

Characteristics of Orientation and Grain-Size Distributions

FSM6S_12040
Thu • 14:45 • 000C

Luca Placidi, Kolumban Hutter
Darmstadt University of Technology, Darmstadt, Germany

We investigate the physical background of Crystal Size Distribution (CSD) and Orientation Distribution Function (ODF) as a useful tool for the analyses of mechanics of polycrystalline materials. The CSD can be used to evaluate the mean grain-size and the ODF gives important information on the degree of anisotropy. Our goal is to show that such distributions have two very important weak points. The CSD provides mean grain-size that depends upon the sensitivity of the microscope. Besides, a random distribution in terms of the ODF does not per se guarantee isotropy. Such shortcomings are overcome when the Theory of Mixtures with Continuous Diversity is applied. It uses in fact the concept of an orientation-and-grain-size mass density and models both, CSD and ODF, such that the cited shortcomings are overcome. Moreover, the evolution equation for the orientation-and-grain-size mass density is automatically given by the balance of mass and one is not forced to provide it in an ad hoc way.

Numerical Homogenization of a Locally Hyperelastic Constitutive Law

FSM6S_12078

Thu • 14:50 • 000C

Antoine Gloria, Claude Le Bris
CERMICS, École Nationale des Ponts et Chaussees, France

A lot of results are available in theoretical homogenization of nonlinear integral functionals. However not much has been done to develop and adapt the numerical counterpart of that multiscale theory in order to compute locally nonlinear composites. First one recalls the main results in nonlinear homogenization that can be applied to energy functionals. Then a multiscale strategy which is designed to deal with large deformations and nonlinearities is presented. Numerically testing the convergence rate of a sequence which is theoretically prooved to converge, one can define the size of a kind of representative volume. Knowing this size, it is possible to validate the numerical strategy. A first test is the computation of a composite material made of two rubbers forming a chessboard microstructure.

Non-Convex Homogenization of Inelastic Composites with Interaction of Material and Structural Instabilities on Different Scales

FSM6S_12118

Thu • 14:55 • 000C

Martin Becker, Christian Miehe
University of Stuttgart, Institute of Applied Mechanics

An effective approach to the modelling of micro-heterogeneous materials is the homogenization method where a representative volume element (RVE) is attached to each macroscopic point. In the case of structural instabilities on the micro-scale the complexity of the problem substantially increases and classical approaches hit their limitations. Goal of the presentation is to clarify the relation between micro- and macro-instabilities and to point out a procedure of non-convex homogenization affiliated to these instability phenomena. Both of these aspects have recently been extended from results in nonlinear elasticity to the incremental setting of finite inelasticity by the authors. This extension bases on the treatment of the homogenization analysis within the context of an incremental variational formulation which provides a quasi-hyperelastic stress potential. A lack of quasiconvexity of the homogenized potential indicates for a priori micro-heterogeneous materials the occurance of structural instabilities on the micro-scale. This leads to the problem of non-convex homogenization where the RVE-size enters the homogenization procedure as an additional variable. The size effect of the RVE and the interaction between micro- and macro-instabilities are discussed in representative numerical examples.

Analysis of a Variational Method Coupling Discrete and Continuum Machanics

FSM6S_12336

Thu • 15:00 • 000C

Xavier Blanc[1], Claude Le Bris[2], **Frederic Legoll**[2]
(1) *Laboratoire J.L.-Lions, Université Paris 6, Paris, France*
(2) *CERMICS, École Nationale des Ponts et Chaussees, France*

The description and computation of fine scale localized phenomena arising in a material (during nanoindentation, for instance) is a challenging problem that has given birth to some multiscale methods. In this work, we propose an analysis of a simple one dimensional method that couples two scales, the atomistic one and the continuum mechanics one. The method includes an adaptative criterion in order to split the computational domain into two subdomains, that are described at different scales. We study both the general case of a convex energy and a specific example of non convex energy, the Lennard-Jones case. In this latter situation, we show that in some sense the most natural approach might be inappropriate, and we propose a way around this difficulty. We also provide a numerical analysis of the corresponding numerical schemes.

