(which is perfectly possible in practice), since in a separate numerical solution of system (4.2) as a result of the errors it is also possible to obtain several different limiting values of v as $r \to 0$.

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EXCITATION OF NATURAL OSCILLATIONS IN A BOUNDARY LAYER BY AN EXTERNAL ACOUSTIC FIELD

A. A. Maslov and N. V. Semenov

UDC 532.526.013.4

INTRODUCTION

The transition from a laminar to a turbulent boundary layer is one of the more important problems of fluid dynamics. However, we still lack accurate models of the process. The principal factors governing transition usually include the instability of the laminar boundary layer (i.e., the mode of development of the perturbations responsible for transition) and its sensitivity (why and how the perturbations responsible for transition are induced in the boundary layer by external oscillations).

A fairly complete review of the theoretical and experimental results on the stability of the supersonic boundary layer is given in [1]. Less attention has been paid to the action of external perturbations on the boundary layer. The possible modes of external perturbation include acoustic oscillations, and in supersonic wind tunnels their contribution predominates [2]. The acoustic perturbations can modify the structure of the flow in the boundary layer investigated and affect the location of the laminar-turbulent transition transition (see, for example, [1]).

New theoretical studies of the excitation of instability waves in a compressible-gas boundary layer by an external acoustic field have recently appeared [3-5]. There has been no experimental research to verify the conclusions of the theory.

One of the possible approaches to the experimental study of boundary layer susceptibility consists in modeling the process of excitation of natural boundary layer oscillations by external, artificially produced acoustic perturbations.

This calls for a source of acoustic oscillations that meets certain requirements. In the case of a supersonic wind tunnel the experimental conditions are such as to make difficult, and sometimes completely impossible the use of traditional sources such as acoustic sirens, Hartmann whistles, lattices, etc. [6].

In [7] the possibility of creating a source of determinate acoustic perturbations on the basis of a discharge—boundary layer system was demonstrated and the resulting

Novosibirsk. Translated from Izvestiya Akademii Nauk SSSR, Mekhanika Zhidkosti i Gaza, No. 3, pp. 74-78, May-June, 1986. Original article submitted June 11, 1985.

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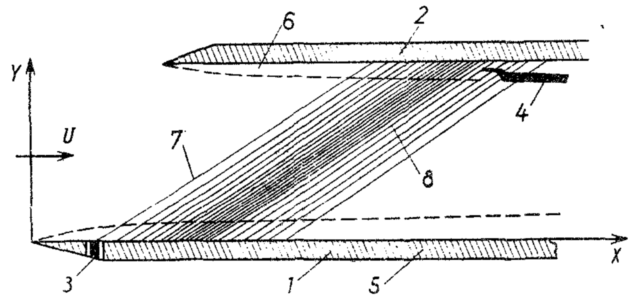

Fig. 1

radiation field was investigated. Using such a source of artificial perturbations we have carried out the first experimental studies of the sensitivity of the supersonic boundary layer. It has been found that on a plate there are zones where the conversion of external acoustic perturbations into natural oscillations of the supersonic boundary layer is most efficient: the leading edge of the plate, the region of the acoustic branch of the neutral curve, and the region of the lower branch of the neutral stability curve.

1. The experiments were conducted in the T-325 supersonic wind tunnel at the Institute of Theoretical and Applied Mechanics of the Siberian Division of the USSR Academy of Sciences, using a reduced degree of turbulence and a working section with an area of 200 × 200 mm [8]. The free-stream perturbations in the working section are mainly determined by the acoustic pulsation mode [9]. The measurements were made at a free-stream Mach number M = 2.0. The unit Reynolds number Re_1 was varied from $5 \cdot 10^6$ m^{-1} to $12 \cdot 10^6$ m^{-1}.

The experimental setup is shown schematically in Fig. 1. The model consisted of two steel plates with tapered leading edges mounted parallel to each other in the horizontal plane. Plate 1, incorporating a surface electrical discharge 3, was rigidly attached to the side walls of the wind tunnel. Plate 2 was fitted with a hot-wire anemometer probe 4. The diagram also shows: 5, 6) the boundary layers on the plate; 7) the Mach line from the discharge; 8) the radiation from the transition zone.

The discharge is triggered between two electrodes mounted 17.5 mm from the leading edge of plate 1 flush with its surface. The electrodes, 0.5 mm in diameter, were made of copper; they were insulated from each other and from the model by ceramic material. The minimum gap between the electrodes was 0.55 mm. The electrodes were mounted in such a way that the discharge was triggered in a plane parallel to the leading edge of plate 1. The electrode voltage supply circuit consisted of: a G3-112 master oscillator, a G2-12 power amplifier, a TVS-110 step-up transformer, the electrodes [7]. The discharge trigger frequency f was varied from 5 to 20 kHz.

Plate 2 was attached to the support rod of the traverse mechanism and displaced in the direction of the coordinates X, Y. Here, X is the longitudinal and Y the transverse coordinate. The origin coincides with the leading edge of plate 1 in the plane passing through the center of the discharge. Probe 4 on plate 2 was attached in such a way that it could be mounted at various distances from the plate surface. The measurements were made in the layer with the maximum pulsations. The distance from the leading edge to the probe, 90 mm, was so selected that on the interval of unit Reynolds numbers Re_1 and frequencies f investigated the probe was situated in the region of instability.

