EXPERIMENTAL STUDY OF THE INFLUENCE OF BLUNT LEADING EDGE OF A FLAT PLATE ON THE GROWTH OF THREE-DIMENSIONAL WAVES IN SUPERSONIC FLOW

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Leading-edge bluntness affects the transition location. Experiments show that an increase in bluntness delays transition and may cause reverse transition. A review of papers on this problem may be found, e.g., in [1]. Recently theoretical studies have been carried out on the stability of supersonic boundary layers on blunt bodies [2]. It is known from stability theory [1] that characteristic waves (Tollmien–Schlichting waves) are intensified in supersonic boundary layer. Self-excited fluctuations in supersonic flat-plate boundary layer were first found experimentally in [3] and the propagation of their phases velocities was also estimated (with the help of artificial disturbances). The experimentally determined values of phase velocities were found to be in close agreement with theory. However, such a comparison is not fully justified because the experimentally determined [3] phase velocity cannot be reduced to any plane wave [4]. This phase velocity represented a certain "mean" value of all wave numbers. The behavior of natural disturbances in a boundary layer on a blunted flat plate was experimentally investigated in [5, 6] but in the study of natural disturbances it has so far not been possible to identify fluctuations of plane waves and such results could be considered qualitative. Local boundary-layer control technique is developed in [4, 7] which allows a detailed study of the wave processes. The technique in [4] is applied to a sharp (leading-edge thickness $b < 0.01$ mm) flat plate [8]. The amplification factor α_i and phase velocity c_x in the streamwise direction obtained in [8] agree well with linear stability theory for Tollmien–Schlichting waves. A thorough analysis of the spectrum of source-generated plane waves in boundary layer is given in [8]. It is shown that for waves with the maximum angle of wave-front to flow χ (from 0 to 5-10°) the spatial spectra have acoustic waves of the same order of amplitude as the vortices. However, even when $\chi > 35°$ it is possible to neglect acoustic disturbances compared to the characteristic waves of the boundary layer. The presence of acoustic disturbances in a boundary layer leads to noise generation not only turbulent but also in developed laminar boundary layers [9]. In spite of the practical importance of the study of the stability of boundary layers on blunt bodies at high speeds (supersonic and especially hypersonic) [2], theoretical study of the problems was carried out thirty years after the solution of corresponding problems on ideal, sharp leading-edge bodies. This is due to the difficulty in the evaluation of the influence of bluntness on the physical processes and insufficient experimental study of the influence of a blunt leading-edge of a flat plate on the growth of disturbances in a supersonic boundary layer.

1. Experiments were conducted in the supersonic wind-tunnel T-325 at the Institute of Theoretical and Applied Mechanics (ITPM) of the Siberian Branch of the Academy of Sciences of the USSR [10] with 200 mm × 200 mm test section at Mach number $M = 2.0$ and unit Reynolds number $Re_1 = 6.5 \cdot 10^6$ m^{-1}.

The test model was a flat steel plate with 14°30' swept leading edge. The plate length was 450 mm, width 200 mm, and thickness 10 mm. The model was mounted horizontally at the midplane of the test section at a zero-degree angle-of-attack. The disturbance source was located within the model. Its principal part was the electrode in a ceramic tube mounted perpendicularly to the plane of the model. Disturbances entered the boundary layer through an orifice at the plate surface. The orifice diameter was 0.5 mm. The coordinates of the source were: $x = 17$ mm, $z = 0$ (x is the streamwise distance from the model's leading edge, and z is the transverse coordinate).

A constant-current anemometer TPT-3 was used to record the disturbances. The hot-wire sensor was a 6-μm-diameter and approximately 1.3-mm-long tungsten wire. The sensor was traversed in all three directions x, y, and z (y is normal to the plane of the model). The

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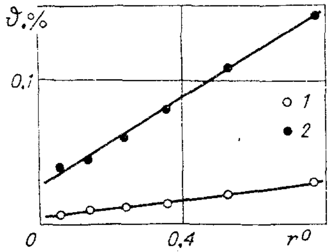

