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Experimental study of a hypersonic shock layer stability on a circular surface of compression

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Abstract

The method of electron-beam fluorescence is applied to study the evolution of natural and artificial periodic disturbances on a developed streaky structure in the shock layer on a circular compression surface model. The model is exposed to a hypersonic nitrogen flow with a Mach number $M_\infty = 21$ and unit Reynolds number $Re_{1\infty} = 6 \times 10^5\ \mathrm{m}^{-1}$. Data on the effect of surface curvature and temperature on disturbance characteristics are obtained. ***To cite this article: S.G. Mironov, V.M. Aniskin, C. R. Mecanique 332 (2004).***

Résumé

L'étude expérimentale de la stabilité d'une couche de choc hypersonique sur une surface circulaire de compression. La méthode de fluorescence par faisceau électronique a été appliqueé pour rechercher l'evolution de perturbations naturelles et artificielles sur une structure longitudinale développée dans la couche de choc du modéle d'une surface á rayon de compression. L'écoulement d'azote autour du modèle est hypersonique avec nombre de Mach $M_\infty = 21$ et nombre de Reynolds unitaire $Re_{1\infty} = 6 \times 10^5\ \mathrm{m}^{-1}$. Les données sont obtenues sur l'influence de courbure et temperature de surface sur les charactéristiques de perturbations. ***Pour citer cet article : S.G. Mironov, V.M. Aniskin, C. R. Mecanique 332 (2004).***

Keywords: Flow mechanics; Hypersonic flow; Shock layer; Hydrodynamic instability

Mots-clés : Mécanique des fluides ; Écoulement hypersonique ; Couche de choc ; Instabilité hydrodynamique

1. Introduction

Information on experimental investigations of the evolution of traveling disturbances on streaky structures on compression surfaces for high Mach numbers and moderate Reynolds numbers, where the boundary layer exists

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in the form of a viscous shock layer, is currently unavailable in the scientific literature. Nevertheless, such studies are extremely important because the characteristics of disturbances in the shock layer on compression surfaces can significantly affect disturbance development in the hypersonic boundary layer, which follows after the viscous shock layer formed on leading edges of the airframe and engine inlets of hypersonic flying vehicles.

The operating conditions of real hypersonic vehicles imply surface cooling, because the stagnation temperature at high Mach numbers can reach several thousand degrees. An acceptable value of the temperature factor on the surface is 0.1 and lower. Currently available experimental data on disturbance parameters in supersonic and hypersonic boundary layers have been obtained for significantly higher values. On the other hand, theoretical research within the framework of the linear stability theory for a compressible boundary layer shows that the decrease in temperature significantly alters the characteristics of wave processes in the boundary layer and scenarios of transition to turbulence. Data on the influence of deep cooling on characteristics of disturbances in the boundary layer could be useful for determining the degree of correspondence between the theory developed for the boundary layer in the absence of the shock wave and the conditions in a hypersonic boundary layer with strong shock wave/boundary layer interaction.

A comparison of development of natural and artificial disturbances in the shock layer under these conditions is of fundamental interest. This is primarily related to distributed receptivity of the shock layer to external disturbances. The use of the method of artificial wave packets allows one to observe the undistorted process of disturbance evolution in the shock layer and reveal the influence of distributed receptivity.

Thus, two challenges of the present study can be formulated:

- investigation of characteristics of natural and artificial traveling disturbances generated in the shock layer on the streaky structure on the compression surface;
- investigation of the influence of compression-surface temperature on the mean flow and fluctuating parameters in the shock layer.

