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GENERATION OF PERTURBATIONS BY A LOCALIZED VIBRATOR IN THE BOUNDARY LAYER OF A NONSWEPT WING

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Origination and development of perturbations generated by a three-dimensional vibrating surface in the boundary layer on an airfoil with a zero slip angle is experimentally studied. Surface vibrations were generated by a Mylar membrane. It is shown that high-amplitude vibrations of a three-dimensional surface lead to simultaneous formation of two types of perturbations in the boundary layer: quasi-stationary streamwise structures and wave packets accompanying them. The presence of regions with favorable and adverse pressure gradients does not exert a significant effect on evolution of streamwise structures but leads first to attenuation and then to amplification of wave packets.

Introduction. The solution of practical problems related to boundary-layer control intended to decreasing the drag of flying and sailing vehicles and calculation of their aerodynamic characteristics implies a complex study of all possible factors that may affect the process of laminar–turbulent transition.

One of the possible actions on the boundary layer is the vibration of a limited sector of the wetted surface (three-dimensional surface vibrator). From the viewpoint of controlling the laminar–turbulent transition, such a surface vibrator may be represented as one of the components of the system designed for reaching a significant delay of transition at the nonlinear stage and in three-dimensional flows. Such a device, including detectors of perturbations, actuators, and a control system, destroys perturbations by means of their mutual suppression or by other methods. The advanced MEMS technology allows production of micron-size devices. In solving problems of fluid and gas mechanics, this technology makes it possible to create microprobes and microgenerators for flow control. Lefdahl and Gad-el-Hak [1] offered a detailed review of various types of sensors and actuators, and also the special features of their manufacturing and utilization. A micromembrane built into the vehicle surface is one of the devices acting on the boundary-layer flow.

At the same time, it is impossible to imagine an actual vehicle or an aerodynamic facility that have no vibrations of the surface exposed to the flow. There are always sectors of the skin, which may vibrate in the case of deformation of the lifting parts of the vehicle or under the action of oscillations, for instance, of the powerplant. In this case, a finite sector of the surface usually oscillates, which is a three-dimensional vibrator. In practice, the law of oscillations of such a vibrator may be arbitrary. These are not obligatory sinusoidal oscillations with extremely low amplitudes. It is not always possible to study the result of action of such a vibrator on the shear flow by the existing theoretical methods.

The first experimental study of excitation of perturbations in the boundary layer in the case of surface vibrations was performed by Gilev and Kozlov [2], who considered the simplest case of a two-dimensional vibrator on a flat plate. A comparison with the theoretical results of Tumin and Fedorov [3] showed that the linear theory of hydrodynamic stability and receptivity in the two-dimensional case described this process correctly at low amplitudes of such vibrations. Quantitative experimental data on excitation of three-dimensional Tollmien–Schlichting waves in the Blasius boundary layer were obtained in [4, 5], where the method of localized vibrators was used. By expanding the "wave trains" into normal modes, a set of stability characteristics of the Blasius boundary layer to three-dimensional Tollmien–Schlichting waves was obtained.

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In view of the rapid development of technical devices, of much interest is the case, where vibration amplitudes are rather high, and perturbations in the shear layer can no longer be considered as linear. Theoretical analysis of this problem has not been performed. Chernorai et al. [6] experimentally studied the origination and development of perturbations generated by a three-dimensional vibrating surface in the Blasius boundary layer. It was shown in that study that the vibrating surface may generate boundary-layer perturbations that differ from Tollmien–Schlichting waves. If the three-dimensional vibrator performs low-frequency oscillations of a comparatively low amplitude, a passive streaky structure is developed downstream. The characteristic longitudinal scale of this structure is significantly greater than the model size. The perturbation, which is alternating regions with velocity excess and defect, is entrained by the flow and decays. Chernorai et al. [6] classified these perturbations as a packet of the Tollmien–Schlichting waves modulated in the transverse direction. Nevertheless, we can conclude on the basis of the studies of [7–9] that these are perturbations of another type, namely, "passive" streaky structures. As the effective amplitude of membrane vibrations increases by approximately a factor of two, a perturbation in the form of a "puff" structure arises in one of vibration half-periods. By the moment, these perturbations have been fairly well studied in model experiments [10–12]. It is assumed that they dominate in the boundary layer at an elevated degree of free-stream turbulence [13, 14]. It follows from the analysis of [13, 14] that, possibly, "passive" perturbations compose the major part of disturbances in the case of elevated turbulence.

