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PECULIARITIES OF FORMATION AND DEVELOPMENT OF RECIRCULATION-FLOW ZONES IN SHEAR LAYERS OF SUPERSONIC FLOWS

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On the basis of the author's experimental studies and analysis of the data available from the literature (Chang, Korkegi, Holden, Settles, Neiland, Zheltovodov, and others), we present, for the case of supersonic streams, the schemes of flows and boundaries where the stability of supersonic and subsonic shear layers is lost (vortex cord and boundary layer) as they interact with shock waves (SW). The loss of stability is accompanied by the occurrence of recirculation-flow zones (RFZ) or by separation. It has been found that the formation of RFZ (separation) in a shear layer depends, in contrast to a developed separation, on the parameters of the layer (such as the minimum Mach number and others) and on the intensity of the SW.

The occurrence of separation or the formation of RFZ due to the interaction of SW with shear layers (boundary layer, vortex cord, or wake) has been observed in numerous studies [1–15]. One of the important problems is to ascertain conditions for the formation of a separation or RFZ in various situations. A further refinement of the flow properties in the stage of transition from conditions of a local separation to a developed (large-scale) separation seems to be necessary.

Gaining a better understanding of such phenomena is of scientific and practical interest, in particular, for designing methods of controlling the aerodynamic characteristics of flying machines. This gap is partly filled in the present work wherein the mechanism of loss of stability due to the formation of RFZ in supersonic and subsonic shear layers as a result of interaction with SW is studied and examples of development of RFZ are given.

The problem formulated can be reduced to the problem of deformation (breakdown) of a shock wave during its interaction with a vortex flow. To this end, we study the interaction of a SW with two characteristic types of regular vortex structures, namely, with a streamwise vortex cord in a supersonic flow and with large-scale regular lateral vortices arising in the boundary layer. These problems can be represented parametrically as the determination of the limiting angles of deflection of a vortex flow on a shock wave

$$\theta_* = f(p_2/p_1,\ \overline{\theta},\ \overline{T}_w,\ \mathrm{Re}_\tau \quad \text{or} \quad \overline{u}_\tau,\ \mathrm{Sr}).$$

Here, in addition to the traditional criteria for similarity such as the Mach number M_1 of the flow, the reduced turning angle $\overline{\theta} = \theta/\sqrt{\mathrm{M}_1}$, the Reynolds number Re, and the temperature factor $\overline{T}_w$ at the wall, parameters are used which characterize in the general case the intensity of the shock wave and the vortex. These are the ratio p_2/p_1 of pressures at the shock wave, the reduced vortex circulation $\mathrm{Re}_\tau = u_\tau d_v/\nu$, or the vorticity level $\bar{u}_\tau$, which is the ratio of the maximum tangential component of the vortex velocity u_τ to the streamwise flow velocity u_1, and the Strouhal number $\mathrm{Sr} = f d_v/u_c$ (f is the frequency of recurrence of large spanwise vortices, d_v is the vortex diameter, and u_c is the convective velocity of transport of vortices).

Both problems were studied experimentally. The interference of a vortex cord with a shock wave was studied on a model which had the form of a cylinder 50 mm in diameter with a conic nose of half angle $\theta_c = 41$–$47°$. The interference of a boundary layer with a shock wave in front of the ramp was studied on an

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axisymmetric-ramp model with an angle $\theta_f = 25.5$ and $27°$. A ramp with a length of 70 mm was mounted on an axisymmetric cone ($\theta_c = 5°$) at a distance of 310 mm from its nose.

The experiments were conducted in the turbulent flow regime in two supersonic wind tunnels with a gradual change of M_1 [M_1 = 1.8–(3.5) 4]. As M_1 decreased from 3.5 (4) to 1.8, the values of Re varied in the range $(3\text{–}6) \cdot 10^7$ 1/m and the velocity head was $q = (0.5\text{–}1.2) \cdot 10^5$ Pa. The wall temperature factor was $\overline{T}_w = 0.92\text{–}1.0$. According to calculations, the thickness of the boundary layer on the cone in front of the ramp was $\delta = 2.0$ mm (±10%).

