2019 4th International Conference on Automation, Mechanical and Electrical Engineering (AMEE 2019)
ISBN: 978-1-60595-655-8

Receptivity Study of Hypersonic Boundary Layer under Freestream Finite Amplitude Continuous Entropy Disturbance with Single Frequency

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Keywords: Hypersonic flow, Boundary layer, Finite amplitude, Entropy disturbance.

Abstract. The DNS method is used to calculate the unsteady flowfield around blunt cone under the action of a single frequency finite amplitude continuous entropy wave. The hypersonic flowfield response to single frequency finite amplitude entropy wave is investigated, and the hypersonic boundary layer receptivity features under single frequency finite amplitude disturbance are explored. The results find that the strong disturbance wave is produced by the interaction of freestream wave with shock wave and boundary layer, and there are regular high-entropy and low-entropy regions in the downstream evolution process. The frequency characteristics of boundary layer disturbance wave are directly related to freestream disturbance wave, and the frequency characteristics become weaker as the disturbance wave evolves downstream. During the development of disturbance downstream, the second, third and fourth (f_2-f_4) order modes in the boundary layer increase relatively. The central disturbance modes of the nose region are the fundamental mode in the boundary layer, and the main disturbance modes in the boundary layer of the downstream region of the flowfield are composed of the fundamental mode (f_1) and the second, third and fourth (f_2-f_4) order modes.

Introduction

The change of aerodynamic parameters on the surface of hypersonic vehicle caused by transition of hypersonic boundary layer will directly determine the aerodynamic and aerothermal characteristics of hypersonic vehicle [1-3], and then affect the overall design of hypersonic vehicle. As the beginning and key stage of transition, receptivity has been widely concerned by many scholars [4-8]. However, most of the studies are focused on the effects of continuous small disturbances or mixed frequency disturbances of freestream. These studies systematically describe the evolution mechanism of disturbances. However, there are essential differences between the single frequency finite amplitude disturbance with the continuous small disturbance of freestream and the mixed frequency disturbance. Therefore, the hypersonic boundary layer response characteristics and the evolution mechanism of disturbance wave under single frequency and finite amplitude disturbances are significantly different from those under freestream continuous small disturbances and multiple mixed frequency disturbances. Using single frequency and finite amplitude disturbance as disturbance source has a key role in revealing the hypersonic boundary layer receptivity under single frequency and finite amplitude disturbance and establishing the basic correlation between freestream disturbance and boundary layer disturbance. It can also provide a new unique perspective for understanding the hypersonic boundary layer receptivity and even the stabilization mechanism of hypersonic flow.

Therefore, based on the single-frequency finite-amplitude disturbance, the direct numerical simulation method is used to simulate the unsteady flowfield with entropy wave. The response of flowfield to the single-frequency finite-amplitude entropy wave is discussed, and the boundary layer receptivity to the single-frequency finite-amplitude disturbance is studied.

Computational Method and Condition

The inviscid terms of the N-S equation are split into positive and negative terms by S-W vector flux splitting method. The 5th order UWENO scheme is used for the inviscid terms discretization. At the same time, the viscous terms are discretized by the 6th order central difference scheme (CDS). The third-order TVD Runge-Kutta method is used for time advance. This method has been verified in the author's previous work [9-10]. In this paper, the calculation model is blunt cone. Its half-cone angle is 8°, the nose area radius is 1mm, and the angle of attack is 0°. Mach number is 6, the freestream temperature is 200K, and the wall temperature is 200K. The Reynolds number is 6000 according to the parameters in the inflow. In order to facilitate the calculation, the freestream parameters are used to deal with the parameters without dimension. The disturbance frequency and amplitude of freestream continuous entropy are 0.25 and 0.08 respectively.