Thus, the problem of affecting the boundary layer by a localized vibrator is nontrivial even in the case of a flat-plate flow. The result of [15] show that the pressure gradient has a significant effect on the development of localized perturbations. Bech et al. [15] describe the results of numerical simulation of the development of three types of perturbations in a flow with a pressure gradient: planar wave packet, waves from a point source, and streaky structures of the "puff" type. The dominating role of the wave component in perturbations under the action of an adverse pressure gradient is demonstrated.

It is known that a predominant growth of streamwise structures of the Görtler vortex type, as compared to two-dimensional Tollmien–Schlichting waves, is observed in the flow past a wing. Based only on the results of the study performed, it is impossible to determine which kind of perturbations will be generated by the vibrator in the boundary layer on the wing. In the present paper, we study experimentally the origination and evolution of perturbations from a vibrating surface in the boundary layer of a nonswept wing at high amplitudes of low-frequency vibrations. The evolution of perturbations is considered in regions with positive and negative pressure gradients.

1. Experimental Technique. The study was performed in an MT-324 wind tunnel of the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences. The wind-tunnel test section has cross-sectional dimensions 200 × 200 mm and a length of 800 mm. The free-stream velocity was $U_0 = 6.6$ m/sec, and the level of flow turbulence ε was less than 0.3%. The model was an airfoil with a 290-mm chord and 200-mm span. The airfoil was mounted horizontally in the test section of the wind tunnel at zero incidence. To study the effect of favorable and adverse pressure gradients on the development of perturbations, the membrane was located at a certain distance from the leading edge of the wing, where the model surface had a large curvature. It was impossible to use the membrane manufacturing technique [6], since it requires cutting of a notch in the model surface of the same size as the vibrating surface, which distorts the main flow. Therefore, the membrane was glued onto the model surface so that, being in an idle condition, it was aligned with the model surface, and a transverse slot 2 mm wide and 17 mm long was cut under the membrane. The membrane was glued at a distance of 17 mm from the leading edge of the airfoil. It was a rectangular elastic (latex) surface 28 × 18 mm reinforced by a Mylar sticker 25 × 15 mm. The membrane was set into motion by pressure oscillations from a loudspeaker connected by a pneumatic line with a chamber under the membrane slot (Fig. 1). Rectangular electric signals of different amplitudes were supplied to the loudspeaker by the generator; as a result, the membrane performed a reciprocating motion with a frequency of 3 Hz, moving from the position at rest to the upward position with an amplitude of (0.6 ± 0.1) mm.

The measurements were performed by a single-wire probe of a constant-temperature hot-wire anemometer. The wire diameter was 6 μm, and its length was about 1 mm. The longitudinal component of velocity fluctuations u' and the mean velocity U were measured at different point in the space (x, y, z). The x axis with the origin at the leading edge of the airfoil was directed along the flow, the z axis with the origin at the axis of symmetry of the membrane was aligned in the spanwise direction, and the y axis with the origin at the airfoil surface was perpendicular to the x and y axes. The free-stream velocity in the tunnel test section was measured by a Pitot–Prandtl tube connected with an inclined liquid-column micromanometer. The hot-wire probe was calibrated in the free stream, opposite to the Pitot–Prandtl tube, at flow velocities 3–20 m/sec so that the error in determining the

