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The goal of this research project is to develop new advanced numerical methods and to perform direct numerical simulation (DNS) studies of transient hypersonic reacting flows over full 3-D maneuvering vehicles. The DNS tools and supporting theoretical approaches are used to gain new fundamental understanding of transition phenomena of 3-D chemically-reacting hypersonic boundary layers. Our research accomplishments in the report period can be classified into three areas. First, we have developed and validated new efficient and high-order accurate numerical methods for the DNS of 3-D hypersonic reacting boundary layers. The new methods include high-order semi-implicit Runge-Kutta schemes and new upwind high-order finite-difference shock-fitting schemes. These new methods were developed in order to overcome the difficulties associated with the DNS of hypersonic reacting flows with shock waves. Second, we have conducted extensive studies on the stability and receptivity phenomena of hypersonic boundary layers over blunt leading edges and elliptical cross-section blunt cones both by direct numerical simulation and by linear stability analyses. Third, the effects of using Burnett equations for rarefied hypersonic flow computations were investigated.

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(AASERT95) Direct Numerical Simulation and Linear Analysis of Stability of Nonequilibrium Hypersonic Boundary Layers

(1 June 1995 to 31 May 1998)

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Contents

1 Abstract

The goal of this research project is to develop new advanced numerical methods and to perform direct numerical simulation (DNS) studies of transient hypersonic reacting flows over full 3-D maneuvering vehicles. The DNS tools and supporting theoretical approaches are used to gain new fundamental understanding of transition phenomena of 3-D chemically-reacting hypersonic boundary layers. Our research accomplishments in the report period can be classified into three areas. First, we have developed and validated new efficient and high-order accurate numerical methods for the DNS of 3-D hypersonic reacting boundary layers. The new methods include high-order semi-implicit Runge-Kutta schemes and new upwind high-order finite-difference shock-fitting schemes. These new methods were developed in order to overcome the difficulties associated with the DNS of hypersonic reacting flows with shock waves. Second, we have conducted extensive studies on the stability and receptivity phenomena of hypersonic boundary layers over blunt leading edges and elliptical cross-section blunt cones both by direct numerical simulation and by linear stability analyses. Third, the effects of using Burnett equations for rarefied hypersonic flow computations were investigated.

2 Objectives

Hypersonic boundary layer laminar-turbulent transition and unsteady hypersonic aerodynamics are fundamental problems which have important practical applications in developing future maneuvering hypersonic lifting vehicles but are currently not well understood [1,2]. In recent years, the approach of DNS has become a powerful tool in the study of the stability and transition of low-speed boundary layers [3–6] and supersonic boundary layers over flat plates [7–13]. However, available DNS methods cannot be applied to hypersonic boundary layers over realistic blunt bodies because the effects of nose bluntness, the presence of shock waves, and the real-gas effects at high temperatures are neglected in the conventional DNS approach.

Therefore, the goal of our AFOSR supported research projects is to develop new advanced numerical methods and to perform DNS studies of transient hypersonic reacting flows over full 3-D maneuvering vehicles. The DNS tools and supporting theoretical approaches are used to gain new fundamental understanding of transition phenomena of 3-D chemically-reacting hypersonic boundary layers. The purpose of this three-year AASERT grant is to support two additional graduate students to perform additional research in support of the research efforts carried out by our ongoing core AFOSR grants. The proposed research tasks for the AASERT grant are:

1. to develop new high-order schemes for the DNS of 3-D hypersonic boundary layer stability with shock waves; and to conduct DNS of stability of nonequilibrium hypersonic boundary layer.
2. to study the linear stability of hypersonic boundary layers, and to investigate the extension of linear stability analysis to low-density hypersonic flow using the Burnett equations.

3 AASERT and Core Grants

This final technical report summarizes our research efforts in the report period. The report covers the research supported by both the AASERT grant (F49620-95-1-0405) and its core grants of F49620-94-1-0019, titled *Numerical Studies of Low-Density Two-Dimensional Hypersonic Flows by Using the Navier-Stokes and Burnett Equations with Nonequilibrium Real Gas Effects* (11/15/93-11/14/96), and F49620-97-1-0030, titled *DNS and Linear Stability Analyses of Unsteady 3-D Hypersonic Wall-Bounded Flows with Real-Gas Effects* (11/15/96-11/14/99). As a result, the contents of this report overlap with the final technical report for the first core grant and annual technical progress reports for the second core grant.

4 Research Accomplishments

4.1 Summary

Our publications related to the grants in the report period are listed in Section 6. The research accomplishments are summarized first, followed by more detailed descriptions of these accomplishments. The paper numbers refer to those used in Section 6.

Our research accomplishments in the report period can be classified into three areas:

1. The development of new efficient and high-order accurate numerical methods for DNS of 3-D hypersonic reacting boundary layers. The new methods include high-order semi-implicit Runge-Kutta schemes and new upwind high-order finite-difference shock-fitting schemes. These new methods were developed in order to overcome the the difficulties associated with hypersonic flow simulation with the existence of strong shock waves, shock/boundary-layer interaction, and real-gas effects. We have subsequently developed and validated 2-D and 3-D computer codes of these methods for the DNS of transient viscous hypersonic flows. The test

results showed that these new schemes are able to achieve efficient and high-order accuracy in the numerical simulation of transient reacting hypersonic boundary flows.

2. The investigation of stability and receptivity of 2-D and 3-D hypersonic boundary layers over blunt leading edges and elliptical blunt cones (Figs. 1 and 2) by DNS and by the linear stability analyses. These test cases serve as a first step in reaching our goal of DNS of 3-D boundary layer transition for lifting hypersonic vehicles.

3. The evaluation of the Burnett solutions for rarefied hypersonic flow applications by comparing them with Navier-Stokes solutions and DSMC results for axisymmetric hypersonic flows over blunt bodies and for hypersonic Couette flow. The Burnett equations were found not to be very significant compared with the Navier-Stokes equations for steady hypersonic flows except in computing the shock-wave structure. Because of these unfavorable results and the fact that hypersonic boundary layer laminar-turbulent transition occurs mainly in the continuum regime, we have shifted the focus of our research to stability and transition of reacting hypersonic boundary layers in the continuum regime governed by the Navier-Stokes equations.

4.2 New High-Order Methods for DNS of Hypersonic Boundary Layers

Direct numerical simulation is a powerful tool for studying the fundamental flow physics of hypersonic boundary-layer transition because no empirical turbulent models are used [6]. Previous DNS studies of supersonic and hypersonic boundary layer transition have been limited to perfect-gas flow over flat-plate boundary layers without shock waves. For hypersonic boundary layers over realistic blunt bodies, DNS studies of transition need to consider the effects of bow shocks, entropy layers, surface curvature, and finite-rate chemistry. It is necessary that numerical methods for such studies are robust and high-order accurate both in resolving wide ranges of flow time and length scales and in resolving the interaction between the bow shocks and flow disturbance waves.

Therefore, our initial research efforts were focused on developing new numerical methods that can overcome these difficulties. We have developed new high-order shock-fitting finite-difference schemes for the DNS of the stability and transition of hypersonic boundary layers over blunt bodies with strong bow shocks and with (or without) thermo-chemical nonequilibrium. The new method includes a set of new upwind high-order finite-difference schemes which are stable and are less dissipative than a straight forward upwind scheme using an upwind-bias grid stencil, a high-order shock-fitting formulation, and third-order semi-implicit Runge-Kutta schemes for temporal discretization of stiff reacting flow equations. The shock-fitting approach makes it possible to use high-order schemes for hypersonic flows behind the bow shocks. Shock capturing schemes are not suitable for DNS because of the loss of accuracy of the shock capturing schemes at the shock waves. Subsequently, 3-D computer codes for these methods were developed and validated. Their numerical accuracy was tested for DNS of hypersonic flows over blunt bodies.

New high-order upwind schemes

Direct numerical simulation of boundary layer stability and transition requires high-order numerical methods in order to resolve a wide range of flow length scales. For hypersonic flow simulations, however, high-order finite difference schemes are often unstable when they are coupled with high-order numerical boundary conditions. In Publications [12], [18], and [8], a new set of stable upwind fifth and seventh-order finite-difference schemes were developed for the direct numerical simulation of hypersonic boundary layers. The new schemes use central grid stencils with built-in numerical dissipation to control the numerical instability. The dissipation errors are designed to be smaller than the phase errors for well resolved length scales and to damp out unresolved shorter length scales. The numerical tests show that these upwind schemes are stable when they are coupled with high-order numerical boundary conditions, and they are more accurate than commonly used stable central schemes.

