INFLUENCE OF A FAN OF RAREFACTION WAVES ON THE DEVELOPMENT OF A DISTURBANCE IN A SUPERSONIC BOUNDARY LAYER

S. A. Gaponov, A. D. Kosinov, A. A. Maslov,
and S. G. Shevel'kov

UDC 532.526

Problems concerning the interaction of a boundary layer with local nonuniformities in supersonic flow have not been sufficiently well studied to date. This is particularly true of the stability of a supersonic laminar boundary layer in complex flows with pressure gradients. The theoretical problem of stability near curved surfaces was examined in [1]. The case of supersonic flow past a convex surface was analyzed. The stabilizing effect of the turn of the supersonic flow at an outer obtuse angle was noted.

The results of an experimental study of boundary-layer stability during its interaction with a fan of rarefaction waves were given in [2]. It was found that artificial disturbances, moving through the fan of rarefaction waves, remained neutral in regions of a moderate positive pressure gradient behind the turn of the flow. This result was also theoretically predicted in [1]. Thus, we should note that, in this case, the history of the flow has an influence on the development of disturbances.

In our work, we attempt to include the influence of the fan of rarefaction waves to depict more clearly its influence on the development of disturbances. To do this, we repeated the measurements made in [2]. However, in this case, the artificial disturbance was introduced into the boundary layer immediately behind the fan of rarefaction waves. In [2], the disturbance source was positioned in front of the turn of the flow.

1. The measurements were made in the T-325 supersonic wind tunnel at the Institute of Theoretical and Applied Mechanics, Siberian Branch of the Russian Academy of Sciences, which has a test section of dimensions 200 × 200 × 600 mm. The conditions of the experiments were: $\mathrm{Re}_1 = U/\nu = 6.75\cdot 10^6\ \mathrm{m}^{-1}$, $F = 2\pi f/\mathrm{Re}_1 U = 0.337\cdot 10^{-4}$, $M_\infty = 2.0$, where Re_1 is the single Reynolds number; ν is the kinematic viscosity; U the velocity at the outer edge of the boundary layer; M_∞ is the Mach number of the incoming flow; f is the frequency of the disturbance; and F is a dimensionless frequency parameter. We carried out the investigation using a constant-current hot-wire anemometer. The sensor was fixed to a tungsten filament 6 μm in diameter and about 1.2 mm in length.

The experiments were done on the same model as in [2], which is an acute steel cone with a vertex angle of 10° and a cylindrical afterbody of diameter 38 mm. We used a variable-current electric discharge as the source of artificial disturbances. This was located in the cylindrical part of the model 7 mm from the break point on the surface. The disturbance penetrated into the boundary layer through an opening ∅ 0.5 mm on the surface of the body. The experimental method is the same as in [2]. We measured the distribution in the amplitude A and phase Φ of the disturbance in a narrow band (1%) at frequency f = 20 kHz along the transverse z and longitudinal x coordinates. As a result of processing the data, we obtained the amplitude $A_{\beta\alpha_r}$ and phase F_β spectra, and also the wave characteristics of the disturbance (phase velocities, angle of inclination of the wave, degree of amplification of the disturbance). Here β and α_r are the wave numbers in the z and x directions.

We made measurements on the cylindrical part of the model for values of the longitudinal coordinate x from 16 to 28 mm. Here x is measured streamwise from the break point of the surface. As was indicated in [3], a moderate positive pressure gradient is observed in this section. The profile of the average velocity is similar to that in a zero-gradient flow on a flat plane. In this case, the boundary layer on the cylinder at x = 15 mm is, in terms of integral characteristics, similar to the boundary layer on a flat plate with $\mathrm{Re} = (\mathrm{Re}_1 x_\ell)^{1/2} = 715$ (x_ℓ is the longitudinal coordinate on the plate, measured from the leading edge).

Novosibirsk. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 2, pp. 52-55, March-April, 1992. Original article submitted January 22, 1991.