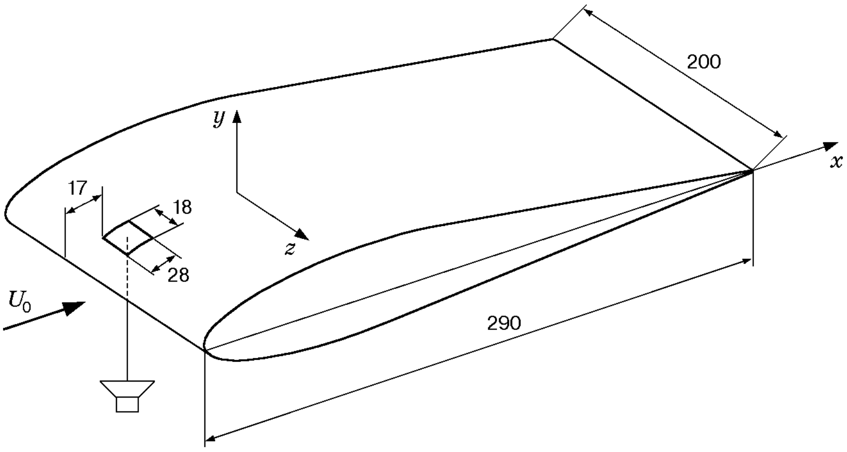

Fig. 1. Schematic of the experiment.

mean velocity was less than 2%. The process of calibration and the experimental equipment used are described in detail in [11, 16].

Signal oscillograms from the hot-wire anemometer bridge were fed into a computer through an analog-to-digital converter and averaged over an ensemble to improve the signal-to-noise ratio, which allowed identification of the valid signal on the background of undetermined noise. Averaging was performed over 30–60 instantiations, depending on the levels of the signal to be identified and noise. Subsequent processing of the measurement results was also performed on a computer with the use of a program of spatial-time Fourier analysis by the technique described in [11].

The process of evolution of perturbations along the transverse coordinate z was measured in the region of their maximum intensity along the normal to the model surface.

2. Experimental Results. Vibrations of the membrane near the leading edge of the airfoil generated a perturbation localized over the transverse coordinate and time, which was entrained downstream. The membrane position near the leading edge was chosen for the reason that the boundary layer here is thin and most sensitive to perturbations being introduced. It was found that the generated perturbation is a "puff" structure, since alternation of regions with excess and defect of velocity in the transverse direction, localization of the structure in the transverse direction [6], and also inclined waves on the sides of the structure were observed. In addition, an analysis of (y–t) diagrams shows that the perturbation maximum is located at a distance $y_{u'\,\max}/\delta \approx 0.5$, i.e., farther from the wall than in the case of the Tollmien–Schlichting wave packet ($y_{u'\,\max}/\delta \approx 0.3$–$0.4$). Here δ is the boundary-layer thickness.

A "puff" structure appeared near the leading edge of the airfoil in the region with a favorable pressure gradient and was entrained downstream to the region with an adverse pressure gradient. Figure 2 shows the velocity distribution above the airfoil. The point $x = 100$ mm separates the regions with favorable and adverse pressure gradients, and the evolution of the "puff" structure in these regions is different.

In the case of a favorable pressure gradient ($x = 0$–100 mm), the evolution of the "puff" structure is the same as on a flat plate in the Blasius boundary layer. Grek et al. [13] studied perturbations generated by vibrations of a membrane located on the surface of a flat plate. The development of perturbations occurred at a neutral pressure gradient. The arising localized streamwise structures extended along the flow because of the difference in velocity of the fore and aft fronts and decayed. Perturbations on the airfoil in the region with a favorable pressure gradient have a similar behavior, since the favorable pressure gradient amplifies the decay of perturbations, in contrast to the neutral pressure gradient. With further motion of the perturbation downstream, the process of its evolution changed, since the pressure gradient changed.

In the region with an adverse pressure gradient ($x = 100$–300 mm), special features appear, which were not observed in the case of a favorable pressure gradient. Figure 3 shows perturbation diagrams. It is seen from Fig. 3a that the fore and aft fronts of the perturbation start to develop downstream; the central part, which is a low-frequency wave packet, remains unchanged. High-frequency oscillations arise at the fore front and, to a smaller extent, at the aft front of the perturbation. These oscillation increase intensely as the structure passes to the region

