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EXPERIMENTAL STUDY OF VORTEX STRUCTURES IN A HYPERSONIC SHOCK LAYER ON A FLAT PLATE

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The characteristics of travelling perturbations of density in a hypersonic shock layer on a flat plate for the Mach number $M_\infty = 21$ *and unit Reynolds number* $Re_1 = 6 \cdot 10^5$ m^{-1} *were experimentally studied by the method of electron-beam fluorescence. The perturbations were generated by interaction of the shock layer behind an oblique gas-dynamic whistle and the leading edge of the plate. The cases of unsteady and quasi-steady interaction were considered. In both cases, vortex disturbances of finite amplitude were generated. The measurements were performed at the fundamental frequency* $F = 0.6 \cdot 10^{-4}$ *and at the harmonic; the streamwise phase velocities, the growth rates of the disturbances, and the angles of wave propagation were obtained. The measurement results are compared with some experimental data for subsonic flows, some particular results of the linear stability theory for compressible flows, and the results obtained on the basis of a simple model of the nonlinear stage of disturbance evolution in a hypersonic boundary layer.*

Experimental research of the evolution of disturbances in the boundary layer in the case of vortex motion of a gas is very important for studying the stability of boundary layers formed on swept wings and concave surfaces. Secondary instability plays an important role in the process of vortex decomposition at the nonlinear stage of vortex development. The main studies in this direction were conducted for subsonic flows (see the review of papers in [1]). The evolution of natural and artificial disturbances on individual and periodic vortices induced in the boundary layer has been experimentally studied lately [2–5]. On the basis of the results obtained, a technique for controlling the development of secondary instability with the help of streamwise steps and grooves (riblets) has been proposed [6]. For super- and hypersonic velocities, there are only some theoretical papers [7–10] devoted to development of secondary instability on Görtler vortices. There are no data on similar experimental studies for high Mach numbers in the literature.

The results of an experimental study of the characteristics of density fluctuations in a hypersonic shock layer on a flat plate with unsteady and quasi-steady vortex disturbances of finite amplitude are described in the present paper.

1. Experimental Equipment and Measurement Techniques. The experiments were conducted in the T-327 hypersonic wind tunnel of the Institute of Theoretical and Applied Mechanics of Siberian Division of the Russian Academy of Sciences for the Mach number $M_\infty = 21$ and unit Reynolds number $Re_1 = 6 \cdot 10^5$ m^{-1} based on the free-stream parameters. The stagnation pressure P_0 in the plenum chamber was 8 MPa and the stagnation temperature was $T_0 = 1100$ K.

The characteristics of density fluctuations were measured in the shock layer on a flat plate 0.35 m long and 0.008 m thick, which was a trapezium with the leading-edge width 0.1 m and the trailing-edge width 0.08 m. The plate was made of blackened aluminum. The wedge angle of the leading edge was 7° and the

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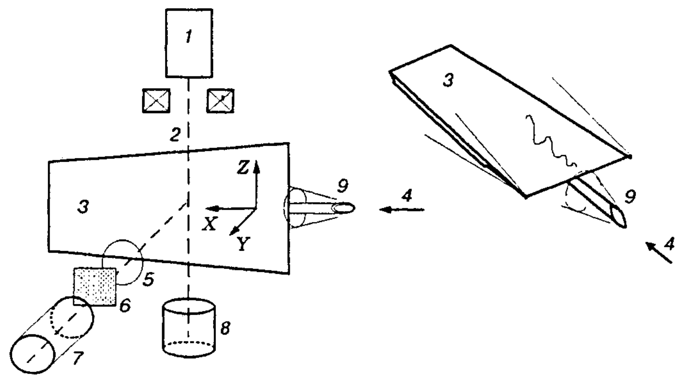

Fig. 1

leading-edge radius was about 0.05 mm. The lateral edges of the plate were made in the form of wedges with an angle of 20°.