The traditional types of diagnostics were used, such as the visualization of the flow pattern by means of a shadow device, including visualization with the use of high-speed filming (frequency $f_c = 31$ kHz), and measurement of pressures on the surface of the body in the flow. In addition, for the ramp with $\theta_f = 27°$, pressure fluctuations at one point of the ramp were measured at distance $\Delta x = 3.5$ mm from its nose ($\Delta x/\delta = 1.8$). For these measurements, a pressure-fluctuation probe (force cell based on of a DMI-06 probe) with a natural frequency $\leqslant 5$ kHz was used.

The principal methodological expedient, which allowed one to obtain detailed characteristics of formation and development of RFZ, was that the value of M_1 was changed in small steps ($\Delta M = 0.1\text{–}0.3$) in each experiment with a given geometry of the model. The experiment was started with a large value of M_1 and conducted as follows. First, M_1 and, consequently, the intensity $\bar{p}_2 = p_2/p_1$ of the wave were decreased (forward variation) and then increased (backward variation).

Let us consider each of the problems in greater detail.

1. Interaction of a Shock Wave with a Supersonic Shear Layer. A free supersonic shear layer can be formed in the propagation of a supersonic jet in a supersonic flow or in the generation of a vortex cord in the flow (with minimum Mach number $M_m > 1$ of the streamwise velocity), for example, by mounting a swept wing. Because of the stability of the vortex cord, it turned out to be a suitable object for studying the problem formulated here.

The formation of a developed RFZ in the interaction of a vortex cord with an intense shock wave in a supersonic flow was found in [6].

The mechanism of the shock wave breakdown and of the vortex-cord deformation, and also the boundary of breakdown in variables θ and $\bar{p} = f(M_1)$, were determined by the author in [7].

Figure 1 shows variations of typical flow patterns and of the deflection angles of the shear layer (θ_c and θ_0) with M_1 for the case of interaction of a vortex cord with a conic shock wave: points 1 refer to a vortex without breakdown, 2 to the onset of breakdown; and 3 to a developed separation zone; θ_0 is the angle of the developed recirculation zone, θ_s is the flow deflection angle corresponding to transition to subsonic flow behind the shock wave ($M_2 = 1$), θ_{II} is the calculated angle, $\theta_{II\,\exp}$ is the experimental limiting deflection angle of the flow on the cone [7], excess of which results in formation of a detached shock wave, and M_{II} is the boundary Mach number of the flow, corresponding to the angle θ_{II}. The crosshatched region of the cone angle $\theta_c = f(M_1)$ corresponds to subsonic flow behind the shock wave attached to the cone nose.

It is shown that as M_1 decreases at θ_c = const ($\theta_c < \theta_s$) the vortex cord passes the shock wave ($M_2 > 1$) without deformation. In the region of angles $\Delta\theta = \theta_s\text{–}\theta_{II}$ corresponding to subsonic flow behind the shock wave ($M_2 < 1$), a straight shock wave, which has departed upstream from the projection of a conic wave for a distance of Δl, is formed in the vortex cord. For $\theta_c > \theta_{II}$ ($M_1 < M_{II}$), the breakdown of the vortex cord occurs along with the formation of a developed circulation zone (the length l_0/d_v of the latter for $\theta_c = 45°$ is approximately equal to 15). In this breakdown, the expansion angles of the developed RFZ correspond, as can be seen from Fig. 1a, to the data obtained in [7] for the case of critical separation of an axisymmetric turbulent boundary layer. Thus, an abrupt decrease from θ_c to θ_0 in the initial flow deflection angle in the interference zone occurs during transition to the regimes with $\theta_c > \theta_{II}$. This is shown by the arrow in Fig. 1a.

