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The Effect of Multi-mode Induced Transition in a Hypersonic Boundary Layers

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Final Progress Summary Report

AFOSR Award #
FA9550-15-1-0353

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ABSTRACT

This study extends the work of Smith [5] to Mach numbers indicative of the hypersonic flight regime and correlate the results to the occurrence of transition. The existing model uses PSE to capture the fully nonlinear interaction of modes in a low-speed, non-reacting, compressible boundary layer. It has the capability to calculate the contributions to surface heating and skin friction from the interaction of homogeneous (e.g. first-mode/second-mode) and inhomogeneous mode interaction (e.g. second-mode/crossflow). This approach captures the more realistic conditions that occur in-flight.

Background

Just as tiny cracks in a structure can cause catastrophic material failure, the interaction and growth of small amplitude flow field disturbances can adversely affect the performance and thermal properties of high speed vehicles. For example, shocks and viscous flow interactions present significant design challenges in hypersonic aeropropulsion because the state of the inlet flow field has a direct effect on propulsion system performance. One particular mechanism that affects the inlet flow field is laminar-to-turbulent transition of the boundary layer. The research proposed will use a computational model to study the impact of instability wave interactions on hypersonic boundary layer transition in an inlet flow field. Experimental data from the Boeing/AFOSR Mach-6 Quiet Tunnel will be used to validate the results obtained from modifications to our existing Parabolic Stability Equations (PSE) code.

Shocks and viscous flow interactions present significant design challenges in hypersonic aeropropulsion because the inlet flow field state has a direct effect on performance. One particular mechanism that affects the inlet flow field is laminar-to-turbulent transition of the boundary layer. Research on the design of leading edge and forebody shapes strongly dominates hypersonic propulsion system design. Early designers were restricted to blunt shapes on their vehicles however the advances in materials research permit current designers wider latitude in body shapes. These advanced materials are also used in vehicle thermal protection systems (TPS). The tradeoff is that many of these materials can sublimate at high-altitude or on atmospheric re-entry forming roughness elements that affect the location of boundary layer transition. Unfortunately, the roughness distribution depends on the material used and the fabrication technique. It is thus important to accurately characterize the hypersonic flow field in consideration with the materials used in the design of the vehicle.

Boundary layer instability and transition is driven by the receptivity, growth, and breakdown of wave-like disturbances. Flow instability can also occur due to the dynamical effects of rotation or streamline curvature. Examples include the flow in the gap between rotating cylinders, as well as the boundary layer over a curved surface. Taylor (cf. Greenspan [1]) studied the stability of low-speed flow between rotating concentric cylinders in which the outer cylinder rotates with an angular velocity Ω_2 and the inner cylinder rotates with an angular velocity Ω_1. He discovered that the instability takes the form of steady, counter-rotating toroidal vortices and that the parameter $T = (\Omega_1^2 - \Omega_2^2)L^4/\nu^2$ determines whether the flow is stable or unstable. Here L is a typical length scale, and ν is the kinematic viscosity of the fluid. This parameter represents the ratio of the centrifugal force (destabilizing) to the viscous force (stabilizing). Görtler was the first to show that this type of instability also occurs in boundary layers over curved surfaces such as those on the forebody ahead of scramjet inlets and of the underside of highly swept wings. Considering the temporal stability of the flow, he found that governing parameter for stability of the flow is $G = Re\sqrt{\kappa}$ where $\kappa = L/R$ is the nondimensional curvature parameter with L a characteristic length scale and R the radius of curvature. Re is the Reynolds number. This parameter, now known as the Görtler number, plays the same role as the Taylor number, T, in the flow between rotating cylinders. The growth of the boundary layer makes the Görtler problem differ significantly from the Taylor problem. The flow between the cylinders is essentially a channel flow problem in which the flow is already fully developed, i.e. a parallel flow.

The parabolic stability equations (PSE) provide an economical means for studying the evolution of wave-like disturbances in boundary layers. The governing equations for these flows are generally elliptic in character so that the value of any flow variable at each point in the domain depends on its values at all other locations in the domain. The PSE allows the solution to be marched downstream after supplying initial conditions at some upstream location $x = 0$. The marching solution is more economical and, as mentioned previously, yields the same results as the direct numerical simulation of the elliptic problem. Early work examined linear instability of boundary layers in low-speed compressible flow using the PSE.