New high-order shock-fitting schemes

For the DNS of hypersonic boundary layers in flow over blunt bodies, the accurate computation of the unsteady curved bow shocks and their interaction with flow disturbance waves are important for the overall accuracy of the simulation. A shock-fitting approach was selected for such simulations because the unsteady bow shocks have a well-defined shape and high-order shock-fitting schemes are much more accurate than shock capturing schemes for computing hypersonic flows behind the oscillating bow shocks with disturbance/shock interaction. The use of the shock-fitting approach makes it possible to use our new fifth and sixth-order upwind schemes for flow fields behind the shocks. Therefore, a new simple formulation for high-order shock-fitting computations has been derived (Publications [12], [18], and [8]). The new shock fitting formulation is much simpler than conventional shock fitting formulas for the high-order discretization of three-dimensional flow equations. Figure 3 shows a 3-D shock fitted grid for direct numerical simulations of the receptivity of hypersonic leading edges.

New semi-implicit Runge-Kutta schemes

The differential equations for reacting hypersonic flows are stiff for explicit numerical schemes. Implicit methods need to be used to integrate the equations efficiently. However, the accuracy of commonly used implicit methods is often only second-order, which is not accurate enough for the direct numerical simulation of boundary layer stability. In Publications [4] and [9], a new set of semi-implicit Runge-Kutta schemes of up to third-order accuracy was developed for the robust and accurate temporal discretization of stiff equations for the DNS of three-dimensional reacting hypersonic flows. These new algorithms are more accurate than conventional implicit methods while maintaining the robustness for efficient calculations. These new schemes have been successfully applied in many transient reacting hypersonic flow computations. However, there is a drawback of semi-implicit Runge-Kutta schemes, as well as conventional Runge-Kutta schemes, that they require four sets of memory requirement for each variable in the flow fields. Such computer memory requirement becomes significantly large for DNS studies which require large memory. In Publication [28], we further derived and tested a new version of the low-storage semi-implicit Runge-Kutta schemes with minimum computer memory requirement for the direct numerical simulation of reacting hypersonic boundary-layer transition. The new third-order low-storage Runge-Kutta schemes require only two levels of memory locations at each stage. We have analyzed the stability properties of the new schemes by a linear analysis, and tested the accuracy and stability of the new schemes in several reacting flow numerical computations as well as model equation calculations. We have also applied the semi-implicit Runge-Kutta schemes to simulate unsteady high-speed flow combustion and detonation when high-order temporal accuracy is required. The new schemes have been incorporated in our new semi-implicit high-order shock-fitting codes for the DNS of hypersonic flows.

Computer code validation

Following the development of the new numerical methods, 3-D computer codes for the DNS of the full Navier-Stokes equations using these new methods with the option of a perfect gas model or the five-species nonequilibrium air model of Park [14] were developed. The numerical methods used in the code are the new fifth or sixth-order upwind shock-fitting finite difference schemes for spatial discretization, and third-order Runge-Kutta schemes for temporal discretization, where the new third-order semi-implicit Runge-Kutta schemes are used for real-gas simulations, and the low-storage Runge-Kutta schemes of Williamson [15] are used for perfect gas simulations.

In Publication [18], the accuracy of the new schemes was validated on several test cases. The code was applied to the DNS of receptivity to freestream acoustic disturbances for a hypersonic boundary layer over a parabola. The results show that the new schemes are very accurate for steady and unsteady simulations of hypersonic flows with physical bow shock oscillations. In Publication [21], extensive testing on the robustness and accuracy of the new semi-implicit Runge-Kutta schemes for stiff equations in 1-D and 2-D reacting flow problems was performed. In Publication [15], the new semi-implicit Runge-Kutta schemes and ENO schemes were applied to the numerical simulation of the interaction of freestream disturbances with a bow shock in reacting hypersonic flows over a blunt circular cylinder. The test results show that the new schemes are accurate and robust for reacting flow simulations.

4.3 DNS of Hypersonic Boundary Layer Stability and Transition

Laminar-turbulent transition in hypersonic boundary layers is a result of a nonlinear response of the laminar boundary layers to forcing disturbances [16]. In an environment with small disturbances, the paths to transition consist of receptivity, linear eigenmode growth or transient growth, and nonlinear breakdown to turbulence. The receptivity mechanism, which converts the environmental disturbances into boundary-layer instability waves, provides important initial conditions of amplitude, frequency, and phase for the instability waves [17–19]. For hypersonic boundary layers over blunt bodies, the receptivity phenomena are altered considerably by the presence of bow shocks over the bodies [20, 21] (Fig. 1). A curved bow shock creates entropy and vorticity layers interacting with boundary layers behind it. The wave fields behind the shock are complex because of the back and forth interaction of disturbance waves between the body and the shock.

Having developed the new DNS methods and validated their associated computer codes, we used numerical simulation as a tool to study the receptivity to freestream disturbances for hypersonic boundary layers over two-dimensional blunt leading edges. The development of first- and second-mode instability waves in the boundary layers and interaction between the bow shock and freestream disturbance waves were studied by both DNS and LST approaches.

DNS of boundary-layer receptivity to freestream disturbances for hypersonic flows over blunt leading edges.

In Publications [19] and [24], the DNS of the receptivity of two- and three-dimensional hypersonic boundary layers to freestream disturbances for a two-dimensional Mach 15 flow over a parabola was performed. The full Navier-Stokes equations were solved by using the new fifth-order shock-fitting upwind scheme. The DNS results were also compared with local linear stability analysis based on mean flow solutions obtained by the numerical simulation. It was found that the instability waves developed in the hypersonic boundary layer behind the bow shock contain both the first and second mode instabilities. The size and the strength of the two regions depend on the frequency of the disturbances. These 2-D studies were then extended to the DNS of receptivity of hypersonic boundary layers to 3-D freestream disturbances. Parametric studies are conducted on the effects of forcing frequency on the receptivity and on the nonlinearity of the wave modes. These simulations not only were the first DNS studies for realistic hypersonic flows over blunt bodies but also demonstrated the feasibility of the DNS studies for hypersonic boundary layers with realistic geometries.

The steady flow solutions for the viscous hypersonic flow over the parabola were first obtained by advancing the solutions to a steady state without freestream perturbations. Figures 4 and 5 show the steady solutions of a set of 160×120 computational grids, steady velocity vectors, and steady entropy contours. The shock is fitted as the outer freestream boundary of the computational domain. The velocity vector plot in Fig. 5 shows the development of the boundary layer along the surface, and the entropy contours show the entropy layer developing at the edge of the boundary layer. It has been found that the accuracy of the stability analysis for hypersonic boundary layers is very sensitive to the accuracy of the mean flow solutions [22]. By using the new high-order shock-fitting scheme, we are able to obtain high-accuracy "clean" mean flow solutions for the unsteady calculations as well as for the LST analyses for hypersonic boundary layers over blunt bodies.

The unsteady simulation was performed by imposing freestream disturbances to the freestream. The results showed that the instability waves developed in the hypersonic boundary layer behind the bow shock contain both the first and second mode instabilities. The results also indicated that external disturbances, especially the entropy and vorticity ones, enter the boundary layer to generate instability waves mainly in the leading edge region. Figure 6 shows the contours for the instantaneous perturbation of the vertical velocity components after the flow field reached a periodic state. The disturbance field is a combination of the external forcing disturbance waves and the T-S waves in the boundary layer. The contours show the development of the Tollmien-Schlichting (T-S) waves in the boundary layer on the parabola surface. From the instantaneous contours in Fig. 6, it is clear that the instability waves developed in the wall have two separate zones. The first zone is located in the region of $x < 0.2$ and the second one is located in the region of $x > 0.2$. It was shown that the instability wave developed in the first region is the first mode instability and that the wave in the second region is the second mode instability. Figure 7 shows the instantaneous perturbation of velocity vectors. The oscillations of the bow shock were resolved by the simulation and can be seen in this figure.

