AN INTERFERENTIAL STREAK INSTABILITY OF HYPERSONIC BOUNDARY LAYER OVER A CIRCULAR CONE

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Summary The objective of this paper is to investigate the stability of hypersonic boundary layer over a circular cone at small angle of attack. After obtaining the steady flow, then two-dimensional multiple disturbances were introduced at inflow section and their spatial evolutions were simulated by DNS method.

I. INTRODUCTION

Laminar-turbulent boundary layer transition has dramatic effects on hypersonic vehicles, such as reentry vehicles and hypersonic cruise vehicles. These effects include heat transfer, skin friction and separation which can hinder the thermal protection of the vehicles. Therefore, it is of importance for vehicle designers to understand the laminar-turbulent transition phenomena and transition mechanism. A series of ground wind tunnel experiments have been conducted to investigate the AoA effects on hypersonic boundary layer transition on a cone since 1960s[1-3]. These experimental data showed that for small AoA with small bluntness, the transition position shift upstream on the windward ray and downstream on the leeward ray, relative to the zero-deg AoA. Although these results provided the transition location, no improved knowledge of the phenomena responsible for this trend was obtained. The transition mechanism is still poor understood, a detailed investigation on generation and development of disturbance wave should be made if we want to know this transition mechanism.

Due to the high cost on hypersonic stability experiments and the progress in computer techniques in recent years, the direct numerical simulation (DNS) has become a powerful tool in boundary layer stability and transition research. A DNS investigation of AoA effects on the stability of hypersonic boundary layer over a circular cone has been carried out in this paper. Mach 6.0 steady flow over a 5º half-angle circular cone (nose radius *R*n=1mm) is obtained by solving Navier-Stokes equations with NND-scheme[4] with the second order accuracy. Based on the linear stability theory results, stability calculations are carried out on the windward and leeward region at 0.5º AoA by solving unsteady Navier-Stokes equations in perturbation form using a modified MacCormack finite difference scheme[5] with the third order accuracy in both temporal and spatial directions

II. COMPUTATIONAL SETUP FOR DNS

Based on the steady flow and LST analysis results, a DNS is carried out to simulate the evolution of the unstable waves and their interactions. The computational domain which were cut between *X*/*R*n=300.0 and *X*/*R*n=401.4 in the streamwise direction. The leeward and windward computational domains for DNS are shown in figure 5. The mesh size of leeward region is 508(streamwise) ×246(circumference) ×81(wall normal), and 508×208×81 on the windward region. Flow conditions are: M_∞= 6, Re$=1\times10^7$, T_∞=79K, T_w=293K, $\gamma=1.4$, Pr=0.72. At the inflow section, the flow variables are set to be incoming variables. At the outflow section, the extrapolation is used to get the flow variables. On the wall, non-slip and iso-thermal conditions are used. The symmetry boundary condition is used at leeward meridian.

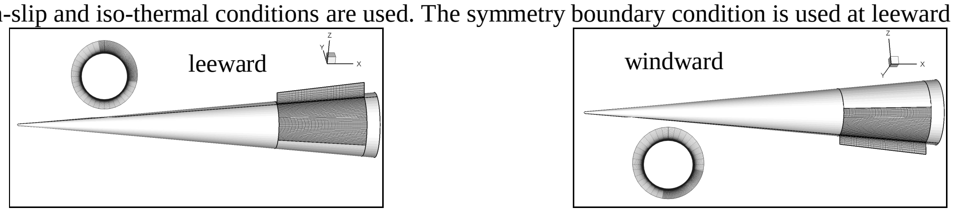

Fig. 1 Schematic of grid in the leeward and windward region

III. EVOLUTION OF UNSTABLE WAVES

Direct numerical simulation starts from steady flow field. A series multiple unstable two-dimensional disturbances are introduced near wall at inflow section around the cone to simulate their spatial evolution and interaction in the boundary layer. The initial unsteady disturbances are introduced as $u' = \varepsilon \sum_{1}^{10} (\omega_i t)$, Where ε = 0.001 is the amplitude of disturbance wave and ω_i is the circular frequency of the most unstable wave predicted by LST based on the local parallel assumption at *X*/*R*n=300.0 around the cone, and $\omega_{i+1} = \omega_i + \Delta\omega$, $\omega_1 = 1.4$, $\Delta\omega = 0.1$.

Fig. 2 shows the perturbation of pressure p' contours on the leeward and windward region at t = 200, and their close-up view are on the right. It can be noticed that: (1) the disturbance waves do not grow persistently, they increase and decay by turns. In the computational process, the different disturbances with different frequency take place wave interference,

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then small amplitude of disturbances regions called "interference region" form; (2) three-dimensional waves in the circumferential direction generate with the development of the two-dimensional disturbances, and the direction is not perpendicular to the streamwise direction which is shown in the close-up view. And these wave packets grow lager after passing the interference region.