FSM7

Education in mechanics

Chairpersons: R. Engel (USA), B. Karihaloo (UK)

Toys and Games in Mechanics Education

Hassan Aref
College of Engineering, Virginia Polytechnic Institute and State University, Blacksburg, USA

FSM7L_10003
Thu • 11:00 • 123

Toys and games have considerable educational potential. In mechanics certain toys and games that particularly lend themselves to analysis have been afforded comprehensive scholarly treatment. A number of toys and games that illustrate basic mechanical principles are presented Experiences in using toys and games for project work with undergraduates is recounted, and some ideas on how to expand the use of toys and games in an educational setting are presented. Examples of mechanical toys and games with relatively simple mechanical principles underlying them include the "Sand Wand", the "Ooze Tube", and the "Shoot the Moon" game/toy. More complicated dynamics is displayed in toys such as "Newton's cradle", "Slinky", the "Euler disk", "Tippe Top", and the rattleback (celt or wobblestone). Apart from analytical mechanics projects the world of mechanical toys opens up a number of "softer" questions that can be used to attract students into the fi eld of mechanics.

African Institute for Mathematical Sciences: a Capacity Building Initiative in Which IUTAM Has an Active Involvement

H.K. Moffatt
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FSM7L_10016
Thu • 11:20 • 123

AIMS (the African Institute for Mathematical Sciences) is an exciting initiative recently launched in Cape Town, South Africa. It involves a collaboration of three local Universities (University of Cape Town, University of the Western Cape, and Stellenbosch University) and the active support of the Faculty of Mathematics of Cambridge University. IUTAM is involved in this initiative through a grant awarded under the ICSU 2004 grants programme; the proposal had the support of fi ve sister International Scientifi c Unions (IUGG, IMU, IUPAP, IUPAC, and IAU), fi ve National Scientifi c members of ICSU (South Africa, Brazil, Egypt, Netherlands and UK) and TWAS (the Third World Academy of Sciences). A workshop on capacity building, involving representatives of the International Scientifi c Unions and representatives of many African States will be held at AIMS in April 2004. The lecture will report on the fi rst year of operation of AIMS, the conclusions of the workshop, and the uses to which the IUTAM grant has been put in support of this imaginative venture.

On Mechanics/Engineering Science Education

Carl T. Herakovich
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FSM7L_10226
Thu • 11:40 • 123

This paper discusses the role of mechanics and engineering science education in a re-engineered 21st century engineering education. The fundamental thesis of the paper is that mechanics education (at least in the United States) has not met the challenges presented by our rapidly changing society where science and technology has replaced engineering as the prime motivator of new ideas. The end result of this is that science and technology is more highly recognized and valued than is engineering. This is no more evident than in the levels of funding by the U.S. government and student enrollments for science and technology as compared with engineering. It is recommended that mechanics become more of an engineering science curriculum with a corresponding increase in courses outside the traditional realm of mechanics and engineering.

Multiimedia Fluid Mechanics: a Flexible Educational Tool for Teaching and Learning Fluid Mechanics

FSM7L_12467
Thu • 12:00 • 123

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This paper describes Multimedia Fluid Mechanics (Homsy, et al., Cambridge Univ. Press, 2001), a new, versatile multimedia tool for education in fluid mechanics. We discuss the pedagogical principles on which it is based, together with a description of many of its features. The presentation of this paper will include a demonstration of these features, with an emphasis on broad educational approaches that apply to all fi elds of Applied Mechanics.