The change in the relative length $\Delta l/l_0$ of displacement of the straight shock wave inside the vortex cord is given in Fig. 1b.

Measurements of pressure $\bar{p}_c = p_c/p_1$ on the surface of the cone ($\theta_c = 45°$) at the point of its intersection with the axis of the undisturbed vortex show that the pressure diminishes gradually with decreasing M_1 in the region $M_2 > 1$ and rapidly falls to the critical value $\bar{p}^0$ of axisymmetric separation during displacement

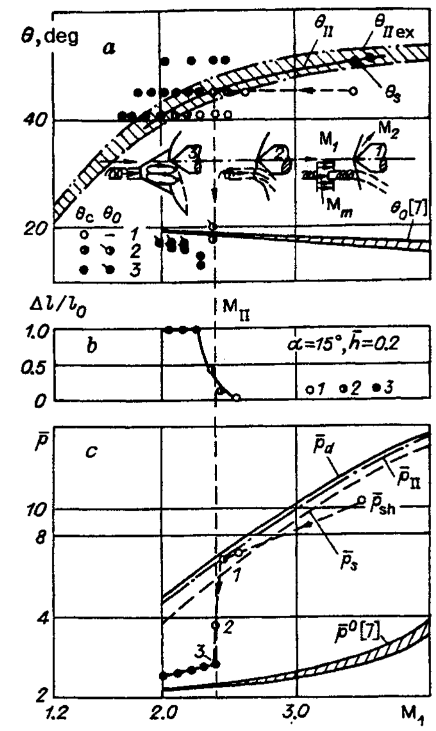

Fig. 1

of the shock wave along the vortex and formation of a developed RFZ (Fig. 1b).

The fact that the position of the vortex cord with respect to the cone axis $\bar{h}$ and the angle α of attack of the vortex generator, i.e., the parameter $\bar{u}_r$, exerts an influence on the beginning of the vortex breakdown is pointed out in [7]. As follows from Fig. 1, at $\bar{h} = 0.2$, the transition process corresponds to some region of variation of M_1 ($\Delta M_1 = 0.1$–0.2). The reverse course of this process conforms to the forward course within the experimental accuracy.

Consequently, the onset of breakdown in the conic shock wave of the vortex cord (supersonic shear layer) does not depend on the viscosity and is determined by the gasdynamic structure of the flow within the vortex jet (mainly by the fall in the velocity profile and in the stagnation-pressure profile). Only in the subsequent stages of development of the breakdown, do essentially viscous effects come into play, extended shear layers formed, and a new stable state with a developed (large-scale) recirculation zone attained.

Thus, it was found in the experiments that the vortex breakdown starts at the cone angles $\theta_c \geqslant \theta_s$ corresponding to $M_2 < 1$. The limiting intensity of the shock wave in this case is $\bar{p}_s$ $(0.86$–$0.92) \cdot \bar{p}_d$, where $\bar{p}_d$ is the increase in pressure in the straight shock wave (Fig. 1c). According to calculations, the condition that the breakdown of the vortex starts at an appropriate value of θ_s ($M_2 = 1$) implies, in the case of interaction of a vortex cord with a plane oblique shock wave, that the limiting intensity $\bar{p}_s$ of the wave is equal to $(0.76$–$0.82) \cdot \bar{p}_d$ at $M_1 = 2$–4. The experimental data of [8] agree with this estimate: $\bar{p}_s = (0.7$–$0.8) \cdot \bar{p}_d$ at $M_1 = 2$–2.5.

Thus, the experiments with the vortex cord confirm the possibility of an undetached deflection of a flow with a supersonic shear layer ($M_m > 1$ and $u_m/u_1 \to 1$) at angles close to the limiting values and the possibility of formation of RFZ at $\theta_c \geqslant \theta_s$. One should expect a similar pattern in the case of interaction of a shock wave with a shear layer between concurrent supersonic flows ($M/M_1 < 1$).