Response of Flowfield to Finite Amplitude Continuous Entropy Disturbance

Fig.1 shows the contours of the instantaneous entropy disturbance of hypersonic flowfield under the action of a single frequency finite amplitude entropy disturbance. It can be clearly seen from the figure that the entropy distribution of hypersonic flowfield has changed obviously due to the finite amplitude disturbance. The entropy increases and decreases alternately are close to the shock wave and in the boundary layer. This demonstrates that strong disturbance waves are produced in the flowfield after the interaction of freestream waves with shock waves and boundary layer, and there are regular high-entropy and low-entropy regions in the downstream. Significant changes in entropy will inevitably change the thermodynamic mechanism in the shock wave layer and boundary layer, and then affect the boundary layer flow state. Fig.2 demonstrates the contours of the velocity of the flowfield. As can be found from the figure, similar to the law of entropy wave disturbance, the change of velocity in the flowfield near shock wave or boundary layer is also significant under the finite amplitude entropy disturbance. Fig.1 and Fig.2 show that when a single frequency finite amplitude entropy disturbance of freestream enters the flowfield, the finite amplitude entropy disturbance first interacts with the bow shock wave, obvious deformation occurred in the region near the bow shock wave. In addition, after shock layer interference, the disturbance wave outside the flowfield enters the boundary layer, and interrelates with the boundary layer. Some new disturbances will be generated [11]. Under the combined function of the disturbance wave, the reflected wave and the boundary layer, the evolution of the disturbances are more complicated. Therefore, the production and evolution of hypersonic boundary layer wave under finite amplitude entropy wave disturbance of freestream will be analyzed in the following sections.

Response of Boundary Layer under Finite Amplitude Continuous Entropy Disturbance

Fig.3 reveals the variation of pressure disturbances under finite amplitude entropy wave in the boundary layer. It can be clearly found from the figure that the pressure disturbances at different locations are periodically distributed and the disturbance characteristics with the period t=4 are very obvious. It is known that the period of the finite amplitude entropy wave in freestream is t=4 (frequency f=0.25), in indicates the frequency characteristic of the boundary layer disturbance wave is directly related to freestream disturbance. It is also found that the evolution of disturbance wave is obviously divided into two regions; namely, the nose region ($x \leq 0$) and the downstream region outside the nose region ($x > 0$). In the nose region, the disturbance wave presents a simple sinusoidal characteristic, and the frequency characteristic is basically consistent with the freestream disturbance wave. However, it can also be seen that the disturbance curve with sinusoidal characteristics also exhibits local small deformation, and the amplitude in the nose region is relatively large. In the downstream region outside the nose, the time-domain curve of disturbance in the boundary layer begins to deform obviously near the nose, and the deformation of the time-domain curve becomes more significant as the disturbance wave development along streamwise in downstream. Obviously, the disturbance wave whose frequency characteristics in the boundary layer are basically consistent with the freestream disturbance wave is the initial disturbance wave of boundary layer, which generated by the interference between freestream disturbance wave and shock wave, and then further interaction with boundary layer. The deformation of time-domain curve is mainly due to the features reflection of the new boundary layer disturbance wave induced by the further interrelation between the initial disturbance wave and the boundary layer. And with the development of the disturbance wave along streamwise, the interference effect of the new disturbance wave on the initial disturbance wave of boundary layer becomes stronger.

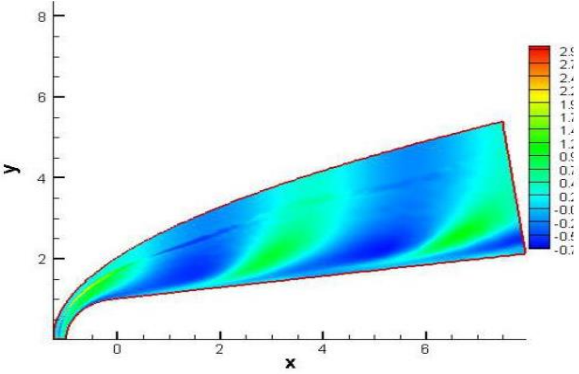

Figure 1. Contour of entropy disturbance.

