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INSTABILITY OF A THREE-DIMENSIONAL SUPERSONIC BOUNDARY LAYER*

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The instability of three-dimensional boundary layers has become an area of intensive theoretical and experimental research in the last decade [1, 2]. Such boundary layers are encountered in particular in the flow of air past swept wings on aircraft in regions of negative and positive longitudinal pressure gradients.

Nearly all of the studies have been conducted for subsonic flow velocities. However, despite the large volume of research, the problem is still not fully resolved: there are qualitative differences between not only the theoretical and experimental data, but also the experimental results obtained by different groups of researchers. The complexity of the problem lies in the fact that together with known Tollmien–Schlichting (TS) waves – the formation of which leads to the transition to turbulence in two-dimensional boundary layers – additional instability waves connected with secondary flows develop in the three-dimensional case. These flows are stationary vortices whose axes are directed mainly along the streamlines of the external flow, as well as some travelling (non-TS) waves. The formation of all of these waves and their relative role in the transition depends heavily on the external conditions.

Only two experiments have been conducted at supersonic velocities [3, 4]. The models in them were circular cylinders positioned at a 45° angle to the incoming flow at Mach numbers M = 10 and 3.5, respectively. The turbulence transition was studied on the basis of measurements of certain integral quantities – without measurement of the development of processes in the boundary layer. Stationary vortices were detected by visualization on the surfaces.

The goal in this investigation is to use measurements made inside a boundary layer to establish if wave processes that are similar to the subsonic case occur in flow about a supersonic airfoil with a sharp leading edge under the "natural" conditions of operation of a wind tunnel.

1. Experimental Equipment and Methods of Measurement. The studies were conducted in the T-325 supersonic wind tunnel at the ITPM (Institute of Theoretical and Applied Mechanics) of the Siberian Branch of the Russian Academy of Sciences. The dimensions of the working part were 200 × 200 × 600 mm at M = 2.0. The unit Reynolds number $Re_1 \approx 6.8 \cdot 10^6$ m^{-1}. Descriptions of the design of the wind tunnel and the turbulence characteristics of its working part were given in [5, 6].

An oblique airfoil model with a lens-shaped profile and a leading edge having a side-slip angle of 45° was used in the experiments. The model was 260 mm long and 200 mm wide. The maximum thickness was 20 mm. The model was positioned horizontally in the working part of the tube at a zero angle of attack.

To determine the flow parameters (M_∞, Re_1, T, U_∞), we measured pressure in the afterburner chamber and static pressure in the working part with balances. Stagnation temperature was measured with a thermocouple. A description of this system was presented in [7]. Measurents of the fluctuation characteristics of the flow during the experiment were performed using instruments and programs developed to measure the transient parameters of a supersonic flow (supersonic boundary layer) [7].

Pulsations were measured using a constant-resistance hot-wire anemometer [7] with sensors made of tungsten wire 6 μm in diameter. The length of the sensor wire was 1.2 mm. The sensor was mounted on a holder inserted in the guide bar of

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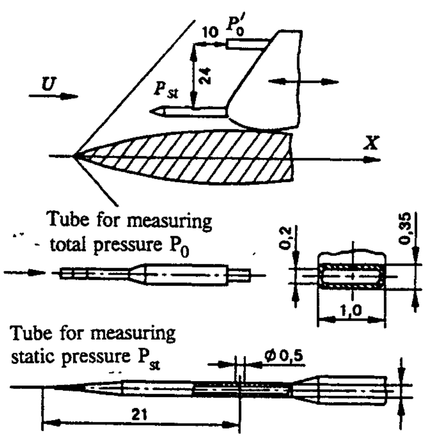

