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EXPERIMENTAL STUDY OF EVOLUTION OF DISTURBANCES IN A SUPERSONIC BOUNDARY LAYER ON A SWEPT-WING MODEL UNDER CONTROLLED CONDITIONS

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Experimental data on stability of a three-dimensional supersonic boundary layer on a swept wing are presented. Evolution of artificial wave trains was studied. The experiments were conducted for Mach number $\mathrm{M} = 2.0$ *and unit Reynolds number* $\mathrm{Re}_1 = 6.6 \cdot 10^6\ \mathrm{m}^{-1}$ *on a swept-wing model with a lenticular profile and a* 40° *sweep angle of the leading edge at zero incidence. Excitation of high-frequency disturbances caused by secondary-flow instability at a high initial amplitude was observed. It is shown that the evolution of disturbances at frequencies of* 10, 20, *and* 30 *kHz is similar to the development of travelling waves for the case of subsonic velocities.*

Introduction. The attention of researchers in various countries is focused on the problem of transition to turbulence in spatial boundary layers [1, 2]. This interest arises from the practical applications of this phenomenon, in particular, similar boundary layers are observed in the flow around a swept wing of an airplane.

Most theoretical and experimental results on stability of a three-dimensional boundary layer were obtained for subsonic velocities [1–8]. The role of steady vortices and travelling waves of secondary-flow instability in the course of transition was studied for different degrees of the free-stream turbulence, and a periodic variation of the amplitude of travelling waves in the spanwise direction was found. The experimental results on the laminar–turbulent transition in three-dimensional boundary layers for $\mathrm{M} > 1$ are described in [9, 10]. Creel et al. [9] registered steady vortices on the side surface of a cylinder model installed at an angle of 45° to the incoming flow using the method of flow visualization for $\mathrm{M} = 3.5$. King [10] observed a similar phenomenon on the side surfaces of a sharp cone at an angle of attack of 4° for $\mathrm{M} = 3.5$. King [10] concluded that crossflow vortices are less susceptible to acoustic disturbances than the fundamental-mode disturbances or Tollmien–Schlichting waves. Some results of numerical investigation of instability of a three-dimensional boundary layer for $\mathrm{M} = 3.5$ are presented in [11].

The first experimental studies of instability of a three-dimensional boundary layer at supersonic velocities were conducted in [12, 13]. Evolution of natural fluctuations in the boundary layer on a swept wing was studied. It was shown that the character of distribution of the mean and fluctuating characteristics of the boundary layer is similar to the case of subsonic velocities. A downstream increase in these disturbances was found in analyzing the spectra of natural fluctuations.

The objective of the present work is an experimental study of evolution of disturbances on a swept-wing model for Mach number $\mathrm{M} = 2$ under controlled conditions.

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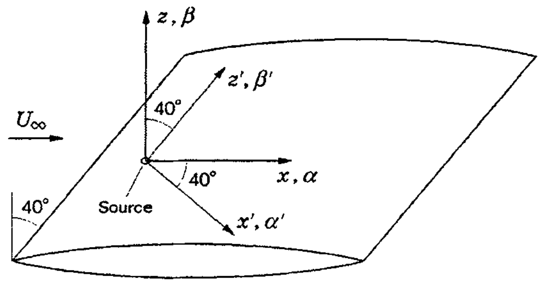

Fig. 1

Experimental Equipment. The experiments were conducted at the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences in the T-325 supersonic wind tunnel with test-section dimensions $0.2 \times 0.2 \times 0.6$ m for Mach number $M = 2.0$ and unit Reynolds number $\mathrm{Re}_1 = U/\nu = (6.6 \pm 0.1) \cdot 10^6$ m^{-1}. A wing model with a 40° sweep angle of the leading edge and a lenticular profile was used in the experiments. The model was mounted at zero incidence in the central section of the test section of the wind tunnel. A sketch of the model and the coordinate system used are shown in Fig. 1. The model length was 0.26 m, its width was 0.2 m, and the maximum thickness was 20 mm. A generator of localized artificial disturbances was used to introduce controlled oscillations in the boundary layer [14]. The operation principle of the generator is based on a spark discharge in the chamber, its construction is described in [15]. Artificial disturbances were introduced into the boundary layer through an orifice in the working surface of the model, the orifice diameter was 0.42 m, and the frequency of discharge ignition was 20 kHz (which corresponds to disturbances at the fundamental frequency). The source of controlled disturbances was located at a distance $x' = (21.4 \pm 0.25)$ mm ($x = 28$ mm) from the leading edge of the model. The origins of the coordinate systems x, y, z and x', y', z' coincided with the position of the source of disturbances. For convenience, the value of the coordinate $z' = 0$ was chosen coincident with $z = 0$.