There are also results in [7] which show that a free suspended recirculation zone forms in a nonisobaric jet during interaction of a vortex cord (or a wake behind a body) with a central shock wave. This zone is not bounded by bodies in the streamwise direction and is shown to be analogous to the zone of boundary-layer separation at a central needle and to that of the vortex wake behind a body.

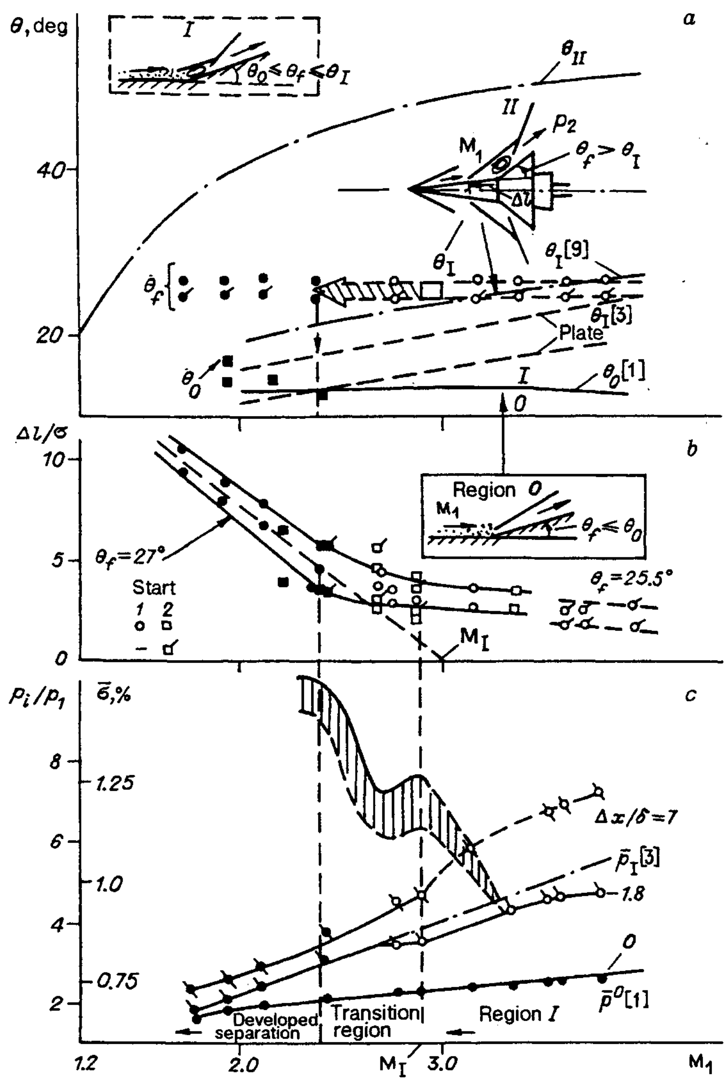

Fig. 2

2. Origin of Boundary-Layer Separation in Front of the Ramp. It is known from studies of the stationary conditions of formation of a separation zone in a near-wall shear layer in supersonic flows [1–5, 9–11] that as the angle θ_f of the ramp or the counterpressure increase, the flow pattern and the character of pressure variation at the wall are significantly changed.

In accordance with this change, three typical flow regimes can be distinguished (Fig. 2a): 0 corresponds to an undetached flow at $\theta_f < \theta_0$; I to the formation and development of a separation, i.e., flow over the ramp with a separation localized in a near-wall part of the boundary layer ($\theta_0 \leqslant \theta_f < \theta_{\rm I}$), $\bar{p}^0 < \bar{p}_2 < \bar{p}_{\rm I}$; II to a flow with a large-scale separation at $\theta_f > \theta_{\rm I}$ and $\bar{p}_{\rm I} = f(\mathrm{M}_1)$. Under these conditions, the expansion angles of the developed separation zone (square symbols in Fig. 2a) correspond approximately to the data for the critical separation angle θ_0 of a plane turbulent boundary layer [1, 3]. Figure 2 gives asymptotic empirical dependences $\theta_{\rm I}$ and $\bar{p}_{\rm I} = f(\mathrm{M}_1)$ for a turbulent boundary layer from the data of [1, 3, 9].