The 2-D simulation was subsequently extended to the DNS of the receptivity of the hypersonic boundary layer to oblique three-dimensional freestream acoustic waves for the same two-dimensional basic flow. Figure 8 shows the three-dimensional shock fitted grids using two computational zones resolved by $160 \times 120 \times 16$ and $200 \times 120 \times 16$ grids respectively. The unsteady flow fields are generated by imposing an oblique freestream disturbance at an angle of $\psi = 45°$ with wave amplitude of $\epsilon = 5 \times 10^{-3}$ and $F = 1770$. Figure 9 show the contours of instantaneous perturbation velocity components after the flow field reaches a periodic state. The instantaneous velocity contours show the development of three-dimensional instability waves in the boundary layer on the surface, similar to the first-mode zone. The second mode region is also generated near the end of computational Zone 1. The figure shows similar trends as two-dimensional wave developments, i.e., the first-mode amplification near the leading edge and the second-mode dominant downstream.

DNS of 3-D hypersonic boundary layers over axisymmetric blunt cones

In addition, we have also extended the previous planar 2-D work to the receptivity of axisymmetric boundary layers to freestream disturbances in Mach 15 flows over a parabolic cone (Publication [23]). The receptivity characteristics of axisymmetric and planar hypersonic boundary layers over blunt bodies were compared. The test case is the receptivity of an axisymmetric boundary layer to weak freestream acoustic disturbance waves for a Mach 15 hypersonic flow past a parabolic blunt cone at zero angle of attack. The axisymmetric steady and unsteady solutions for velocity vectors are shown in Fig. 10. The bow shock and development of boundary layers along the body surface are shown in this figure. The figure also shows the unsteady instantaneous perturbations of the velocity vectors for the receptivity of the axisymmetric Mach 15 flow over the parabolic cone with zero angle of attack. The results show that new schemes can resolve 3-D transient hypersonic flow with physical bow-shock oscillations accurately. The receptivity characteristics of axisymmetric and planar hypersonic flow over blunt bodies are studied and compared. Compared with the planar case, the axisymmetric flow over a blunt cone has much higher after-shock Mach numbers and much fuller boundary layer profiles. Consequently, the axisymmetric first mode wave generated by the receptivity process has longer wave length and smaller growth rate than the planar case.

DNS of 3-D hypersonic flow over elliptical cross-section cones.

Hypersonic flow over a 3-D blunt body experiences strong lateral pressure gradients that turn the streamlines away from the axial direction, inducing a skewed boundary layer profile with crossflow. The inflected crossflow velocity profile exhibits an inviscid instability. The character of the crossflow instability is well-established for subsonic and moderately supersonic flows over swept wings and certain model problems such as rotating disks, cones, and spheres [23]. Stability computations [24] have shown that crossflow increases the amplification rate and skewness of the most unstable first mode wave, and the most amplified second mode wave may be oblique to the freestream flow. Recently, Poggie and Kimmel [25] have done experimental work to examine stability and transition on a full 3-D configuration and to demonstrate a case in which the crossflow stability had a significant influence on boundary layer transition.

Our purpose is to conduct numerical studies of both steady and transient 3-D hypersonic flow over elliptical cross-section cones. We have extended our previous study of the receptivity of hypersonic boundary layers over parabolic blunt leading edges to the DNS of 3-D hypersonic flows over the cones. The first test case is the receptivity of a hypersonic boundary layer to freestream monochromatic planar acoustic disturbances for a Mach 15 and Reynolds number 6026 flow over a 2:1 elliptical cross-section blunt cone as shown in Fig. 2. Figure 11 shows the steady viscous hypersonic flow over a 2:1 elliptical cross-section blunt cone at Mach number 15. The bow shock is captured exactly as the outer computational boundary. The results show that the elliptical cross-section cone generates steady secondary cross flow in the boundary layer due to the uneven strength of the bow shock over the body. It is expected that the cross flow instability plays an important role in the transition of the hypersonic boundary layers. We are currently in the process of conducting receptivity studies of such hypersonic flow over the blunt cones to freestream acoustic disturbances. The receptivity studies are carried out by imposing acoustic disturbances in the freestream. The subsequent interaction with the bow shock and wave development in the boundary layer are simulated by using the full nonlinear Navier-Stokes equations. Work is underway to conduct transient flow simulations for the receptivity of hypersonic boundary layers over an elliptical cross-section blunt cone. The final results will be reported in the AIAA Aerospace Science Meeting in Reno, NV, January 1999.

4.4 Linear Stability Analysis of Hypersonic Flows

Much of our knowledge on the stability properties of supersonic and hypersonic boundary layers is based on the LST work of Mack [26,27]. For hypersonic flow over blunt bodies, the stability characteristics of hypersonic boundary layers over a blunt cone corresponding to Stetson's experiments [28] have been studied using LST [22,29–31]. Though some observations on the effects of bluntness and the entropy layer are consistent with linear stability analysis, the second-mode instability and the general amplification characteristics in the blunt cone flows do not agree with the experiments. The reason for the discrepancy is currently not clear. Possible reasons include the fact that the LST for hypersonic flow over a blunt cone has the difficulty of obtaining highly-accurate steady base flow for the stability equations. In addition, the effects of the bow shock and non-parallel boundary layers on the disturbance fields may not be adequately considered in the LST. Because DNS can provide the detailed solutions of the unsteady flow fields, the discrepancy between the LST and experiments may be resolved by comparing with DNS results. Therefore, LST analysis of the stability of hypersonic boundary layers over blunt bodies was conducted for comparison with the DNS results.

As a first step, we (Publications [7] and [16]) have developed two compressible global linear stability codes and have studied the linear stability of hypersonic Couette flows which are currently not well understood. High-Mach-number instability modes had not previously been found for compressible Couette flow at finite Reynolds numbers [32]. Unstable second modes were found for Mach 5 and 10 flow with critical Reynolds numbers to be around 9×10^4 and 2.6×10^5 respectively. The neutral stability curves for those Mach numbers are shown in Fig. 12. The effects of Mach numbers, three dimensionality, and the wall cooling on the stability of hypersonic Couette flow were also studied. We have also done detailed studies on the effect of viscosity on the acoustic instability of supersonic wall-bounded Couette flows. We found that two families of wave modes, modes I and II, are unstable at finite Reynolds numbers, where mode II is the dominant instability among the unstable modes. These two families of wave modes are acoustic modes created by sustained acoustic reflections between a wall and a relative sonic line when the mean flow in the local region is supersonic with respect to the wave velocities. The effects of viscosity on the stability of the two families of acoustic modes were studied by comparing the viscous results at finite Reynolds numbers with the inviscid results. We showed, for the first time, that viscosity plays a destabilizing role in both mode I and mode II stability for supersonic Couette flow in a range of Reynolds numbers and wavenumbers.

In Publications [22] and [26], we have subsequently been studying the linear stability of 3-D hypersonic boundary layers over blunt leading edges. The linear stability analysis is performed using a global spectral collocation method accounting for the shock effects by using Rankine-Hugoniot shock conditions on the upper boundary. It is shown that in addition to the boundary layer first modes and higher modes (Mack modes), the linear stability of the hypersonic flow between a bow shock and a parabolic leading edge has a new family of modes, shock modes. The shock modes are important mainly in the shock layer. In addition, the boundary layer modes are also affected by the existence of the shock.

4.5 Burnett Equations

The Burnett equations are a higher-order approximation to the Boltzmann equation than the Navier-Stokes equations for rarefied gas flows. We had developed numerical methods for simulation of hypersonic flows using the Burnett equations and evaluated their usefulness for potential applications to hypersonic flows in the rarefied gas flow regime.

In Publication [1], the general 3-D components of the Burnett stress and heat-flux terms were derived from the general tensor forms and extended our numerical method for solving the planar 2-D augmented Burnett equations to axisymmetric ones. The Burnett solutions were compared with Navier-Stokes solutions and DSMC results. In Publication [2], the Burnett solutions for Couette flow at various Mach numbers and Knudsen numbers were evaluated by comparing them with the DSMC results. The results showed that when the Burnett equations are valid, the Burnett solutions are not very different from the Navier-Stokes results. The only exception is that the Burnett solutions predict a much thicker shock wave than the Navier-Stokes equations in the temperature profiles across the shock waves, which may be significant for some applications.