The oscillations were measured by a constant-temperature hot-wire anemometer with a 1 : 10 ratio of the bridge arms and a frequency range to 500 kHz. Single-wire tungsten probes of diameter 5 μm and length 0.8 mm were used. The overheat ratio of the wire was 0.8, and the measured disturbances corresponded to mass-flow fluctuations. Artificial disturbances were measured in the layer with $y/\delta = 0.6$ (δ is the boundary-layer thickness and y is the coordinate normal to the model surface). In this layer, the amplitude of disturbances reached the maximum value. The fluctuating and mean characteristics of the flow were measured by an automated data acquisition system [15]. The fluctuating signal from the hot-wire anemometer was measured by a 10-digit analog-to-digital converter with a time step of 1 μsec, and the mean voltage in the bridge diagonal was measured by an Shch1516 voltmeter. To improve the signal-to-noise ratio, the signal was simultaneously summed over 500 realizations; the length of each realization was 400 μsec. The amplitude of the mean oscillograms of the fluctuating signal was controlled in the course of experiments. This allowed rather accurate determination of the boundaries of the introduced wave packet relative to the spanwise coordinate z'. The frequency spectra of disturbances were determined by the discrete Fourier transform

$$e'_{f\beta'}(x', y) = \frac{2}{T} \sum_{j,k} e'(x', z'_j, y, t_k) \exp\left[-i(\beta' z'_j - \omega t_k)\right],$$

where $e'(x', z'_j, y, t_k)$ is the digital oscillogram of the fluctuating signal from the hot-wire anemometer averaged over the realizations and T is the length of one realization in time. We note that Gaponenko et al. [8] used a similar procedure for analyzing the data on evolution of disturbances in a three-dimensional boundary layer at a subsonic flow velocity. The amplitude and phase of disturbances were found after the discrete Fourier transform from the formulas

$$A_{f\beta'}(x', y) = \{\mathrm{Real}^2[e'_{f\beta'}(x', y)] + \mathrm{Imag}^2[e'_{f\beta'}(x', y)]\}^{0.5},$$

$$\Phi_{f\beta'}(x', y) = \arctan\{\mathrm{Imag}\,[e'_{f\beta'}(x', y)]/\mathrm{Real}\,[e'_{f\beta'}(x', y)]\}.$$

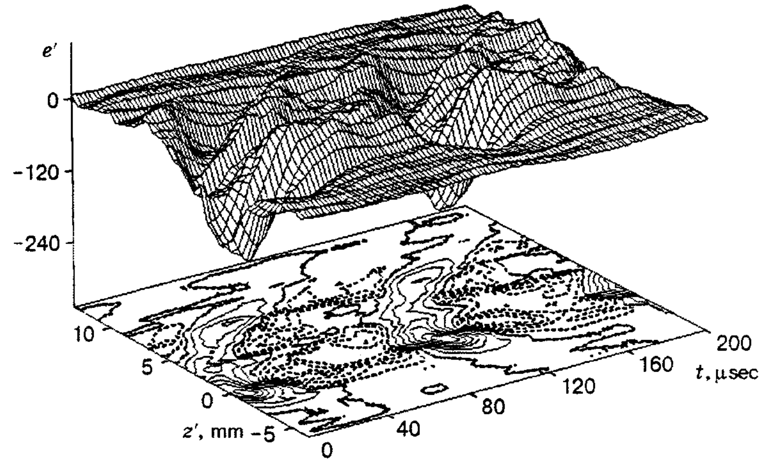

Fig. 2

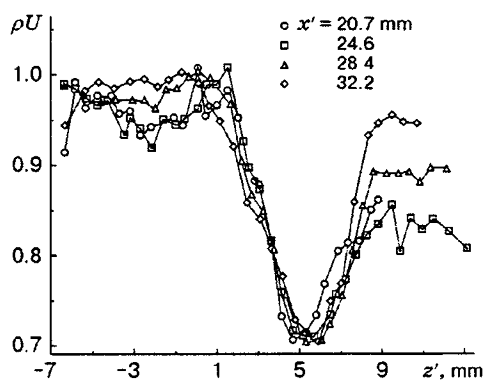

Fig. 3

The absolute values of mass-flow fluctuations $(\rho u)'$ were determined by the method proposed by Kosinov et al. [16].