The perturbations in the boundary layer on plate 2 and in the free stream between the plates was recorded by means of a TPT-3 dc hot-wire anemometer [10]. In the experiments we used probes with a tungsten wire 6 μm in diameter and 1.2 ± 0.1 mm in length. The voltage fluctuations from the anemometer output were fed to a U2-8 selective amplifier tuned within a narrow band to the frequency investigated and recorded by a voltmeter built into the amplifier. For determining the phase of the signal investigated relative to the source of the perturbations we used a S1-17 double oscillograph synchronized with the burning discharge. The accuracy of phase determination was 5-7°.

During the experiments we checked the flow regime between the plates. A Pitot tube, mounted in the free stream above the anemometer probe, was used to measure the total pressure behind the normal shock. To measure the static pressure we tapped a hole 0.8 mm in diameter in plate 2 at the level of and offset 10 mm from the probe. From the total and static pressures obtained we calculated the Mach number between the plates.

2. The surface discharge 3 creates perturbations in the laminar boundary layer 5 which as they move downstream are amplified several times. This process is accompanied by acoustic radiation into the external flow [7]. We will briefly consider the principal characteristics of this radiation.

The distribution of the amplitude A of the perturbation radiated into the free stream in the direction of the longitudinal coordinate X has two maxima. The first, rather narrow maximum is caused by the discharge itself and is propagated along the Mach line 7. The second maximum 8 corresponds to the radiation from the transition zone and is propagated along a line close to the Mach line. The radiation frequency coincides with the arc trigger frequency. At a distance $Y < 15\delta$ (δ is the thickness of the boundary layer in the transition zone) the principal contribution to the radiation is made by Tollmien—Schlichting waves, but these are damped much more quickly than the acoustic waves, and at greater distances only acoustic perturbations are observed. The radiation is propagated mainly in the plane XY, the fraction of inclined waves in the transverse direction being unimportant. For the various wind tunnel operating regimes and arc trigger frequencies f the radiation was observable up to $Y \sim 50\delta$. At greater distances the artificial radiation could not be distinguished against the natural background.

This source of controllable artificial perturbations can be used for the experimental investigation of the stability and sensitivity of the supersonic boundary layer.

3. Perturbations of given frequency and determinable phase are radiated from the plate incorporating the discharge into the free stream. This radiation has two maxima. As the plate 2 is displaced along the X, Y coordinates in the perturbation field, the radiation maxima impinge on different parts of the plate and provoke a different response of the boundary layer to the external perturbations.

Figure 2 shows a typical perturbation amplitude distribution A(X) as a function of the X coordinate of the leading edge of plate 2 (distance between the leading edges of the plates in the longitudinal direction) for a fixed value of the Y coordinate (distance between the plates). The data were obtained for Y = 40 mm, f = 10 kHz, and $Re_1 = 9.7 \cdot 10^6\ m^{-1}$. In Fig. 2 the numbers 1-6 denote the maxima of the perturbations in the boundary layer due to the action of the external radiation. The points 7 were obtained with the discharge switched on, the points 8 with the discharge switched off. The maximum 6 corresponds to the onset of transition on plate 2, and the presence of the other maxima of A(x) indicates that there are points on the model in the neighborhood of which the generation of perturbations in the laminar boundary layer is more intense. The radiation maxima produced by the discharge—boundary layer system, impinging in the neighborhood of these points, cause an increase in the perturbations in the boundary layer on the model.

In order to confirm our conclusion concerning the existence of singular points we made measurements of A(X) for f = 10 kHz, $Re_1 = 6.1 \cdot 10^6\ m^{-1}$ and various distances Y between the plates. In Fig. 3 we have plotted the X coordinates of the maxima of the perturbations in the boundary layer on the second plate against the distance Y between the plates (the maxima are numbered in the same way as in Fig. 2). Clearly, as the Y coordinate decreases, the maxima of the perturbations in the boundary layer are shifted towards the origin. From the values of the abscissas and ordinates it is possible to estimate the angle between the axis and the direction of displacement of the X coordinates of the maxima. It is approximately equal to 30—36° (in Fig. 3 the angle seems greater owing to the different scales in the X and Y directions), which corresponds to the inclination of the Mach lines for M = 2.0—1.7.