2. Experimental equipment and measurement technique

The model is a two-dimensional circular compression surface (width 0.1 m, length 0.15 m, and maximum thickness 0.022 m) made of blackened aluminum. The compression-surface radius is $R = 0.28$ m, and the arc length is 0.11 m. The model forebody is a 7° single-sided wedge smoothly transformed into a circular surface at a length of 0.015 m. The nose bluntness is 0.1 mm. There are channels for the cooling liquid inside the model. An obliquely cut gas-dynamic whistle is attached to the flat base surface of the model (Fig. 1). The whistle is a cylindrical tube closed on the rear end; the front end is cut at an angle of 20° to the tube centerline; the inner and outer diameters are 6 and 8 mm, respectively. The distance between the whistle tip and the leading edge of the model is chosen such that the edge intersects only a narrow segment of the conical shock wave emanating from the whistle. Pressure oscillations inside the whistle arise because of the dynamic pressure disbalance over the tube cross section, which is caused by the oblique cut of the front end face. The structure and operating principle of the gas-dynamic whistle are described in [1]. The rear end of the whistle contains a piezoceramic probe for pressure oscillations. The probe signal is used to monitor the frequency and intensity of pressure oscillations and as a reference signal in data processing.

The measurements were performed for the following test conditions. The stagnation temperature was $T_0 = 1150$ K, the free-stream Mach number was $M_\infty = 21$, the unit Reynolds number was $Re_{1\infty} = 6 \times 10^5\ \mathrm{m}^{-1}$, and the gas velocity was $U_\infty \cong 1500$ m/sec. The total relative intensity of density fluctuations n'_Σ/n_∞ was $\cong 0.5\%$. The initial relative amplitude of periodic perturbations of density n'/n_∞ was $\cong 0.2\%$. The initial amplitude of periodic perturbations of density at the harmonic frequency was $\cong 0.07\%$. Here, n'_Σ is the total value of root-mean-square density fluctuations in the frequency range $f = 1$–40 kHz, n' is the root-mean-square value of density fluctuations at a certain frequency, and n_∞ is the mean free-stream density. The characteristics of periodic traveling disturbances

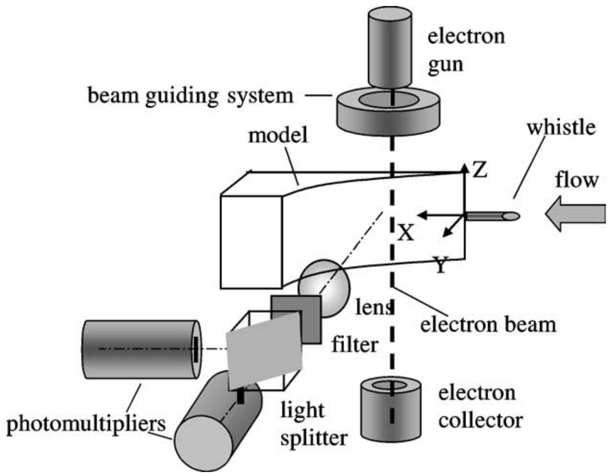

Fig. 1. Scheme of measurements.

were measured at the fundamental frequency and at the harmonic frequency. The fundamental frequency of controlled periodic disturbances varies within the range $f = 7.5$–10.5 kHz.

The measurements were performed for two substantially different ranges of the temperature factor of the surface $T_w/T_0 = 0.26$–0.28 and 0.07–0.085, which are hereinafter called the ‘warm’ and ‘cold’ surface. The lower range of temperatures is obtained by pumping liquid nitrogen through the model.

The quasi-steady streaky structure and the cirsoid traveling periodic disturbances were introduced into the shock layer owing to interaction of a small segment of the oscillating conical shock wave induced by the whistle and the leading edge of the compression surface. A zone of reduced static pressure with a time-dependent transverse size is formed in the wake behind the interaction region. Both a steady streaky structure in the form of a pair of counterrotating vortices and periodic disturbances traveling on this structure are formed. A more detailed description of the disturbance-generation process can be found in [2]. A special insert in the whistle, which fills the resonator volume, allows one to eliminate oscillations and study the development of only natural disturbances on the streaky structure.