However, our attempt in obtaining numerical Burnett solutions for 2-D hypersonic flow over a sharp leading edge was not successful due to the severe nonequilibrium effect near the leading edge. It is also reported that Forrest Lumpkin at NASA Ames could not obtain solutions of the augmented Burnett equations for expanding flow in the highly rarefied base region of a cylinder [33]. These difficulties together with the analytical analysis on the entropy properties of the Burnett equations by Comeaux et al. [33] at Stanford University suggest that the Burnett equations may not be appropriate for hypersonic flow that is very far from the continuum regime. In other words, for hypersonic flow with large local Knudsen numbers, especially in the expansion flow, the computations of the Burnett equations will fail to obtain solutions. Thus, the applications of Burnett equations to steady nonequilibrium hypersonic flow probably may not be very significant for many situations, and may not work for flow with very high local Knudsen numbers.

Overall, the Burnett equations may not be significant for steady hypersonic flows at very high nonequilibrium conditions except for computing the shock structure. Therefore, we have shifted the focus of our investigation to the stability equations for hypersonic flows using the Navier-Stokes equations, because the stability and transition of hypersonic boundary layers occurs at higher Reynolds number in the continuum regime.

5 Personnel

In the original proposal for the grant, two full-time students were supposed to be supported to conduct research for a three-year period. During the actual course of the research, however, eight students were fully or partially supported by the AASERT grant because of the graduations or the changes of students and because of some partial support for research done by several graduate students who were mainly supported by the core AFOSR grant related to this AASSERT grant.

The following students were partially supported by the grant:

1. Mr. Sean H. Hu, a Ph.D. student mainly supported by the grant. Research topics: Linear and nonlinear stability analysis of and PSE calculations for hypersonic boundary layers.

2. Mr. Chong W. Whang, a Ph.D. student mainly supported by the grant. Research topics: DNS of 3-D hypersonic boundary layers with Görtler vortices on blunt concave surfaces in front of hypersonic inlets.

3. Mr. Haibo Dong, a Ph.D. student. He was supported by the grant for a short period of time to work on the development of new efficient semi-implicit parallelized DNS methods for 3-D hypersonic boundary layers.

4. Mr. Martin Y. Ma, a Ph.D. student. He was supported by the grant for a short period of time to work on the DNS of nonequilibrium reacting 3-D hypersonic boundary layers.

5. Mr. Mahidhar Tatineni, a Ph.D. student. He was supported by the grant for a short period of time to work on the code development and validation for the DNS of 3-D hypersonic boundary layers.

6. Mr. Theodore K. Lee, a Ph.D. student. He was supported by the grant for a short period of time to work on the development of shock-capturing methods for DNS of hypersonic boundary layers.

7. Mr. Jack J. Yoh, a Ph.D. student mainly supported by the grant. He left UCLA on August 1997. Research topics: new low-storage semi-implicit Runge-Kutta schemes for DNS of reacting hypersonic flows.

8. Mr. Abdlmonem Beitelmal, a Ph.D. student. He left UCLA after about one month of working in our lab. Research topics: DNS of hypersonic flows.

The following students did thesis research work for the research projects supported by the grant, but they were not financially supported by the AASERT grant:

1. Mr. Gregory H. Furumoto, a Ph.D. student. He obtained his Ph.D. degree in mechanical engineering at UCLA in March 1997. He currently works for the Aerospace Corporation. Research topics: unsteady shock/boundary-layer interaction in nonequilibrium reacting hypersonic flows.

2. Mr. Anthony J. Sclafani, a M.S. student. He obtained his M.S. degree in aerospace engineering at UCLA in June 1997. He currently works for the Boeing Company. Research topics: Parallel computations of reacting hypersonic flows.

6 Publications

The following publications were completed from work supported by the ASSERT and core grants:

In Journals or Books:

1. X. Zhong and G. H. Furumoto, "Augmented Burnett Equation Solutions over Axisymmetric Blunt Bodies in Hypersonic Flow," *Journal of Spacecraft and Rockets*, Vol. 32, No. 4, pp. 588-595, 1995.

2. X. Zhong and K. Koura, "Comparison of Solutions of the Burnett Equations, Navier-Stokes Equations, and DSMC for Couette Flow," In *Rarefied Gas Dynamics*, Vol. I, edited by J. Harvey and G. Lord, Oxford University Press, Oxford, pp 354-360, 1995.

3. C.-E. Chiu and X. Zhong, "Numerical Simulation of Transient Hypersonic Flow Using the Essentially Nonoscillatory Schemes," *AIAA Journal*, Vol. 34, No. 4, pp. 655-661, 1996.

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9 Figures

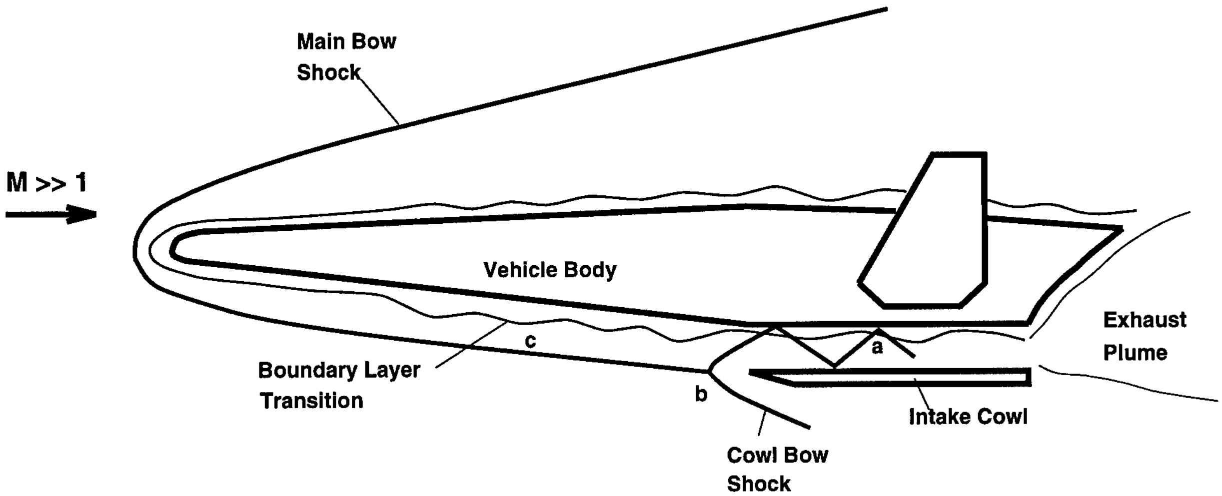

Figure 1: A schematic of a generic hypersonic lifting vehicle with boundary-layer transition and shock/boundary-layer interaction.

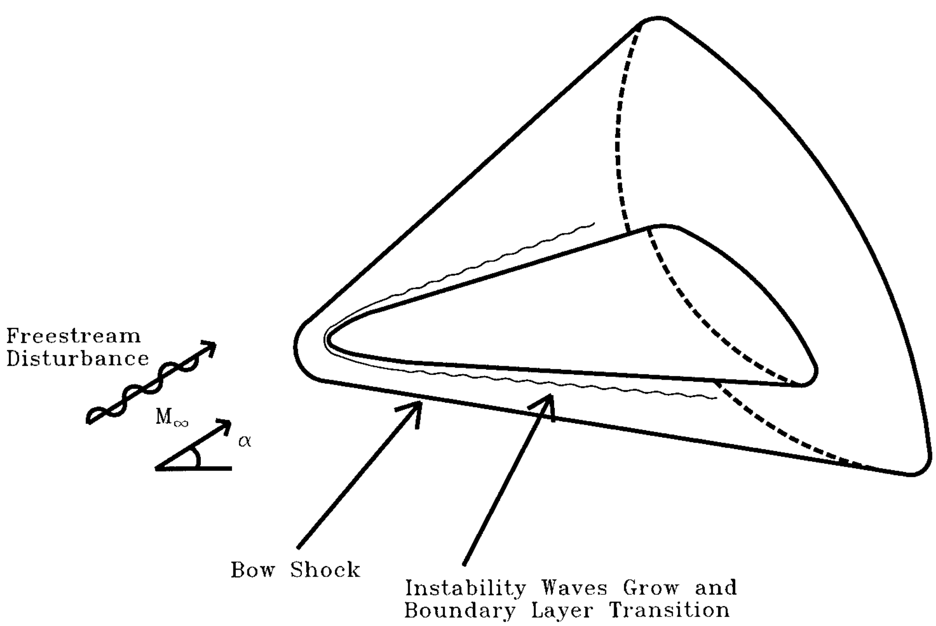

Figure 2: The hypersonic flow field in the direct numerical simulation of 3-D reacting hypersonic boundary-layer receptivity to freestream disturbances over a blunt elliptic cross-section cone.