Fig. 1

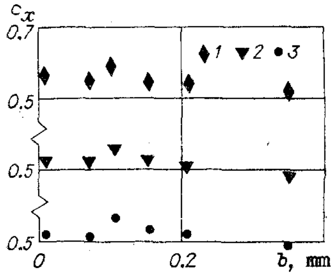

Fig. 2

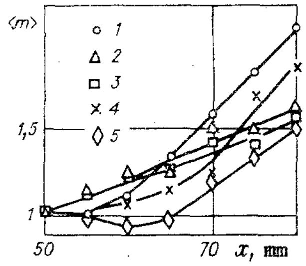

Fig. 3

measurement of distance in x and z directions was accurate to 0.1 mm. The measurements were made at intervals of 5 mm in x, and 0.2 to 0.5 mm in z. While traversing the sensor along x and z coordinates the voltage across the anemometer bridge was maintained constant (this was realized by moving the sensor in the y-direction) which approximately corresponds to measurements along the line of constant velocity with y/δ = constant (δ is the boundary-layer thickness).

The selective amplifier U2-8 was used as the frequency filter. The fluctuation amplitude in a narrow band was recorded by a built-in rms voltmeter in U2-8. The phase of the signal relative to the source of disturbances was determined with the help of two-beam oscilloscope S1-17 synchronized with the hot charge.

The measured data were analyzed by evaluating the amplitude-phase Fourier spectra with respect to β (the wave number in z-direction). The amplitude distribution along z had zero values at the ends of the intervals which allowed finite limits for integration. The evaluation of amplitude spectra with respect to α_r (wave number in the streamwise direction) was carried out as in [8].

The wave-front inclination to the flow was determined from the equation $\chi = \pm\arctan(\beta/\alpha_r)$, and the disturbance phase velocity in x-direction was obtained from $c_x = 2\pi f/\alpha_r U$, where f is the disturbance frequency, and U is the free-stream velocity.

The spatial-amplification factor for the Tollmien–Schlichting waves was determined from [3]

$$-\alpha_i(\mathrm{Re},\ \beta) = 0.5\partial \ln[\langle m\rangle(\mathrm{Re},\ \beta)]/\partial\, \mathrm{Re},$$

where $\mathrm{Re} = (\mathrm{Re}_1 x)^{1/2}$ and $\langle m\rangle$ (Re, β) are amplitude spectra of fluctuations in mass flow. The method of least squares was used. A second-degree polynomial was used as an approximation. A more detailed description of the method is given in [8].

2. The influence of the leading-edge radius on wave characteristics of three-dimensional disturbances was investigated at a frequency of 20 kHz which corresponds to a nondimensional frequency parameter $F = 0.375\cdot 10^{-4}$, where $F = -2\pi f/\mathrm{Re}_1 U$. The sensor was sensitive to fluctuations in mass flow $\langle m\rangle$ and stagnation temperature $\langle T_0\rangle$. It is possible to distinguish these fluctuations by making measurements at different sensor temperatures T_w [11, 12]. It was possible to realize this in the present experiment. Figure 1 shows results of analysis of fluctuations observed in the boundary layer for natural and force (points 1 and 2) disturbances in the region of maximum fluctuations for f = 20 kHz and x = (Re = 650) in the plate model with b = 0.007 mm. Here $r^0 = Q/G$, Q is the sensor sensitivity to mass flow fluctuations and G is the sensitivity to stagnation temperature fluctuations. The ordinate represents the total fluctions $\vartheta = \langle e\rangle/G$, where $\langle e\rangle$ is the rms value of the output signal from the hot-wire anemometer. The given data can be approximated by strength lines and according to [12] the

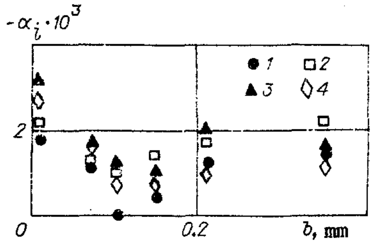

Fig. 4

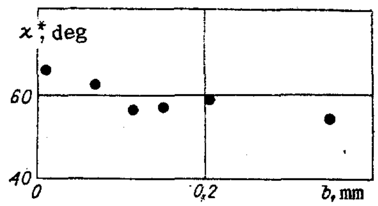

Fig. 5

equation for fluctuations can be expressed in the form $\vartheta = \langle m \rangle r^0 + \langle T_0 \rangle$. Then the mass flow fluctuations can be determined from $\langle m \rangle = |\partial\vartheta/\partial r^0|$, and the stagnation temperature fluctuations from $\langle T_0 \rangle = \vartheta(0)$. From these results $\langle m \rangle = 0.031\%$ and $\langle T_0 \rangle = 0.004\%$ for natural fluctuations, and $\langle m \rangle = 0.152\%$ and $\langle T_0 \rangle = 0.26\%$ for forced disturbances.

