DIRECT NUMERICAL SIMULATIONS OF HIGH-SPEED BOUNDARY LAYER TRANSITION INCLUDING ADVERSE PRESSURE GRADIENTS

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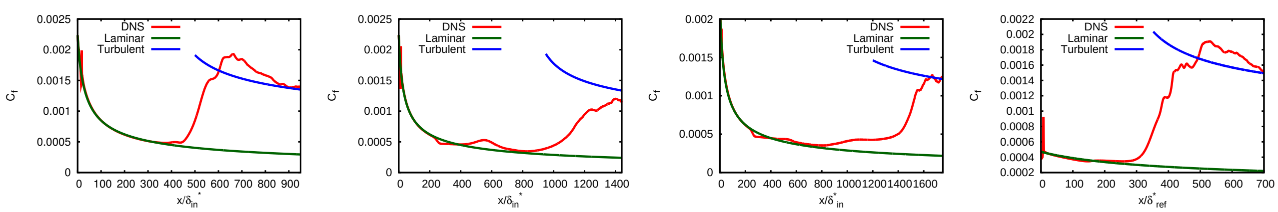
Summary Direct numerical simulations of high-speed boundary layer transition at $M_\infty = 6$ for zero pressure gradient and adverse pressure gradient were undertaken using different disturbance forcing. The oblique breakdown mechanism leads to an earlier transition location than the Mack second mode 2D and 3D forcing and produces an overshoot in heat transfer and skin friction.

INTRODUCTION

Determining the transition location is important for the prediction of heat transfer and skin friction of high speed boundary layer flows but the physical mechanisms of boundary layer laminar to turbulent transition for high speed flows is poorly understood. Transition to turbulence for high Mach number flows is fundamentally different from that of subsonic and supersonic flows. Under hypersonic flow conditions, higher instability modes of an acoustic nature [1] exist. Because these modes have higher growth rates at high Mach numbers, alternative pathways in transition to a fully turbulent flow in high speed boundary layer flows have been suggested. While the growth rates of these Mack modes are higher at high Mach numbers, their nonlinear behavior is not well understood. In the current work, three different transition scenarios are explored to determine the breakdown path for each and their potential as transition mechanisms.

METHODOLOGY

To study these different transition scenarios, Direct Numerical Simulations (DNS) of a boundary layer flow on a flat plate are undertaken. The general curvilinear form of the compressible Navier Stokes equations is solved in non-dimensional conservation form [2]. The numerical scheme for spatial discretization is a sixth-order accurate compact scheme [3] implemented on a staggered grid. The time integration of the fluid equations is carried out by a fully implicit second-order Beam-Warming scheme in order to overcome the time step restriction. To capture eddy-shocklets which spontaneously develop in high speed turbulent flows a shock capturing scheme is used. The current implementation is based on the formulation of [4] called LAD (localized artificial diffusivity).
Based on the potential transition mechanisms suggested in previous work three different transition scenarios are explored in the present work. The main focus is on oblique breakdown, which has been shown to be a potential mechanism for transition in supersonic flows [5]. Oblique breakdown is caused by the growth of two oppositely oriented oblique instability waves. Two other possible mechanisms involve higher frequency Mack second mode instabilities. For the second case, a 2D Mack second mode is forced to investigate the possibility of either subharmonic or fundamental resonance. For the third case two oblique Mack second mode waves are forced at the same frequency as the Mack 2D case, but with a non-zero spanwise wavenumber. The forcing is very similar to the oblique breakdown, except a high frequency Mack second mode is forced. The frequencies and spanwise wavenumbers of the disturbances are determined using linear stability theory and the disturbances are excited through wall suction and blowing, see [6] for details.



(a) Oblique Breakdown: ZPG (b) Mack 2D: ZPG (c) Mack 3D: ZPG (d) Oblique Breakdown: APG

Figure 1: Skin friction coefficient averaged in span and time. Van Driest II correlation for turbulent flow is also shown.

RESULTS

Both zero pressure gradient and adverse pressure gradient boundary layers with edge Mach numbers near 6.0 and isothermal walls were studied. Zero pressure gradient results are emphasized here. Figure 1 shows the development of the skin friction coefficient for all three cases along with turbulent and laminar correlation. The results for the adverse pressure gradient cases are qualitatively similar except that the linear growth rates for disturbances are higher and the breakdown process is quicker. Even though the growth rates and amplitudes of the disturbances are higher in the Mack 2D and 3D