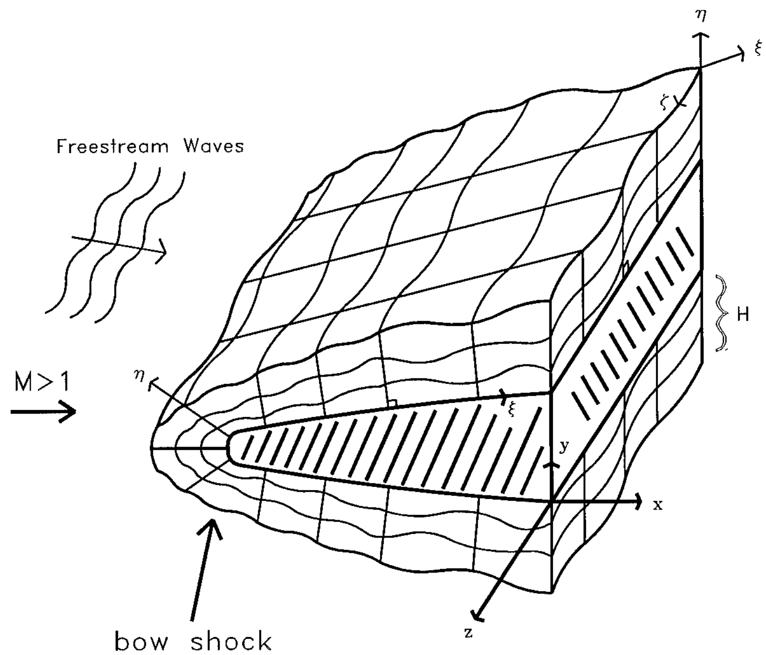

Figure 3: A schematic of 3-D shock fitted grids for the direct numerical simulation of hypersonic boundary-layer receptivity to freestream disturbances over a blunt leading edge.

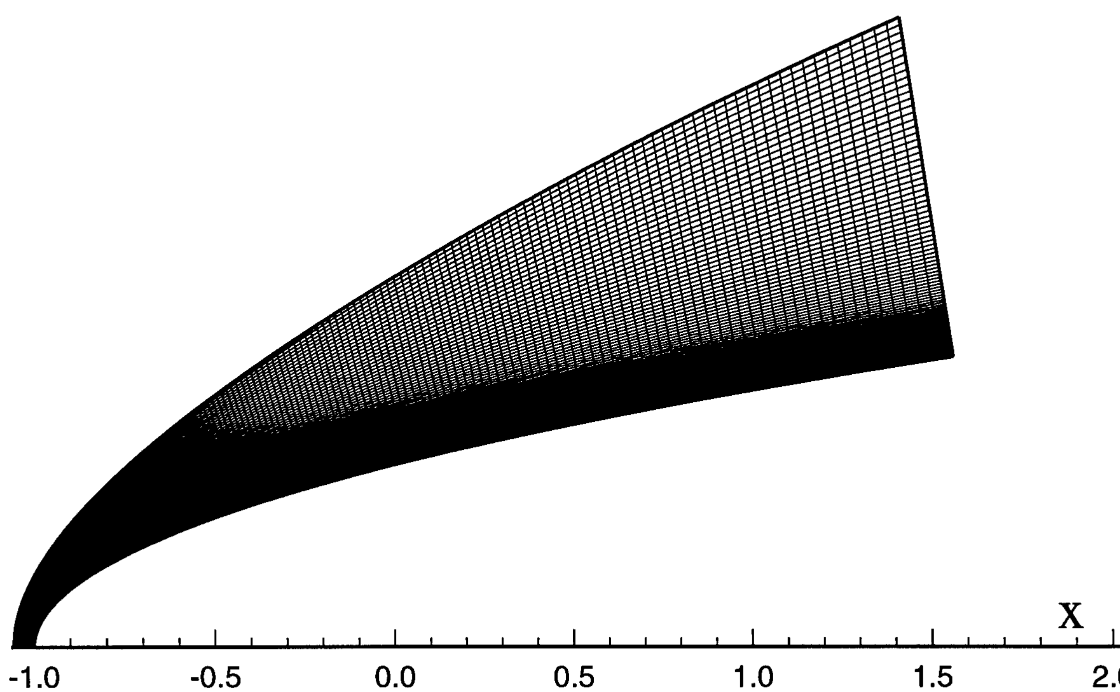

Figure 4: Computational grid for the DNS of the receptivity to a weak freestream monochromatic planar acoustic waves by a hypersonic boundary layer over a parabola. The bow shock shape is obtained as the numerical solution for the freestream grid line. ($M_\infty = 15$ and $Re_\infty = \rho^*_\infty U^*_\infty d^* / \mu^*_\infty = 6026.55$)

