Hypersonic boundary layer receptivity on flat plate with blunt leading edge due to acoustic disturbance

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Abstract. In the process of hypersonic boundary layer transition, the leading edge receptivity due to free-stream acoustic disturbance provides unstable perturbations in boundary layer with initial amplitudes, which is one of hot issues in the study about transition mechanism. The receptivity of leading edge is influenced by many factors, involving geometry parameters, disturbance types, etc., among which the bluntness plays a key role for generating disturbances. In order to reveal the mechanism of bluntness influence on the boundary layer transition, investigations into the acoustic receptivity on flat plates with sharp and blunt leading edge are carried out. The flow conditions are as follows: Mach number 6, Reynolds number $1e7/m$, adiabatic wall. By introducing two-dimensional plane fast and slow acoustic waves into the free-stream, the whole receptivity process of free-stream disturbances passing through shock wave into boundary layer is simulated with high-order accuracy DNS method. With sharp leading edge as a reference, the generation mechanism of the perturbations near blunt leading edge and its influence on the boundary layer downstream are analyzed. Some conclusions are obtained: for acoustic disturbances in hypersonic free-streams, the receptivity mechanism of blunt leading edge is different from that of sharp leading edge; both the fast and the slow mode can be produced respectively near the sharp leading edge by the fast and the slow acoustic wave, while only fast mode appears near the blunt leading edge; the receptivity of blunt leading edge due to the fast acoustic is stronger than that due to slow acoustic, and is also stronger than that of the sharp leading edge in a certain region of boundary layer downstream.

1. Introduction
In high Mach number flows, a temperature peak will occur around the leading edge of the aircraft due to aerodynamic heating. Blunt leading edge is usually adopted in the thermal protection design to reduce the heat-transfer peak. However, the leading edge bluntness not only affects the heat-flux, but also affects the transition process of boundary layer downstream. The transition onset will change as the bluntness is increased. Specially, the “transition reversal” phenomenon of blunt cone is related to nose tip bluntness, and may be caused by the enhancement of disturbances near the blunt nose[1, 2].

The free-stream disturbances in hypersonic flow first pass through the shock wave generated at the leading edge, and then enter the boundary layer. This process is called “receptivity” of boundary layer due to external disturbances. The leading edge region is one of the main source of the boundary layer perturbation, which provides the initial amplitude, frequency and phase for the evolution of the
downstream disturbance and affects the development of unstable waves together with the internal instability in the boundary layer[3, 4].

According to the disturbance generation ways, the receptivity process can be divided into two types: artificial receptivity and natural receptivity. The natural receptivity is caused by free-stream disturbances (acoustic, vorticity, entropy) with small amplitude. There is a strong interference between the free-stream disturbance and the perturbation modes in the boundary layer, and also a conversion mechanism between different wave modes[1, 5]. Usually there are many kinds of unstable wave in the receptivity process, such as the first mode, second mode, and high-order mode, etc. So, compared with the subsonic boundary layer, the hypersonic boundary layer receptivity problem is much more complex[6].

The receptivity theory proposed by Fedorov et al.[7, 8] indicated that the fast and the slow acoustic wave in high speed free-stream can stimulate two kinds of disturbance mode in the boundary layer of flat plate, and unstable second modes evolve in the downstream region. Their researches showed that different modes have different receptivity to acoustic wave, and the fast and the slow wave can effectively stimulate fast and slow modes respectively. However, the efficiency of the fast acoustic exciting slow mode or that of the slow acoustic exciting fast mode is at least one order of magnitude lower than in the previous case. Theoretical analyses of Fedorov et al.[7] also indicated that the receptivity of slow acoustic is stronger than that of fast acoustic under the adiabatic condition. It should be noted that these results were obtained under the condition of sharp leading edge. Therefore, these conclusions may not be suitable for the blunt leading edge case.