The measurements were performed by the method of electron-beam fluorescence [11]. The scheme of measurements is shown in Fig. 1. Probing electron beam 2 was generated by electron gun 1, which had a magnetic system for controlling the beam location. The electron beam propagated across hypersonic flow 4 parallel to the plane of plate 3. The beam current was controlled by the magnitude of current of the collector of electrons 8 located outside the flow. The optical system for nitrogen-fluorescence registration consisted of fast lens 5, light filter 6, and photomultiplier 7. The coordinate system (X, Y, Z) is shown in Fig. 1. The location of the measurement point was varied along the streamwise coordinate X by moving the plate along the flow axis within the range from (-5) to $+210$ mm relative to the leading edge of the plate and along the transverse coordinate Y by moving the plate across the flow within the range from -15 to $+15$ mm relative to the flow axis. The location of the measurement point was varied along the spanwise coordinate Z by moving the optical system for fluorescence registration along the electron-beam axis within the range -20 to $+50$ mm relative to the axis of symmetry of the plate. The spatial resolution of the optical system was 2 mm in the X and Z directions; the Y resolution was of order of 3 mm, which was determined by the size of glowing.

Disturbances introduced into the shock layer of the plate were generated by interaction of its leading edge with a vibrating shock layer induced by hypersonic flow around oblique whistle 9 (Fig. 1). As is shown in [12], the flow around the whistle is accompanied by periodic radial oscillations of its shock layer, which creates conditions for generation of perturbations. When a conical shock wave intersects the leading edge of the plate in the region of their interaction, the flow is located at negative incidence because of turning of the streamlines on the shock wave. Because of that, a flow region with lower pressure and density is formed. The calculations within the framework of the model of full viscous shock layer [13] showed that the pressure in the region of interaction is three times lower than the pressure in the undisturbed region. The gas moves from the periphery to the low-pressure region, and a gas flow moving upward from the plate is formed, which generates a pair of counterrotating vortices extended in the streamwise direction. Depending on the depth of penetration of the leading edge into the shock layer and the amplitude of oscillations of the latter, it is possible to obtain both purely unsteady vortices and quasi-steady vortex structures with imposed oscillations.

The model for generation of oscillations and the construction of the whistle are described in [12]. In the present work, the whistle was a copper tube 0.15 m long with external diameter 0.008 m and internal diameter 0.006 m with an oblique front face at an angle of 20°; a moving, tightly fitted piston with a probe for pressure fluctuations was located inside the whistle. The source was cooled by running water to maintain a constant temperature of the resonator walls. The frequency of oscillations could be controlled by moving the piston along the tube. The signal of the probe for pressure fluctuations served as a reference signal for identification of the valid signal on the background of wide-band noise. The streamwise distance from the tip of the whistle to the leading edge of the plate was 40 mm. The tube of the source was located under the plate and was bent to create an optimal angle 8.5° between the tube axis and the free-stream direction. This angle ensured the maximum value of intensity of pressure fluctuations inside the whistle (140 dB). The distributions of the constant and variable components of the signal of the optical system were obtained prior to experiments by transverse measurement of the shock layer of the whistle by an electron beam in the cross section where the plate edge was located. From these data, according to technique [12], we evaluated the span of shock-wave oscillations, which was equal to 0.2 mm. The depth of penetration of the plate edge into the shock layer was controlled by changing the crossflow distance between the leading edge of the plate and the tube surface.

The measurements were conducted for a fixed frequency $f = 8.3$ kHz and its harmonic, which, under the present test conditions, corresponds to the frequency parameter $F = 0.6 \cdot 10^{-4}$ and $1.2 \cdot 10^{-4}$ [$F = 2\pi f/(\mathrm{Re}_{1e} U_e)$, where Re_{1e} and U_e are the Reynolds number per meter and the gas velocity calculated from the parameters behind the shock wave on the plate]. The measurements were performed in the maxima of density fluctuations in the shock layer. The results showed that the positions of maximum fluctuations coincide with the line $Y = 0.75\Delta$ (Δ is the shock-wave position relative to the surface, which was obtained by electron-beam visualization of the flow on the plate). Within 10%, the maxima of fluctuations were located on the line of constant mean density in the shock layer on the plate.

