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Experimental Investigation of Supersonic Boundary-Layer Receptivity

Abstract

The leading-edge receptivity of a supersonic boundary layer on a flat plate to controlled acoustic disturbances is experimentally studied. It is found that external disturbances spreading upstream with negative phase velocities do not cause a response in the boundary layer. The acoustic disturbances with positive phase velocities generate oscillations in the boundary layer. The receptivity coefficients were obtained for the latter case.

Introduction

At present it is generally recognized that transition is connected with the loss of stability of the initial laminar flow and with the receptivity of boundary layers. By receptivity we mean the process in which external disturbances generate unstable waves inside boundary layers (Morkovin, 1957). The majority of theoretical and experimental investigations on receptivity were carried out for subsonic flow. Mack (1975) theoretically studied the interaction of acoustic waves and a supersonic boundary layer for the first time. He found that eigen oscillations can exceed the amplitude of acoustic waves a few times. Recently other theoretical studies of leading-edge receptivity of supersonic boundary layers to external acoustic waves have appeared (Duck 1990, Fedorov & Khokhlov 1992, Gaponov 1995).

Fedorov & Khokhlov (1992) examined the case of arbitrary incidence angle of the external wave falling on the leading edge, and invented two mechanisms of generation. The first is connected with sound diffraction, the second with diffusion of acoustic waves on the leading edge. They found that the generation of unstable waves in the boundary layer depends on the incidence angle of the acoustic wave and on whether the sound source is located above or below the model. Gaponov studied the generation of boundary-layer oscillations by a longitudinal sound field and found that the intensities of the disturbances in the boundary layer depend on the spatial orientation of the external acoustic wave.

The receptivity problem of supersonic boundary layers has almost not been investigated experimentally. One of the few examples is Kendall (1975), who measured the receptivity coefficient between free-stream pulsations and the disturbances in the boundary layer at Mach numbers in the range 1.6 to 8.5. The receptivity problem can be solved with the help of external controlled disturbances, which generate eigen oscillations in the boundary layer. Using an external disturbance source Maslov & Semionov (1986) could experimentally establish

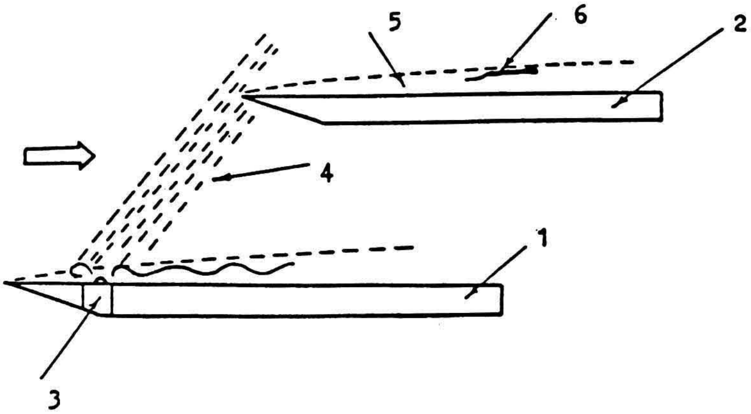

Figure 1: Scheme of the experiment: plates (1 & 2); discharge (3); acoustic radiation (4); measured boundary layer (5); hot-wire probe (6).

the regions of maximum boundary-layer receptivity on a flat plate to acoustic disturbances. These regions are: a) the leading edge of the plate; b) the area corresponding to the acoustic branch of the neutral curve; and c) the area corresponding to the lower branch of the neutral stability curve. Maslov & Semionov (1989) studied the wave structure of disturbances in the boundary layer when the maximum of the sound radiation fell on the leading edge of the flat plate. These data were compared with the wave structure of disturbances generated by a point source in the boundary layer (Kosinov *et al.*, 1990a). These results show the complex process of the transformation of an acoustic wave to unstable waves within the supersonic boundary layer.