As for the hypersonic receptivity process of flat plate with sharp leading edge, Ma et al.[9, 10] have carried out many direct numerical simulations of fast acoustic wave by using high-order shock fitting method. They found that there are stable I and II modes in the boundary layer, which play the role of energy conversion between free flow acoustic and Mack mode, and that different modes have different receptivity properties to acoustic incidence angle. Egorov et al.[11] and Malik et al.[12] respectively carried out numerical simulations on the receptivity process of Mach 6 flows over sharp leading edge flat plate, involving the influence of fast and slow acoustic waves, wall temperature and incidence angle. Their results showed that the receptivity of slow acoustic is greater than that of fast acoustic, and is more likely to cause boundary layer transition. We have also verified this phenomena in a similar simulation[13], which is consistent with Fedorov’s receptivity theory.

However, in the case of blunt leading edge, the receptivity of fast and slow acoustic waves is different from that of sharp leading edge. Several two-dimensional direct numerical simulation results showed that the disturbances caused by the fast acoustic wave is stronger than that caused by the slow acoustic. For example, in the Mach 15 blunt wedge acoustic receptivity studies carried out by Zhong[14], the amplitude of entropy disturbance caused by fast acoustic wave is about 50% larger than that of slow acoustic. In the numerical simulation of blunt flat plate, Malik et al.[12] found that the amplitude of wall pressure fluctuation caused by fast acoustic wave is one order of magnitude higher than that of slow acoustic wave when the leading edge radius is increased to 0.2 mm. In recent years, Cerminara et al.[15] conducted numerical simulations on hypersonic flows over blunt wedge with half cone angle of 20°. They found that the wall pressure fluctuation caused by fast acoustic wave is about one order of magnitude higher than that of slow acoustic wave in the frequency range of 50–500kHz. Moreover, in the simulation of 3-D free-stream acoustic receptivity of a swept blunt wedge with half cone angle of 4°, they also found that the location of wall friction rise (transition) caused by fast acoustic wave is earlier than that caused by slow acoustic. In the simulation of cone transition process, Balakumar et al.[17] also found that when slow sound wave is introduced into the free-stream, the transition onset on the sharp-tipped cone is in good agreement with the wind tunnel experiment, while the transition of the blunt nose cone lags behind the experimental measurement. These studies showed that the receptivity of fast and slow acoustic wave in free-stream is different under different bluntness conditions, and the efficiency of fast acoustic wave is higher in the case of blunt nose.
Then, how does the blunt leading edge affect the receptivity due to fast and slow acoustic waves, and how the disturbances near the leading edge and in boundary layer downstream are generated and evolve? The researches on these questions will help us to understand the characteristics and mechanisms of free-stream acoustic wave in hypersonic boundary layer transition, and to interpret the phenomenon of “transition reversal”.

In this paper, the acoustic receptivity of blunt leading edge is investigated in hypersonic flows over two-dimensional flat plates. By introducing fast and slow acoustic waves into the free-stream, the receptivity processes of flat plates with sharp and blunt leading edge are directly simulated by high-order accuracy numerical methods. The disturbances in the flow fields are analyzed by fast Fourier transform method (FFT) and linear stability theory (LST). The generation mechanism of the leading edge disturbances and the evolution characteristics of the perturbations in the boundary layer downstream are discussed to understand the transition process of hypersonic boundary layer.

2. Numerical methods

2.1. Governing equation

The governing equation used in present studies is the two-dimensional compressible Navier-Stokes equation for complete gas:

$$\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} = 0$$  \hspace{1cm} (1)

where \(Q\) is a conserved variable: \(Q = (\rho \, \rho u \, \rho v \, e)^T\), \(\rho\) and \(e\) are the density and total energy per unit volume of gas respectively, and \(u\) and \(v\) are the velocity components. \(E\) and \(F\) are the vector flux in curvilinear coordinate system, including convection term and viscous term. Using the complete gas equation of state, the viscosity coefficient satisfies Sutherland formula.