It is of great interest to determine of the moments at which a local separation originates and a large-scale separation begins to from. Although progress has been achieved in calculating such flows by numerical methods (see [16], for example), experiment remains to be the most reliable way of solving the problem. It was found experimentally that the beginning of local separation corresponds approximately to the critical pressure ratio at the shock wave [10] and hence to the flow deflection angle equal to the critical separation angle $\theta_f \approx \theta_0$ of a plane turbulent boundary layer (Fig. 2a). The same characteristics were obtained for the case of interaction between a shock wave incident on the wall and the boundary layer [2].

According to the classical concepts, the main evidence of developed separation is that not only the near-wall but also the outside part of the boundary layer deflects from the wall surface. The boundaries of the onset of this regime determined by various methods in [3, 9] for plane and axisymmetric flows are shown in Fig. 2a. We refined the boundary of transition to developed separation (a crosshatched arrow in Fig. 2a) in experiments with flow around a conic ramp by analyzing the data on variation in the length $\Delta l/\delta$ of a detached RFZ (Fig. 2b) and pressure fluctuations $\bar{\sigma}$ on the surface of the ramp (Fig. 2c). The point of the arrow (Fig. 2a) corresponds to the typical value of M_I, determined (with allowance for accuracy) from Fig. 2b and c, and the tail of the arrow corresponds to the onset of developed separation, determined from pressure fluctuations.

The length Δl was found from measurements of the distance from the ramp nose ($\theta_f = 27°$) to the base of the detached shock waves for two opposite generatrices of the cone in the shadow picture of the flow (Fig. 2b). The region of linear growth of the separation length approximately up to $\Delta l/\delta = 3$ is observed as M_I decreases. After some transition region, this region is replaced by the region of a more rapid, practically linear growth of the separation zone (filled circles).

The value of M_I was determined from the data in Fig. 2b by extrapolation of filled circles (up to $\Delta l/\delta = 0$) conducted by using the least square fit method (dashed line). The value $M_I = 3.0\,(\pm 0.2)$ obtained therewith is close to $M_I = 2.9$ found from pressure fluctuations (Fig. 2c) for the start of the transition region. The location of the end of the transition region determined from pressure fluctuations agress well with the beginning of a new linear region for the data in Fig. 2b. Determined in such a manner, the onset of the transition to developed separation (the beginning of the crosshatched arrow in Fig. 2a) fits well the generalization in [9].

It is found that the boundary values of M_I obtained in the forward variation coincide with those obtained in the backward variation (see symbols marked with slashes).

The character of pressure values obtained in the measurements and averaged over the length of the ramp is qualitatively the same as in experiments with a flat ramp [11], where the flow characteristics were studied at $M_1 = 2.85$ for $\theta_f = 8°$ (region 0), 16° (region I), 20° (the boundary value ($\approx \theta_I$) or the beginning of the transition region), and 24° (developed separation). It is interesting that the ratio of pressures in the separation region in the vicinity of the top of the angle reaches the critical value $\bar{p}^0$ for the two-dimensional case at $\theta_f = 20$–$24°$ (Fig. 2a, generalization [3]) only when the region where a developed separation starts to form is reached. Examples of variation in pressure $\bar{p}_i = p_i/p_1$ at points of the ramp ($\theta_f = 27°$) located at distances $\Delta x/\delta = 0$, 1.8, and 7 from the nose are given in Fig. 2c for the axisymmetric model.