Experimental conditions

The experiments were performed in the supersonic wind tunnel T-325 of the Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences with the test section dimensions 600 x 200 x 200 mm^3, at Mach number $M = 2$, unit Reynolds number $Re_1 = 6.6 \times 10^6$ m^{-1}. The model is presented in Fig. 1. It consists of two flat plates, mounted at zero angle to the flow. Vortical and acoustic disturbances were generated by using a surface discharge with frequency $f = 20$ kHz as described by Maslov & Semionov (1987) and Kosinov *et al.* (1994). Plate 1 contains the surface discharge and can be moved in normal direction. Plate 1 was placed below plate 2. In this case generation of disturbances in the boundary layer by the controlled external acoustic field takes place near the leading edge of plate 2. Disturbances were registered by a constant temperature hot-wire anemometer; a probe with a tungsten wire of 5 μm diameter and 1.2 mm length was used. The probe could be moved along three coordinates with the help of a traversing device with an accuracy of 0.1 mm for the longitudinal and spanwise coordinates (x and z, respectively), and 0.01 mm for the normal coordinate y. The hot-wire signal was processed by a computer with a 10 bit 1 MHz A/D converter. Synchronous summation of the signal up to 200 points was carried out in the experiments for improvement of the signal-to-noise ratio. Amplitudes $A(f,x,z)$ and phases $\Phi(f,x,z)$ of the initial acoustic disturbances and oscillations in the boundary layer of plate 2 were measured. The discrete Fourier transformation was used to define the complex wave-number spectra (Kosinov *et al.*, 1990b). After transformation, the data were presented as $A_f(\chi)$, $\Phi_f(\chi)$ - distributions of the amplitude and phase of disturbances at $f=$const over the wave inclination angles defined by

$$\chi = \mathrm{arctg}(\beta/\alpha_r), \tag{1}$$

where α_r, β - wave numbers are in x- and z-direction respectively. Wave numbers $4\alpha_r$, β were defined from the relation

$$A_f(\alpha_r,\beta)\exp(i\Phi(\alpha_r,\beta)) = \frac{1}{T}\sum E(x_i,z_j,t_k)\exp(-i(\alpha_r x_i + \beta z_j - 2\pi f t_k)), \tag{2}$$

where $E(x_i,z_j,t_k)$ denotes the oscillations as obtained from the hot wire, and T denotes the realization time. To define the ratio between the disturbances generated in the boundary layer and the amplitude of the acoustic waves falling on the leading edge, a receptivity coefficient K was calculated from the relation

$$K(\chi) = \frac{A_f(\chi)_{x=x_i^*}}{A_f(\chi)_{x=x_0}} \tag{3}$$

Results

To define the initial amplitude of the fluctuations in the free stream, the disturbance field was measured in the plane of plate 2 (while plate 2 itself was temporarily removed). Fig. 2 shows the amplitude and phase distributions $A_0(x)$, $\Phi_0(x)$. Here the coordinate x was measured downstream from the border of radiation. To analyze the obtained data it is useful to present a simplified physical model of the disturbances source. An electric arc was drawn on the surface of plate 1. We propose that the vortices are generated with distinct directions of rotation in the yx plane in front of and behind the arc. Besides the disturbances T-S waves appear in the boundary layer of plate 1 and propagate downstream. This process is accompanied by the sound radiation into the external flow. Using this physical model and distributions of $A_0(x)$ and $\Phi_0(x)$ we can choose the characteristic zones, corresponding to the different types of external disturbances. The zone $1.5 < x < 5$ mm approximately corresponds to vortex radiation in front of the discharge, while the zone $9 < x < 13$ mm corresponds to vortex radiation behind the discharge and the zone of radiation of travelling waves is $x > 14$ mm.