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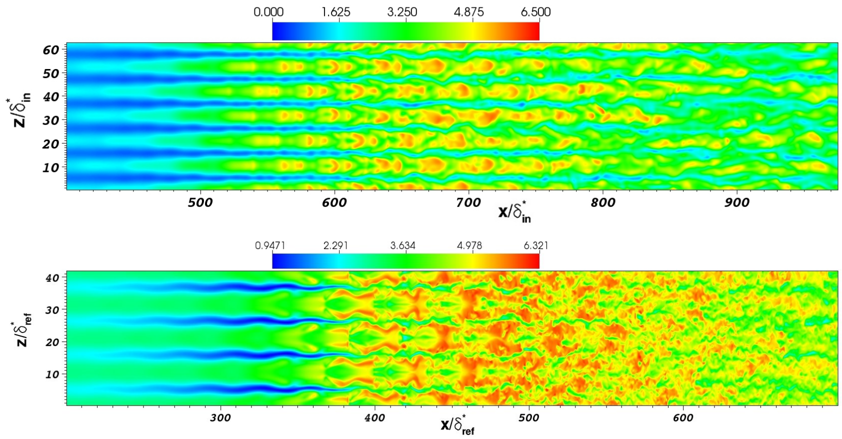

Figure 2: x-z plane views of streamwise velocity contours for oblique breakdown. Top: y/δ^*_{in}=1.0 plane in ZPG case; bottom: APG boundary layer at y/δ^*_{in}=1.5. As in figure 1 the range of $x/\delta^\star_{in}$ for APG case is smaller.

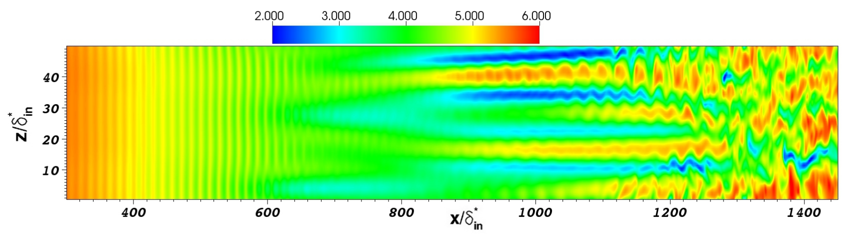

Figure 3: 2D slice of contours of streamwise velocity at $y/\delta^*_{in} = 4.5$. Initially 2D Mack mode instabilities grow and saturate, followed by streaks, and eventual breakdown to turbulence can be seen.

cases, the transition location for both 2D and 3D Mack modes is significantly further downstream from the oblique breakdown transition location. Note the range of $x/\delta^\star_{in}$ in figure 1(d) is smaller than in figure 1(a) and points to the more rapid breakdown with APG. In the oblique breakdown case, the two initially forced oblique instability waves grow to large amplitude and interact to produce streamwise vorticity which then creates streaks of high and low momentum/thermal energy and overshoots in both skin friction and heat transfer, which have been observed in some experiments. These streaks then develop secondary instabilities and breakdown. Figure 2 shows this development. For the Mack second mode forcing cases, the initial disturbances grow large and their amplitudes saturate. Secondary instabilities then grow and produce streamwise streaks of high and low momentum/thermal energy. These streaks eventually breakdown but much further downstream. This process can be seen for the 2D Mack forcing in figure 3.

CONCLUSIONS

The oblique breakdown mechanism leads to the earliest transition location in flat plate high speed boundary layers and overshoots in both skin friction and heat transfer. For all of the transition mechanisms explored, streak breakdown plays a major role in the final stages of breakdown. Adverse pressure gradient does not qualitatively change the behavior of the transition mechanisms except that the transition processes occur more quickly.

References

[1] Mack, Leslie M. 1969 Boundary layer stability theory. Jet Propulsion Laboratory Doc 900-277(Rev A.).

[2] Nagarajan, S., Lele, S. K. & Ferziger, J. H. 2003 A robust high-order compact method for large eddy simulation. *J. Comp. Phys.* **191**, 392–419.

[3] Lele, S.K. 1992 Compact finite-difference schemes with spectral-like resolution. *J. Comp. Phys.* **103**, 16–42.

[4] Kawai, S., Shankar, S. K. & Lele, S. K. 2010 Assessment of localized artificial diffusivity scheme for large-eddy simulation of compressible turbulent flows. *J. Comp. Phys.* **229**, 1739–1762.

[5] Mayer, C. S. J., von Terzi, D. A. & Fasel, H. 2011 Direct numerical simulation of complete transition to turbulence via oblique breakdown at Mach 3. *J. Fluid Mech.* **674**, 5–42.

[6] Franko, Kenneth 2011 Linear and Nonlinear Processes in Hypersonic Boundary Layer Transition to Turbulence. PhD thesis, Department of Aeronautics & Astronautics, Stanford University, Stanford, California.