Homogeneous interactions of vortices in compressible boundary layers have the same qualitative behavior as in incompressible flows. The mean flow correction quickly alters the boundary layer velocity profile so that it has an inflection point. In incompressible flows such as those studied by Benmalek and Saric [2], the inflectional mean flow profile develops more slowly. Swearingen and Blackwelder [3] reported that the total streamwise velocity developed into a "mushroom" profile in which the region low momentum fluid was pushed farther into the boundary layer and away from the wall. The results of Smith and Haj-Hariri[6] establish that this phenomenon also occurs in compressible flows.

The asymptotic theory of Hall [4] predicts that the flow will ultimately separate due to the pinching of the two low momentum points on either side of the mushroom structure. The distribution of shear stress found by Smith [5] reveal that the appearance of this structure corresponds to a saturation of the fundamental vortex mode. The shear stress does reach a minimum when the boundary layer profile is the most inflectional but never attains a zero value. Also near the end of the computational domain, the shear stress starts to increase indicating the onset of transition. Hence separation does not occur.

The analysis of nonlinear interaction in Smith [5] also provides information on the Görtler vortices' effect on heat transfer at the surface. These results augment the research of Smith and Haj-Hariri [6] for incompressible flows. There it was shown that vertical component of the mean flow correction induced a pumping action that removes hot fluid near the surface and mixes it with cooler fluid from the boundary layer's edge; thereby enhancing the heat transfer rate at the wall. The temperature profile of the mean flow correction shown in Smith and Haj-Hariri [6] displays the same type of behavior as in the weakly nonlinear result but with a more dramatic increase in heat transfer. The disturbance velocities develop similarly in the presence of heating as they do when the surface is adiabatic. Hence heating does not affect the location where the boundary layer begins to transition and has a minimal effect on the development of the vortices.

The interaction of TS waves and vortices is shown to depend on the amplitudes of the initial disturbances. When the initial disturbances have the same amplitude, the resulting flow structure is very different from that of either homogeneous interactions TS wave or Görtler vortices alone. The distinctive feature is the dominance of an induced vortex mode. The results of Malik and Hussaini[7] also show the dominance of the induced vortex mode however in their work its energy level never surpasses that of the fundamental mode. This is due to the fact that they used a parallel mean flow. The results of Smith[5] were the first to show that it is this mode that dominates the transition process.

When the initial amplitude of the vortices exceeds the initial amplitude of the TS waves, the distribution of energy in Fig. 5.5 of Smith [5] shows that the boundary layer will proceed toward transition in much the same way as a boundary layer with homogeneous interactions. When the initial amplitude of the TS waves is greater than that of the vortices, the induced vortex mode is again the fastest growing mode. Considering each of these situation leads to the conclusion that the TS waves must have an initial amplitude greater than or equal to that of the waves to have an effect on the development of the primary vortex modes. The effect of transition on inlet performance is not always detrimental. Some experiments show that the transitional boundary layer actually improves inlet performance by reducing the separation extent. [8] .

As outlined above, the mechanisms for low-speed, ideal flow transition have been studied extensively and are relatively well understood. The same cannot be said of hypersonic boundary layer transition. Although the first mode is similar to TS waves in low speed flow, measurements indicate that their growth and potential for interaction are decidedly different. Crossflow instability (e.g. counter-rotating vortices) may also dominate the transition process at high angles of attack. The interaction of instability modes may drive transition in unpredictable ways thereby affecting thermal protection system design and material selection. The program plan that follows describes our intended contribution to understanding the impact of nonlinear interactions these phenomena.

Program Plan & Technical Approach

The proposed study extends the work of Smith [5] to Mach numbers indicative of the hypersonic flight regime and correlate the results to the occurrence of transition. The existing model uses PSE to capture the fully nonlinear interaction of modes in a low-speed, non-reacting, compressible boundary layer. It has the capability to calculate the contributions to surface heating and skin friction from the interaction of homogeneous (e.g. first-mode/first-mode) and inhomogeneous mode interaction (e.g. first-mode/crossflow). This approach captures the more realistic conditions that occur in-flight.

Often numerical models are only as good as the experimental data upon which they are validated. In the event of experimental data contamination, model results may be suspect as well. The approach proposed here is more fundamental in that the results on transition will not depend on empirical data. Empirical data will be used to characterize materials used in thermal protection of hypersonic vehicle/projectile components.

Accomplishments

One of the key factors in aerodynamic vehicle design of hypersonic flight vehicles involves the consideration of surface heat loads. The laminar-to-turbulent boundary layer transition is accompanied by large changes in surface heat load The interaction of instability modes may drive transition in unpredictable ways. The project contributes to understanding the impact of nonlinear interactions these phenomena. During Year2 progress was made to extend previous work to Mach numbers indicative of the hypersonic flight regime and correlate the results to the occurrence of transition. The resulting modifications enable calculation of the contributions to surface heating and skin friction from the interaction of homogeneous (e.g. first-mode/first-mode) and inhomogeneous mode interaction (e.g. first-mode/crossflow). It is our thesis that this approach will capture more realistic in-flight conditions.