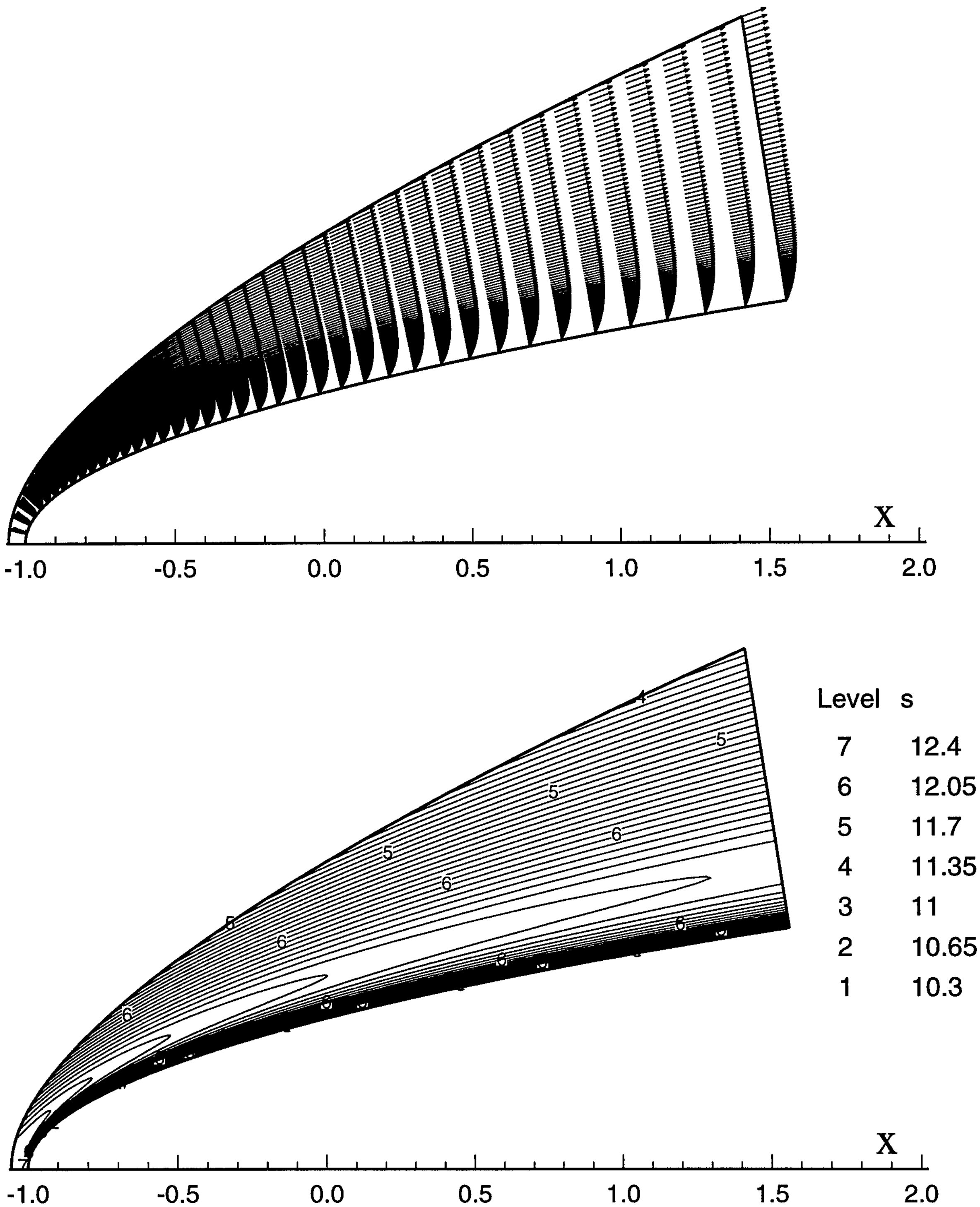

Figure 5: Steady base flow solutions of velocity vectors and entropy contours for the DNS of the receptivity to a weak freestream acoustic waves by a hypersonic boundary layer over a parabola ($M_\infty = 15$ and $Re_\infty = 6026.55$).

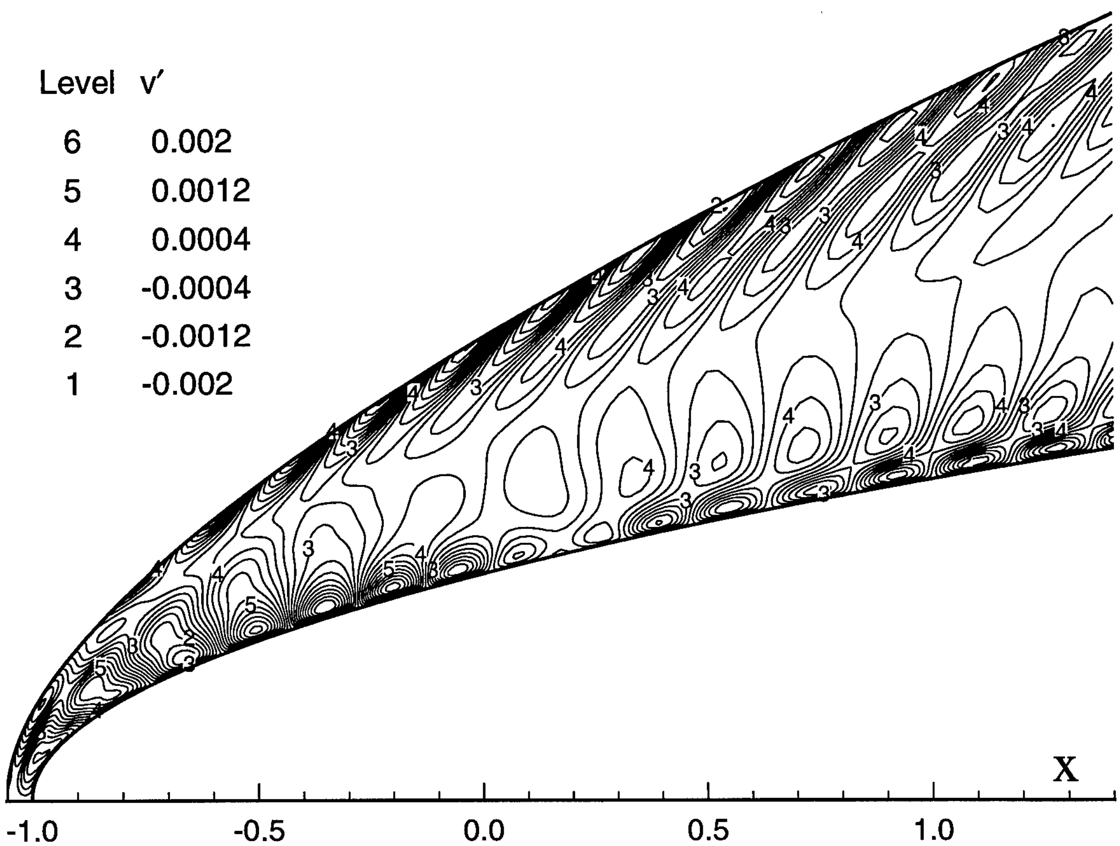

Figure 6: Instantaneous vertical velocity perturbation contours for the DNS of the receptivity to a weak freestream acoustic waves by a hypersonic boundary layer over a parabola ($M_\infty = 15$ and $Re_\infty = 6026.55$).

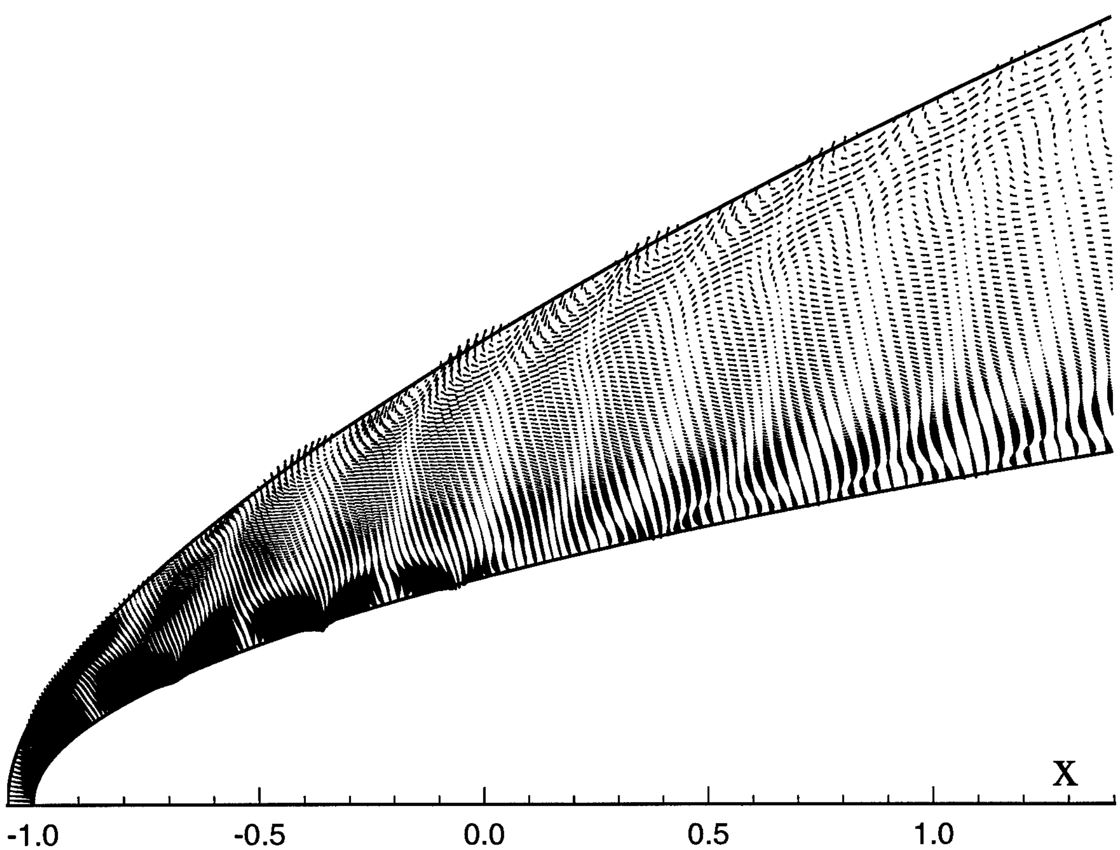

Figure 7: Instantaneous perturbations of the velocity vectors for the DNS of the receptivity to a weak freestream acoustic waves by a hypersonic boundary layer over a parabola ($M_\infty = 15$ and $Re_\infty = 6026.55$).

