SUPERSONIC BOUNDARY-LAYER RESPONSE TO FREESTREAM DISTURBANCES

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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 hypersonic atmospheric and reentry vehicles. The nature of the boundary layer over the vehicles affects the aerodynamic performance of the vehicle as well as thermal protection system and propulsion system requirements. In hypersonic flight vehicles experience much higher skin friction and surface heat transfer in transitional and turbulent flow than in laminar boundary-layer flow. Transition delay results in significant drag reduction and can greatly reduce aerodynamic heating loads. Therefore a fundamental demand exists for accurate boundary-layer transition prediction tools to design vehicles for hypersonic flight conditions.

At super- or hypersonic speeds temperatures on flight vehicle surfaces are in the region of permissible material limits. To avoid conservative ablative systems leading egdes with large radii are necessary to reduce the thermal load. Due to the bluntness of the body a bow shock occurs upstream of the body. The shock curvature causes an inviscid entropy layer, which interacts with the boundary layer. The resulting high pressure gradient and the entropy layer change the characteristics of the boundary layer and the dynamics of the shock/boundary-layer interaction, which is why the pressure distribution, heat transfer, separation, reattachment, and flow stability, which have a major impact on the design of high speed aircraft and hypersonic aerospace vehicles, are modified. The analysis of these effects provides a better understanding of the fundamental flow structure. This research focuses on the effects of leading-edge bluntness on boundary layers in high speed flows and the consequent effects on shock/boundary-layer interactions.

The presentation consists of three parts: the computation of steady base flow, the linear stability analysis and the receptivity simulations. The steady supersonic flow field around a blunt flat plate with semicircle leading edge is numerically simulated by solving the governing equations for mass, momentum and energy. Smooth distributions of the first and second derivatives of the flow quantities in the wall normal direction are required on a well resolved grid for the linear stability analysis to accurately capture stability characteristics of the flow. The local linear stability analysis is carried out assuming parallel flow. The receptivity simulations are related to planar freestream fast acoustic disturbance waves. The unsteady flow solutions are obtained by imposing these disturbances on the steady base flow. The simulations cover the interaction of the disturbances with the shock wave and the receptivity of the boundary layer.

The steady and unsteady supersonic flow field around a blunt flat plate is computed using a spectral collocation method. The bow shock wave is treated as an outer boundary to obtain a shock-free domain. The entire computational domain is covered by an multi-block mesh, which allows to effiently resolve strongly localized features without overresolving smooth regions of the solution. The patching technique enables a fully parallelized algorithm on contemporary concurrent computer achitectures. The inviscid part of the compressible Navier-Stokes equations is rewritten into a combination of planar waves, which are aligned with the numerical grid. At the block interfaces this wave information is simply exchanged due to the characteristic wave speed. Averaging of the one-sided approximations of the viscous terms at the interfaces accounts for their elliptical nature. Continuity of the viscous fluxes is enforced by a penalty term, which is proportional to the jump of the viscous fluxes. We apply a high-order explicit time integration scheme to obtain an accurate method to resolve unsteady flow structures of small amplitudes.

The simulations focus on the supersonic flow over the windward side of a blunt adiabatic flat plate with nose radius $R_n^* = 1.0$ mm at a freestream Mach number $M_\infty = 2.5$, a Reynolds number based on the nose radius of the plate $Re_\infty = 9.9 \cdot 10^3$ and at angles of attack $\alpha = 0°, 3.7°, 7°$. The response of the supersonic flow over a blunt flat plate to forcing freestream disturbance waves is numerically simulated by superimposing weak monochromatic fast acoustic waves on the base flow variables of the steady state solution.

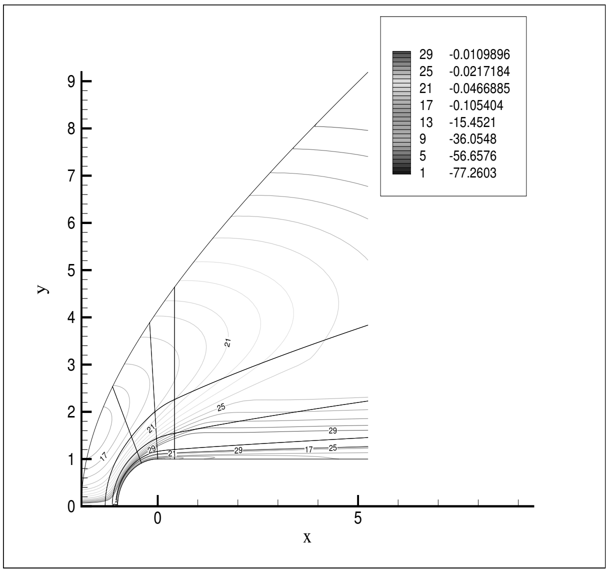

Fig. 1: Steady vorticity field over a blunt flat plate at $M_\infty = 2.5$. Lines represent subdomain boundaries