At the first stage of signal processing, the fast Fourier transform was used to calculate the mutual amplitude and phase spectra between the fluorescence intensity fluctuations and pressure fluctuations inside the whistle. This allowed us to exclude the effect of the "shot" poise of the photocurrent, free-stream disturbances, and eigenoscillations of the shock layer on the plate. The spectral amplitude was proportional to the product of the electron current and the square root of the reference-signal intensity. The influence of variation of these parameters on the measurements was excluded by normalization of the amplitude of the spectra to their magnitude. The measurement data along the spanwise coordinate Z were corrected with account of the decrease in the signal of the optical system caused by scattering of electrons in the gas. The method for calculation of attenuation functions was described in [13].

After that, we calculated the amplitude and phase spectra from the wavenumbers β ($\beta = 2\pi/\lambda_Z$, where λ_Z in the spanwise wavelength) using the Hamming spectral window. From the spectra obtained, we determined the dependence of the wave amplitudes and phases on the streamwise coordinate X and found the growth rates, the streamwise phase velocities, and the angles of propagation of density waves in the shock layer.

2. Measurement Results. Two regimes of interaction of the plate edge and the shock layer of the whistle were provided in the experiments: (1) generation of unsteady vortices; (2) formation of a steady pair of vortices with oscillations imposed on them.

(1) When the plate edge is introduced by 1 mm into the shock layer on the whistle, the span of shock-wave oscillations is greater than this value, and a region of unsteady interaction is observed, where the vortex is formed only during some part of the period of oscillations. The vortex motion of the gas leads to deformation of the mean flow field, namely, the mean density field. Figure 2 shows the distribution of molecular density n/n_n (n_n is the density of molecules in an undisturbed shock layer) averaged over several X cross sections (filled points). The vertical bars in the graph indicate the root-mean-square scatter of the measurement data over the cross sections. It is seen that the distortion of the mean density field does not exceed 5%. The character of this distortion corresponds to a pair of counterrotating vortices, since the region of lower density on the plate axis is adjacent to two regions of elevated density located away from the centerline, which confirms the assumption about the mechanism of generation of disturbances. An oscillogram of density perturbations at the fundamental frequency for the cross section located at a distance $X = 60$ mm from the plate edge is shown in Fig. 3a (T is the time). The positive values of density perturbations are marked by solid isolines and the negative values are marked by dashed curves. It follows from a comparative

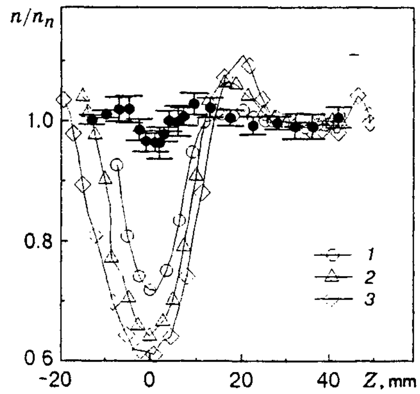

Fig. 2

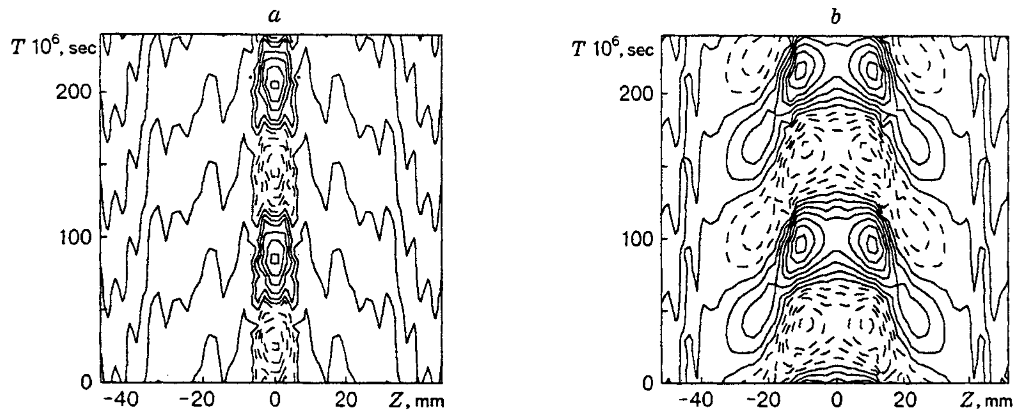

Fig. 3

analysis of Figs. 2 and 3a that the region of perturbations corresponds to the region of deformation of the mean density field.

