WAVE STRUCTURE OF ARTIFICIAL PERTURBATIONS IN A SUPERSONIC BOUNDARY LAYER ON A PLATE

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Laminar low transition into turbulence in boundary layers is caused by the development of unstable natural vibrations in many cases [1, 2]. An experimental study of the mechanisms for exciting such vibrations and the laws of their development is one of the directions in investigations on the origin of turbulence. The investigations are carried out in supersonic wind tunnels, in whose working parts the perturbations are acoustic in nature, as a rule. The "natural" acoustic background influences the laminar-turbulent transition in models.

The excitation and development of vibrations in the boundary layer of models depend on their frequency-wave spectra. Determination of the frequency-wave spectra of the "natural" perturbations in aerodynamic installations is difficult and, consequently, the data obtained experimentally for them describe the phenomenon only qualitatively. Lately a new approach has appeared in the experimental investigations by using controllable artificial (external or internal for the boundary layer) perturbations [3-6].

The wave structure (in the phase velocities) of perturbations being developed in a supersonic boundary layer under internal excitation from a point source and under external excitation caused by acoustic waves incident from outside, is investigated experimentally in this paper and a comparison is performed.

1. The experimental data are obtained in the supersonic wind tunnel of the Siberian Branch of the Institute of Theoretical and Applied Mechanics, Academy of Sciences of the USSR, T-325 with 200 × 200 mm working section dimensions at a Mach number $M = 2$. All the measurements are executed in the boundary layer of a flat plate. A plate 10 mm thick, 200 mm wide, and 450 mm long was fastened horizontally in the central plane of the wind tunnel working section at a zero angle of attack. The plate leading edge was pointed at a 14°30' angle and had the thickness $b < 0.1$ mm. The perturbations in the plate boundary layer were recorded by a dc thermoanemometer TPT-3. Sensors of tungsten wire with 6 μm diameter and ≈1.3 mm length were used. The sensor was shifted along x, y, z coordinates (x is the longitudinal, y is the normal, and z is the transversal Cartesian coordinate). Fluctuation measurements were performed for a fixed frequency in the 1% band. The signal phase relative to the perturbation source was determined by using a double-beam oscilloscope. Its sensitivity was maintained constant for sensor motion along the x and z coordinates because of small displacements along y so that the voltage in the bridge diagonal of the thermoanemometer was maintained constant. The magnitude of the wire heating is 0.8, which assured the predominant contribution of mass flow rate fluctuations to the nonstationary signal. All the measurements were performed in a layer with a maximal fluctuation level.

Double Fourier transformation in the wave numbers β (z is the wave vector component) and α_r (x is the component) were executed for the data processing. The obtained wave α_r spectra for the fixed $\beta = \text{const}$ had a set of peaks. The phase velocities c_x were later determined in the x direction and the slopes of the wave vector in the flow direction χ corresponding to these peaks by means of the formulas $c_x = 2\pi f/\alpha_r U$, $\chi = \arctan(\beta/\alpha_r)$ (U is the unperturbed stream velocity, and f is the perturbation frequency). The method applied is traditional for investigating boundary layer stability by using artificially introduced spatial wave packets and is described in greater detail in [5].

Two schemes for introducing the artificial perturbations into the supersonic boundary layer were used in the experiments. In the first case the perturbations were excited directly into the boundary layer of the model being investigated by using a periodic electrical discharge analogously to [5]. The discharge occurred in a chamber located within the model.

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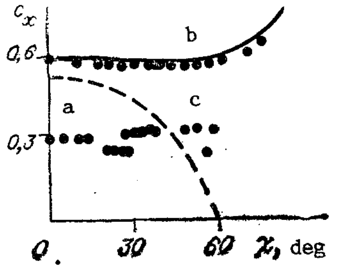

Fig. 1

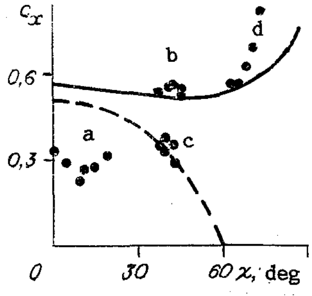

Fig. 2

The perturbations penetrated into the boundary layer through a 0.5 mm diameter hole in the model surface with the coordinates z = 0, x = 17.5 mm. In the second case the perturbations were generated on the model leading edge by an external artificial acoustic field generated by a discharge-boundary layer system. For this an upper plate of 200 × 300 × 5 mm dimensions with a surface electrical discharge was arranged parallel to the model under investigation at a distance of y = 45 mm. The discharge was triggered on two electrodes perpendicularly to the flow at a 17.5 mm distance from the plate leading edge. The length of the electrical arc was ≈1.5 mm for a ≈0.5 mm width. The triggering scheme is analogous to [5].

The periodic electrical discharge generated natural vibrations in the boundary layer of the upper plate which were developed downstream. The perturbation development was accompanied by acoustic wave radiation into the unperturbed flow between the upper plate and the model under investigation. The plates were disposed such that the acoustic vibrations of maximal amplitude, emitted by the transition zone, were incident on the leading edge of the model being investigated and generated perturbations whose development was recorded by using the thermoanemometer. Such an approach to the experimental investigation of the susceptibility of supersonic boundary layers was first proposed in [3, 4]. Zones responsible for the generation of natural boundary layer waves by an external acoustic field were determined there. One such zone turned out to be the leading edge of the model being exposed.