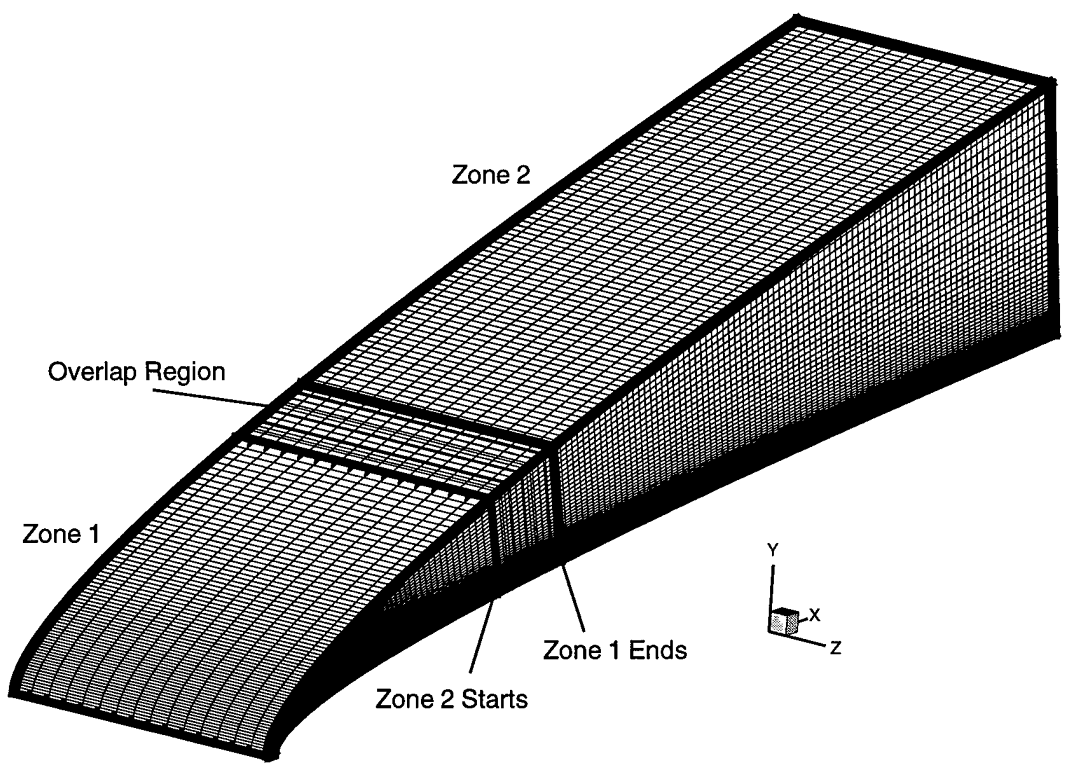

Figure 8: Computational grid for 3-D hypersonic boundary layer receptivity to freestream oblique disturbance waves using two overlap zones ($M_\infty = 15$ and $Re_\infty = 6026.55$).

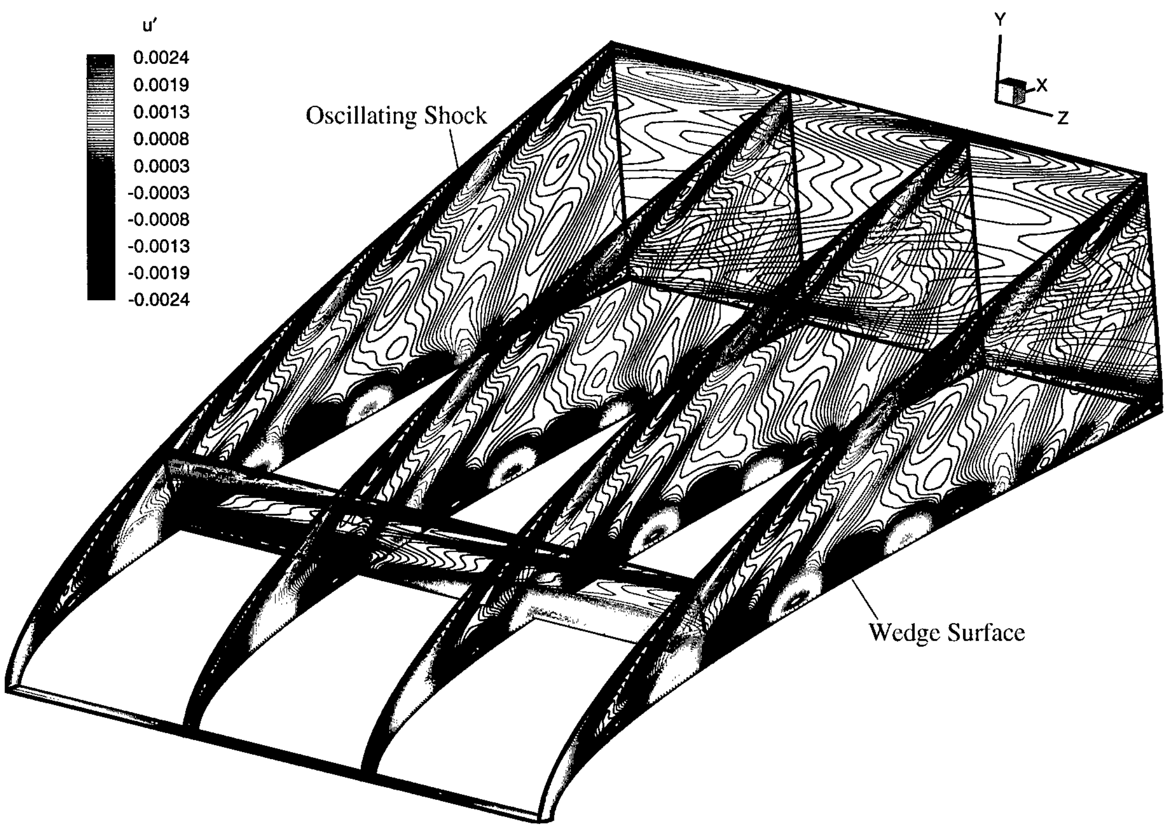

Figure 9: Contours of the instantaneous horizontal velocity components u' for the receptivity to freestream disturbances for 3-D hypersonic boundary-layer over a parabolic wedge ($M_\infty = 15$, $Re_\infty = 6026.55$, and $F = 1770$).