Task 1: Extend previous work to hypersonic Mach numbers. Hypersonic transition is sensitive to a variety of parameters and inlet flow conditions. Therefore, it becomes important to use the same geometries in experiment and computations (i.e. no flat plates). The results of this task will be a multi-mode interaction model of hypersonic transition using conical and inlet geometries. The previous results of Smith[5] describe the interaction of T-S and Görtler vortices in a low speed compressible boundary layer flow. The analysis is three-dimensional fully nonlinear for Mach numbers 0.8-3. The initial disturbances are obtained from a linear stability code and are then permitted to develop and interact nonlinearly using the PSE :

$$\mathbf{\Psi}(x,y,z,t) \;=\; \hat{\mathbf{\Psi}}(x,y)\,\chi(x,z,t)$$
$$\chi(x,y,z) = \exp\,[\int_{x_0}^{x} a(x)\,dx \;+\; i\beta\,z - i\omega\,t]$$
$$a(x) \;=\; \gamma(x) + \,i\,\alpha(x)$$

$$\frac{\partial}{\partial x} \rightarrow a\,\Psi \,+\, \frac{\partial \Psi}{\partial x}$$
$$\frac{\partial^2}{\partial x^2} \rightarrow a^2\,\Psi \,+\, 2\,a\,\frac{\partial \Psi}{\partial x} + \frac{\partial a}{\partial x}\,\Psi$$

Normalization

$$\frac{\partial \hat{\mathbf{\Psi}}(x, y_{max})}{\partial x} = 0$$
$$\int_0^\infty \frac{\partial u}{\partial x}\,u^\dagger\,dx = 0$$

The computational code evaluates the fully nonlinear interaction two disturbance classes in a hypersonic boundary layer.

- **Nonlinear Terms**

$$A_{nm}\,\frac{\partial \mathbf{\Psi}_{nm}}{\partial x} \;+\; B_{nm}\,\frac{\partial^2 \mathbf{\Psi}_{nm}}{\partial y^2} \;+\; C_{nm}\,\frac{\partial \mathbf{\Psi}_{nm}}{\partial y} \;+\; D_{nm}\,\mathbf{\Psi}_{nm} \;=\; F_{nm}/\Gamma_{nm}$$
$$\Gamma_{nm} \;=\; \exp\,[\int_{x_0}^{x} a_{nm}(x)\,dx]$$
$$F \;=\; \left\{\sum_{r=-R}^{R}\sum_{s=-S}^{S}\,\hat{\mathbf{\Psi}}_{rs}(x,y)\,\chi_{rs}(x,z,t)\right\}\times\left\{\sum_{k=-K}^{K}\sum_{l=-L}^{L}\,\hat{\mathbf{\Psi}}_{kl}(x,y)\,\chi_{kl}(x,z,t)\right\}$$
$$\times\left\{\sum_{p=-P}^{P}\sum_{q=-Q}^{Q}\,\hat{\mathbf{\Psi}}_{pq}(x,y)\,\chi_{pq}(x,z,t)\right\}$$
$$\chi_{nm}(x,y,z) = \exp\,[\int_{x_0}^{x} a_{nm}(x)\,dx \;+\; i\,n\beta\,z - i\,m\omega\,t]$$

Measured incoming flow fields will be used as the mean flow field to the extent possible. This approach serves as the first level of calibration for the computations.

The PSE code was modified to use a blunt/sharp cone as the mean flow rather than the original swept wing mean flow (Figure 1). Also, an analytical transformation for a blunt cone shown in as well as a physical representation of a flared cone, shown in Figure 2, are being used for testing.