Results and Analysis. The results on evolution of controlled disturbances in the boundary layer on a swept-wing model were obtained in one set of experiments. The measurements were conducted in x' cross sections by moving the hot-wire probe along the z' coordinate, i.e., parallel to the leading edge of the model (Fig. 1), in the layer of maximum fluctuations in the boundary layer for a constant value of the y coordinate. Oscillograms of mass-flow fluctuations along the spanwise coordinate z' were obtained for $x' = 20.7$, 24.6, 28.4, and 32.2 mm. We note that the averaging method used in the experiments allowed us to identify only fluctuations correlated with the source of disturbances.

The oscillograms and isolines of the amplitude of disturbances for $x' = 28.4$ mm are shown in Fig. 2. The solid and dashed curves (for isolines) correspond to positive and negative values of the amplitude. As for the case of a flat plate, the disturbances are localized in a narrow region [17]. The wave train in the boundary layer on a flat plate was symmetric, whereas the wave train on a swept wing is asymmetric. The oscillograms near $z' = 0$ have a tenon-shaped form, which was also observed in flat-plate experiments with high initial disturbances [17, 18]. However, degeneration of high-frequency oscillations was not observed in the experiments presented here.

Introduction of artificial disturbances distorted the mean flow in the boundary layer. This indicates a nonlinear regime of generation of the source and a high amplitude of initial disturbances. The distributions of the mass-flow rate ρU over the spanwise coordinate z' (obtained by parallel transfer of the z' coordinate along the x axis beginning from the first measurement cross section), which are normalized to the maximum flow-rate value, are plotted in Fig. 3. The dependences $\rho U(z')$ were obtained in the boundary layer at a constant distance from the swept-wing surface. The minimum of $\rho U(z')$ near $z' \approx 4.5$–6.0 mm observed in all distributions is caused by a steady streamwise perturbation. Steady vortices in a three-dimensional boundary layer were observed in experiments [9–12]. In contrast to the results of these papers, the size of a steady perturbation obtained in our experiments is several times greater than the scale of cross-flow steady vortices. The position of the minimum of $\rho U(z')$ shifts downstream (along x) at an angle of 3.0–3.5° to the x axis, which indicates the downstream entrainment of cross-flow vortices in the boundary layer in the region of the present measurements. This result is similar to that obtained by Gaponenko et al. [8] for a three-dimensional boundary layer at low subsonic velocities of the flow. The amplitude of the steady perturbation is about 30% and remains practically unchanged. The results shown in Fig. 3 were obtained by processing hot-wire data using the method described by Kosinov et al. [19].

After the Fourier transform of periodic oscillograms in time, we obtained amplitude–phase distributions of the disturbances along z'. The distributions $A_f(z')$ and $\Phi(z')$ obtained for all the above-mentioned coordinates x' for the fundamental energy-carrying frequencies are given in [20]. We describe briefly these results. It was found that the amplitude of oscillations with frequencies 10, 20, and 30 kHz decreases with increasing x' within the range $x' = 20$–25 mm. Probably, suppression of the Tollmien–Schlichting waves by the favorable pressure gradient occurred. The growth of disturbances was observed downstream. A slight (3–4°) smearing of the wave train was observed in the course of its evolution. The z' distributions of the amplitude of disturbances for frequencies of 20 and 30 kHz had two maxima (the right maximum near $z' \approx 7$ mm and the left maximum near $z' \approx 0$). The growth rate of disturbances that refer to the right maximum was much greater. By means of a frequency-wave analysis of the array of fluctuation oscillograms relative to z' and x', we determined the wave characteristics of disturbances with $f = 10$, 20, and 30 kHz. Figure 4 shows the amplitude–phase β' spectra of disturbances for $f = 10$ (a) and 20 kHz (b) for $x' = 20.7$, 24.6, 28.4, and 32.2 mm. The amplitude and phase distributions of disturbances along z' and the amplitude–phase spectra along β' are reminiscent of similar distributions obtained for a subsonic flow at a significant distance from the source [8]. Predominant growth of the phase along the wing span in the vicinity of the right maximum of the amplitude is typical of travelling waves in a three-dimensional boundary layer. From the amplitude spectra in Fig. 4, it follows that the greatest increase is observed for disturbances with a 10-kHz frequency for $\beta' = 0.2$–0.7 rad/mm. On the basis of the phase spectra of disturbances, we can conclude that there exists a range of wavenumbers where the streamwise phase growth is almost linear for $\beta' = \text{const}$, which allows us to determine the streamwise wavenumber. As in [8], for each fixed value of β', we determined first the streamwise wavenumber α_r and then α'_r along the x' axis: $\alpha'_r = \alpha_r / \cos 40° - \beta' \tan 40°$. The angle of inclination of the wave vector χ' in the plane (x', z') was found from the formula $\chi' = \arctan(\beta'/\alpha'_r)$. The resultant dependences $\alpha'_r(\beta')$ and $\chi'(\beta')$ are plotted in Fig. 5. It follows from these results that the disturbances with the highest amplitude for $f = 10$ kHz, like for $f = 20$ kHz, have an angle of inclination of the wave vector in the plane (x', z') between 60 and 120°. The disturbances with frequency of 30 kHz did not increase in this flow region. The angle of the group-velocity vector obtained for the most unstable disturbances was about 43° in the plane (x', z'), which coincides with the direction of downstream entrainment of the steady disturbances with account of revolution of the coordinate system.