Fig. 3 shows the distribution of A_0 over α_r, obtained after processing the data presented in Fig. 2. The amplitude is normalized by its maximum. The

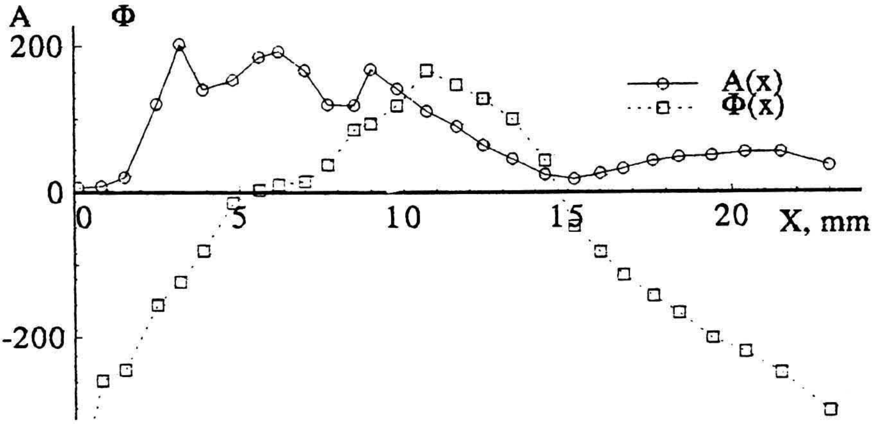

Figure 2: Dependence $A_0(x)$, $\Phi_0(x)$ of controlled initial disturbances at the plane of plate 2 (while plate 2 was removed).

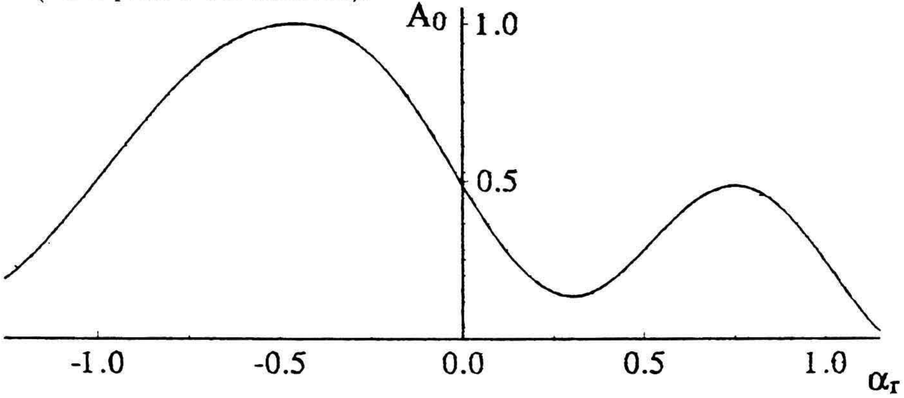

Figure 3: α_r-spectra of controlled initial disturbances (data of Fig. 2).

distribution $A_0(\alpha_r)$ has two peaks with $\alpha_r = -0.45$ and $\alpha_r = 0.75$ rad/mm. The first peak corresponds to radiation of the vortex in front of the discharge, and the second peak corresponds to the radiation of the other zones. Values of α_r were used for the computation of the disturbance phase velocity in x-direction by

$$C = \frac{2\pi f}{\alpha_r U}. \tag{4}$$

Here U is free stream velocity. $C = -0.54$ was obtained for the first zone of radiation. The negative C corresponds to upstream spreading disturbances. For the other zones the phase velocity is $C \approx 0.33$ (acoustic disturbances).

To define β-spectra the initial distributions $A_0(z)$ and $\Phi_0(z)$ were measured at x equal to 3.5, 11 and 23 mm, corresponding to different zones of radiation. The leading edge of plate 2 was installed at these three locations, where external disturbances were measured. The distributions $A(z)$, $\Phi(z)$ of disturbances