The amplitude of perturbations n' normalized to the free-stream density n_∞ varied within 0.1–0.2% over the plate length. An analysis of β-spectra showed that quasi-two-dimensional disturbances with spectrum-base width ± 0.5 rad/mm are formed in the shock layer at the fundamental frequency and at the harmonic frequency with the maximum of fluctuations at zero wavenumber β. On the basis of phase and amplitude β-spectra calculated in streamwise cross sections $X = 60$, 80, 100, 170, 190, and 210 mm, we obtained the streamwise phase velocities of the disturbances C_X. It was found that the streamwise phase velocity is constant along the plate and depends only on the wavenumber β. In a narrow region near the plate edge ($X < 30$ mm), the phase velocity decreases to a value close to 0.3, which is in agreement with the data of Maslov et al. [14] who studied the initial region of vortex formation. Figure 4 shows the dependences $C_X(\chi)$ of the streamwise phase velocity on the angle of wave propagation relative to the flow for the fundamental frequency and for the harmonic (curves 1 and 2, respectively). The velocities are normalized to the gas velocity behind the shock wave U_e. The angles of wave propagation χ were calculated from the relation $\chi = \arctan(\beta/\alpha)$, where $\alpha = 2\pi f/(C_X U_e)$. For comparison, curve 3 in Fig. 4 shows the dependence $1 - 1/(\mathrm{M}_e \cos\chi)$, where M_e is the Mach number behind the shock wave. According to linear stability theory for compressible flows, the disturbances with phase velocities lower than curve 3 belong to the acoustic mode; if the phase velocity is above curve 3, the disturbances belong to the vortex mode. It is seen from Fig. 4 that the disturbances at the fundamental frequency propagate as acoustic for angles $\chi < 20°$. For greater angles, vortex disturbances are observed. The streamwise phase velocity of the disturbances at the harmonic

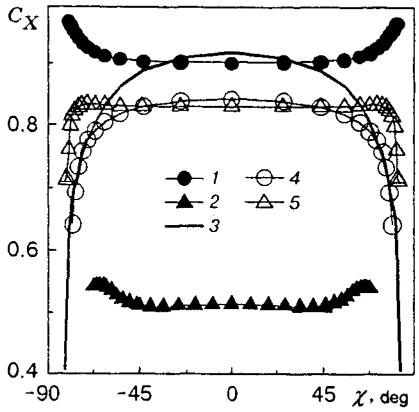

Fig. 4

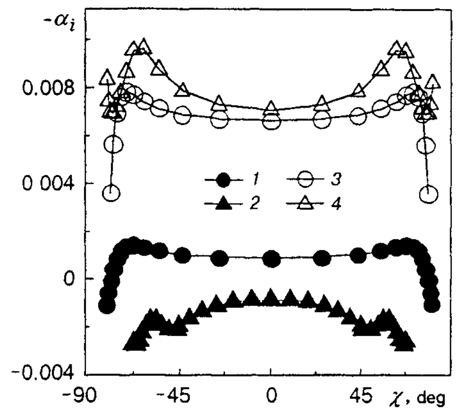

Fig. 5

frequency turned out to be significantly lower than at the fundamental frequency and corresponded to the acoustic mode for all angles.

The growth rates of the perturbations $-\alpha_i$ were calculated from the amplitude β-spectra in the standard manner. Figure 5 shows the dependences $-\alpha_i(\chi)$ of the disturbance growth rate versus the angle of wave propagation for the fundamental frequency and harmonic (curves 1 and 2, respectively). It is seen that the disturbances at the fundamental frequency increase and those at the harmonic frequency decay.