All measurements were performed by the method of electron-beam fluorescence of nitrogen, adapted to measuring density fluctuations [3]. The mean density and density fluctuations were determined on the basis of the constant and variable components of fluorescence intensity, with allowance for electron-beam scattering in the gas and collisional quenching of electron-excited nitrogen molecules. The measurement layout is shown in Fig. 1. The procedures for treating the measured signals are described in [2,3]. Since the flow around the model is strongly affected by flow rarefaction [4], an iterative procedure for reconstruction of the mean density [5] was used; in this procedure, the density is calculated simultaneously with the gas temperature, which enters the expression relating the fluorescence intensity and gas density [3].

3. Mean flow parameters

Electron-beam visualization of the flow around the model showed that the shock-layer thickness increases from the model tip to the point $x \cong 60$ mm, whereas the shock-wave slope relative to the flow direction decreases. With further increase in the coordinate x, vice versa, the shock-layer thickness decreases, and the shock-wave slope increases. Visualization also showed that the shock-layer thickness on the cold surface is much smaller than that on the warm surface. The mean density distributions across the shock layer showed that a decrease in shock-layer thickness is accompanied by a greater ‘fullness’ of the mean velocity profile.

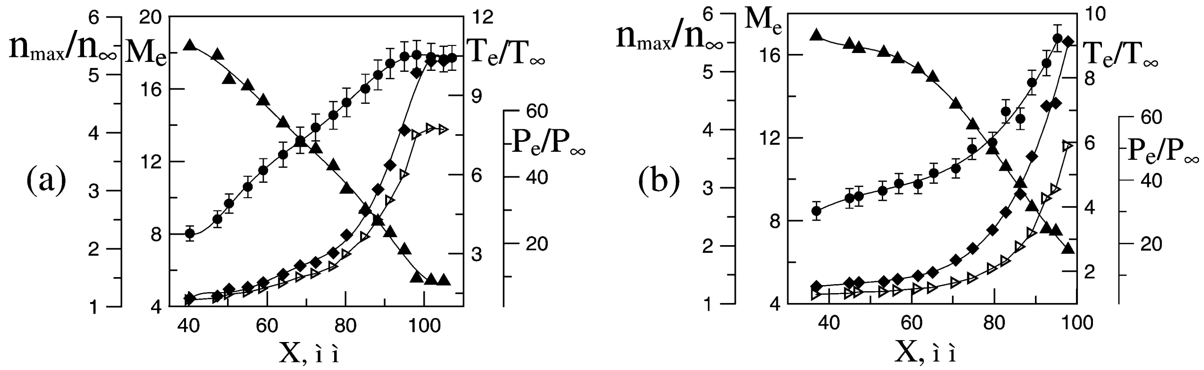

Fig. 2. Maximum of a mean density in the shock layer (●), Mach number (▲), temperature (■) and pressure (▷) behind shock wave versus X coordinate.

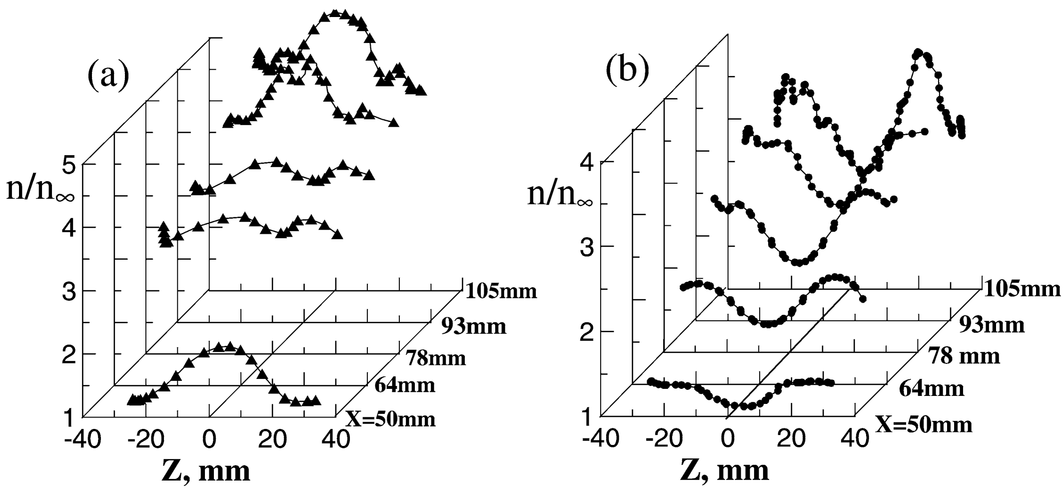

Fig. 3. Mean density profiles in transversal direction for warm compression surface in normal coordinate sections: (a) $y/\Delta = 1.0$; (b) $y/\Delta = 0.6$.