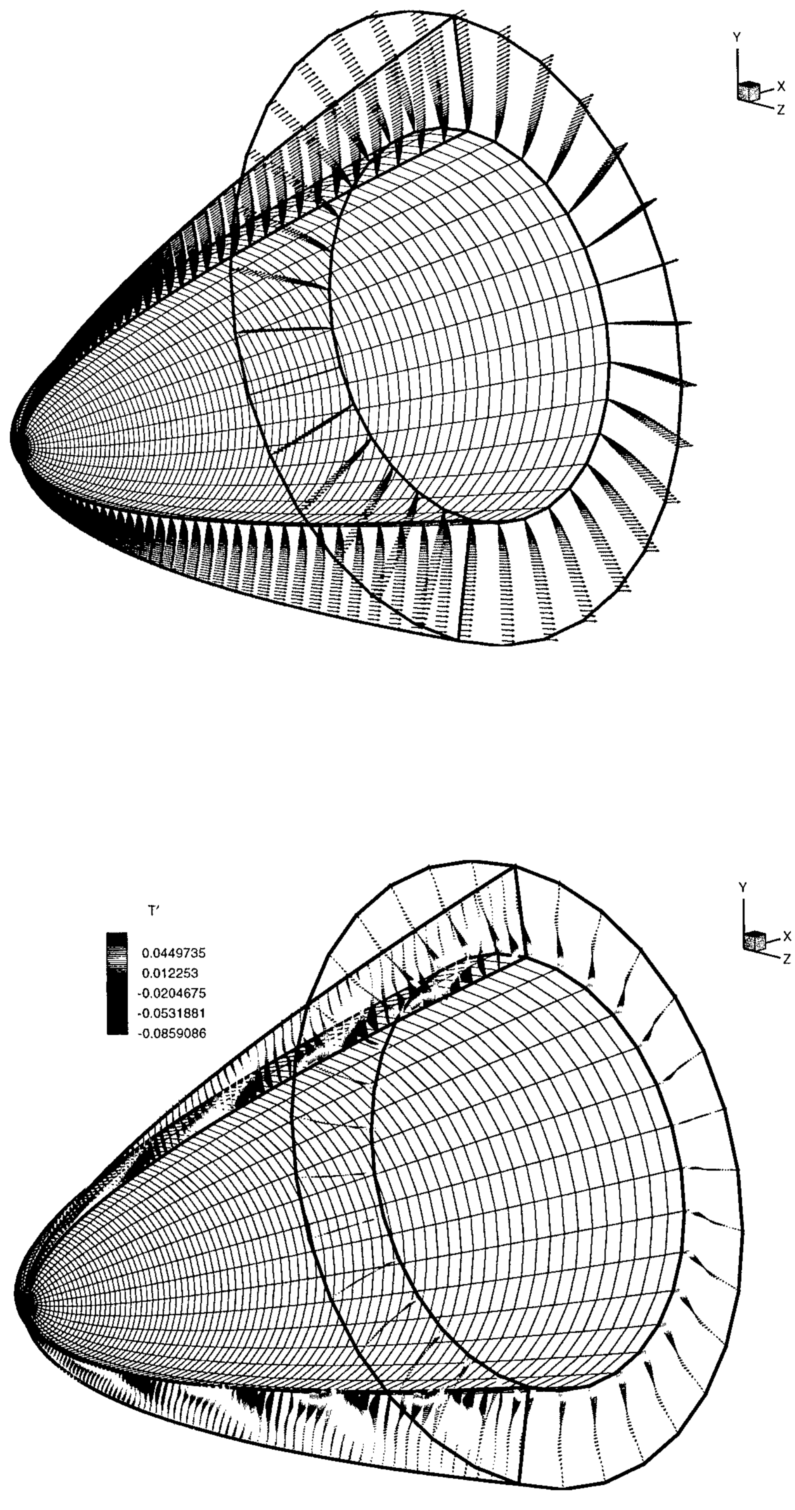

Figure 10: Solutions of steady and unsteady simulations of axisymmetric Mach 15 viscous hypersonic flow over a blunt cone (Upper figure: steady velocity vectors, lower figure: instantaneous perturbations of velocity vectors caused by the receptivity to freestream sound at a nondimensional frequency $F = 1770$).

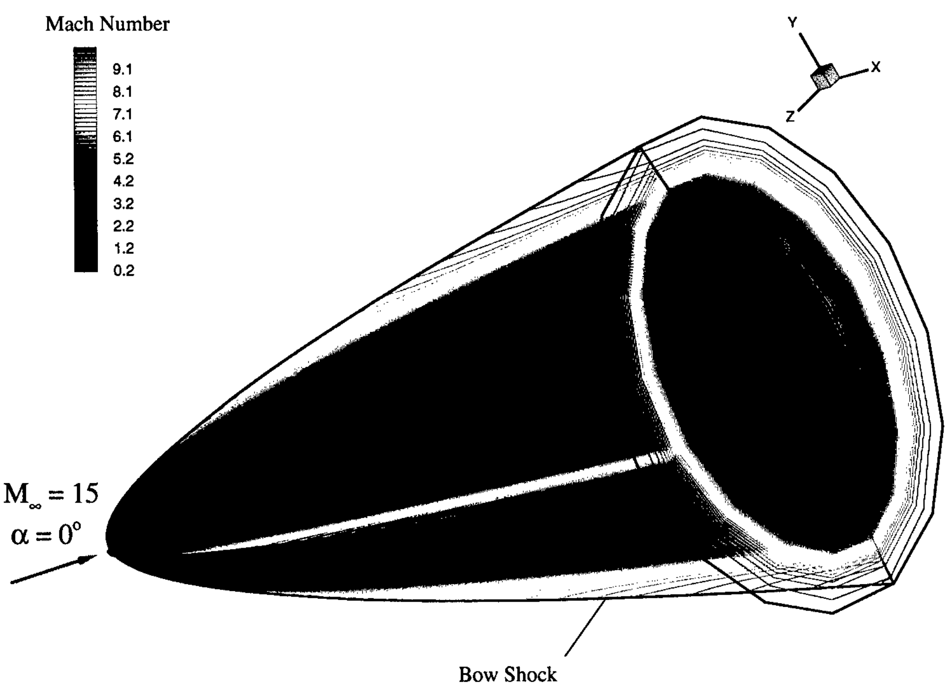

Figure 11: Mach number contours for steady viscous 3-D hypersonic boundary layer flow fields over a 2:1 elliptic cone. ($M_\infty = 15$ and $Re_\infty = 45561$).

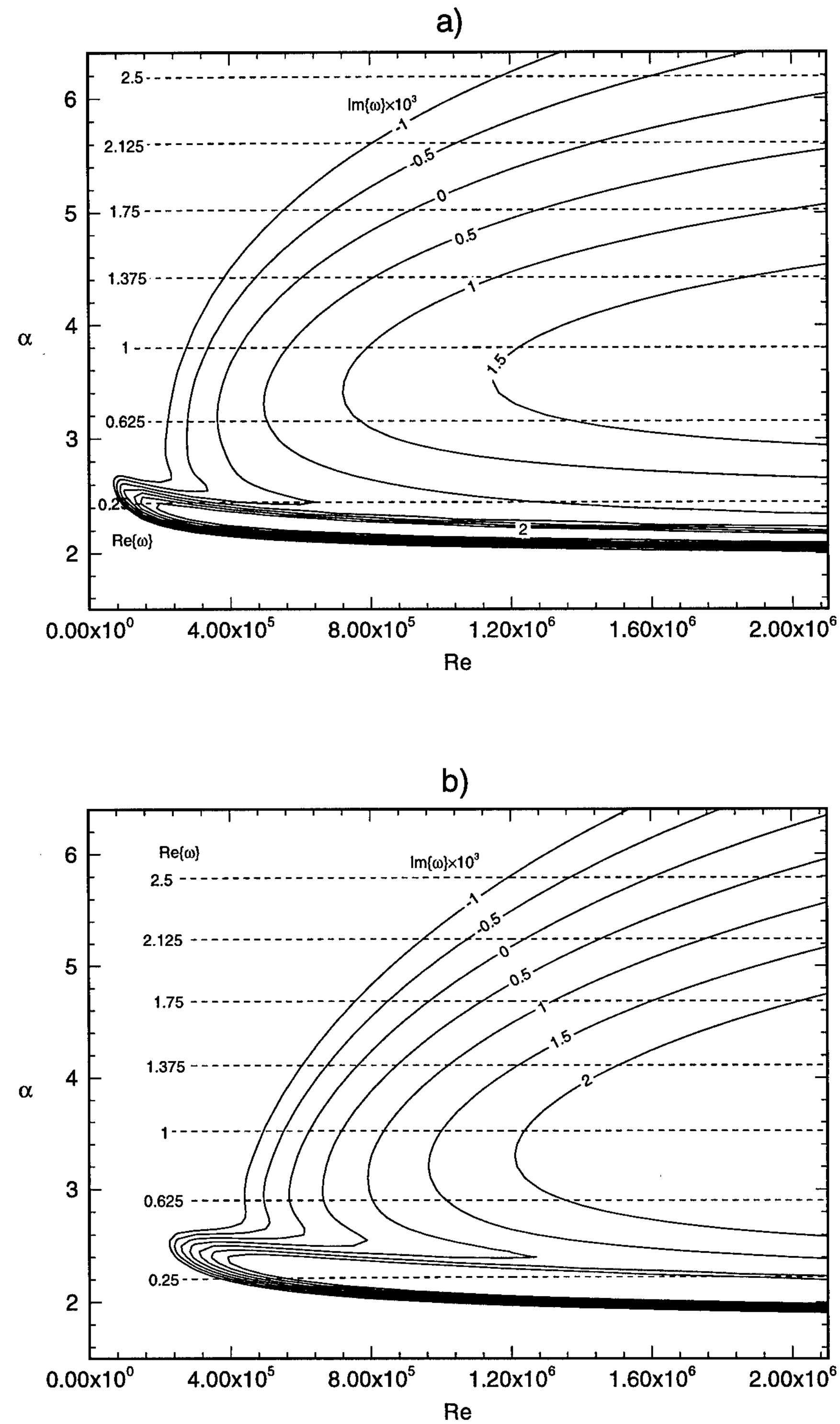

Figure 12: The second mode growth rate contours for hypersonic plane Couette flow as a function of wave number α and Reynolds number: a) $M_\infty = 5.0$, b) $M_\infty = 10.0$.