2. Investigation of the wave development in a flat plate boundary layer at M = 2, generated by a periodic pulse source within the boundary layer is described in [5]. It is obtained in those experiments that vortices (Tollmien–Schlichting type waves) and acoustic waves are developed downstream under local excitation of perturbations by using a periodic discharge in a laminar boundary layer. Here the development of the natural vibrations occurs in conformity with the predictions of the linear theory of hydrodynamic stability [2]. The fraction of sound waves is greatest for two-dimensional perturbations ($\chi = 0$) and can reach one order as compared with the vortices in the neighborhood of the second branch of the neutral stability curve. Let us consider the perturbation structure in the phase velocities in greater detail. A wave portrait of the perturbations being developed in a supersonic boundary layer from a point source is represented in Fig. 1. Data are obtained for Re = 655 and the frequency parameter $F = 0.55 \cdot 10^{-4}$ ($\mathrm{Re} = (Ux/\nu)^{0.5}$, $F = 2\pi f\nu/U^2$). The points are experimental results, the solid line is computations of the phase velocities of the boundary layer natural vibrations [5], while the dashes corresponding to $c_x^*(\chi) = 1 - (M\cos\chi)^{-1}$ separates the vortex and acoustic perturbation domains. It is known that three-dimensional waves in a supersonic boundary layer refer to the subsonic (with respect to the free stream) vortex perturbations if $c_x > c_x^*$ (the upper domain from the dashed curve) and to the supersonic (acoustic waves correspond to it outside the boundary layer) if $c_x < c_x^*$.

The experimental points in Fig. 1 can be separated into three groups (the letters a, b, c) according to the phase velocities. The perturbations in the domain a refer to the supersonic. The experimental points therein are grouped to form levels. The step in χ could be made small in the data processing, however, the discontinuities in the levels c_x are not filled in and the transition to another level would occur. It is shown in [5] that a much higher level exists but the interpretation of these results is difficult as yet because of the lack of a theoretical foundation. The subsonic perturbations in the domain b correspond to the well-known analog of the Tollmien–Schlichting waves. These experimental data are in agreement with computations and the range of χ from 0 to 80° is filled continuously for point source generation of perturbations within a boundary layer. Perturbations from this domain are studied sufficiently well in [5], where it is shown that their amplitude yields the predominant contribution to the signal (up to 90-95%) for χ > 30-35° (for fixed β). The perturbations in the domain c also refer to the subsonic but the question of whether they are described by existing theories remain open.

The results of investigating the wave structure of perturbations generated by external controllable waves in the boundary layer showed that vortical and acoustic waves are developed downstream during perturbation generation on the leading edge in a laminar boundary layer and the fraction of sound waves is highest for two-dimensional perturbations ($\chi = 0$). The wave portrait of the perturbations generated at the leading edge by external controllable acoustic perturbations and being developed in a supersonic boundary layer is represented in Fig. 2. The curves in Fig. 2 are analogous to the curves in Fig. 1 and are obtained for nearby values of the experiment parameters ($Re = 650$, $F = 0.5 \cdot 10^{-4}$). The experimental points in Fig. 2 are grouped exactly as in Fig. 1 but there is also a distinction. In particular, the subsonic perturbations corresponding to domain b in Fig. 1, form two groups (marked by the letters b and d) in Fig. 2, while the perturbations from domain c are on the sonic (dashed) line.

Let us compare the results of Figs. 1 and 2. The wave portrait of an emitter is actually represented in Fig. 1 and the wave portrait of the perturbations occurring because of reaction of the boundary layer of the model under investigation to the exposure of its leading edge, in Fig. 2. The conformity of the domains a in Figs. 1 and 2 visibly exists. Outside the boundary layer the perturbations from the domains a are sound waves. They damp out slightly as the coordinate y increases and are magnified by the boundary layer of the plate being investigated. Theoretical models describing such magnification have been developed and are presented in [1], say. Subsonic perturbations from the domain b in Fig. 1 damp out intensively outside the boundary layer and probably do not reach the model being exposed. In the opposite case the domain in the neighborhood of the continuous line in Fig. 2 would be filled completely, i.e., it can be concluded that perturbations from the emitter domain b play no substantial part in the wave processes of the boundary layer of the model being exposed.

The extraction of two perturbation groups (domains b and d) in Fig. 2 can be related to wave generation on the leading edge of the model being exposed by supersonic perturbations corresponding to domain a of Fig. 1. Perturbations from the domain d in Fig. 2 with slopes $\chi \approx 60\text{-}70°$ are the fastest growing (having the maximal degrees of growth [6]). Perturbations from domain b in Fig. 2 with slopes $\chi \approx 45°$ would have the greatest amplitudes in the spectrum, i.e., they are excited with maximal generation coefficients. At this time there are no theoretical researches that could explain why namely oblique waves with $\chi \approx 45°$ are generated most intensively in the boundary layer. Still more complicated is the question of the interpretation of the perturbations in the domains c in both figures. Obtaining them was totally unexpected and no explanation has yet been forthcoming.

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