

# Visitor Research Report

**Visitor Name:** Mr. Christian Mayer  
University of Arizona

**Area of Research:** Modeling of Unsteady Flow Phenomena

**Period of Visit:** July 7, 2008 through July 18, 2008

## Goal:

My graduate research focuses on the understanding of the physical mechanisms responsible for the transition process of a laminar supersonic boundary layer to turbulence. This transition process is a major unresolved topic in fluid dynamics, especially for boundary layers at supersonic speeds. Although significant progress has been made in recent years, crucial aspects of the transition physics are still in the dark. Considerable progress toward the understanding of high-speed boundary layer transition is however vitally important for developing reliable transition prediction models that can be used for the design and safe operation of advanced flight vehicles. The crucial need for reliable transition prediction methods for high-speed applications is due to the fact that transition to turbulence in supersonic boundary layers is associated with considerable increases in heat loads on the structure of the flight vehicles. In addition to surface heating, transition to turbulence also has a significant effect on the aerodynamic performance of high-speed flight vehicles as the skin friction for turbulent boundary layers is considerably higher than for the laminar boundary layer.

## Strategy:

The tools I am using in order to reach my research goal are called linear stability theory (LST) and direct numerical simulations (DNS). The first approach is based on linearizing the governing equations, called Navier-Stokes equations, about the laminar, supersonic boundary layer and solving them for infinitely small wave-like disturbances. This method provides information about the initially linear stage of transition. In the second approach, the Navier-Stokes equations are solved directly without any further assumptions and simplifications using finite difference schemes. In our research group at the University of Arizona, we currently use two different numerical programs for our DNS, which were developed in our group, to study transition phenomena for compressible flows. In the first code developed by Harris (1996), the spatial derivatives in wall-normal and streamwise directions are approximated by one-sided split-finite differences. Comparable to MacCormack's method (MacCormack 1969), alternating between forward and backward differencing during the time integration (e.g. fourth-order Runge-Kutta method) leads to an overall higher-order method, in our case third-order (Rudy 1987, Harris 1996). A periodic solution is assumed in the spanwise direction and, consequently, a Fourier transformation is applied. The code was parallelized using OpenMP and exhibits

excellent parallel speedup on shared memory supercomputers such as the SGI Altix systems.

In order to resolve the wide range of length scales arising in a transitional flow even higher-order methods for the spatial discretization are desirable then applied in the code from Harris (1996). Hence, Laible (2008) (see also the visitor research report from Andreas Laible) has developed a new compressible Navier-Stokes solver in our research group where all spatial derivatives are approximated using high-order upwind and central differences. This code was parallelized using the Message-Passing Interface (MPI), which allows for computations on shared and distributed memory supercomputers.

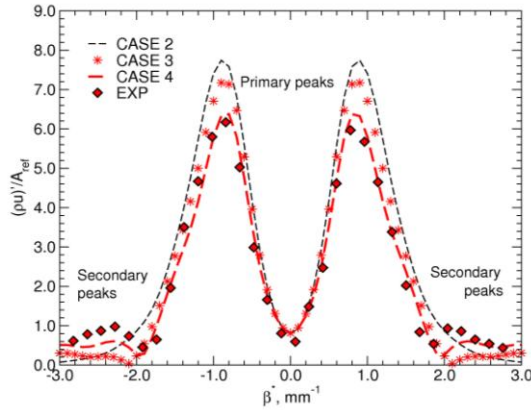
### **Accomplishments:**

A summary of all my accomplishments during my graduate studies at the University of Arizona can be found in Mayer et al. (2007), Mayer & Fasel (2008) and Mayer et al. (2008). Here, an example from Mayer et al. (2007) is presented in more detail. In this study, the weakly nonlinear transition regime for a flat-plate boundary layer at Mach 2 was investigated and the numerical results were compared to the experimental data from Kosinov et al. (1994). Kosinov and his co-workers discovered a new transition mechanism in their experiments, called asymmetric subharmonic resonance. Scrutinizing the experimental data, however, suggests the presence of an additional breakdown mechanism. Understanding this mechanism was one part of my graduate studies at the University of Arizona. Therefore, I have performed DNS of a supersonic flat-plate boundary layer at Mach 2. These DNS were set up to match the flow conditions and the forcing method of the experiments by Kosinov and co-workers (Kosinov et al. 1994, Ermolaev et al. 1996). In the numerical simulations, the weakly nonlinear transition regime agrees very well with the experiments. Typical results from these simulations (abbreviated as CASE 2-5) and the experiments are shown in figure 1 and 2. Both figures show the mass-flux disturbance  $(\rho u)'$  for different streamwise positions and spanwise wave numbers at a constant wall-normal location  $y^*/\delta^* = 0.53$  for the frequency 20kHz (the dominant forcing frequency in both, the simulations and the experiments). Figure 2, furthermore, exhibits certain characteristics of the additional breakdown mechanism in the experiment, as for example the equally spaced maxima in spanwise direction (denoted by  $\beta$ ). These maxima can only be caused by an oblique breakdown mechanism, which was first discovered by my advisor (Fasel et al. 1993) using DNS and has not yet been confirmed in any experimental study. Hence, if oblique breakdown was indeed present in the experiments by Kosinov et al. (1994), it would be the first experimental evidence for this breakdown mechanism.