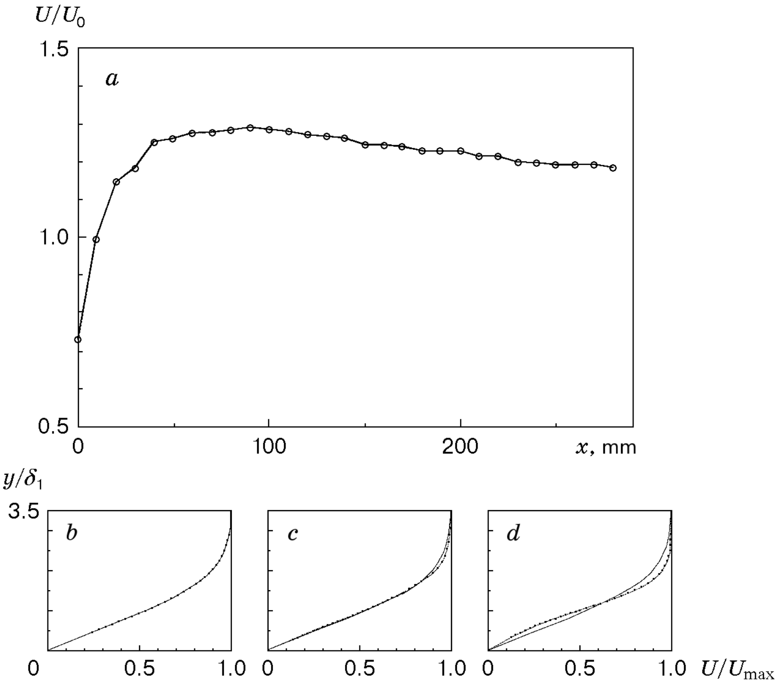

Fig. 2. Velocity distribution at the outer edge of the boundary layer along the airfoil chord (a) and profiles of the mean velocity normal to the wall (points) as compared to the Blasius profile (solid curves) for $x = 45$ mm and $\delta_1 = 0.45$ mm (b), $x = 125$ mm and $\delta_1 = 0.95$ mm (c), and $x = 245$ mm and $\delta_1 = 1.92$ mm (d) (δ_1 is the displacement thickness).