The normalized mean density n/n_∞ in the shock layer and the relative gas temperature T_e/T_∞ behind the shock wave for the warm and cold compression surfaces were calculated on the basis of measured fluorescence intensity. After that, other gas-dynamic quantities were calculated with the help of relations on the shock adiabat. Fig. 2 shows the maximum mean density in the shock layer $n_{\max}/n_\infty$, gas temperature behind the shock wave T_e/T_∞, Mach number M_e, and pressure P_e/P_∞ as functions of the streamwise coordinate x. The subscript e indicates the quantities behind the shock wave. A significant increase in mean density, pressure, and temperature of the gas behind the shock wave along the model is associated with the surface curvature and with the influence of gas rarefaction on the flow in the vicinity of the model tip [4]. The Mach number averaged over the model length is $\cong 11.5$ for the warm surface and $\cong 12.5$ for the cold surface. The Görtler number G ($G = [(U_e\delta/\nu)(\delta/R)]^{1/2}$, $\delta = (\nu x/U_e)$) averaged over the model length is $\cong 10.5$ and $\cong 11.5$, respectively. For high Mach numbers, these values correspond either to a stable region [6,7] or to weak centrifugal instability [8]. The estimates based on the data of [9] revealed the absence of laminar separation on the compression surface for these conditions.

The presence of the streaky structure leads to deformation of the mean density field in the transverse direction z. Fig. 3 shows the deformation of mean density in the shock layer on the warm surface in the cross sections $y/\Delta = 1.0$ (a) and 0.6 (b) (Δ is the shock-layer thickness). A similar deformation of the mean density field is

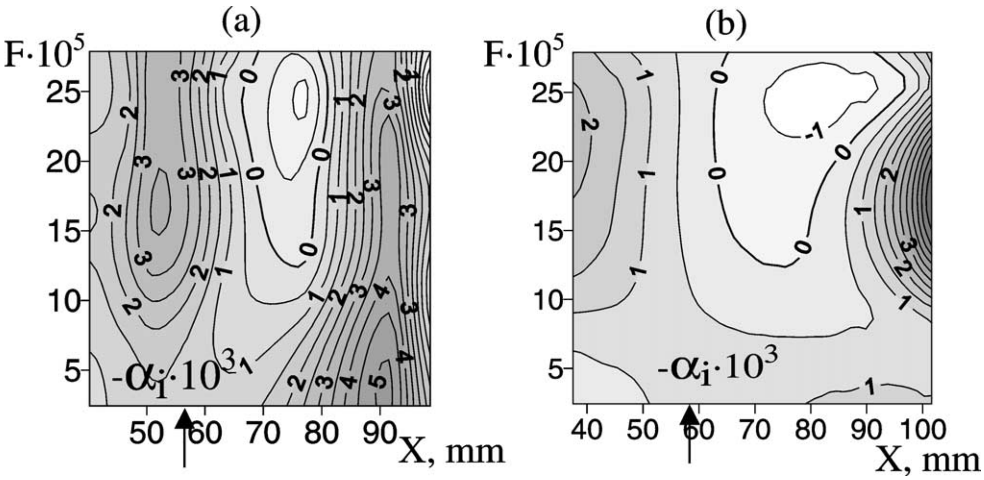

Fig. 4. Iso-lines of a growth rate values of natural disturbances for (a) warm and (b) cold compression surface.

observed on the cold surface. Such a deformation can be induced by two counter-rotating vortices, which generate a flow uprising from the surface along the model centerline and downward flows on both sides of the centerline. This feature makes the streaky structure qualitatively similar to an isolated pair of the Görtler vortices. The maximum value of the relative deformation of mean density in the streaky structure $\Delta n/n$ varies along the model from $\cong$ 30% to $\cong$ 50%. Visualization of the limiting streamlines with the use of a mixture of chalk and vacuum oil showed that a pattern corresponding to origination of a streaky structure arises on the warm surface. In particular, it contains a convergence line similar to that obtained in [2].