2.2. Numerical scheme

The convection term is discretized with the fifth-order weighted compact nonlinear (WCNS-E-5)[13] explicit finite difference scheme:

$$E'_j = \frac{75}{64h} (\bar{E}_{j+1/2} - \bar{E}_{j-1/2}) - \frac{25}{384h} (\bar{E}_{j+3/2} - \bar{E}_{j-3/2}) + \frac{3}{640h} (\bar{E}_{j+5/2} - \bar{E}_{j-5/2})$$  \hspace{1cm} (2)

In the above formula, \(\bar{E}_{j+1/2} = E(\bar{U}_{j+1/2})\) is the numerical flux of the element boundary, and \(\bar{U}_{j+1/2}\) is obtained by weighted nonlinear interpolation of the original variable at the element boundary. The viscous term is discretized by the sixth-order accuracy central scheme.

The implicit time advancing method of LU-SGS is used to solve the steady flow field. When the unsteady flow field is solved, the time term is discretized by the second order implicit three-point difference method:

$$J^{-1} \frac{3Q^{n+1} - 4Q^n + Q^{n-1}}{2\Delta \tau} + R(Q^{n+1}) = 0$$  \hspace{1cm} (3)

The dual time step method is used to solve this equation, and the virtual time term \(\Delta \tau^*\) is added at the left end of the above formula:

$$\left[ J^{-1} \left( \frac{1}{\Delta \tau} + \frac{3}{2\Delta \tau} \right) I + M(Q^n) \right] \Delta Q^{n+1} = \left[ J^{-1} \frac{3Q^n - 4Q^{n-1} + Q^{n+1}}{2\Delta \tau} + R(Q^n) \right]$$  \hspace{1cm} (4)

Here \(\Delta \tau^*\) is the virtual time step, and \(\Delta \tau\) is the real time step. In this equation, \(\Delta Q^{n+1} = Q^{n+1} - Q^n\), and \(n\) is the number of real time advancing steps and \(p\) is the number of sub iterations. LU-SGS method is also used in the sub iteration process to convergence solutions. When the sub iteration converges, \(Q^{n+1} = Q^{n+1}\), the solution of equation (3) is obtained. The convergence criterion of sub iteration is that the residual error is less than 0.01. The real time step \(\Delta \tau\) is not restricted by computational stability, and can be larger according to physical problems. The numerical methods
used in this paper have been verified in direct numerical simulations of typical hypersonic boundary layer receptivity cases[13].

3. Computational conditions

3.1. Flow conditions
In this paper, direct numerical simulations of free-stream acoustic receptivity are carried out for two kinds of leading edge flat plates with length of L = 1500 mm and leading edge radii of Rn = 0 and 5 mm. The free-stream parameters are as follows: M∞ = 6, Re∞ = 1.0 × 10^7/m, T∞ = 61K, adiabatic wall. In order to distinguish the disturbance waves in the boundary layer, the grid-spacing along the streamwise direction is determined to ensure at least twenty grid points per wave-length. In the normal direction, the mesh is clustered near the wall to ensure that about eighty points are within the boundary layer.

3.2. Plane acoustic wave
The free-stream disturbance is a weak monochromatic plane acoustic wave with zero incidence angle, that is, the wave front is perpendicular to the plate. Before reaching the shock wave, the acoustic wave can be written in the following dimensionless form:

\[
\begin{bmatrix}
\rho' \\
u' \\
v' \\
p'
\end{bmatrix}_e = \begin{bmatrix}
\rho' \\
u' \\
v' \\
p'
\end{bmatrix}_\infty e^{i(k_x x - \omega t)}
\]  

(5)

The acoustic amplitude satisfies the following relations:

\[|\nu'_e| = |\rho'_e|, M'_e = |\rho'_e|/\rho_\infty = \varepsilon, |v'_e| = 0\]

In the above formula, k_x is the dimensionless wave number, and ε is a small quantity which is the amplitude of free-stream acoustic wave. The dimensionless circular frequency of disturbance wave, \(\omega = k_x(1 \pm M'_e)\) for fast and slow acoustic. In this paper, the acoustic amplitude is set to \(\varepsilon = 5 \times 10^{-4}\), and the frequency is \(f = 50 \text{ kHz}\).