High-frequency oscillations of controlled disturbances were excited simultaneously in a wide range of frequencies. The most intensely excited oscillations correspond to 100, 120, and 150 kHz. The high-frequency oscillations were practically equal to zero in initial x' cross sections but increased with increasing x' coordinate. The appearance of high-frequency oscillations is also confirmed by the experiments of Levchenko et al. [13] who studied instability of a three-dimensional supersonic boundary layer on a swept-wing model under natural conditions. A high-frequency wave train was observed in the region $f = 140$–165 kHz in the spectra of natural oscillations. The excitation of a high-frequency wave train under controlled and natural conditions seems to be related to the cross-flow instability.

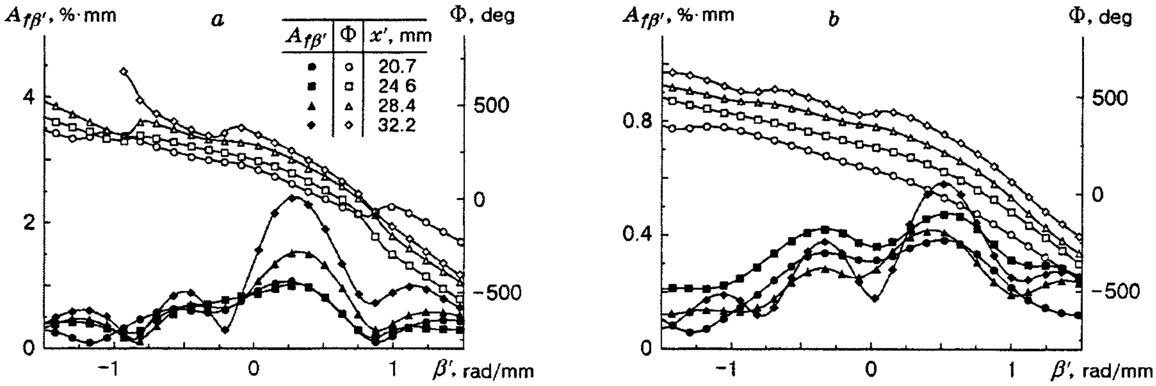

Fig. 4

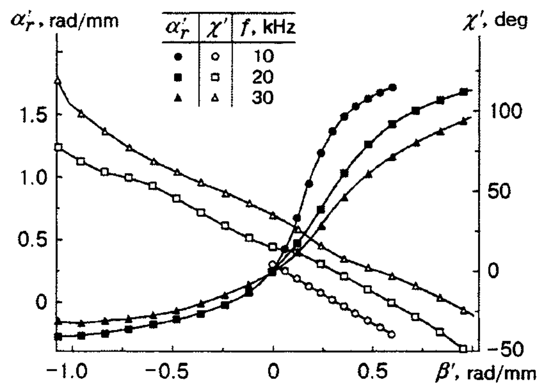

Fig. 5

Conclusions. We can draw the following conclusions from the present experimental study of stability of a spatial supersonic boundary layer on a swept-wing model under controlled conditions.

1. The amplitude of a steady cross-flow disturbance was about 30% in our experiments. The direction of entrainment of this disturbance made an angle of about 3° with the external stream direction.

2. The evolution of disturbances at frequencies of 10, 20, and 30 kHz is similar to the development of travelling waves for subsonic velocities. The angle of inclination of the wave vector for energy-carrying disturbances is directed across the flow, and the group-velocity vector is aligned with the steady cross-flow disturbance.

3. Excitation of high-frequency disturbances increasing downstream was observed. The results obtained correlate with experimental data for natural disturbances.

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