Visitor Research Report

Visitor Name: **Mr. Andreas Laible**
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Area of Research: **Modeling of Unsteady Flow Phenomena**

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

Goal:

Transition of supersonic wall bounded flows from the laminar state to turbulence presents a major challenge in fluid-dynamics research. In contrast to incompressible flows, where the understanding of the transition process has made considerable progress over the past decades, the nonlinear breakdown mechanisms relevant for high-speed flows are still somewhat illusive. Thus, it is the objective of my Ph.D. research to investigate the underlying physical mechanisms leading to turbulence at supersonic speeds. In particular, a 7° half angle cone at Mach 3.5 is investigated using Direct Numerical Simulation (DNS). This project is carried out in close collaboration with NASA Langley, where corresponding experiments will be conducted. Hence, the goal of this visit was to exchange information and improve the collaboration on supersonic transition research. The primary focus of my research lies in the late stages of transition, a regime where primary waves reach finite amplitude levels, secondary instability mechanisms set in and the flow eventually becomes turbulent.

Strategy:

Direct Numerical Simulation (DNS) is employed for the investigation of transitional and turbulent flows. The governing equations for the numerical code are the compressible Navier-Stokes equations in conservative variable formulation. The time integration is performed with a standard 4^{th}-order accurate Runge-Kutta scheme. The spatial discretization is based on high-order accurate finite differences. In particular, the derivatives of the viscous terms and the source term are calculated by 6^{th}-order non-compact central differences in the downstream direction and 4^{th}-order non-compact central differences in wall-normal direction. In the spanwise direction the code offers the option between high-order compact differences (up to 10^{th}-order accuracy) and a pseudo-spectral descretization using Fourier modes. The inviscid fluxes are divided into an upwind flux and a downwind flux using van Leer splitting (van Leer 1982}. Then, grid centered upwind differences (Zhong 1998} with up to 9^{th}-order accuracy are applied to evaluate the derivatives for these fluxes. These grid centered upwind differences are derived using a variable parameter, which prescribes the degree of upwinding. This parameter is tuned such that the numerical damping introduced through the upwind-biased stencils is kept at a minimum, and at the same time, numerical stability is ensured. All stencil coefficients are derived on a stretched grid. For more details concerning the numerical algorithm, the interested reader is referred to Laible *et al.* 2008.

Accomplishments:

The main objective of my two week visit at NIA was to improve the collaboration between experimental efforts at NASA Langley and numerical simulations performed at the University of Arizona. The fruitful discussions with several researchers at NASA Langley, as well as the visit of the experimental facilities will benefit both my research and the collaboration with NASA Langley. So far, we developed a new high-order accurate Navier-Stokes solver that is especially tailored towards accurate and efficient simulations of flow for cone geometries at supersonic speeds. This code has been thoroughly validated by comparing results obtained with small amplitude disturbances to linear stability theory (see Figure 1). Moreover, a possible scenario for transition in supersonic flows that we are investigating is oblique breakdown. Using numerical simulations of a flat plate, Thumm 1991 and Chang & Malik 1994 demonstrated that this breakdown may be a relevant transition mechanism. Our preliminary simulations of a circular cone at Mach 3.5 indicate that oblique breakdown may also be a viable route to transition for the cone geometry at wind tunnel conditions (see Figure 2).