4. Numerical simulation and discussion
The direct numerical simulation process of free flow acoustic receptivity is as follows: firstly, the high-order accuracy steady flow calculation is carried out to obtain the basic flow field when the residual error converges to the machine zero; secondly, the small acoustic wave is introduced into the upstream entrance of the calculation domain, and the unsteady flow calculation method and high-order scheme are used to directly simulate the process of free-stream acoustic wave passing through shock wave and entering the boundary layer flow field. When the disturbance propagates to the whole flow field and forms a periodic solution, the perturbation field is obtained by subtracting the steady basic flow from the instantaneous flow field. The characteristics of the disturbance wave near the leading edge and in the boundary layer are studied by flow stability theory and Fourier spectrum analysis and then the acoustic receptivity mechanism in the leading edge and the evolution properties of the disturbance in the boundary layer are discussed.

4.1. Mean flow
The premise of receptive numerical simulation is to obtain high-order accuracy steady basic flow. Figure 1 shows the Mach number distribution in the flow field of the flat plates with sharp and blunt leading edges. The sharp flat plate generates a weak oblique shock wave from the leading edge, while the blunt plate generates a strong bow shock wave at the leading edge, and there is a subsonic region near the blunt leading edge. The two mean flow fields are smooth and have no obvious numerical
oscillations. Figure 2 shows the velocity and temperature profiles of boundary layer at seven stations with $x = 100 \sim 1000\text{mm}$. Compared with the sharp flat plate, the velocity of the boundary layer edge of the blunt plate is lower, the temperature is higher and the boundary layer is thicker. The numerical results of the sharp plate agree well with the similarity solutions at each station, which shows that the calculation results of the mean flow are reliable.

![Figure 1. Mean flow over sharp and blunt flat plate.](image1)

4.2. Numerical simulation of acoustic receptivity of flat plate leading edge

In the hypersonic flow field of a flat plate, there is a certain range of subsonic region between the bow shock wave and the stagnation point of a blunt leading edge plate. Theoretically, an infinitely thin plate with a sharp leading edge produces only one oblique shock wave, and there is no stagnation point region. This is an important difference between the blunt leading edge and the sharp leading edge. In this paper, the receptivity difference of fast and slow waves near sharp and blunt leading edges is analyzed by taking the free-stream acoustic wave with frequency of 50 kHz as an example. Since the pressure fluctuation is the main disturbance component of acoustic wave, the analysis of the disturbance wave is mainly based on pressure fluctuations.

Figure 3 shows the distribution of instantaneous pressure fluctuation caused by fast and slow acoustic waves near the sharp leading edge. The thin gray line in the figure represents the position of oblique shock wave. It can be seen that the disturbance field is divided into three different regions by the oblique shock wave and the boundary layer: there is free-stream acoustic disturbance outside the shock wave; when the free-stream disturbance passes through the oblique shock wave, the fluctuation along the shock direction alternates positively and negatively; the disturbances at the leading edge tip propagates along the downstream flow to form boundary layer disturbance. The amplitude of perturbation caused by the fast and the slow acoustic wave is very small, close to free-stream acoustic.
Figure 3. Pressure fluctuations near sharp leading-edge ($R_n = 0$ mm).

Figure 4 shows the distribution of instantaneous pressure fluctuation near the blunt leading edge, in which the contour level range is the same as that in Figure 3. Similar to the case of sharp leading edge, the perturbation field behind bow shock wave is mainly divided into two regions, but the disturbance intensity near the blunt leading edge is significantly greater than that of the sharp leading edge. When the free-stream disturbance is fast acoustic, it causes stronger pressure perturbation than the slow acoustic wave.

