MULTIBODY DYNAMICS: BRIDGING FOR MULTIDISCIPLINARY APPLICATIONS

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Summary Simple or complex systems characterized by large relative motions between its components find in the multibody dynamics formalisms the most general and efficient computational tools for their analysis. Initially restricted to the treatment of rigid bodies, the multibody methods are now widely used to describe the system components deformations, regardless of their linear or nonlinear nature. The ease of including in the multibody models different descriptions of the contact problems, control paradigms, equations of equilibrium of other disciplines is demonstrated here to show the suitability of these approaches to be used for multidisciplinary applications.

MULTIBODY DYNAMICS METHODS AND INTEGRATION WITH OTHER DISCIPLINES

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.

FLEXIBILITY OF THE SYSTEM COMPONENTS

Multibody models for which the flexibility of the system components play a fundamental role in their behavior efficiently describe a large number of mechanical and structural systems of high importance. Vehicles, space satellites, deployable structures, machines operating at high speeds or robot manipulators are just some of the applications where the systems undergo large rigid body motion while their components experience structural deformations. The correct modeling of these systems requires that the formulations used in their description not only account for the motion and deformation of their components but also describe their inertial coupling. The methodology applied here uses an updated Lagrangean formulation to obtain the continuum mechanics equations of motion of a general flexible body. The finite element method is then used to obtain a representation of the flexible bodies suitable to the description of any general flexible component of the multibody system in a computational environment. The equations obtained at this stage are computationally inefficient due to their high nonlinearity. The use of a lumped mass formulation and a change of nodal coordinates lead to much simpler equations of motion, still accounting for the inertial coupling between large rigid body motion and the body flexibility. In the sequel of proposed methodology it is shown that if the flexible body material behavior is linear and the deformations are small the equations obtained can be greatly simplified by using the component mode synthesis. In order for the flexible bodies to be used in the multibody system model it is required that a set of kinematic joints, describing algebraic constraints between the system coordinates, are defined. The concept of virtual bodies provides a general framework to develop general kinematic joints. The application of the formulation proposed to the study of the comfort and stability of road vehicles allows appraising the treatment of the system deformations. The virtues and shortcomings of the formulation proposed are appraised through applications to vehicle structural impact cases and to highly deformable structures.

CONTACT MODELS FOR MULTIBODY DYNAMICS

The simulation of vehicles and structures under contact and impact conditions requires accurate descriptions of the structural and mechanical characteristics of the colliding bodies and suitable contact models. The models must be computationally efficient, especially if they need to be used in different stages of the design process. A formulation able to handle the large rigid body motion of the system components and their nonlinear deformations is discussed here. A continuous contact force model based on Hertzian contact, including energy dissipation, is shown to be suitable to handle both rigid and flexible body contact. A second model based in the addition and deletion of kinematic constraints between flexible body nodes and contacting surfaces is presented to represent flexible body impact. The friction forces are used with both contact models. The influence of the different contact and structural models in the system response is discussed through a simple application to the impact of a flexible beam. The suitability of the approach proposed for the design of complex multibody systems under impact conditions is further exemplified with an application to vehicle rollover, which involves all the major features of the formulation. Other type of applications where the contact force models play a fundamental role, and that are discussed here, are those concerned with railway dynamics.

BIOMECHANICS MODELING

The biomechanics, being in itself a multidisciplinary area, has its fundamentals in the scientific disciplines that deal with physiology and applied mechanics. The computer-aided modeling of the human body biological phenomena enables the designer to think, understand and decide the different stages of the design or of the analysis. The part of the biomechanics that deals with the motion of the human body allows for the integration of realistic models of the human body and of the phenomena associated to them in computer environments that range from the pure entertainment to the design of complex medical equipment for diagnosis or rehabilitation. The multibody dynamics formulations that support the biomechanical models for the study of human motions are described and presented here. The principles for modeling the human body motion through their large anatomical segments for the study of human gait, vehicle occupants in crashworthiness or athletic performance are reviewed in this work. It is shown through applications how these biomechanical multibody models enable the quantification of the potential for the injury of vehicle occupants during a crash or the internal muscle efforts of a person during different physical activities. In the process of discussing this type of applications, the use of the optimization procedures is presented for the solution of the muscle force sharing problem.

CONTROL OF MULTIBODY SYSTEMS

The use of multibody dynamics formulations to support the development of specific control models is exemplified here through applications to the automatic control of the angular orientation of a multibody system based upon the preservation of its angular momentum and to the development of a virtual driver for a vehicle running in a given track. The control strategy used for the human spatial attitude in a zero gravity environment is hierarchical and decentralized arranging the control stages in levels of attributions and complexity. At a lower level the controllers are responsible for handling each of the multibody degrees-of-freedom forcing them to follow prescribed reference motions through the use of error feedback. Middle level controllers coordinate the lower level controllers so that each of the multibody subsystems achieve prescribed reorientation. These reorientations are defined by a higher level controller with the final objective of reorienting the complete multibody system to reach a different attitude. The control laws associated with the controllers are parametrically adjusted for the biomechanical model under analysis. The results obtained are discussed in face of the modeling assumptions made and control laws used. The second application is to devise a multibody based methodology that allows for the design of a vehicle virtual driver, which can be used in the search of optimal vehicle trajectories for given manoeuvres. In order to achieve this objective it is necessary to have detailed vehicle and road models that can simulate with accuracy a driving scenario, to develop a proper control strategy for the vehicle, and to use a set of parameters of the detailed model that represent the interaction between the control model and the vehicle model. A simplified control model for the vehicle, which makes use of extended bicycle model, is implemented. The outcome of the controller based on the bicycle model is used to control a detailed multibody model of the real vehicle, including all suspension elements and tire/road forces, which provide the observed motion. The only variables that the control acts upon are the steering wheel angle and vehicle wheels' torques, which represent the traction and braking.

STRUCTURE-FLUID INTERACTION

The models for the fluid-structure coupling keep getting more and more advanced with the feasibility of complex 3D computations on fluid-structure interaction problems. Based on the work by Moeller et al. [12,13] this problem is solved by using a computer code aimed at simulating complex flexible multibody systems (linear elastic bodies) and another code aimed at the analysis of incompressible viscous flow. The types of problems that can be efficiently simulated in the framework of flexible multibody dynamics are elastic problems with gross overall displacements and rotations but small vibrations. Typical examples of this type of problems are wind turbines, helicopters and pumps. In the context of strongly coupled fluid-structure interaction, the motion of the structure can be the only significant nonlinearity affecting the fluid domain. If a standard finite element model was to be used, due to the possible large overall motion of the structure, it would be necessary to use a geometrically nonlinear finite element analysis for the structure, even though the actual deformation of the solid is within the linear elastic range. Then if the deformations in a moving coordinate system are small it is reasonable to use a small strain formulation for the solid in this reference frame. Besides from getting faster evaluation of element terms, the representation of the solid in this new coordinate system also eliminates the need for solving nonlinear equations for the solid deformations. The overall motion is still described by nonlinear equations that need to be solved at each time step, unless a fully explicit algorithm is used to integrate the equations for the solid. For long time dynamic behavior of structural systems it is often computationally more efficient to integrate a modally decomposed structural system because the frequency spectrum of the solid is reduced and the size of the system is reduced to the number of eigenfrequencies considered reducing in this form the computational cost.

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