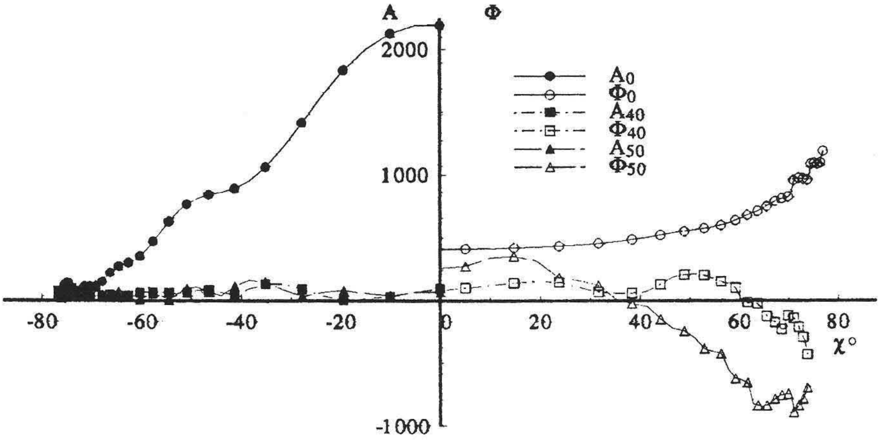

Figure 4: Amplitudes and phases of initial disturbances and oscillations in the boundary layer for leading-edge coordinate $x = 3.5$ mm.

were measured in the boundary layer of the plate 2 at x^* equal to 40 and 50 mm (here x^* is the distance from the leading edge). The amplitude β-spectra were calculated. In this way the structure of the external disturbances and the waves generated by them in the boundary layer were defined. The measurements allow to make a quantitative estimation of the transfer function between initial and eigen oscillations. Fig. 4 shows amplitude and phase spectra over χ of the external disturbances and oscillations excited by them in the boundary layer at $x = 3.5$ mm. Obviously, the amplitude of excited oscillations is close to zero. Consequently the receptivity coefficients are close to zero for the excited oscillations by the upstream spreading disturbances. Hence, external disturbances with negative C do almost give no response in the supersonic boundary layer.

Let us consider the analogous results for other zones. Fig. 5 shows the distributions of $A_f(\chi)$ and $\Phi_f(\chi)$ of the external disturbances and the oscillations excited by them in the boundary layer at $x = 11$ mm. It should be noted that the distributions of $A_f(\beta)$ and $\Phi_f(\beta)$ are similar (Kosinov *et al.*, 1994) in the free stream and in the boundary layer, but the difference of phase velocities leads to the non-coincidence in magnitudes of χ. Amplitudes of inclination waves with $\chi \approx 10^o$ and $\chi \approx 30^o$ become maximum in the radiation of the second zone, and disturbances with $\chi \approx 30^o$ are mainly generated in the boundary layer.

Fig. 6 shows the distributions of $A_f(\chi)$ and $\Phi_f(\chi)$ of external disturbances and the oscillations excited by them in the boundary layer at $x = 23$ mm. Here the distributions of $A_f(\chi)$ and $\Phi_f(\chi)$ are similar in the external flow and in the boundary layer. The main amplitude peaks are observed at $\chi = 0$, which is in good agreement with results of Maslov & Semionov (1987), where the radiation from travelling waves was studied. The oblique waves have smaller amplitude, but for $\chi \geq 35^o$ the amplitude of oscillation in the boundary layer is larger than the amplitude of external disturbances. It may be noted that the distributions of $A(z)$ and $\Phi(z)$ are coinciding qualitatively with the results of Maslov & Semionov