Fig. 1

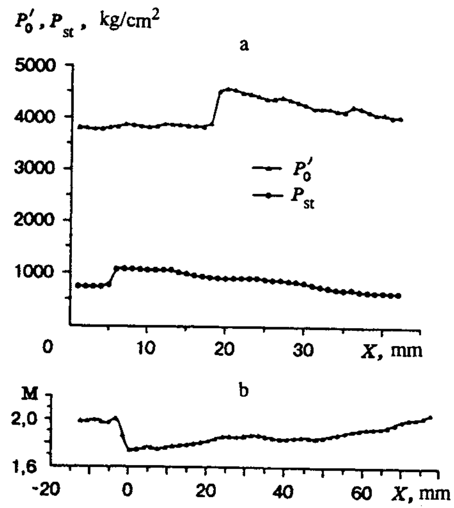

Fig. 2

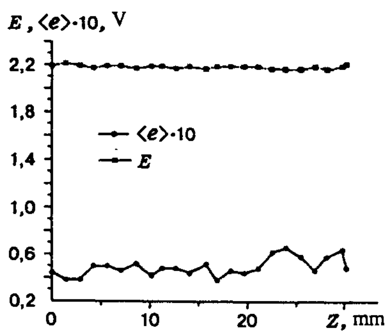

Fig. 3

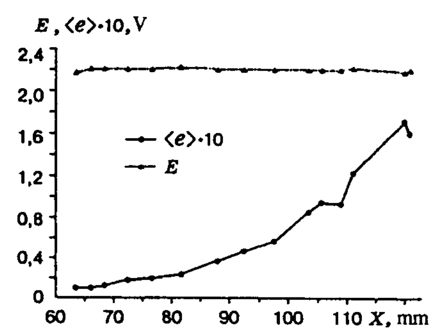

Fig. 4

a coordinate plotter. The latter could be used to move the sensor along three coordinates: X, Y, and Z. The sensor was connected to the model along the Y coordinate by the electrical contact of its tip against the wing. Measurement accuracy was 0.1 mm along the X and Z axes and 0.01 mm along the Y axis.

The pulsations in the layer were measured with the anemometer at their maximum value in terms of y/δ (where δ is the thickness of the boundary layer). As the sensor was moved along the coordinates X and Z, the voltage in the diagonal of the anemometer bridge was kept constant as a result of displacement of the sensor along the coordinate Y – which corresponded to measurements along lines of equal velocity. The degree of overheating of the sensor wire was 0.8, which means that 90% of the fluctuation signal from the anemometer consisted of fluctuations of mass flow rate.

Pressures behind the shock wave in the flow above the model (in the free flow) were determined with tubes that measured total $P_0'(x, y, z)$ and static $P_{st}(x, y, z)$ pressure. The pressures were determined from the readings of the wind-tunnel balances. The shapes and dimensions of the tubes used to measure total and static pressure are shown in Fig. 1.

2. Measurement Results. It is known that the movement of a flow past a supersonic swept airfoil is accompanied by its acceleration along the entire airfoil. Figure 2a shows the results of measurement of absolute values of static pressure P_{st} and total pressure P_0'.

The corresponding distribution of Reynolds numbers is shown in Fig. 2b. Measurements of total pressure behind the shock were made at Y = 38 mm from the surface of the model (at the point of maximum thickness), while static pressure was measured at Y = 14 mm. In this case, the coordinate X = 0 corresponded to the passage of the tubes through the shock wave.

The transient characteristics of laminar boundary layers under "natural" conditions were measured to reveal the main processes that take place in the transition to turbulence. The quantitative information obtained in this case has no particular value except for certain reference points (such as the point corresponding to the "beginning" or "end" of the transition), since the wave processes that take place in the boundary layer depend quantitatively and sometimes qualitatively on the composition