Figure 4. Pressure fluctuations near blunt leading-edge ($R_n = 5$ mm).

The perturbation strength can be reflected by the amplitude of wall pressure fluctuation. Figure 5 shows the pressure fluctuation amplitude distribution near the leading edge of both sharp and blunt flat plate ($x < 50$ mm). In the case of sharp leading edge, the disturbance decreases slightly after passing through the leading edge, and then increases slowly. However, in the case of blunt leading edge, the disturbance amplitude in stagnation point area ($x < 0$ mm) is very large, and gradually attenuates in the downstream flow. In both cases, the perturbation caused by the fast acoustic wave is stronger than that caused by the slow acoustic. When the leading edge is blunt, the disturbance produced by both the fast and the slow acoustic is stronger than the sharp leading edge. In addition, the disturbance amplitude produced by the fast acoustic is about twice that of the slow acoustic.

Figure 5. Amplitude distribution of pressure fluctuation on flat plate surface.

The difference of the pressure fluctuation field between the blunt leading edge and the sharp leading edge indicates that there are different modes of disturbance. Figure 6 shows the phase velocity distributions along the x-direction of the wall pressure disturbance near the leading edges. $1+1/M_\infty$ and
1-1/\(M_s\) represent the phase velocities of fast and slow free-stream acoustic, respectively. The phase velocity is obtained by the derivative of phase angles along x-direction. Details about the calculation are shown in reference[9].

The phase velocity of perturbations in the downstream region of the sharp leading edge is close to that of the fast and the slow acoustic wave respectively, that is, the fast acoustic wave excites a fast mode, while the slow acoustic wave excites a slow mode. This phenomenon is consistent with the results of Ma et al.[9,10], which indicates that the perturbations in downstream boundary layer are directly excited by the free-stream acoustic waves.

However, the acoustic receptivity of the blunt leading edge is different from that of the sharp leading edge. No matter whether the free-stream acoustic wave is fast or slow, the disturbance phase velocity in boundary layer downstream of the blunt leading edge is close to that of the fast acoustic wave. This is consistent with the linear analysis of acoustic wave/shock wave on blunt cone[18]. In the vicinity of the blunt leading edge, the phase velocity of the disturbance wave is smooth and continuous, while the phase velocity near the sharp leading edge fluctuates greatly. This fluctuation on the sharp flat plate is mainly due to small pressure perturbation amplitude which is easy to be disturbed by numerical oscillations near the oblique shock. The bluntness changes the phase velocity and the amplitude of perturbations in boundary layer, indicating that the leading edge is an important region affecting the disturbance waves in the boundary layer downstream.

![Figure 6. Distribution of phase velocity deduced by pressure fluctuation along flat plate surface.](image)

The sharp leading edge can excite both the fast and the slow mode, while the blunt leading edge only stimulates the fast mode. What is the mechanism that leads to only fast modes in the case of blunt leading edge? This problem has not been explained in the previous studies and needs further analyses.

4.3. Generation mechanism of perturbations near blunt leading edge

Due to the different geometry shapes of sharp and blunt leading edge, the flows near stagnation zone are different, which results in different acoustic receptivity. In order to understand the generation mechanism of perturbations near leading edge, Figure 7 shows the temporal variation of instantaneous pressure fluctuation fields caused by fast acoustic waves in one time period of free-stream acoustic. It can be seen from the figure that after passing through the shock wave and contacting the wall surface, the free-stream acoustic wave generates strong disturbances in the stagnation area of the blunt leading edge. The generated disturbances spread around in a fan-shaped manner and propagates upstream and downstream at the same time, producing new disturbances including reflected and diffracted waves. The reason for this phenomenon is that there is a certain subsonic region near the stagnation zone after the bow shock wave, where perturbations can propagate forward and backward. This process is different from that in supersonic regions, where perturbations can only propagate downstream. The serials of contour show that the disturbances near stagnation area is very strong and moves downstream. Obviously, the region around leading edge is the source of disturbances in the boundary layer downstream. After passing through the shoulder of the blunt leading edge, the pressure perturbation propagates downstream and is in the same direction as the mean flow velocity, which results in a phase velocity of local fast acoustic wave. According to the results in figure 6, it can be seen that the phase velocity is close to the free-stream fast acoustic, and belongs to fast mode.
Figure 7. Evolution of pressure fluctuation near blunt leading edge (fast acoustic wave).