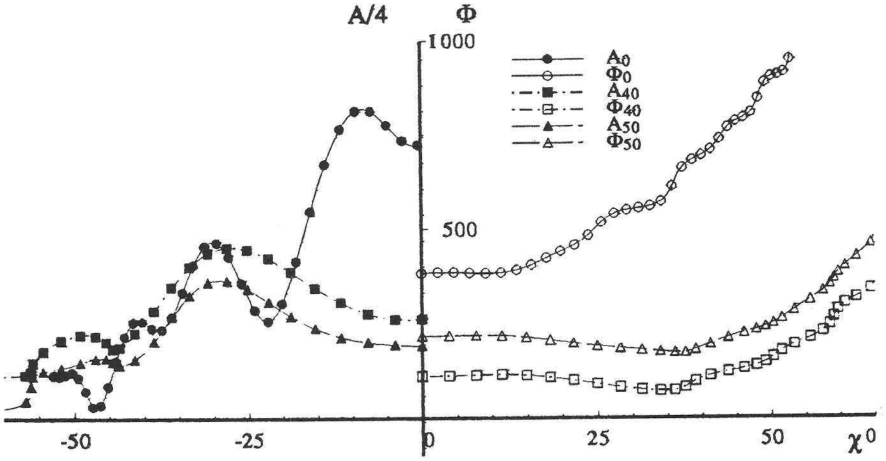

Figure 5: Amplitudes and phases of initial disturbances and oscillations in the boundary layer for leading-edge coordinate $x = 11$ mm.

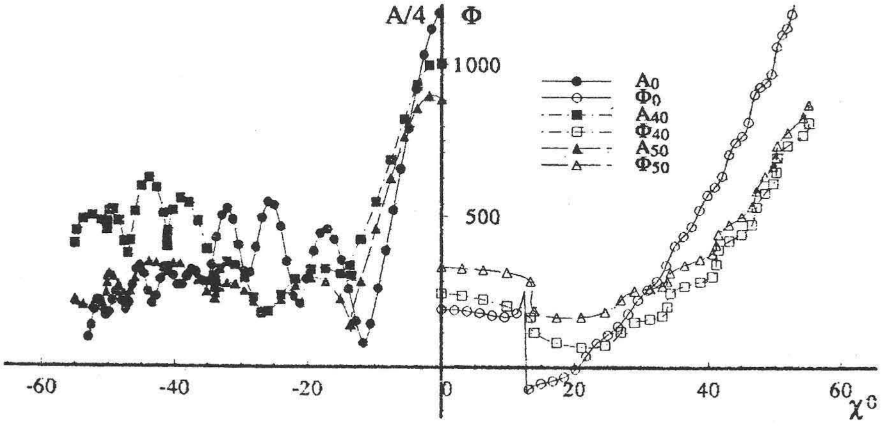

Figure 6: Amplitudes and phases of initial disturbances and oscillations in the boundary layer for leading-edge coordinate $x = 23$ mm.

(1989), where the disturbances in the boundary layer were excited by sound falling from above on the plate leading edge. The modulations in $A(x,z)$ were observed in both experiments, which points to the existence of several types of disturbances in the boundary ayer.

Fig. 7 shows the receptivity coefficients $K(\chi)$ for the second and third zone. For the second zone two characteristic regions of amplified disturbances over χ are selected. The first region is within 10^o, where the receptivity coefficients are minimum, and the second region is $\pm(20^o - 40^o)$, where the coefficients are maximum. The data are presented for a disturbance amplitude that is above one third of the maximum amplitude. This is the reason that the receptivity coefficients for the third zone are presented the $-6^o \leq \chi \leq 6^o$ too. There is a difference in the receptivity coefficients for various zones in corresponding c. One of the reasons may be the distinct nature of external waves: radiation of