The relative pressures at the corner point of the ramp on such a model are equal to the critical ratio of pressure $\bar{p}^0$ over the studied range $M_1 = 3.8$–1.8. According to the bound in [9], this corresponds to regimes that are close to a developed separation. The increase in pressure on the ramp ($\Delta x/\delta = 1.8$) at $M_1 < 2.6$) corresponds to the dependence $\bar{p}_I = f(M_1)$ [3].

It is noteworthy that the boundary value $M_1 = 3.0$ (± 0.2) determined in Fig. 2b corresponds to the typical change in the dependence for the given root-mean square values of pressure fluctuations $\bar{\sigma} = \sigma/0.7p_1M_1^2$, measured at a point located near the base of the ramp ($\Delta x/\delta$, Fig. 2c). As the Mach number decreases, a region of stabilization of fluctuations is observed starting with $M_1 = 2.9$ at a level of $\bar{\sigma} > 1\%$. Note that the corresponding values of $\bar{\sigma}$ obtained on the same model for a true cone [17] are 0.2–0.36% at $M_1 = 3.5$–2. As M_1 increases, the transition from region I with a local separation zone ($M_1 > M_I$) to region II with a developed separation, where the separation angle in the RFZ becomes equal to θ_0 (Fig. 2a), corresponds to a transition region $\Delta M = 0.3$–0.4, where $\bar{\sigma}$ increases rapidly (Fig. 2c). In accordance with the behavior of pressure fluctuations, values $M_1 = 2.4$ and 2.9 can be regarded as the left-hand and the right-hand boundary of the region of transition to developed separation.

Thus, the main physical conclusion of other investigations that the formation of a developed separation occurs at values $\theta_I > \theta_0$ and $\bar{p}_I > \bar{p}^0$ that exceed significantly the threshold magnitudes for separation is confirmed. A definite relationship is found between the behavior of averaged characteristics and pressure fluctuations under these conditions. Note that the data presented correspond to the range of Reynolds numbers $Re_\delta = (0.6\text{–}1.2) \cdot 10^5$ with respect to the thickness of the boundary layer. To exclude totally the possible influence of the laminar turbulent transition on the character of fluctuations, it is necessary to repeat similar studies at larger Reynolds numbers.

It is obvious that a more profound study of the nonstationary characteristics of the interaction is needed to ascertain the peculiarities of formation and development of the separation. The assumption of the unsteady character of interaction between the shock wave and the boundary layer interaction was made by Bogdonov as early as in 1955. Later, it was confirmed experimentally by Holden [2]. Publications dealing with this topic have increased in number considerably in recent years. Crucially new results have been obtained by American researchers (see [12–15], for example). On the basis of fine measurements of the pressure fluctuations on the wall in front of the ramp ($\theta_f = 16$, 20, and 24°) at $M_1 = 2.85$, it was shown [12] that the character of pressure fluctuations in an undisturbed boundary layer is mainly due to the turbulent convection induced by large-scale turbulent vortices arising in the layer with frequency $f = (5\text{–}10)$ kHz. On the basis of correlation dependences for the pressure fluctuations (for a ramp with $\theta_f = 24°$ mainly), the conclusion was made that the pressure fluctuations in the zone where separation occurs (the zone of intermittence) depend on the oscillations of the shock wave, and convection of turbulence plays no special role. In the separation zone itself, the pressure fluctuations are complex in structure, which is determined by several factors. These are the large vortices moving downstream above the separation zone, the disturbances propagating along the wall (from the attachment zone of the detached shear layer at the ramp) in the opposite direction, and residual effects of the oscillating shock wave. The shock wave is shown to have a three-dimensional structure in the spanwise direction, which can be related to the corresponding structure of large eddies.