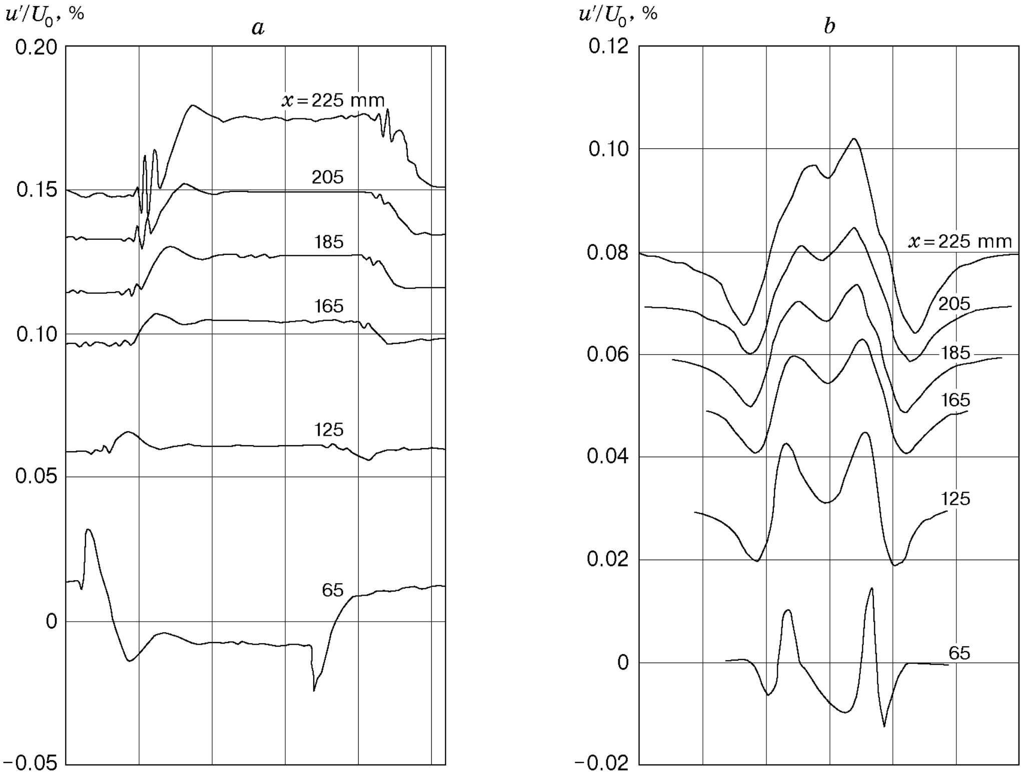

Fig. 3. Oscillograms of velocity fluctuations u' for various values of x at $z = 0$ (a) and along the transverse coordinate z at $t = 125$ msec (b).