During the experiments the Mach number of the flow between the two plates was checked. It was found to be smaller than the free-stream Mach number and to depend on the relative position of the plates. For values of the X coordinate corresponding to the maxima 1—5 the Mach number between the plates depends mainly on the distance

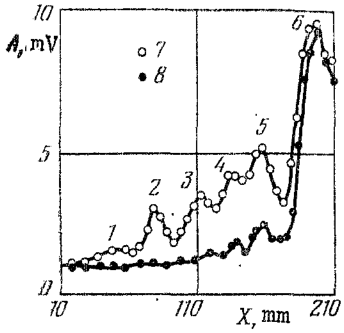

Fig. 2

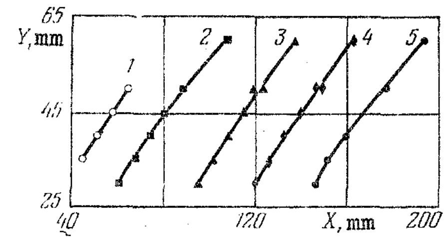

Fig. 3

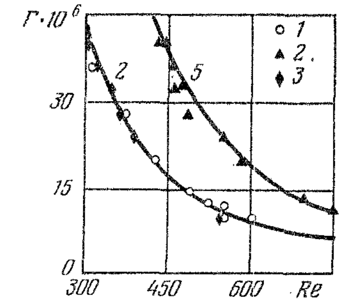

Fig. 4

between the plates. Thus, for Y = 60 mm M ~ 1.96; for Y = 50 mm M ~ 1.93; and for Y = 40 mm M ~ 1.90. The onset of transition 6 is characterized by a sharp decrease in the Mach number between the plates to M = 1.65. Thus, from Fig. 3 we conclude that as the Y coordinate decreases the X coordinates of the maxima are displaced along the Mach lines.

Since the radiation from the plate incorporating the discharge is also propagated along the Mach lines, in order to find the regions of maximum sensitivity of the boundary layer it is possible to employ simple geometric constructions.

In determining the regions of maximum sensitivity certain difficulties arise owing to the fact that the artificial radiation has two intensity maxima. In determining which A(X) maxima in the boundary layer on the plate correspond to radiation from the discharge itself striking points in whose neighborhood generation is more intense and which maxima correspond to the incidence of radiation from the transition zone we are assisted by the fact that at the working arc striking voltages the transition zone on the plate with a discharge is only slightly displaced as compared with the plate without a discharge. Acoustic radiation is emitted from the transition zone even without the discharge being switched on, but on a broad frequency interval, and coincides in position (though not in amplitude) with the radiation from the plate with the discharge switched on. Therefore, when the discharge is switched off, there remain only the perturbation maxima in the boundary layer due to radiation from the transition zone striking the regions of maximum sensitivity of the boundary layer, and the maxima associated with the discharge itself disappear. Thus, maxima 1 and 2 (see Fig. 2) are caused directly by the radiation from the discharge, and maxima 3, 4, and 5 by the radiation from the transition zone.

We continue the Mach lines in Fig. 3 until they intersect the first plate. Now, taking into account the fact that the discharge occurred 17.5 mm from the leading edge and the perturbation maximum corresponding to transition 95-110 mm from that edge (depending on the flow regime), we can show that maxima 2 and 5 are caused by radiation striking the leading edge of plate 2. This conclusion is confirmed by the following measurements. For a distance between the plates Y = 40 mm we obtained distributions similar to that shown in Fig. 2 for various values of the unit Reynolds numbers Re_1 and arc trigger frequencies f. The perturbation maxima 2 and 5 corresponding to the incidence of radiation on the leading edge were not displaced, but the maxima corresponding to the other regions of greatest sensitivity of the boundary layer were shifted in the direction of the X coordinate. From these data we determined the distances l from the leading edge of plate 2 to the singular points. For the perturbations caused by the discharge itself this distance was equal to the difference between the X coordinates of maxima 2 and 1; for the pertubations caused by the transition zone to the difference between the X coordinates of maxima 5 and 3 and 5 and 4. The distances l were used to calculate the Reynolds numbers of the singular points: $Re = \sqrt{Re_1 l}$.

In Fig. 4 we have plotted the Reynolds numbers of the singular points against the dimensionless frequency parameter $F = 2\pi f/(URe_1)$, where U is the velocity of the undisturbed flow. Points 1, 3, and 4 correspond to the maxima with the same numbers in Fig. 2. The data obtained may be compared with the neutral curves constructed for natural perturbations on the same apparatus [11]. Curve 2 corresponds to the lower branch of the neutral stability curve, and curve 5 to the acoustic branch (maximum amplification of the acoustic perturbations by the laminar supersonic boundary layer). The curves were constructed by averaging numerous experimental data for the Mach number M = 2.0 and various free-stream unit Reynolds numbers Re_1. From the comparison it is clear that maxima 1 and 4 are caused by the incidence of radiation in the neighborhood of the acoustic branch, and maximum 3 by the incidence of radiation in the neighborhood of the lower branch of the neutral curve.

It should be noted that the boundary layer is quite sensitive to external acoustic perturbations. As already noted above, the artificial radiation was distinguishable from the natural perturbation background only up to distances from the plate incorporating the discharge $Y \sim 50\delta$. However, in the boundary layer on the second plate a significant response to the artificial perturbation was observed even at a distance $Y \sim 80\delta$. Measurements were not made at greater distances Y owing to the small size of the working section of the T-325 supersonic wind tunnel.

From these results we may conclude that the conversion of external acoustic perturbations into natural oscillations of the boundary layer on a flat plate is most intense in the following neighborhoods: the leading edge of the plate; the acoustic branch of the neutral curve; and the lower branch of the neutral stability curve.

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