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GENERATION OF THE LOCALIZED DISTURBANCES BY THE VIBRATING SURFACE*

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Appearance and development of disturbances generated by 3-D vibrating surface in Blasius boundary layer are studied experimentally. The experiments were conducted under the controlled conditions where the preservation of phase information made it possible to obtain profound and accurate data, qualitative as well as quantitative, on the object under study. Surface vibration was provided by the loudspeaker working in the blowing-suction regime. Detailed hot-wire measurements showed that in case when the surface produces oscillations of low frequency and small amplitude, the packet of disturbances with the characteristics of Tollmien — Schlichting (TS) waves is observed downstream. When the effective amplitude is increased two times "blowing" leads to the appearance of the new type of disturbances: "puff"-structures, which have other characteristics of development in the boundary layer than Tollmien — Schlichting waves.

1. INTRODUCTION

In recent years the interest to study localized streamwise vortex structures grows considerably [1 – 4]. It is connected with the fact that the studies of laminar-turbulent transition at low and especially high free stream turbulence as well as in the flows with Taylor — Goertler vortices or cross-flow vortices show the important role of these disturbances in the formation of turbulent spots as well as turbulence in general. It is known [5] that in the studies of the so-called "natural transition" the appearance of turbulent spots is observed in most scenarios of transition in the boundary layer, i. e., the areas of turbulence localized in time and space whose development downstream leads to the formation of turbulent boundary layer. It is necessary to mention that the appearence of turbulent spots is possible only from disturbances localized in time and space. Experimental studies under "natural" and model conditions show that turbulent spots in most cases appear as a result of development of the localized vortices of Λ-structure type, hairpin-like vortices, etc., at low free stream turbulence [6]. At high free stream turbulence under "natural" conditions the smoke vizualization of flow in the boundary layer points to the presence of "streaky structures" stretched downstream and localized in the transverse directions [7 – 9]. Turbulent spots under "natural" conditions appear as a result of generation and growth of high frequency wave packets on these streaky structures [8, 9]. On the other hand, the transition under conditions of formation in the boundary layer of stationary vortices of Taylor — Goertler type or "cross-flow" vortices is also connected with the development of the high frequency secondary disturbances on them [10 – 12]. These stationary structures represent counter or co-rotating vor-

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tices which, contrary to the described above formations which are convective disturbances of limited size, do not move with a flow [13]. Thus, the problem of studying the appearance, development and transformation in turbulence of the localized disturbances is very important. If in case of low free stream turbulence streamwise vortices (Λ-vortices) appear as a result of spatial evolution of 2-D instability waves or packets of waves, the appearance of the streaky structures at high free stream turbulence is connected with interaction of greatly disturbed free stream with the boundary layer, probably, mechanisms responsible for their breakdown are still common. In particular, it was shown that the appearance of turbulent spots in the flows with streamwise structures (including Λ-vortices) may take place through the process of generation and development of the increasing high frequency wave packet which is generated by interaction of streamwise localized structures with other disturbances, in particular with Tollmien — Schlichting (T — Sch), wave as it is seen from papers [8, 14, 15]. More detailed study of the problems and the results on the later stages of transition are presented in monograph [16].

The following results of the studies of the development characteristics of the localized nonstationary structures which are prior to the formation of turbulent spots can be mentioned. It was found that Λ-vortex represents localized vortex which consists of two counter-rotating vortices ("legs" of the structures) closed by the head on the upper edge of the boundary layer [17]; velocity of its propagation is approximately equal to the local mean velocity in the boundary layer. The so-called horseshoe-like, hairpin-like and other vortices have the same structure. The detailed study [14] showed that single Λ-structure can damp as well as grow downstream and be transformed into turbulent spot. It was found that the growth of Λ-structure is connected with the development of the secondary high frequency disturbance in the "legs" of the structure. It was shown that frequency of the secondary disturbance decreases because of continuous stretching of Λ-structure at its downstream propagation. Mechanism of the secondary high frequency breakdown of Λ-structures is observed at their periodic generation (see also [14]).

First quantitative results of the study of streamwise localized structures of "streaky" type were obtained in the model experiments in which these structures were modelled by different sources generating this disturbance on the model wall as well as by introducing disturbances from the free stream [3, 15, 18, 19]. The last method allowed one to model the transformation of the disturbances from the free stream at high free stream turbulence into eigen disturbances of the boundary layer. It was shown that the detailed measurements of the development characteristics of disturbances generated by various sources, the localized structures with the same characteristics were realized in the boundary layer: the scale of the structures in the transverse direction correspondent to the boundary layer thickness is preserved at their propagation downstream, i. e., they are localized; intensity maximum by normal to the wall is located higher than for 2-D T — Sch wave, in the middle of the boundary layer; velocity of their propagation is approximately equal to the local mean velocity in the boundary layer, due to it the velocity of the development of disturbance leading edge (which is near the upper edge of the boundary layer) is $0.8U_0$ and trailing edge (near the wall) is $0.5\ U_0$, because of that the disturbance is continuously stretched and deformed along the flow; amplitude peak of disturbances decreases downstream but due to their streamwise stretching integrally along the longitudinal coordinate they may grow. Data on smoke visualization of the artificially generated in the laminar boundary layer localized disturbance (streaky-structure), introduced from the free stream [9] and visualization of the similar disturbances obtained by generation through the cross slot on the model surface show their qualitative similarity, and the comparison with the results of paper [7] showed the coincidence of the main quantitative characteristics of natural disturbances (position of amplitude maximum, spanwise size, velocity of propagation, spectrum) observed under "natural" conditions at high free stream turbulence, of streaky structures with the characteristics of disturbances obtained artificially.