Figure 8 shows the evolution of disturbances induced by the slow acoustic wave. The process of disturbance generation is similar to that of fast acoustic. Due to the shorter wave length compared with the fast acoustic, the action range of the slow acoustic in one wavelength is relatively small, so the influence area is smaller. Similar to the case of the fast acoustic wave, due to the subsonic flow near the stagnation region, new reflected and diffracted waves are generated and evolves in the form of fast mode.

Figure 8. Evolution of pressure fluctuation near blunt leading edge (slow acoustic wave).

Figure 9 shows the amplitude distribution of pressure fluctuation on the stagnation line. Taking the free-stream acoustic amplitude as a reference, the perturbations induced by the fast and the slow acoustic wave are compared. When the acoustic waves pass through the shock, the fluctuation amplitudes increase by more than two orders of magnitude, and then decay rapidly. After a certain distance from the shock, the amplitudes increase gradually and reach the maximum at the leading edge stagnation point (x = -5 mm). The disturbance amplitude caused by the fast acoustic at stagnation is about 80 times of free-stream acoustic amplitude, and the receptivity of the slow acoustic wave is weaker, about 40 times.

From the observations on the evolution process of the leading edge perturbations, it can be known that the reflected and diffracted waves generated in the subsonic region near the leading edge are the main reasons for the difference in the acoustic receptivity between the blunt and the sharp leading edge. In the subsonic region of the blunt leading edge, when the disturbance generated by free-stream acoustic wave evolves downstream, it will propagate at the speed of local fast acoustic (1+1/Ma), thus a fast mode is formed in the downstream boundary layer. Therefore, no matter whether the free-stream acoustic is fast or slow, the fast mode will occur in the boundary layer downstream of the blunt leading edge, which explains the cause of the fast mode in figure 6. The generation mechanism of the disturbance mode of blunt leading edge is described in figure 10, which clearly shows the receptivity process of free-stream acoustic wave for blunt leading edge.
Figure 9. Evolution Distribution of pressure fluctuation amplitude along stagnation line (Rn = 5 mm).

Figure 10. Schematic diagram of perturbation generation near blunt leading edge.

4.4. Influence of bluntness on downstream boundary layer
The amplitude and the phase velocity of disturbances generated from the sharp and the blunt leading edge are different. How these disturbances affect the perturbation evolution in boundary layer downstream is the main content of this section. Taking the 50 kHz free-stream fast and slow acoustic waves as an example, the receptivity process of a flat plate with length of 1500 mm is numerically simulated. By comparing the amplitude, the phase velocity and the structure of perturbations in the boundary layer, the influences of different leading edges on the receptivity downstream is analyzed.

Figure 11 presents the phase velocity distribution of the disturbance caused by the fast and slow acoustic waves in the flat plate boundary layer, in which numerical results are compared with the fast and slow modes of stability analyses. The LST results are used for the sharp flat plate, while the PSE calculation considering the nonparallel effect is adopted for the blunt flat plate. The related stability analysis methods are detailed in literature[19]. For the sharp flat plate, in the range of x < 1000 mm, the phase velocity of disturbances excited by the fast acoustic fluctuates around the phase velocity of LST fast mode, while the phase velocity of disturbance wave excited by the slow acoustic fluctuates around the phase velocity of LST slow mode. In the vicinity of x = 1150 mm, the phase velocity of the fast and slow modes is the same, and then the Mack second mode appears. The oscillations of phase velocity calculated by DNS is attributed to the influence of various disturbance modes and the free-stream acoustic wave in the numerical simulation. Different from the sharp leading edge plate, on the blunt flat plate only the fast mode is present. In the range of x < 1000 mm, the phase velocity of the perturbation in the boundary layer is in good agreement with that of PSE fast mode. The divergence of phase velocity computed from DNS in the boundary layer downstream is due to small amplitudes caused by perturbation attenuation.
Figure 11. Phase velocity of boundary layer disturbance.