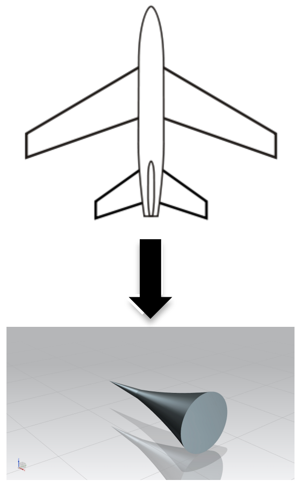

Figure 1: PSE code boundary layer profile change

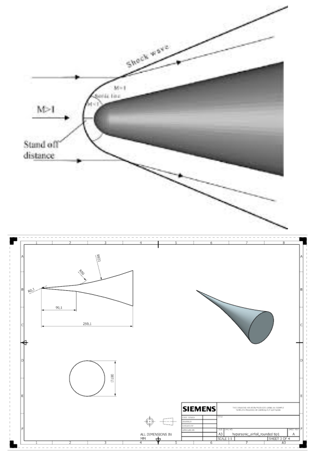

Figure 2: Mean flow configurations

Mean flow. The geometries of interest in this study require a three-dimensional boundary layer based on the wind tunnel test geometries. The students produced the mean flow calculation for the Boeing/AFOSR Mach-6 Quiet tunnel (BAM6QT) models. Published geometries for the flared cones used in the BAM6QT tunnel were used to first develop CAD models for the test models (Fig 1 and 2) and then used to generate the meshes for the mean flow calculations.

The flow conditions of interest correspond to the nominal maximum quiet flow Reynolds number in the BAM6QT, namely, a freestream Mach number of $M_\infty = 6$, unit Reynolds number Re $= 12 \times 10^6$ per meter, freestream static pressure of 702.62 Pa, and a freestream temperature corresponding to $T_\infty = 51.92$ K. The temperature of the model surface, T_w, is equal to 300 K [17].

The working fluid is air and the constitutive relations for a Newtonian fluid are used: the viscous stress tensor is linearly related to the rate-of-strain tensor, and the heat flux vector is linearly related to the temperature gradient through Fourier's law. The coefficient of viscosity is computed from Sutherlands's law, and the coefficient of thermal conductivity is computed by assuming a constant Prandtl number Pr = 0.71 [17].

Transition calculations. Preliminary calculations on the flared cone geometry show the presence of first and second mode instabilities (Figure 3). Transition on the geometries of interest occurs over a larger portion of the body. Also, depending on the application/angle-of-attack, all three mechanisms may be present and important. Data from the Quiet tunnel which demonstrates these flow features will be used to validate the calculations. The next step required is validation with the data from the flared cone experiments at Purdue. Students traveled to Purdue to view the wind tunnel test procedure and to collaborate with graduate students. It is anticipated this this collaboration will continue.

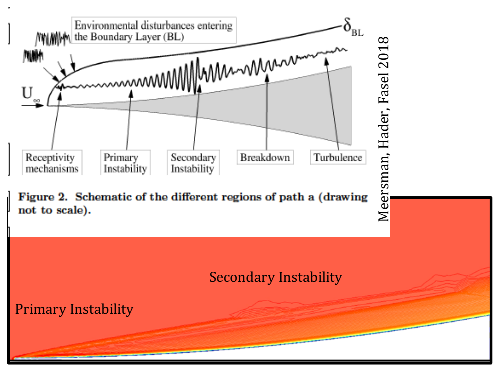

Figure 3: Instability Development

The initial contributions to surface heating by the mean flow correction (MFC) from the multimode interaction were also calculated and are presented in Figure 4 below. This is the primary pathway to increasing skin friction and thereby aerodynamic heating. In hypersonic boundary layers, some authors posit [21, 22] that that the interactions between a second-mode wave and a single first-mode wave are not strong but that spanwise mean-flow-distortion can be created by a pair of first-mode waves. Consequently, the second mode, the spanwise MFD and the fundamental oblique wave can be involved in a resonance downstream, which makes the spanwise MFD and oblique wave increase sharply. These assertions will be evaluated in a subsequent study

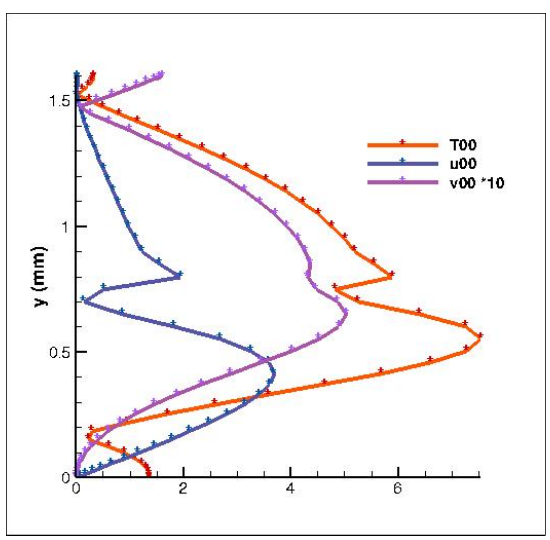

Figure 4: Mean flow corrections(MFC)