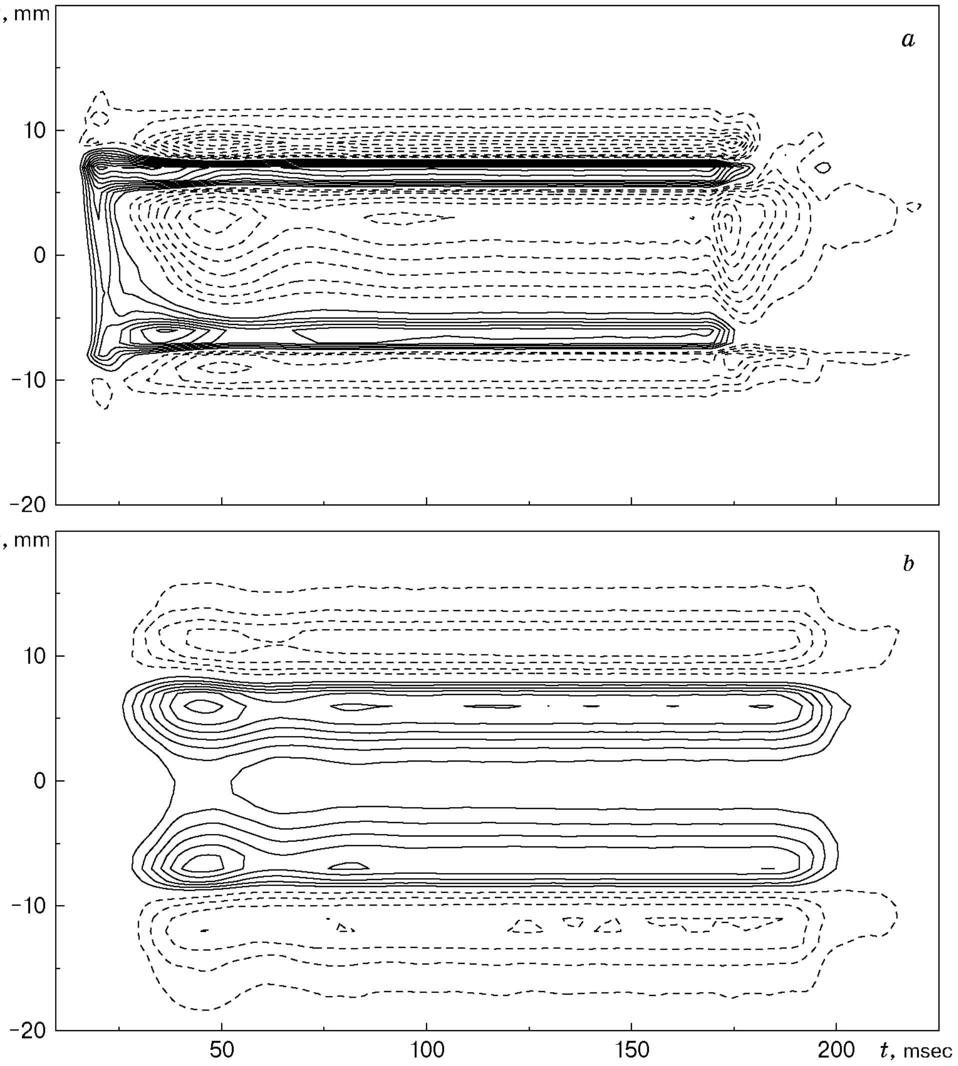

Fig. 4. Evolution of a boundary-layer perturbation generated by a vibrator in the region with a favorable pressure gradient [isolines of velocity fluctuations u' in the plane (z, t) at the level $y = y_{u'\,\max}$]: the solid and dashed curves refer to velocity excess and velocity defect, respectively; (a) $x = 65$ mm, $U = 0.45U_0$, $(u'/U)_{\min} = -0.04$, $(u'/U)_{\max} = 0.045$, and $\Delta(u'/U) = 0.005$; (b) $x = 125$ mm, $U = 0.47U_0$, $(u'/U)_{\min} = -0.02$, $(u'/U)_{\max} = 0.035$, and $\Delta(u'/U) = 0.005$.

with an adverse pressure gradient. The difference in oscillations at the fore and aft fronts is, apparently, explained by the special features of membrane operation. The upward motion of the membrane is more intense than its downward motion.

Figures 4 and 5 show the evolution of a “puff” structure. At large distances from the membrane ($x =$ 165–225 mm), the Tollmien–Schlichting waves developed on the leading and trailing edges of the “puff” structure (“moustaches”) are clearly seen. Their amplitude is comparable with the amplitude of the “puff” structure and amounts approximately to $(0.01–0.03)U_0$ and even exceeds it at the final stage of perturbation evolution.

The “moustaches” are two waves propagating at an angle of 45° to the x axis on both sides of the perturbation. The length of the waves is about 30 mm. Nevertheless, we cannot argue that the membrane length (28 mm) determines the wave length. The closeness of these values may be a mere coincidence. The dynamics of development of “moustaches” was studied under frequency filtration of the “puff” structure at different stages of evolution. The direct and inverse Fourier transforms in time and filtration of low-frequency components (lower than 70 Hz) were used. The analysis showed that high-frequency oscillations decay as the perturbation moves to the regions with favorable and neutral pressure gradients ($x = 65$–125 mm) and are amplified in the region with an adverse gradient ($x = 125$–225 mm), since the Tollmien–Schlichting waves are sensitive to changes in the pressure gradient.