On the basis of data obtained mainly for a developed separation ($\theta_f = 24°$, flow over a cylinder and others) Dolling and L. Brusniak noted [13] that there is a correlation in the intermittence zone between the frequencies of shock wave oscillations and those of the bursts in the near-wall part of the boundary layer. At the same time, it was pointed out that an interpretation of the interference under study is a difficult task because of simultaneous manifestation of two physical effects: up- and downstream oscillating motions of the shock wave which are superimposed on the convective downstream transfer of large-scale turbulent vortices. It was shown that turbulent fluctuation occur in the region of subsonic flow (i.e., in RFZ) and also global fluctuations of this region as a whole.

On the basis of computer-assisted measurements of pressure fluctuations in front of a ramp with the aid of eight microphones, Boitnott [14] simulated the trajectory of movement of a shock wave for the case of flow around a ramp with $\theta = 28°$ at $M_1 = 5$, which corresponds to the boundary values of θ_I and M_I. It is asserted that this motion has no apparent or periodically recurring structures. The base point of the shock wave oscillates in a random manner, its upstream velocity exceeding the downstream velocity.

Nevertheless, studying the same model, on the basis of a correlation between some types of turbulent motions in the boundary layer and the movement of the shock wave, Eringil and Dolling [15] inferred that the high-frequency oscillations of the shock wave are caused by large-scale structures convected into the region of interaction.

Thus, despite considerable progress in studying complex unsteady phenomena, all known attempts to draw a unified, physically clear picture of the stages of origination and development of separation have not been successful. The concepts of the nature of unsteadiness are diverse and contradictory. This appears to be connected with insuffucient data on the visualization of the unsteady pattern and hence with the absence of a logical physical model of flow. Difficulties in designing such a model are also due to the lack of data on the unsteady character of discrete flow regimes.

In order to explain the peculiarities of unsteady flow observed in the stage of formation of developed separation, we analyzed the behavior of large-scale spanwise vortices existing in the outer region of the boundary layer. The main idea is that the peculiarities in the behavior of such vortices should manifest themselves, first, in regimes corresponding to the upper part of region I where the intensity of the shock wave base has a maximum ($\bar{p} \to \bar{p}_\mathrm{I} > \bar{p}^0$), and therefore, a noticeable periodic deformation of the shock wave on the vortices is possible. The pattern of this deformation might be analogous to the interaction of a vortex ring

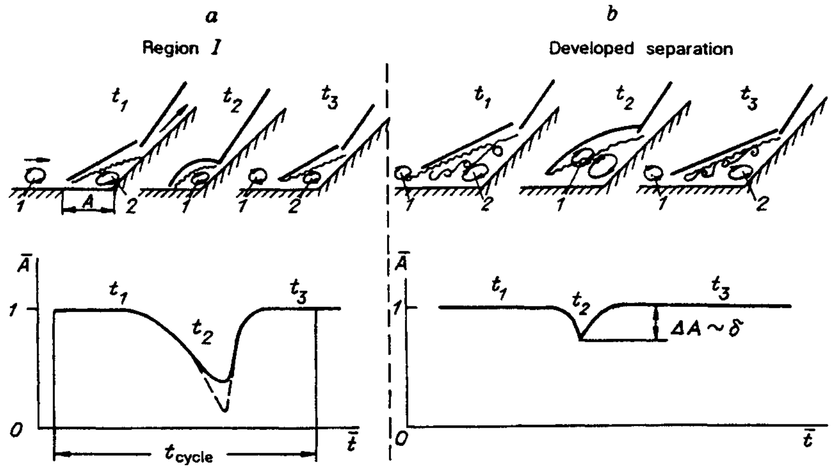

Fig. 3

with a plane shock wave. This interaction is characterized by local warping and bulging of the shock wave in the vicinity of the ring [18]. Second, it was suggested that the departure of the external part of the boundary layer away from the surface in the stage of development of separation can also influence the peculiarities of unsteady separation.