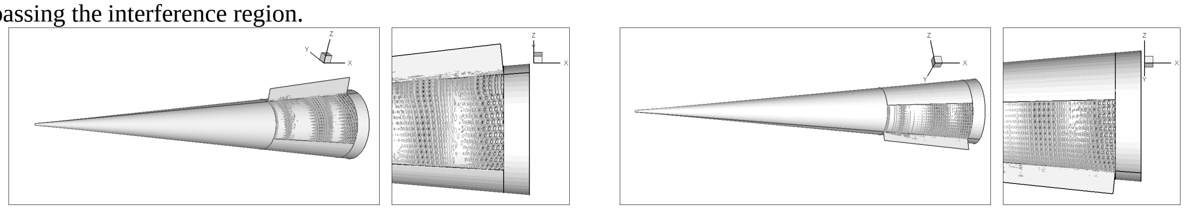

Fig. 2 Perturbation pressure p' contours on the leeward and windward

IV. INTERFERENTIAL STREAK PHENOMENA

In order to investigate the cumulative effect of the disturbances wave along time, the maximum of the perturbations of velocity components, pressure and density are obtained. Fig. 3 gives the iso-surface plots based on the maximum perturbations of pressure. It can be seen that a kind of "interferential streak" structure forms on the leeward and windward region. That may be another new instability mode differing from the Mack mode.

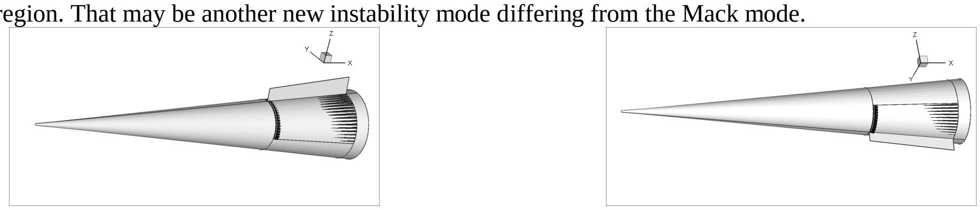

Fig. 3 Iso-surface of maximum perturbation pressure p'

In order to confirm the interferential streak phenomena in hypersonic boundary layer over the circular cone, a numerical test of interferential streak has been made. Considering a 2D traveling wave $u(x,y)=\sin(\lambda_N \cdot x+\omega_T)\cdot\exp(-100(y-y_N)^2)\cdot\exp(0.5x)$, where λ_N is denoted for the length of different wave, x is stream wise direction, y is lateral direction, ω_T is variable of time and y_N is lateral position of the wave. Fig. 4 gives the contours of these seven different waves in x-y plane. Fig. 5 shows the interferential streak phenomena by obtaining the maximum amplitude of the wave at different position in x-y plane. We can find that different wave interact each other, then the interferential streak forms along the x direction. This result gives a proof to the interferential streak phenomena which was obtained by solving the 3D Navier-Stokes equations in perturbation form.

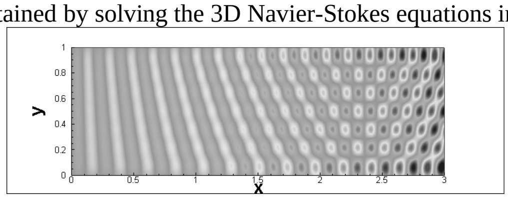

Fig. 4 Wave contours in x-y plane

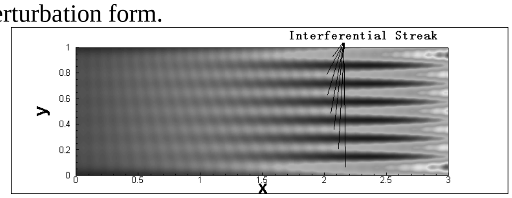

Fig. 5 Interferential streak in x-y plane

V. CONCLUSIONS

The numerical results show that three-dimensional waves in the circumferential direction generate, and their asymmetric development of the unstable waves around the cone are the result of the small AoA, though it is only 0.5 degree. Small AoA changes the boundary layer thickness contrast to zero AoA, it also changes its instability property. A kind of interferential streak instability was found along the streamwise direction which may be beneficial for us to understand the transition leeside-forward and windside-aft for smooth cones at small angle of attack. Therefore, further study is needed to understand this instability mechanism.

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