Stability characteristics were measured at an overheat $a_w \geq 0.6$ or (with the consideration of specific working conditions, i.e., Re_1 and M) with $Q \geq G$, then for natural disturbances the contribution of mass flow fluctuations to the anemometer signal >90% and for forced disturbances >85%.

3. After the introduction of an electric charge, the boundary layer was excited. A spatial wave packet developed downstream of the disturbance source and it exceeded the natural disturbances by 5 to 8 times. In all cases the wave packet was practically symmetric relative to the plane z = 0 passing through the center of the source. With an increase in Re the wave packet spread for every leading-edge bluntness. The spreading boundary for the wave packet had a wavy nature, especially strongly defined for b = 0.21 and 0.35 mm, and the width of the packet was different for all b. For the test range of coordinates (50 mm $\leq$ x $\leq$ 80 mm) the angle θ at which the wave packet spread was close to 12° and did not depend on b. Theoretical estimates of θ for a flat plate with sharp leading edge made by the author in [13] give 13.6°.

Since an increase in b leads to significant changes in the mean flow near the model, some distinct characteristics appeared during the selection of the measurement layer (y/δ = const). The maximum amplitude of fluctuations along y was found for the measurements. When b $\leq$ 0.15 mm there was one maximum of fluctuations in the boundary layer (Re = 650); for b = 0.21 and 0.35 mm there were two comparable maxima. The choice was made in favor of the inner maximum in view of its greater sensitivity (2 to 3 times compared to the outer maximum) to artificial disturbances. The nature of the outer maximum and its role were not investigated in the present study.

The amplitude and phase spectra of disturbances obtained from Fourier transformation of given signal amplitude and phase along the x and z coordinates are as a whole similar to the data given in [4, 8]. For β ~ 1 rad/mm a maximum was observed in the amplitude spectra of β which shifted towards lower values of β with increase in Re. Estimates of amplitude spectra of α_r with b = 0.01; 0.07; 0.15; 0.21; and 0.35 mm showed that for β $\geq$ 0.3-0.4 rad/mm the spectra basically carry information on waves with one α_r. For β from 0 to 0.1 rad/mm there were also peaks in the spectra with different α_r with amplitudes comparable with each other. This result is similar to that described in [8].

Phase velocities corresponding to the highest peak in α_r-spectra are shown in Fig. 2 as a function of b determined at Re = 650 (points 1-3 are for waves with χ = 70, 57, and 41°). It is seen that with increase in b the phase velocity decreases slightly. In the range of χ from 35 to 75°, there is a similar behavior of c_x. The value of c_x agrees well with theoretical estimate for Tollmien–Schlichting waves [4, 8]. This gives a basis for the comparison of results on the growth of plane waves with a single value of χ for different b.

Figure 3 shows the growth of disturbances (mass flow fluctuations) for χ = 65° at b = 0.01; 0.07; 0.15; 0.21; and 0.35 mm (points 1-5). Results are normalized with respect to the value of the first measured point. The maximum growth of amplitudes with increase in Re corresponds to b = 0.01 mm.

It is more convenient in considering the growth rate of plane waves to compare the results with computations. Figure 4 gives α_i (Tollmien–Schlichting waves) as a function of b, where 1-4 are disturbances with χ = 41, 51, 65, and 70° (Re = 650). A nonmonotonic behavior is observed for the change in values of α_i with b, with a minimum in the range of b from 0.1 to 0.15. For χ = 70° this minimum is less defined. A similar reverse in values of α_i could finally lead to the reverse transition observed in some studies. Following [2], the reason for "reversal" can be explained by additional influence of entropy layer on the boundary layer with increase in leading-edge bluntness, but this problem requires special investigation.

Figure 5 shows the change in the angle of the most unstable disturbances χ^* with b. The values of χ^* decrease with increasing leading-edge bluntness, with the strongest influence of bluntness being observed for $b \leq 0.1$ mm.

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