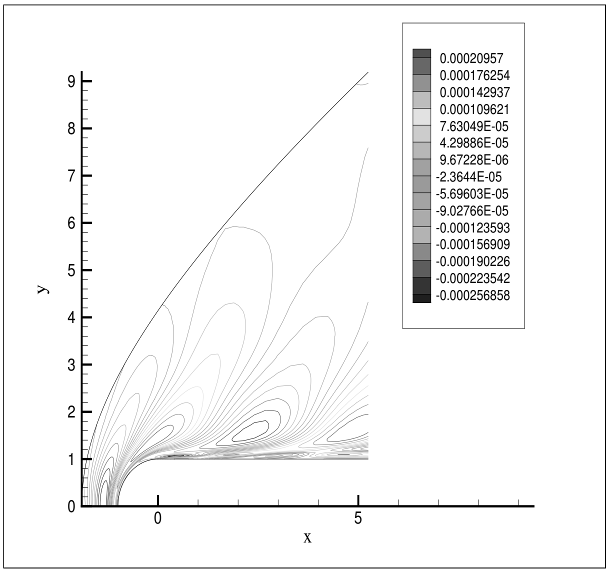

Fig. 2: Contours of entropy perturbations induced by fast acoustic waves. ($f^* = 5 \cdot 10^4$ Hz)

Fig. 1 shows the numerically simulated steady vorticity field over a blunt flat plate at $\alpha = 0°$. Besides the boundary layer an rotational inviscid flow field behind the shock wave is clearly visible. The entropy layer interacts with the developing boundary layer and influences its stability behaviour and therefore the laminar-turbulent transition. Furthermore, Fig. 1 evidences the solution to be smooth and continuous on the subdomain boundaries. Contours of entropy perturbations induced by fast acoustic waves at a forcing frequency $f^* = 5 \cdot 10^4$ Hz are plotted in Fig. 2. Different wave patterns occur due to the exitation of discrete modes additional to the STOKES waves.

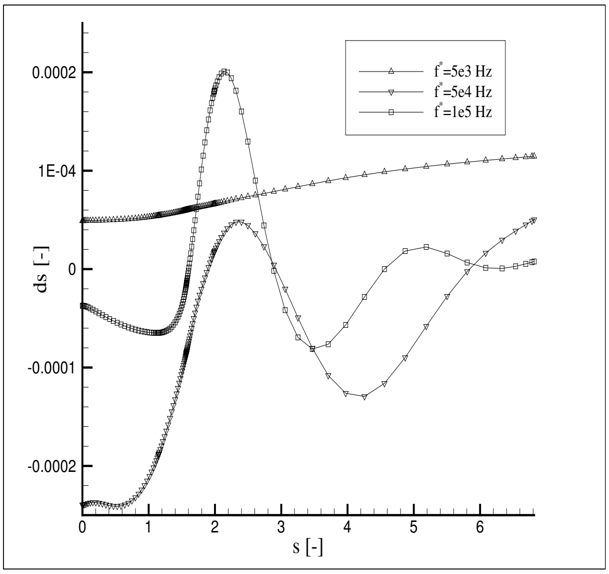

Fig. 3: Entropy disturbances on the body surface induced by freestream fast acoustic waves ($f^* = 5 \cdot 10^3, 5 \cdot 10^4, 1 \cdot 10^5$ Hz)

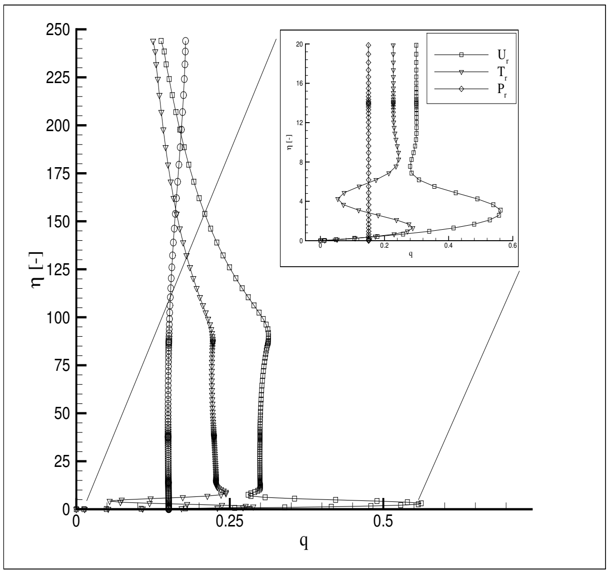

Fig. 4: Wall-normal distributions of eigenfunctions U_r, T_r, P_r for $f^* = 39580$ Hz at position $s = 6.8$ obtained by linear stability analysis

Instantaneous entropy disturbances on the body surface induced by freestream fast acoustic waves for forcing frequencies $f^* = 5 \cdot 10^3, 5 \cdot 10^4$, and 10^5 Hz are shown in Fig. 3. While the entropy disturbances at $f^* = 5 \cdot 10^3$ Hz vary only slightly with the body coordinate s strong amplifications for $f^* = 5 \cdot 10^4$ and 10^5 Hz occur near the location of the discontinuity of the surface curvature ($s_{curv} = 1.5708$). This evidences the importance of the leading-edge region in the receptivity simulations. The wall-normal distributions of the eigenfunctions U_r, T_r, P_r for $f^* = 39580$ Hz at position $s = 6.8$ obtained by linear stability analysis are depicted in Fig. 4. Unlike conventional stability computations the non-uniform leading-egde flow field leads to non-vanishing disturbance amplitudes outside the boundary layer.