(2) When the plate edge is introduced to the depth of 1.2 mm into the shock layer of the whistle, a quasi-steady interaction regime is observed; it is characterized by the formation of a region of significant deformation of the mean flow field along the plate. The distributions of the mean density n/n_n across the plate are shown in Fig. 2 for the cross sections $X = 30$, 130, and 210 mm (curves 1–3). The magnitude of deformation of the mean flow field increases downstream reaching 40%. The character of deformation also corresponds to propagation of a pair of vortices, since the region of lower density is adjacent to the regions of elevated density.

The asymmetry of deformation of the density field relative to its value in an undisturbed shock layer, which is observed in Fig. 2, is related to the nonlinear character of the mean density distribution over the plate along the Y axis. The measured and calculated data for the mean characteristics of the flow field in the shock layer on the plate in the absence of perturbations can be found in [13]. The maximum deviations of density from unity are observed if the shock wave shifts 1 mm away from the plate (lower density region) and toward the plate (elevated density region). Evaluating the deformations of the mean velocity field in the shock layer from data [13], we obtain 5% of the free-stream value. For the unsteady regime, the distortions of the mean density field are small and rather symmetric; the deformation of the mean velocity field does not exceed 0.6%.

A typical oscillogram of the spanwise distribution of density fluctuations is shown in Fig. 3b for the cross section $X = 210$ mm. It follows from a comparative analysis of Figs. 2 and 3b that there are two maxima of fluctuations corresponding to the slopes of the low-density region; the phase of fluctuations changes by 180° when passing from the region of low mean density to the region of elevated density. In regions with elevated density, the intensity of fluctuations turned out to be significantly lower.

The amplitude of perturbations n'/n_∞ rapidly increases along the plate from 0.6 to 6% at distances from the plate edge $X = 30$–210 mm. An analysis of β-spectra showed that quasi-two-dimensional disturbances with spectrum-base width ± 0.5 rad/mm are again formed at the fundamental frequency and at the harmonic frequency with the maximum of fluctuations at zero wavenumber β. At distances 30 to 210 mm from the plate edge, the streamwise phase velocities depend only on the spanwise wavenumber. For distances less than 30 mm from the plate edge, the phase velocity decreases to a value close to 0.3, as in the previous case. Most probably, this is related to the existence of a transient flow region at the plate edge. Figure 4 shows the streamwise phase velocity C_X as a function of the wave-propagation angle χ for the fundamental frequency and for the harmonic (curves 4 and 5). For this flow regime, the phase velocities are close and, for most angles, correspond to the acoustic mode of disturbances.

In contrast to the unsteady regime, the dependence of the amplitudes of β-spectra on the streamwise coordinate cannot be described by an exponential function at distances greater than 170 mm from the plate edge because of the dramatic decrease in the growth rate of the disturbances. This indicates a significantly nonlinear process of evolution. Figure 5 shows the disturbance growth rates $-\alpha_i$ at the fundamental frequency and harmonic (curves 3 and 4) versus the wave-propagation angle, which were calculated at distances from the plate edge $X = 30$–150 mm. The values of the growth rates at two frequencies turned out to be close and significantly greater than in the unsteady regime.

3. Discussion of Results. It should be noted that the regions of the maximum intensity of disturbances coincide with the regions of the maximum mean density gradient, where a spanwise gradient of the mean velocity arises. A similar phenomena was noted in [1] and experimentally verified in [2–4]. The disturbance intensity is greater in the zone of the upward flow from the plate, which is in agreement with data [5]. An increase in the disturbance growth rate for the quasi-steady regime by almost an order of magnitude as compared to the unsteady regime is possibly related to the presence of a significant spanwise gradient of the mean velocity, deformation of the normal velocity distribution, and manifestation of inviscid instability of the flow [3, 4, 10].