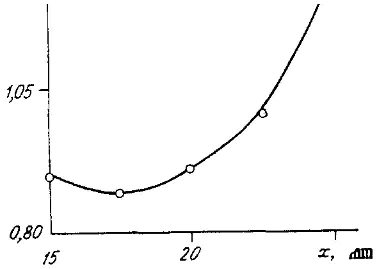

Fig. 1

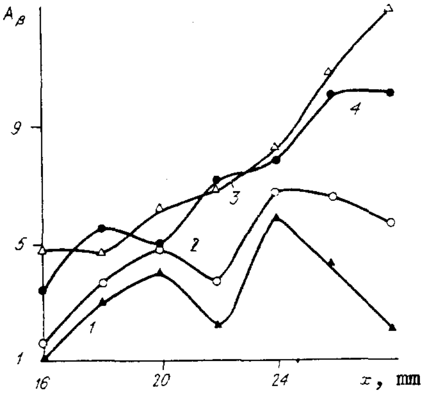

Fig. 2

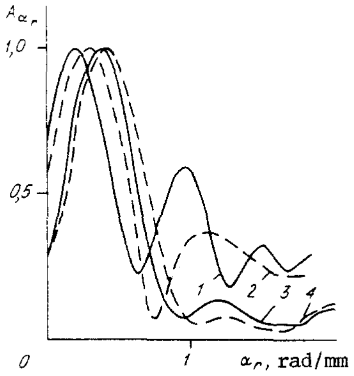

Fig. 3

2. We examine the development of natural disturbances at the frequency being studied. (A natural disturbance is one which arises in the boundary layer due to external, uncontrolled factors, such as acoustic noise from the walls of the test section, vibrations, and so on.) The integral amplitude of the pulsations of mass discharge in terms of wave numbers α_r and β are shown as a function of longitudinal coordinate x in Fig. 1. Note that the disturbance is increased markedly with power index $-\alpha_i \sim 4 \cdot 10^{-3}$ for x = 22 mm. For the boundary layer on a flat plate, vortical disturbances (Tollmien–Schlichting waves) grow with power index $-\alpha_i = 2.5 \cdot 10^{-3}$ beginning at Re ≈ 700, according to the data from [4, 5]. The increase in the degree of growth of disturbances on a cylinder compared to a flat plate can be explained by the moderate positive pressure gradient, and also by the somewhat larger value of Re. However, this result contradicts the experimental data of [2]. As noted above, the artificial disturbances, which move through the fan of rarefaction waves, remains close to neutral (see Fig. 6 in [2]). Intense amplitude beats were observed, which led the authors to conclude that the wave structure of the developing disturbances is complex. In addition to vortical (subsonic) disturbances with phase velocity $C_x > C_x^*$, acoustic (supersonic) disturbances with $C_x < C_x^*$, and regular disturbances whose phase velocity lies in the interval $1 < C_x < 1 + 1/(M \text{ cox } \chi)$ also developed in the boundary layer. Here $C_x^* = 1 - 1/(M \cos \chi)$, and χ is the angle of inclination of the wave vector of the disturbance to the flow direction. Let us examine the nature of the development of artificial disturbances obtained in our work. The growth in the amplitude of the disturbance in the zone of measurement for wave numbers β is similar to that given in [2]. It is shown in Fig. 2 (curves 1-4 correspond to β = 0, 0.31, 0.67, 1.20). Disturbances with β = 0.67 grow most vigorously: their amplification power is $\alpha_i \sim 6 \cdot 10^{-3}$, which is close to that for natural disturbances. Amplitude beats are virtually nonexistent, that is, the one plane wave with angle of inclination χ = 55° is the primary contribution to the disturbance. Its phase velocity is C_x = 0.5, which corresponds to a Tollmien–Schlichting wave. Beats exist for other values of β, which indicates the complex structure of the disturbances.

A similar character of the development of artificial disturbances was obtained in [6] for a flat plate, that is, for zero-gradient flow. We will examine the composition of the disturbances in more detail. Figure 3 shows the α_r amplitude spectra of the disturbances. The solid lines plot out the results of [2], the broken lines are our results, where for curves

1 and 2 $\beta = 0$, and for 3 and 4 $\beta = 0.61$. There is a significant difference in the spectra only for $\beta = 0$. If in the first case the phase velocity of the disturbance, corresponding to the fundamental peak, is $C_x = 1.12$, which corresponds to regular disturbances, then in the second $C_x = 0.79$ and the disturbances already pertain to Tollmien–Schlichting waves. This data supports the supposition that the appearance of regular disturbances is related to the fan of rarefaction waves. We note that the contribution of acoustic waves with $C_x < 0.3$ (the second peak in the plots in Fig. 3) to the disturbances moving through the fan of rarefaction waves is larger than in the case where the disturbance is introduced on the cylindrical part of the model.

Curves 3 and 4 in Fig. 3 are very similar. In both cases, the fundamental peak is determined by Tollmien–Schlichting waves with $C_x \approx 0.6$. The influence of the acoustic waves (second peak) in disturbances with $\beta = 0.61$ is, in the results of [2], somewhat greater than in our work, but the difference is not great. Similar results were obtained for other values of β. In this connection, it is difficult to explain the behavior of waves with $\beta = 0.7$, introduced before and after the turn of the flow, in terms of linear stability theory. It is possible that the first case did not avoid the nonlinear interaction of the plane and three-dimensional waves at the fundamental frequency and its harmonics. To verify this assumption, methods to experimentally investigate the nonlinear processes must be devised. We note, however, that even theoretically the problems of linear development of waves in flows with local nonuniformities are virtually unstudied.

Thus, artificial disturbances introduced after the turn grow similarly to natural disturbances, while those introduced before the turn remain neutral. From this, we can assume that flow nonuniformity engendered in the supersonic boundary layer in the turn of the flow, is the generator of disturbances, and plays a role similar to that in the region of the tip of the model. Acoustic waves outside the boundary layer in the region of the nonuniformity give rise to vortical disturbances. A more detailed conclusion requires further study.

LITERATURE CITED

1. S. A. Gaponov and G. V. Petrov, "Stability of a supersonic boundary layer at the turn of the flow," Izv. Sib. Otdl. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 18(5) (1987).
2. A. D. Kosinov, A. A. Maslov, and S. G. Shevel'kov, "Stability of a supersonic boundary layer behind a fan of rarefaction waves," Prikl. Mekh. Tekh. Fiz., No. 3 (1989).
3. A. D. Kosinov, A. A. Maslov, and S. G. Shevel'kov, "Supersonic laminar boundary layer behind a fan of rarefaction waves," Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 21(6) (1988).
4. V. A. Lebiga, A. A. Maslov, and V. G. Pridanov, "Experimental investigation of the stability of a supersonic boundary layer on a flat insulated plate," Arch. Mech., 31, No. 3 (1979).
5. V. I. Lysenko and A. A. Maslov, "Effect of cooling on supersonic boundary-layer stability," J. Fluid. Mech., 147, 39 (1984).
6. A. D. Kosinov, A. A. Maslov, and S. G. Shevel'kov, "Experimental investigation of the wave structure of a supersonic boundary layer," Prikl. Mekh. Tekh. Fiz., No. 5 (1986).