4. Characteristics of natural disturbances

The measurements of the spatial distribution of natural disturbances of density showed that the main energy of fluctuations at all frequencies for the warm and cold surfaces is concentrated immediately under the shock wave. The growth rates of natural disturbances $\alpha_{i.}$ ($\alpha_i = -0.5 \cdot d(\ln(n'))/d\sqrt{Re_{\mathrm{ex}}}$) were calculated along the line of the maximum fluctuations. The calculation results are plotted in Fig. 4 as iso-lines of identical growth rates in the plane (streamwise coordinate x-dimensionless frequency parameters F) for the (a) warm and (b) cold surfaces ($F = (2\pi \cdot f)/(Re_{1\infty} \cdot U_\infty)$). The arrows indicate the point of the minimum inclination of the shock wave to the flow. The decrease in the growth rate behind the minimum inclination, where the shock-layer thickness decreases, is clearly visible. The decrease in the growth rate of natural disturbances with decreasing surface temperature can be seen by comparing Fig. 4 (a) and (b). A subsequent increase in the growth rate of disturbances in the graphs is most probably related to the action of an adverse pressure gradient.

5. Characteristics of controlled periodic disturbances

The measurements of the phase shift of periodic traveling disturbances with respect to the whistle signal showed that there are two phase dependences on the streamwise coordinate x in the shock layer, for both the fundamental and harmonic frequencies and for both the warm and cold compression surfaces. Both phase dependences are linear with respect to the coordinate x, the phase shift between them is close to 180°, but the slopes of the dependences are slightly different [5]. This indicates that two types of waves (indicated by 1 and 2) are developed in the shock layer. The measurements of the amplitude distributions of natural disturbances across the shock layer revealed the existence of two maximums correlating with the phase dependences (1, 2) [10]. One maximum (1) corresponds to the shock-wave region, and the other (2) is located closer to the model surface.

A comparison of the transverse distributions of the amplitude of periodic fluctuations and transverse distributions of the mean density showed that the main energy of fluctuations is concentrated in the region of deformation of the mean density field, i.e., in the region of existence of the streaky structure. The maximums of fluctuations are located in the region of the maximum gradient of the mean density along the coordinate z. In particular, the maximums for waves (1) and (2) correspond to the maximums of the mean density gradient in Fig. 3 (a) and (b), respectively.

The spectra of transverse wavenumbers β of periodic disturbances showed that the spectra of waves of both types are located in a narrow region $\beta = \pm 0.2$ rad/mm with a maximum at $\beta = 0$ for all disturbance frequencies and surface temperatures. This testifies that the traveling disturbances are two-dimensional. The finite width of the β-spectra, as was shown in [2], is associated with the finite width of the streaky structure along the coordinate z. Two-dimensionality of the waves allows one to compare the values of the streamwise phase velocity with the data of the linear stability theory. Fig. 5 shows the phase velocity of controlled disturbances C_x normalized to the gas velocity behind the shock wave averaged over the model length. Data for the fundamental frequency and harmonic frequency are given; the numbers correspond to the above-mentioned wave types. The dashed curves show the boundaries separating the regions of existence of subsonic and supersonic disturbances, which were calculated on the basis of the mean Mach numbers behind the shock wave M_e. As the surface temperature decreases, the phase velocities of all waves become supersonic, i.e., go outside the dashed band.