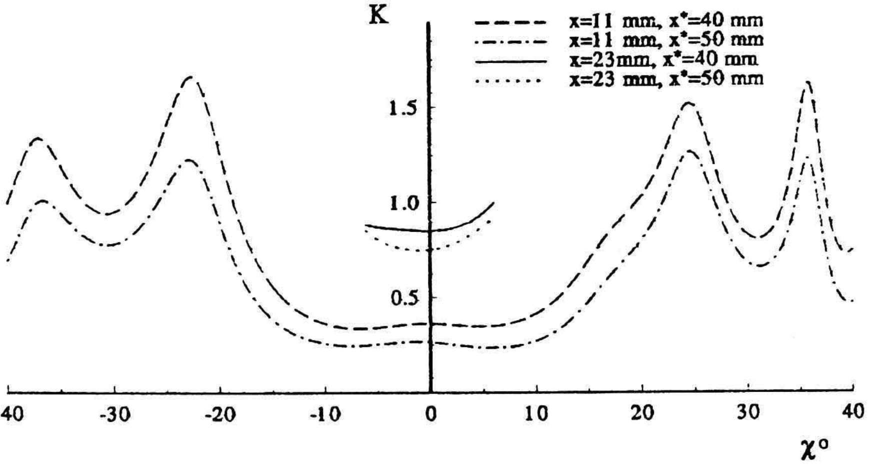

Figure 7: Dependence of the receptivity coefficient K on χ.

the second zone is due to the stationary sources and radiation of the third zone is due to travelling waves. These results correspond with theoretical conclusions (Fedorov & Khokhlov 1992, Gaponov 1995). The experiments also show that oblique waves are more amplified than the waves at $\chi \approx 0$. This experimental result with theoretical results obtained by Gaponov (1995).

Conclusions

Experimental data for the leading-edge receptivity in a supersonic boundary layer at Mach number 2 were obtained. Using controlled acoustic disturbances, the receptivity coefficients for different inclination waves were determined. It was found that the linear excitation of unstable waves in the supersonic boundary layer depends on the initial phase velocities and wave inclination of the external disturbances. The maximum receptivity coefficient corresponds to oblique waves with χ angles from 20 to 40 degrees.

Acknowledgements

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References

Duck, P.W. 1990 – The response of a laminar boundary layer in supersonic flow to small amplitude progressive waves. *J. Fluid Mech.* **219**, 423-448.

Fedorov, A.V., Khohlov, A.P. 1992 – Supersonic boundary layer receptivity to the acoustic disturbances. *Izv. Akad. Sci. USSR. Zh. Mech. Zhid. G.* **1**, 40-47. (in Russian).

Gaponov, S.A. 1995 – On the interaction of a supersonic boundary layer with acoustic waves. *J. Thermophysics & Aeromechanics* **3**, 181-189.

Kendall, J.M. 1975 – Wind tunnel experiments relating to supersonic and hypersonic boundary-layer transition. *AIAA J.* **3**, 290-299.

Kosinov, A.D., Maslov, A.A., Semionov, N.V. 1994 – Methods of controlled disturbances generation for experimental investigation of supersonic boundary layer receptivity. in: Proceedings of ICMAR-7, Part 1 (A.M.Kharitonov ed.). Russia, Novosibirsk, 138-144.

Kosinov, A.D., Maslov, A.A., Semionov, N.V., Shevel'kov, S.G. 1990a – Wave structure of artificial disturbances in a supersonic boundary layer on a flat plate *J. AMTP* **31**, 250-252.

Kosinov, A.D., Maslov, A.A., Shevelkov, S.G. 1990b - Experiments on the stability of supersonic laminar boundary layers. *J. Fluid Mech.* **219**, 621-633.

Mack, L.M. 1975 – Linear stability theory and the problem of supersonic boundary layer transition. *AIAA J.* **3**, 423-448.

Maslov, A.A., Semionov, N.V. 1986 – Excitation of eigen boundary layer oscillation by external acoustic field. *Izv. Akad. Sci. USSR. Zh. Mech. Zhid. G.* **3**, 74-78. (in Russian).

Maslov, A.A., Semionov, N.V. 1987 – Radiation of acoustic oscillations from the supersonic boundary layer. *Izv. SO AN SSSR. Seria tech. nauk.* **2**, 58-63. (in Russian).

Maslov, A.A., Semionov, N.V. 1989 – Structure of artificial disturbances, caused by the external acoustic field, in the supersonic boundary layer. *Izv. Akad. Sci. USSR. Zh. Mech. Zhid. G.* **3**, 113-117. (in Russian).

Morkovin, M.V. 1957 – On transition experiments at moderate supersonic speeds. *J. Aeronaut. Sci.* **7**, 480-486.

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