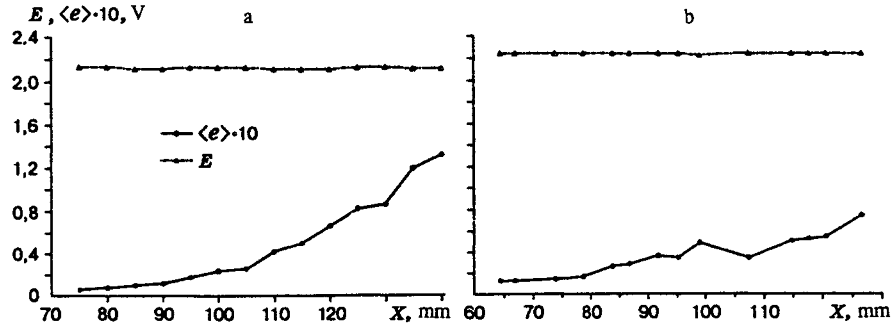

Fig. 5

and level of the external perturbations (the "receptivity" problem) and are different in different wind tunnels (this applies even to low-turbulence tunnels). Thus, electrical signals from a hot-wire anemometer are used instead of hydrodynamic parameters as the measured values.

Figure 3 shows the results of measurements of the standard deviation of velocity pulsations $<e>$ inside the boundary layer (X = 80 mm) in the transverse (parallel to the leading edge) direction. The values of $<e>$ were obtained in a frequency range up to 100 kHz after the signal was amplified tenfold. Here, E is the mean voltage in the diagonal of the anemometer bridge. The measurements were made with a constant mean voltage E.

While special measurements confirmed that the field of velocity fluctuations outside the boundary layer was uniform, inside the layer there was a clear tendency toward the establishment of a certain periodicity. Such a periodic change in fluctuation velocity might be attributable to the corresponding periodic change in mean velocity in the transverse direction at Y = const. The scatter of the amplitude and scale of periodicity should not cast doubt on the accuracy of the measurements. A similar situation is seen in experiments conducted at subsonic velocities under "natural" conditions due to the randomness of external turbulent perturbations [8]. In a supersonic wind tunnel, the external perturbations are sound waves generated by a turbulent boundary layer on the tunnel walls – which are of course partly random in nature.

Figure 4 shows the development of natural perturbations downflow. The measurements were made in the boundary layer with a constant mean velocity. The surface of the model was covered by varnish in order to be able to visualize the flow and determine the position of the transition by means of subliming coatings. In this case, the point of the "end" of the transition was fixed at X = 120 mm with a Reynolds number $Re_t = 0.8 \cdot 10^6$. This value of Re_t is 2.5-3 times lower than the Re_t obtained for nongradient flow in a boundary layer in the given wind tunnel. It should be noted that $Re_t \approx 2 \cdot 10^6$ in experiments conducted on a flat plate under the same conditions. It can be suggested that the reduction in the transitional Reynolds number in the given case is due to the roughness of the surface, despite the stabilizing effect of acceleration of the flow along the airfoil. As a result, the surface was carefully polished in all subsequent experiments.

Figure 5a and b, shows results of measurement of the development of perturbations downflow. The measurements were obtained with different values of mean velocity (different distances from the surface) for a polished surface. Although the end of the transition was not reached under the given conditions, we did clearly establish an increase in the perturbations. Oscillograms of the pulsations across the boundary layer at the end of the measurement region had the form typical of the nonlinear stage. Thus, unsteady perturbations also developed in this case. It can be seen from Fig. 5 that the perturbations began to increase in amplitude roughly with X ≈ 60 mm. In experiments conducted on a flat plate, an integral (with respect to frequency) increase in perturbations was seen beginning with a distance of 120 mm from the leading edge at the same values of Re_1. We should also point out that in the given case the boundary layer develops under conditions whereby the flow is accelerating along the model. This acceleration has a stabilizing effect on the development of instability waves in the main flow (TS waves) [9]. Thus, the increasing perturbations that were observed must be waves generated by instability of the secondary flows.

In conclusion, we should point out that we have just described the first experiments to study the instability of a three-dimensional supersonic boundary layer created with flow past a swept-wing model. The experiments allowed us to establish a fundamental difference between the nature of instability in gradient two-dimensional and three-dimensional supersonic boundary layers.

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