Fig. 6 shows the growth rate of artificial disturbances α_i versus the streamwise coordinate x for waves of type (1) and (2), for the fundamental frequency and harmonic on the warm (a, b) and cold (c, d) compression surfaces. For comparison, the graphs show the growth rates of natural disturbances on the corresponding frequencies. The arrows indicate the position of the minimum slope of the shock wave and the point where the shock-layer thickness starts to decrease. The regions bounded by the dashed curves show the growth rates of artificial disturbances measured under the same conditions in experiments on a warm flat plate [2]. The growth rates at the harmonic frequency display a more clear decrease in the region of the minimum slope of the shock wave. Despite a large error in growth-rate determination, the dependences for natural and artificial disturbances are in qualitative agreement. The growth rate decreases with decreasing shock-layer thickness, which is caused both by the surface curvature and by a decrease in surface temperature. A further increase in the growth rate is most probably related to the presence of an adverse pressure gradient. This conclusion is supported by a comparison with the growth rate on the streaky structure on the warm plate [2], where the shock-layer thickness was significantly greater.

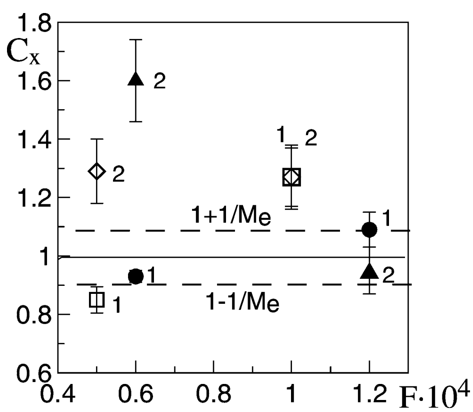

Fig. 5. Phase velocities of artificial disturbances, (●, ▲) warm, (□, ◇) cold surface of compression.