Shadow high-speed motion pictures indeed show that under conditions of local separation at $M_1 = 2.9$–3.5 one can observe periodic deformation of the base of a shock wave that arises in front of the ramp. The typical flow pattern for one cycle and an example of change in the amplitude of the high-frequency oscillations of the shock wave are shown in Fig. 3a. The change in the shock wave from linear to convex (in the second frame) is interpreted as being due to the interaction of the shock with a large vortex. This process is periodic (at $\theta_f = 27°$ and $M_1 = 3.5$, we have $f = 7.8$ kHz ($\pm 10\%$ and Sr = 0.03). It can be assumed that a more intense and larger-scale vortex 1 from the outer part of the boundary layer supersedes vortex 2 in the local separation zone and impedes, during a certain part of the cycle, the upstream propagation of disturbances, i.e., acts as a short-time constrictor. At $M_1 = 2.8$–2.5, the length of the separation zone begins to increase more rapidly, while the intensity of the shock wave base and the influence of the interaction between the vortex and the shock wave on the overall pattern become weaker.

Apparently, as the outer part of the boundary layer is displaced together with vortices 1 into the RFZ, the upstream transfer of disturbances in the transition region is intensified.

During formation of a developed separation ($M_1 \leqslant 2.4$), vortex 1 behind the shock is completely displaced from the surface together with the separated mixing layer, and the disturbances coming to the separation zone from the attachment zone begin to play the main role. This leads to low-frequency oscillations of the shock wave $f \sim 1$ kHz, which are superimposed with high-frequency disturbances ΔA arising from the interaction of the vortex with the shock wave. However, these disturbances are of minor importance. Note that this system is much more complicated than that occurring during the formation of separation. This is probably the reason why no significant progress in understanding the physics of unsteady processes was made in [13], where precisely this system was studied.

The character of variation of the Strouhal number with M_1, which reflects the high-frequency interactions of large vortices with a shock wave (with $f = 4$–8 kHz), corresponds qualitatively to the variation of the pressure fluctuations $\bar{\sigma}$ over the surface of the ramp. In particular, a saturation of the value $\mathrm{Sr} \approx 2 \cdot 10^{-2}$ at $M_1 \sim M_I$ and the growth of Sr at $M_1 < M_I$ are observed [$\mathrm{Sr} = (2\text{–}4) \cdot 10^{-2}$ at $M_1 = 2.7$–2.2].

Thus, the difference in the behavior of vortices, so to say, "visualizes" different phases of the development of the large-scale separation and refines the boundaries of this process.

Although more thorough studies and more detailed information about the unsteady flow characteristics are required, the results obtained and the proposed model of the interaction open up new possibilities in solving the problem formulated and also in controlling the process of development of separation. Taking into account the proposed physics of unsteady effects is also significant in designining new models of such flows.

Thus, it is tentatively established that during the formation of a developed separation there occur typical changes in the features of the periodic interaction of the shock with large-scale vortex structures that are formed regularly in the turbulent boundary layer. A physical model is suggested which accounts for unsteady effects in the stage of formation of a developed separation. A preliminary experimental confirmation of this model is obtained. The boundaries of formation of the developed separation are refined.

Summing up the study of formation of RFZ for two types of shear layer (a vortex cord and a boundary layer) in quasistationary flows, we note that in both cases a peculiar sequence of changes in the flow pattern occurs even with the forward variation of the process (during gradual increase in the counterpressure). At $\bar{p}_2 > \bar{p}^0$ ($\theta_i > \theta_0$), the flow is not fully developed and only at $\bar{p}_2 > \bar{p}_*$ ($\theta_i > \theta_*$) does a large-scale recirculation zone form. This zone has the limiting parameters ($\bar{p}^0$, θ_0) of the averaged flow, which are typical for developed separation and are essentially independent of the type of shear layer. In addition, a certain stabilization of unsteady processes in the near-wall separation zone is observed.

However, the conditions and the mechanism of origination of RFZ depend essentially on the type of shear layer and, in particular, on the characteristic minimum Mach number of the flow in it ($M_m \gtrless 1$) and are determined by unviscid or(and) unsteady effects.

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