The fact that the dependences $C_X(\chi)$ and $-\alpha_i(\chi)$ are qualitatively and quantitatively close for the fundamental frequency and harmonic at a quasi-steady interaction of the shock layer of the whistle and the plate edge may be due to the appearance of a three-dimensional flow in the shock layer and the evolution of nonlinear processes. The close characteristics of the fluctuations at two frequencies can be explained using a simple model [15], which describes the emergence of harmonics in a hypersonic shock layer for finite-amplitude disturbances. According to Kimmel and Kendall [15], the harmonics arise due to nonlinearity of the mean flow parameters (velocity and density) at intense oscillations of the boundary layer normal to its surface. The characteristics of the harmonics are rigorously related to the characteristics of oscillations at the fundamental frequency, and the harmonics are not independent waves.

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REFERENCES

1. W. S. Saric, "Görtler vortices," *Annu. Rev. Fluid Mech.*, **26**, 379–409 (1994).
2. A. A. Bakchinov, G. R. Grek, B. G. B. Kligmann, and V. V. Kozlov, "Transition experiments in a boundary layer with embedded streamwise vortices," *Phys. Fluids*, **A7**, 820–832 (1995).
3. A. V. Boiko, V. V. Kozlov, V. V. Syzrantsev, and V. A. Shcherbakov, "Experimental investigation of high-frequency secondary disturbances in a swept-wing boundary layer," *Prikl. Mekh. Tekh. Fiz.*, **36**, No. 3, 74–83 (1995).
4. A. V. Boiko, V. V. Kozlov, V. V. Syzrantsev, and V. A. Shcherbakov, "Effect of the internal structure of the streamwise vortex on the evolution of travelling disturbances," *Teplofiz. Aeromekh.*, **4**, No. 4, 369–380 (1997).
5. V. Ya. Levchenko and V. A. Shcherbakov, "Instability of a three-dimensional boundary layer on a swept wing," *Prikl. Mekh. Tekh. Fiz.*, **38**, No. 3, 32–38 (1997).
6. A. V. Boiko, V. V. Kozlov, V. A. Scherbakov, and V. V. Syzrantsev, "Transition control by riblets in a swept wing boundary layer with an embedded vortex," *Eur. J. Mech. B Fluids*, **16**, 465–482 (1997).
7. R. E. Spall and M. R. Malik, "Görtler vortices in supersonic and hypersonic boundary layers," *Phys. Fluids*, A1, 1822–1835 (1989).
8. M. R. Malik and M. Y. Hussaini, "Numerical simulation of interactions between Görtler vortices and Tollmien–Schlichting waves," *J. Fluid Mech.*, **210**, 183–199 (1990).

9. Y. Fu and P. Hall, "Nonlinear development and secondary instability of large amplitude Görtler vortices in hypersonic boundary layers," *Eur. J. Mech. B Fluids*, **11**, 465–510 (1992).
10. Y. Fu and P. Hall, "Effects of Görtler vortices, wall cooling and gas dissociation on the Rayleigh instability in a hypersonic boundary layer," *J. Fluid Mech.*, **247**, 503–525 (1993).
11. A. A. Maslov, S. G. Mironov, and A. N. Shiplyuk, "Experimental study of density fluctuations in the hypersonic boundary layer on a flat plate," *Prikl. Mekh. Tekh. Fiz.*, **37**, No. 6, 51–60 (1996).
12. A. A. Maslov and S. G. Mironov, "Experimental study of a hypersonic low-density flow around a semi-closed cylindrical cavity," *Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 6, 155–160 (1996).
13. V. N. Vetlutsky, A. A. Maslov, S. G. Mironov, et al., "Hypersonic flow on a flat plate, experimental results and numerical modeling," *Prikl. Mekh. Tekh. Fiz.*, **36**, No. 6, 60–67 (1995).
14. A. A. Maslov, S. G. Mironov, and A. N. Shiplyuk, "Experimental electron-beam study of perturbations in a hypersonic shock layer on a plate," in: *Proc. of the 8th Int. Conf. on the Methods of Aerophysical Research*, Part 3, Novosibirsk (1996), pp. 212–215.
15. R. L. Kimmel and J. M. Kendall, "Nonlinear disturbances in a hypersonic laminar boundary layer," AIAA Paper No. 91-0320 (1974).