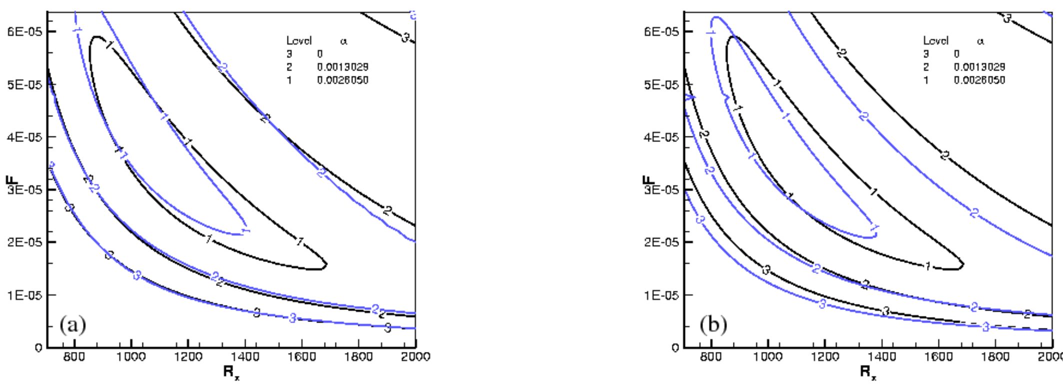

Figure 1 ─ Comparison of stability diagrams for azimuthal mode *k = 16* obtained by different criteria: (a) LST (black) – disturbance density maximum (blue), (b) LST (black) –kinetic disturbance energy (blue).

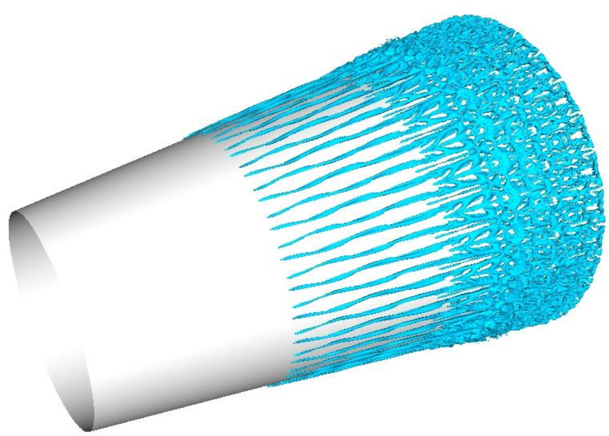

Figure 2 ─ Instantaneous visualization of Q-criterion (Q =5000) for an oblique transition scenario simulation for the circular cone geometry at zero angle of attack.

Future Work:
More numerical simulations into the nonlinear transition and turbulent flow regime are planed. In particular, the previously mentioned oblique breakdown will be investigated in more detail. The question if oblique breakdown plays an important role in "natural" transition will be addressed by increasing the complexity of the initial condition. Up to this point transition (in our numerical simulations) was initiated by only a single pair of oblique waves. In future simulations the spectrum of the small amplitude disturbance waves, which initiate transition, will be broadened, thus allowing multiple frequencies and wave numbers to reach finite amplitude levels early in the transition process.

Pending Publications: -

Seminar Presented:
The seminar that I presented was titled "Numerical Investigation of Supersonic Transition for a Circular Cone at Mach 3.5." After a brief introduction and a short review of work done in the area of superonic transition, a newly developed high-order accurate Navier-Stokes code was described. This code was validated against linear stability theory (LST) by performing simulations, where small amplitude disurbances are introduced into the boundary layer of a 7˚ half angle cone. Furthermore, investigations of the linear stability regime were presented. Last but not least, preliminary simulations, where a pair of oblique waves grows to a finite amplitude level and thus initiates transition, were shown.

References:

Chang, C.L. and Malik, M.R., 1994, *"Oblique-mode breakdown and secondary instability in supersonic boundary layers,'* J. Fluid Mech. vol.**273**, pp. 323-360.

Laible, A.C., Mayer, C.S.J., and Fasel, H.F., 2008, *"Numerical Investigation of Supersonic Transition for a Circular Cone at Mach 3.5,"* AIAA-2008-4397.

Thumm, A., 1991, "*Numerische Untersuchungen zum laminar-turbulenten Strömungsumschlag in transsonischen Grenzschichtströmungen,*" PhD thesis, Universität Stuttgart.

van Leer, B., 1982, "Flux-*Vector Splitting for the Euler Equations,*" in International Conference on Numerical Methods in Fluid Dynamics, vol. **170**, pp. 507-512, Springer-Verlag.

Zhong, X., 1998, "*High-Order Finite-Difference Schemes for Numerical Simulation of Hypersonic Boundary-Layer Transition,*" J. Comp. Phys. **144**, 662-709.