Figure 12 shows the amplitude variation of wall pressure fluctuations on the sharp flat plate. The pressure fluctuation increases slowly in the downstream region and reaches saturation at about $x = 700$ mm. After the synchronous position ($x = 1150$ mm) of the fast and the slow mode, the amplitude starts to increase rapidly, and its growth-rate is very close to that of Mack second mode calculated by LST. In figure 13, the rope-like structure in the numerical schlieren graph of DNS also indicates that the second mode appears downstream. In the upstream region, the amplitude of wall pressure fluctuation caused by the fast acoustic wave has a large oscillation, which corresponds to the phase velocity fluctuation in figure 11.

Figure 12. Comparison of fluctuation amplitude variation between DNS and LST on sharp leading-edge flat plate.

Figure 13. Numerical schlieren of flow over flat plat with sharp leading-edge (fast acoustic wave).

Figure 14 describes the pressure fluctuation amplitude on the wall of the blunt flat plate, which shows different characteristics from that of the sharp flat plate. The wall pressure fluctuation caused by the fast wave is stronger than that caused by the slow wave. In addition, the amplitude of the blunt plate is stronger than that of the sharp plate in the region of $x < 500$ mm, indicating that the blunt leading edge has an enhancement effect on the disturbance in a certain range of boundary layer downstream. When $x > 500$ mm, the perturbation in the boundary layer of the blunt flat plate gradually weakens, and there is no unstable wave similar to that in the sharp flat plate flow. In fact, we did not find any instability mode in the flow stability analysis on the blunt flat plate, which is consistent with the DNS results.
5. Summary

In this paper, the free-stream acoustic receptivity of hypersonic flat plates with the sharp and blunt leading edges are investigated by means of direct numerical simulation. Based on the fast Fourier transform and the flow stability theory, the acoustic receptivity mechanism and disturbance evolution characteristic of two-dimensional flat plate are analyzed. The major results are summarized as follows:

1) The hypersonic acoustic receptivity mechanisms near the sharp and blunt leading edge are different. The subsonic flow between the leading edge wall and the bow shock wave is the reason for generating different disturbance modes on the sharp and the blunt leading edge.

2) The disturbance near the sharp leading edge is dominated by the interference of free-stream acoustic waves and the shock wave. The fast acoustic wave generates the fast mode, and the slow acoustic produces the slow mode. These two kinds of acoustic waves can stimulate Mack second mode in the boundary layer downstream.

3) The disturbance near the blunt leading edge is dominated by the reflected and the diffracted wave generated from the subsonic stagnation region. Under the condition of blunt leading edge, both the fast and the slow acoustic wave only produce the fast mode. The receptivity of the fast acoustic wave is larger than that of the slow acoustic wave. In a certain range of the boundary layer downstream, the disturbance originating from the blunt leading edge is stronger than that from the sharp leading edge.

The blunt leading edge can produce stronger disturbance waves in the boundary layer upstream, which is helpful to explain the phenomenon of “transition reversal” found in hypersonic transition problems. Although some receptivity mechanisms of sharp and blunt leading edges under single frequency acoustic wave are discussed at present, it is not clear whether the relative size of bluntness and acoustic wave length affects the receptivity of leading edge, and whether the vorticity wave and the entropy wave have the similar physical mechanisms. In order to further reveal the role of bluntness in the generation and evolution of disturbances in boundary layer, we will continue to carry out researches in this field, hoping to understand the influence of leading edge receptivity on boundary layer transition.

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