Rigid Body Dynamics: Student Misconceptions and Their Diagnosis

FSM7L_12642
Thu • 12:20 • 123

D.L. Evans[1], Gary L. Gray[2], Francesco Costanzo[2], Phillip Cornwell[3], Brain P. Self[4]
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(2) *Engineering Science and Mechanics Dept., Pennsylvania State University*
(3) *Rose-Hulman Institute of Technology*
(4) *US Air Force Academy*

As pointed out by a rich body of research literature, students subjected to traditional instruction in math, science and engineering, often do not adequately resolve the misconceptions that they either bring to a subject or develop while studying a subject. That literature includes the fi eld of particle mechanics, but does not include rigid body mechanics. This paper presents results of research on the important, but troublesome-to-students, concepts in rigid body mechanics so that instructors in undergraduate dynamics courses can be more informed in the nuances and intricacies of student learning of this subject. Student focus groups conducted at three different universities have been used in this research, followed up by testing of students at an additional four universities. The results are being used in the development of an easy-to-administer, easy-to-score assessment instrument that can reveal whether these common misconceptions have been affected by instruction. The instrument, called the Dynamics Concept Inventory is patterned after the Force Concept Inventory (FCI) instrument of Halloun and Hestenes, which is in wide use in physics education.

Web-Based Instructional Units for Teaching Mechanics

FSM7L_12752
Thu • 12:40 • 123

Kamal B. Rojiani[1], Rakesh K. Kapania[2], Yong Y. Kim[2], Jing Li[2]
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A series of novel web-based instructional units that facilitate the teaching of basic concepts in mechanics are developed. The instructional units are delivered over the Web as HTML documents containing embedded Java applets. The instructional units are independent and self-contained and can be integrated in a variety of mechanics courses. Each instructional unit presents the fundamental concepts, theoretical background, instructions for running the Java applet, example problems, exercises and a feedback form. The advantage of providing these instructional units as web documents is that they can be accessed from anywhere. Examples of instructional units developed include Mohr's circle for two- and three-dimensional stress, shear center for open and closed thin walled sections, section properties of built-up sections and beam analysis. The advantages of using Java applets for teaching are discussed. The approach presented provides students with a dynamic interactive learning environment that can signifi cantly enhance their understanding of basic mechanics concepts.

Mechanics – a New Internet Tutor

FSM7S_11724
Thu • 14:30 • 000D

Aleksandr Kositsyn
Odessa State Academy of Civil Engineering and architecture, Dept. of Theoretical Mechanics, Odessa, Ukraine

In teaching theoretical mechanics there is quite often a gap between learning theoretical models by a student and comprehension of a possibility of their practical use. To help learning Mechanics, to show how abstract models work in engineering tasks, to make Mechanics more attractive are the basic ideas which were incorporated in the concept of the website Mechanics (URL: www.emomi.com). The history of engineering knows many cases when mistakes have resulted in serious consequences. The analysis of such incidents from the point of view of mechanics happens rather instructive. The site pages <Situations> and <Practice – theory> are devoted to such analysis. On-line control of skills on mechanics, applets,

educational literature, biographies of scientists, inventors, articles on a history of engineering and many other topics each one can explore on the Site, which one regularly fi lls up. The Site is useful for young educators too.

Teaching Mechanics as an Engineering Science in China

Yilong Bai
Institute of Mechanics, CAS, Beijing, China

FSM7S_11765
Thu • 14:35 • 000D

Promoted by Prof Tsien HS, the education in mechanics in China is made as an engineering science. And the graduates are trained to be between engineer and scientist. The main points are as follows. It is an independent discipline to bridge natural science and engineering. It is not only engineering, but concerns common issues in engineering. And it is a guide to new trades in industry, with new concepts, theories and methods. It is aimed at engineering. Since the objects are usually complex systems in practice, it is a necessity for the graduates to grasp the main governing mechanisms, to develop proper models and to get approximate conclusions in agreement with observations. The ability building should include mathematics as a tool, natural sciences as basis, being familiar with problems and methods in engineering and being able to extract the implications from practical problems to form natural laws.