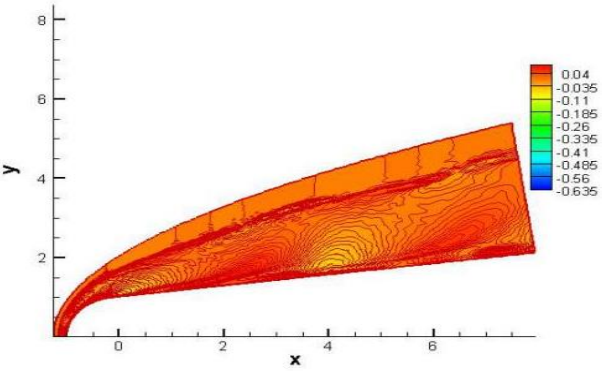

Figure 2. Contour of velocity disturbance.

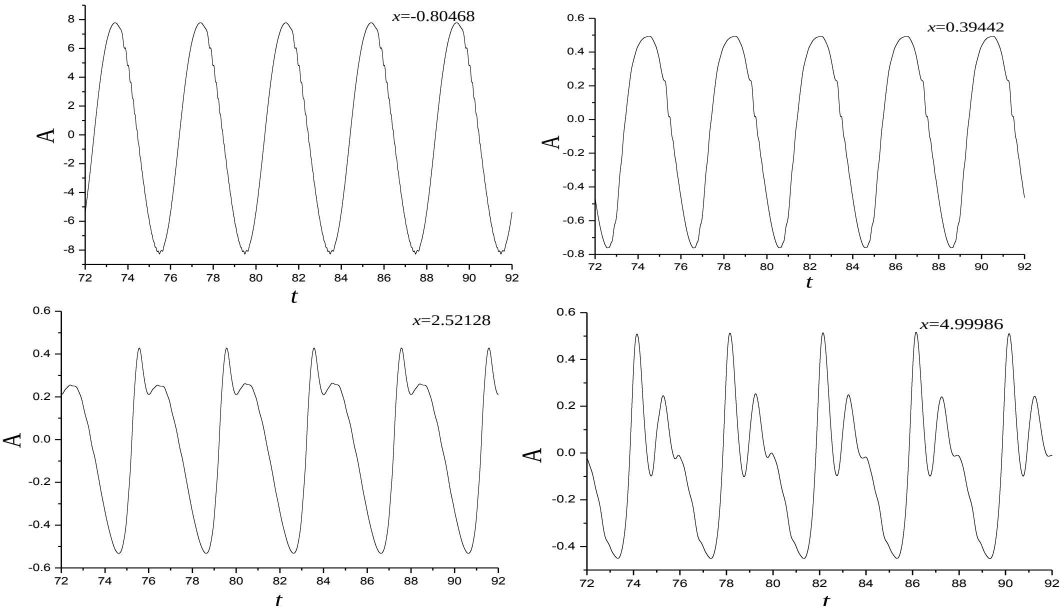

Figure 3. The time-domain curves of pressure disturbances at different positions.

Fig.4 shows the amplitude-frequency figure of pressure disturbances at 4 observation points. It can be found that the pressure disturbance amplitude in the nose region is obviously higher than that in the non-nose region under the interference of the normal shock wave. During the development of the disturbance along streamwise in downstream, there are mainly fundamental and harmonic waves with f=0.25n in the boundary layer. (*f*=0.25n, n is an integer). The amplitude of the inhomogeneous frequency wave can be neglected. The amplitude of fundamental frequency mode decreases rapidly in the nose region, from 8.02 at x=-0.80486 to 0.746 at x=-0.00237. When x=7.3338, the amplitude of fundamental frequency disturbance wave decreases to 0.217. The rate of fundamental frequency disturbance amplitude decreases significantly in the non-nose region comparing with that in the nose region. It also can be found that although the fundamental mode decays continuously along streamwise, the fundamental frequency disturbance wave is always the central disturbance mode in the boundary layer in the whole computational domain. In the process of disturbance developing along streamwise in downstream, the component of the second, third and fourth order mode in the boundary layer increase relatively. The main disturbance mode in the boundary layer of the nose region is the fundamental mode. The central disturbance modes in the boundary layer of the downstream region of the flowfield are composed of the fundamental modes and the second, third and fourth order mode.