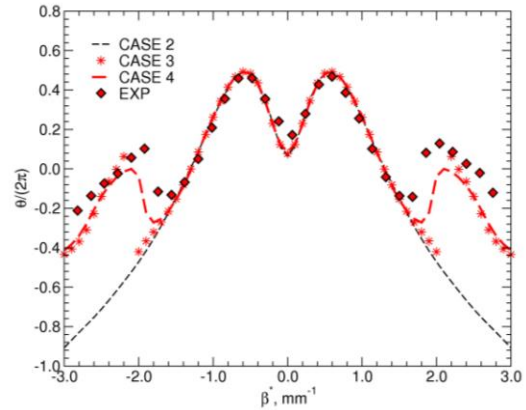
### **Future Work:**

My visit at NIA was very important for my future work since it enabled me to coordinate my future research efforts with researchers at NASA Langley Research Center. New transition experiments for a conical boundary layer at Mach 3.5 will be performed in the Quiet Wind Tunnel at NASA Langley with a  $7^\circ$  half-angle cone. These experiments will be very similar to those by Kosinov et al (1994) and Ermolaev et al. (1996). The

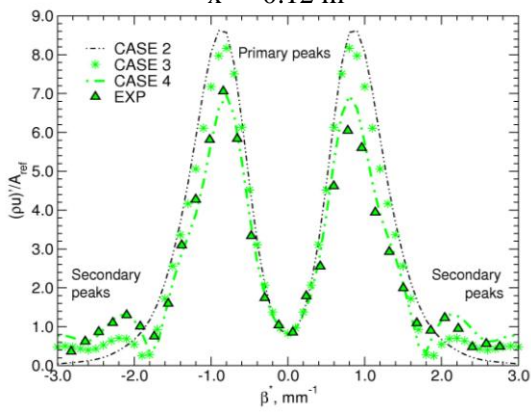
knowledge gained from my previous work for Mach 2 will, therefore, help to understand the transition mechanisms for the new flow conditions. This work will be conducted in close cooperation with Meelan Choudhari from NASA Langley.



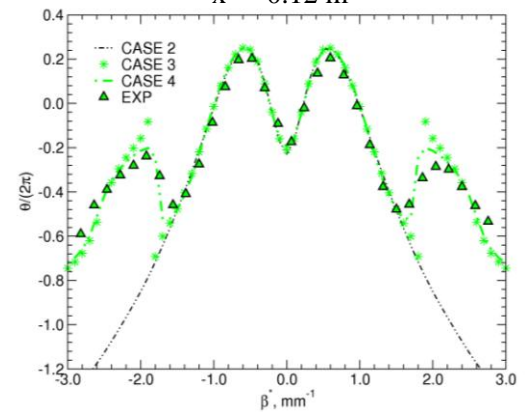
a) Spanwise amplitude distribution,  $x^* = 0.12$  m



b) Spanwise phase distribution,  $x^* = 0.12$  m

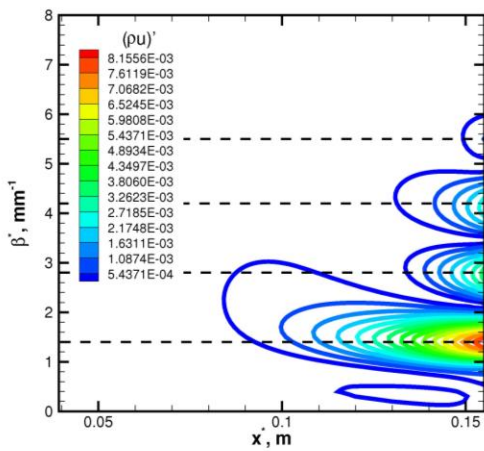


c) Spanwise amplitude distribution,  $x^* = 0.13$  m

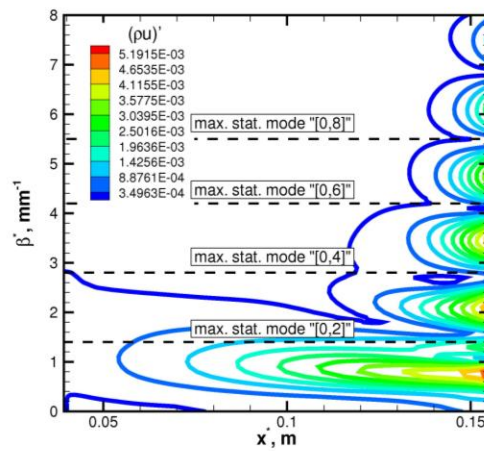


d) Spanwise phase distribution,  $x^* = 0.13$  m

**Figure 1.** Spanwise amplitude and phase distribution of the mass flux disturbance  $(pu)'$  for different streamise positions at a constant wall-normal location  $y^*/\delta^* = 0.53$ . Cases 2-4 represent simulations with increasing forcing amplitude.



a) steady modes (CASE 5)



b) fundamental frequency (CASE 5)

**Figure 2.** Contour levels of the Fourier amplitudes for the mass flux disturbance  $(pu)'$  at wall-normal location  $y^*/\delta^* = 0.53$  for different streamwise and spanwise locations.

**Pending Publications: -**

**References:**

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