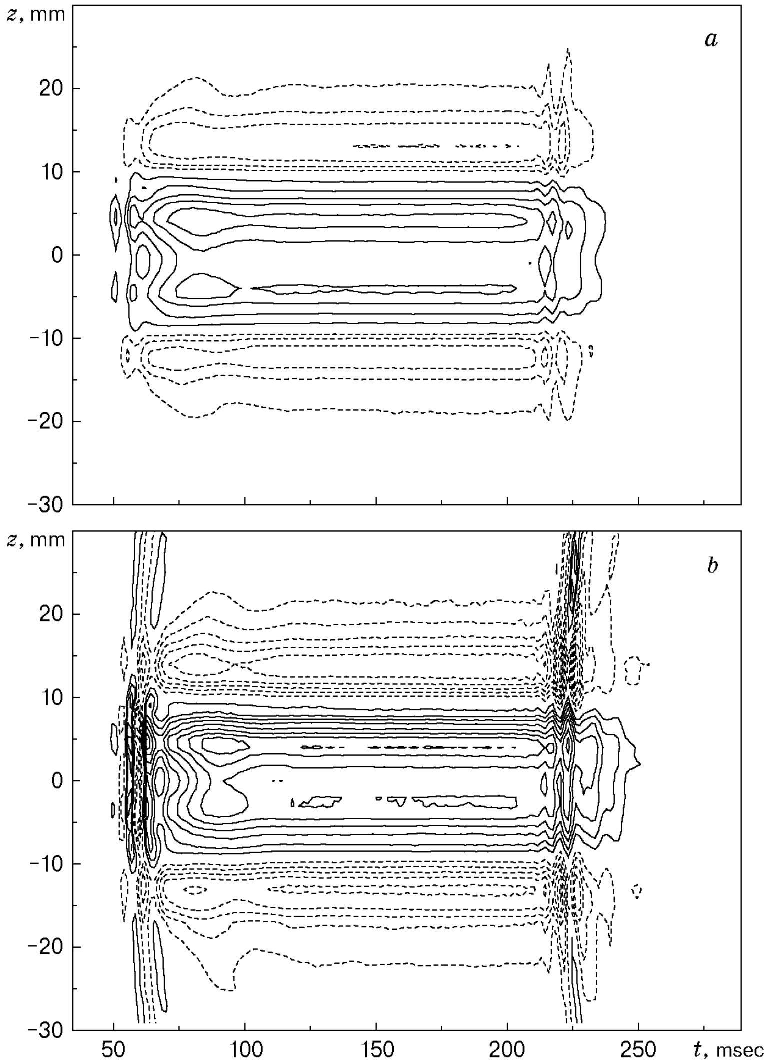

Fig. 5. Evolution of a boundary-layer perturbation generated by a vibrator in the region with an adverse pressure gradient: (a) $x = 205$ mm, $U = 0.44U_0$, $(u'/U)_{\min} = -0.02$, $(u'/U)_{\max} = 0.025$, and $\Delta(u'/U) = 0.005$; (b) $x = 225$ mm, $U = 0.57U_0$, $(u'/U)_{\min} = -0.035$, $(u'/U)_{\max} = 0.04$, and $\Delta(u'/U) = 0.005$; notation same as in Fig. 4.

It is known that streamwise pressure gradients have a significant effect on amplification of the Tollmien–Schlichting waves. This is responsible for the emergence of the Tollmien–Schlichting waves exactly at the front of the perturbation and their growth in the region with an adverse pressure gradient. The maximum velocity gradient dU/dx in our case is observed at the fore front of the perturbation. Under an additional effect of the free-stream pressure gradient, it is at the front of the perturbation that the "moustaches" originate and start to develop. The absence of "moustaches" may be expected if structures with smooth fronts are generated.

Low-frequency components, which form the "puff structure, are not very much affected by the change in the pressure gradient (insensitivity of low-frequency fluctuations of pressure gradients was also noted in the experiments of [17, 18]). In the region with a favorable pressure gradient, the "puff" structure decays. In the case of low amplitudes, the perturbation amplitude decreases when the "puff" structure enters the region with an adverse pressure gradient. However, under a favorable pressure gradient, the "puff" structure increases. Possibly, the reason is its interaction with the Tollmien–Schlichting waves. It was established in the experiments of [13, 19] that the interaction of "puff" structures and Tollmien–Schlichting waves leads to an increase in the perturbation amplitude and formation of a turbulent spot, even if the "puff" structure and Tollmien–Schlichting waves decayed, being generated independently.

It should be noted that the effect of low-frequency components on the boundary-layer evolution becomes weaker at large distances from the membrane. Rapidly growing Tollmien–Schlichting waves start to play the major role; they cause a premature separation of the boundary layer and formation of turbulent spots.

A special feature of development of the perturbation is the merging of two regions with the excess of velocity, which are formed at the membrane edges (see Fig. 3b). At the initial stage, they are separated by a region with the defect of velocity. As the structure moves downstream, these regions become wider, and finally they merge. The width of these regions is proportional to the doubled thickness of the boundary layer.

Conclusions. Oscillations of a three-dimensional vibrator located near the nose part of an airfoil generate simultaneously two types of perturbations in the boundary layer: quasi-steady streamwise structures of the "puff" type and wave packets that accompany the streamwise structures. The streamwise structures developed in the flow give birth to unstable regions at the fore and aft fronts, where an intense growth of wave packets consisting of a planar wave and a pair of inclined waves occurs in the case of an adverse pressure gradient. The wave packets are modulated over the transverse coordinate owing to the nonuniform three-dimensional mean flow in these regions, which is caused by the streamwise structures. Further downstream, the streamwise structures weakly decay with an insignificant variation in the characteristic transverse size and retain their localization in the transverse direction. The laminar–turbulent transition may be caused by secondary oscillations developed on the streamwise structures [20] and wave packets arising on the perturbation fronts.

Thus, a micromembrane built into the surface of a nonswept wing model is a source of both instability wave packets and streamwise localized perturbations.

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