Education and Tutorial on Fluid Mechanics on the Basis of Computer Laboratory

Vasily P. Yaremchuk, Mikhail K. Ermakov, Sergei A. Nikitin, Vadim I. Polezhaev
Institute for Problems in Mechanics, Russian Acedemy of Sciences, Moscow, Russia

FSM7S_11869
Thu • 14:40 • 000D

The paper presents experience in the education and tutorial in modeling of the diffusion, equilibrium stability and elementary fbws, heat and mass transfer with the use of the computer system COMGA (COnvection in MicroGravity and Applications). This system provides modeling of the free and forced convection on the basis of the Navier–Stokes equations (the Boussinesq approach). It was developed and systematically used in the Laboratory of the Mathematical and Physical Modeling in Fluid Dynamics IPM RAS since early of the 90th. The computer laboratory as the intellectual shell of this system was realized on the last stage of the development. It includes the microgravity and ground-based applications with the use of high performance personal computers. A paper is focused on the basic aspects of fluid dynamics and heat/mass transfer such as hydrostatic equilibrium, stability of the steady fbw, study of the elementary of the buoyancy-driven, surface-tension gradients driven and forced convecitve fbws and multi-parametric analysis. Applied tutorial for microgravity fluid mechanics and technological fluid dynamics are also presented.

Education in Mechanics in Latvia Higher Schools

Vitauts Tamuzs(1), Janis Viba(2)
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(2) *Riga Technical University, Institute of Mechanics, Riga, Latvia*

FSM7S_12259
Thu • 14:45 • 000D

The historical review of mechanics development in Latvia from 18. Century till to the present day is given. Engineer and inventor in the fi eld of rockets techniques Fridrihs Canders (1887–1933), which was born in Riga and graduate the Riga Politechnically institute (1914), is mentioned. The fi rst remarkable authors N. Rozenauers (1890–1970) of mechanics textbooks in Latvian language are mentioned also. Variations and birth of mechanical direction courses after Second World War are more considered. Is shown that the main learning subjects in the area of mechanics are included in study programs four large Latvia higher schools. The main scientifi cally and textbooks of mechanics, that are made and published by Latvian scientists and professors, are given. The main study programs and courses of mechanics in Latvian higher schools are mentioned.

Simulator, Nohguchi Bottle, of Soil Liquifaction for Education

Yasuaki Nohguchi
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FSM7S_12488
Thu • 14:50 • 000D

The phenomenon of liquefaction is one of the most interesting demonstrations for science education because it illustrates the strange behaviors that go beyond the realm of common sense. For this purpose we developed a simulator named Licky which can easily simulate this phenomenon any time, anywhere and on many occasions. The simulator comprises a closed bottle, fluid, granular material and some pins. This simulation is set up by shaking the bottle and by mixing the fluid and granular material. The liquefaction is generated by hitting the bottle, and as a result under certain conditions the pin rises to the surface of the sediment of the granular material and under other conditions sinks into the sediment. In this paper we introduce the fundamental theory of the law of similarity and the mechanism for setting up this apparatus.

Mechanics Education in Sweden

FSM7S_12603

Thu • 14:55 • 000D

Anders Bostrom
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The role of mechanics in engineering programs in the swedish university system is described in some detail. Recent and on-going changes, partly due to the Bologna process, are mentioned. This in particular involves a more clear division into batchelor, master and PhD levels, where traditionally the batchelor level has been missing in Sweden. On the master and PhD levels the quantity and quality of the students are more or less satisfactory and their performance is also good in general. On the batchelor level there are problems with many students performing too poorly. There is a great challenge in trying to change this, e.g. by new learning or examination methods.

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12348	62	12423	51	12502	26	12578	408	12664	271
12349	134	12424	195	12505	211	12579	211	12665	268
12350	334	12425	122	12508	126	12582	317	12666	249
12351	210	12427	36	12509	123	12583	76	12667	298
12354	245	12429	90	12510	80	12584	212	12669	348
12356	80	12430	183	12511	373	12585	141	12671	162
12358	310	12431	122	12514	279	12586	387	12673	32
12359	211	12432	28	12516	386	12587	156	12674	390
12361	33	12433	252	12518	310	12588	298	12675	180
12363	156	12434	242	12520	246	12590	100	12676	68
12364	342	12435	408	12521	405	12591	134	12678	223
12365	163	12436	178	12522	51	12592	101	12679	361
12372	122	12437	65	12527	386	12593	365	12680	293
12373	408	12438	141	12528	118	12594	266	12682	285
12375	175	12439	172	12531	297	12596	96	12684	298
12376	114	12440	160	12533	386	12598	127	12685	246

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