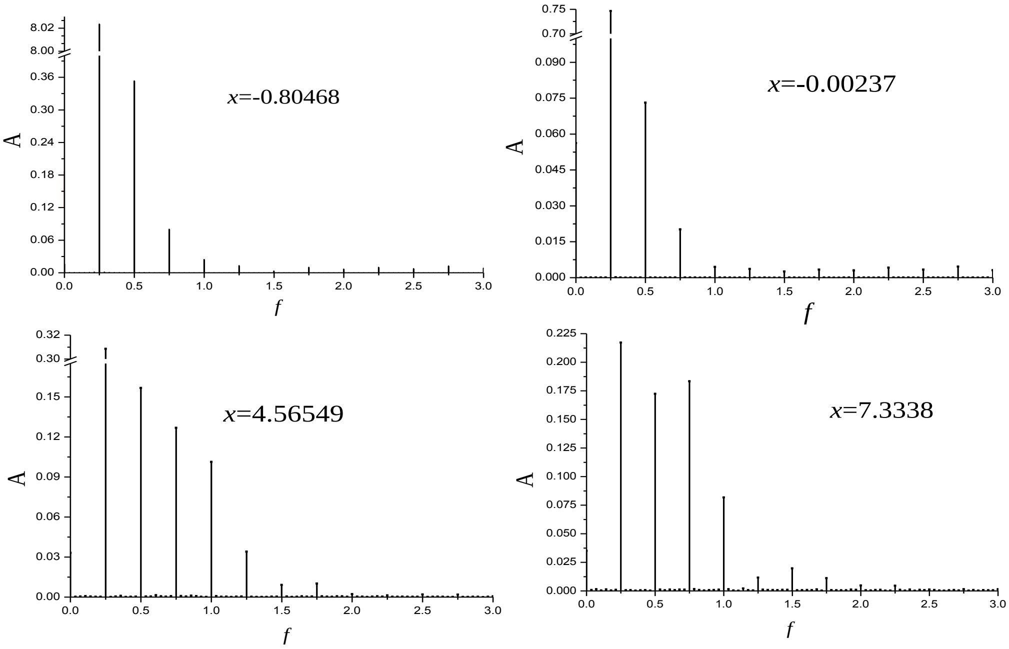

Figure 4. The amplitude-frequency diagram of boundary layer pressure disturbances.

Conclusions

The hypersonic unsteady flowfield of blunt cone is simulated by DNS method in present work. The hypersonic boundary layer receptivity under finite-amplitude disturbance of single frequency is studied. It can be concluded that, 1) after the interaction of freestream waves with bow shock waves and boundary layer, strong disturbance waves are generated in the flowfield, and regular high-entropy and low-entropy regions appear in the downstream evolution process. 2) The frequency features of the boundary layer disturbance wave are directly related to the free flow disturbance wave. As the disturbance wave evolves downstream, the frequency characteristics become weaker. 3) The fundamental frequency disturbance wave is the central disturbance mode in the propagation of disturbance wave in the boundary layer. During the development of disturbance downstream, the second, third and fourth order modes in the boundary layer increase relatively. The central disturbance modes in the nose region boundary layer are the fundamental mode, and the main disturbance modes in the downstream region boundary layer are composed of the fundamental mode(f_1) and the second, third and fourth (f_2-f_4)order modes.

Acknowledgments

The authors sincerely thanks to the financial support of the equipment pre-research common technology project of the 13th five years plan (Grant No. 41402010201).

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