These initial results of the PSE computations are promising and qualitatively agree with other computational results on these geometries. Further testing and validation will be performed as well as the dissemination of the study's results

Task 2 Modification

In project year 2, it was decided that the following original Task 2:

> **Task 2: Apply Task-1 computational model to Inlet flow field transition.** Fan et. al.[8] have suggested that intentional transition of the hypersonic boundary layer at the inlet may be an effective method to reduce separation in order to facilitate inlet start and improve total pressure recovery. Their experiments on a model two-stage inlet showed that the inlet separation was greatly reduced if the boundary layer was tripped such that the inlet follow was in transition. The purpose of this task is to calculate the effect of the ingestion of the transitional boundary layer developed from the multi-mode instability wave interaction flow on pressure recovery. We also intend to examine the effect of different boundary layer inlet states to determine if the type of instability mechanism triggering the transition is important on the inlet performance or if it is enough to know whether or not the boundary layer is transitional, regardless of the mechanism.

should be modified based on hypersonic program priorities. Instead, our research group compared results from the Peking University group and the results Reed/Fazel for the flared cone. We found that although there were similarities between the Peking University and the Reed/Fazel data, differences in foundational assumptions prevented a one-to-one comparison.

The revised Task 2 also involved a collaboration that was catalyzed during a discussion at a the AFOSR Hypersonics Program Review. This new collaboration involves the Boeing/AFOSR Mach-6 Quiet tunnel at Purdue University. The combination of the computational data from other groups and high-speed transition measurements will serve as another means of calibration for our code.

Integration of Research and Education

Parts of the research are well-suited for an undergraduate research project or a capstone design project. Howard University ranks first as the highest producer of African-American graduates with science and engineering doctoral degrees nationally, according to the National Science Foundation. The report, "Role of HBCUs as Baccalaureate-Origin Institutions of Black S&E

Doctorate Recipients," examines educational trends over the past two decades and compares private and public schools and Historically Black Colleges and Universities (HBCU) with non-HBCU institutions to determine how many of their students later earn doctoral degrees in science and engineering fields.

The STEM disciplines -- science, technology, engineering and mathematics -- are assigned a high priority at Howard. An important dimension of the University's mission is the preparation of African American and other underrepresented students for doctoral-level graduate study and professional careers in the STEM disciplines. Incorporating undergraduates in the research, in addition to the graduate student supported by the proposal, will familiarize them with AFOSR/AFRL careers.

A graduate student initially worked on the project and then and a portion of a post-doc's time was used to complete some of the tasks. The tasks for the graduate student/post-doc were as follows:

- PSE Code Modification
- Validation with previous computational study
- Chen Flared Cone CAD
- DNS
- LST initial Conditions
- NL PSE

The data analysis and code validation are continuing.

One undergraduate student intern also participated in the project. The intern learned hypersonic flight fundamental principles and participated in some of the computational work. The intern also will work on the CAD drawings of the test cones used in the hypersonic transition experiments conducted at Purdue University.

Dissemination of results

The results of the study have been submitted to the AIAA AVIATION summer meeting and the winter meeting. The conference papers will be extended for submission to the appropriate AIAA Journals. The preference is for Graduate/undergraduate student authors to be conference presenters when feasible.

Summary

The danger of hypersonic weapons currently in development by our U.S. adversaries pose a threat to our defense systems due to their maneuverability and the altitude at which they fly [9]. Although there are currently no effective defenses against hypersonic weapons, part of developing that defense involves an understanding hypersonic boundary layers so that we can not only predict vehicle trajectories and aerodynamic heating of our hypersonic vehicles, but also that of our adversaries. A significant step towards achieving this goal is the ability to predict and control when the boundary layers on hypersonic vehicles transition.

There have been many approaches employed to investigate hypersonic transition. Direct numerical simulation (DNS), parabolic stability equations (PSE) and detached eddy simulation (DES) are the most popular. Each has its advantages, however for this study the PSE will permit control of disturbance interactions to discern their effect on transition, surface heating and skin friction. The results of this study can then be compared with experiments to identify the mechanics driving transition in these experiments. Neither of these previously mentioned approaches has the ability to identify a specific nonlinear modal interaction driving transition on specific hypersonic delivery system without the work of this study. Subsequent studies will use the code developed by this project to study the impact of multimode transition on aerodynamic heating due to nonlinear interactions of second-mode and Görtler modes.

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Sonya T. Smith, Ph.D.

Program Officer

The AFOSR Program Officer currently assigned to the award

Ivett A. Leyva, Ph.D., P.E.

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Abstract

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Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

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Appendix Documents

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