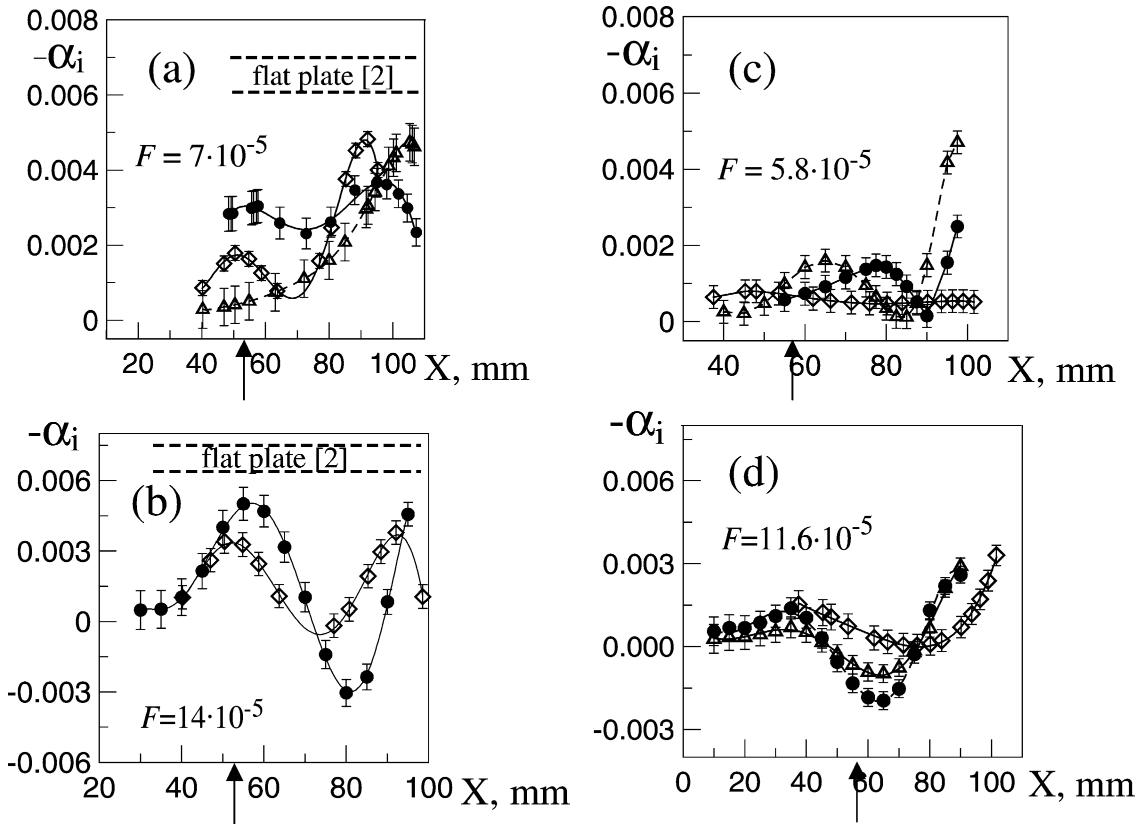

Fig. 6. Increments of disturbances versus X coordinate; (a, b) – warm, (c, d) cold surface of compression; (△) – artificial wave type (1), (◇) – artificial wave type (2), (●) – natural disturbances.

6. Conclusions

The stabilizing effect of a decrease in the shock-layer thickness and an increase in 'fullness' of the mean density profile on the growth rate of natural disturbances is demonstrated. It is shown that a decrease in surface temperature also stabilizes the development of natural disturbances via a decrease in shock-layer thickness.

Introduction of controlled periodic disturbances into the shock layer has been found to give rise to two wave types. In the direction normal to the surface, one wave is located in the region of the shock wave, and the other is located closer to the compression surface. In the transverse direction, both waves are localized in the region of the streaky structure. The maximum fluctuations of periodic disturbances are associated with transverse gradients of the mean density. Both waves are quasi-two-dimensional. It is shown that the phase velocity of both wave types becomes supersonic as the surface temperature decreases. Qualitative similarity of the influence of the shock-layer thickness on the growth rate of natural and controlled disturbances is demonstrated.

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References

[1] A.A. Maslov, S.G. Mironov, Experimental investigation of the hypersonic low-density flow past a half-closed cylindrical cavity, Fluid Dynamics 31 (1996) 928–932.
[2] S.G. Mironov, A.A. Maslov, Experimental study of secondary instability in a hypersonic shock layer on a flat plate, J. Fluid Mech. 412 (2000) 259–277.
[3] S.G. Mironov, A.A. Maslov, An experimental study of density waves in hypersonic shock layer on a flat plate, Phys. Fluids A 12 (2000) 1544–1553.
[4] P.J. Harbour, J.H. Lewis, Preliminary measurements of the hypersonic rarefied flow field on a sharp plate using electron beam probe, in: C.L. Brundin (Ed.), Rarefied Gas Dynamics, Academic Press, New York, 1967, pp. 1031–1046, Suppl. 2.
[5] V.M. Aniskin, S.G. Mironov, Evolution of controlled disturbances in the shock layer on the compression surface, J. Appl. Mech. Tech. Phys. 44 (2003) 635–639.
[6] N.M. El-Hady, A.K. Verma, Görtler instability of compressible boundary layers, AIAA J. 22 (1984) 1354–1355.
[7] R.E. Spall, M.R. Malik, Goertler vortices in supersonic and hypersonic boundary layers, Phys. Fluids A 1 (1989) 1822–1835.
[8] D. Aymer de la Chevalerie, A. Fonteneau, L. de Luca, G. Cardone, Görtler-type vortices in hypersonic flows: the ramp problem, Exp. Therm. Fluid Sci. 15 (1997) 69–81.
[9] D.A. Needham, J.L. Stollery, Boundary layer separation in hypersonic flow, AIAA Paper, No 66-455, 1966.
[10] V.M. Aniskin, S.G. Mironov, Development of periodic disturbances on a streaky structure in the hypersonic shock layer on surface of compression, Thermophys. Aeromech. 11 (2004) 35–42.