Unfortunately, at study of transition under "natural" conditions considerable difficulties appear which are connected with the random disturbances exciting the boundary layer. That is why we can definitely speak about the growth of coefficients of "natural" disturbances that they are close to the corresponding characteristics of the "model" disturbances. In paper [20] authors called these structures "puff", they took this term which is used for decsription of one type of disturbances observed in transition in the circular tube. At present time it coexists with the terms "convective localized disturbance" and "streaky structures". All these terms denote disturbances with the characteristics mentioned above. It should be noted that there is similarity of the "legs" of Λ-structure with streaky structures which allowed one to speak about the streamwise structures as about the whole class of disturbances which take place at the stages prior to full turbulization of the boundary layer.

A question arises if the streamwise structures could appear from other sources inside the boundary layer, in particular from the vibrating surface. It is important to know from the practical point of view since vibration of surface is typical of the modern flying vehicles and wind tunnel set-ups and they are in a wide range of frequencies. That is why they can generate disturbances of various types including "puff"-structures. First experimental study to excite disturbances in the boundary layer on the flat plate at vibration of 2-D surface was conducted in [21]. A comparison with the theoretical results [22] showed that linear theory of hydrodynamic stability and receptivity for 2-D case describes correctly this process at small amplitudes of vibrations.Numerical experimental data on excitation of 3-D T — Sch in the waves Blasius boundary layer were obtained in paper [23] in which the method of the localized vibrators was used. The characteristics of stability of the Blasius boundary layer to 3-D T — Sch waves were obtained by decomposition of "wave trains" into normal modes.

In the present paper the appearance and development of disturbances over the 3-D vibrating surface in Blasius boundary layer at small and large amplitudes of vibration of low frequency are studied.

2. EXPERIMENTAL EQUIPMENT AND MEASUREMENT TECHNIQUE

Investigations were conducted in the wind tunnel MT-324 of ITAM, SB RAS with the cross section of the test section 200 × 200 mm and the length of 800 mm. Flat plate made from plexiglass was used as the model (Fig. 1, *a*). Its length was 730 mm, width 200 mm and thickness 10 mm. It was placed horisontally in the test section of the wind tunnel. To prevent the flow separation at the sharp leading edge of the model, the flap was placed at a certain angle in the region of model trailing edge. Through in cavity a plate measuring 90 × 25 mm, was placed at a distance of 125 mm from the plate leading edge, it was covered from the

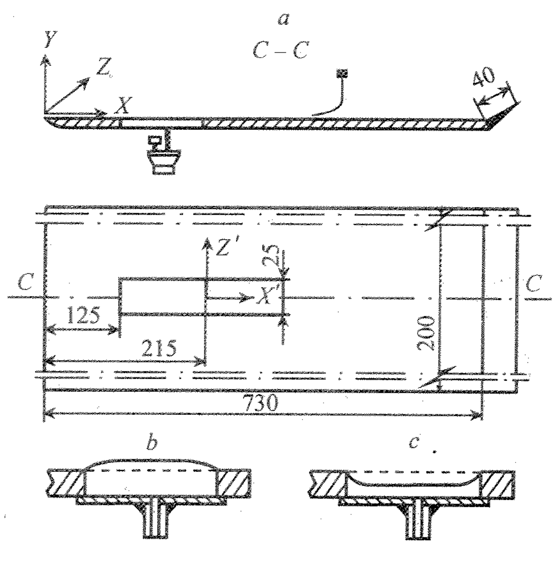

Fig. 1. Experimental set-up (*a*). Membrane shape at "blowing" (*b*) and "suction" (*c*) of gas.
Dimensions are in mm.

working side by lavsan membrane. Hermetical cavity under membrane was connected by tube with the loudspeaker which caused periodic fluctuations of pressure inside it. Membrane was transferred in the normal to surface direction with the amplitude $(0.4 - 0.5) \pm 0.1$ mm to both sides from equilibrium which made up 15 % of the boundary layer thickness in the frequency range 0.5 – 1 Hz. Frequency and amplitude of disturbances were excited by a sound generator. Free stream velocity was 6.6 m/s, turbulence degree did not exceed 0.3 %. The range of the investigated Reynolds numbers was Re = 580 – 860, where Re — Reynolds number calculated by the displacement thicknes.

All measurements were conducted by single-wire probe of hot-wire anemometer with constant temperature. The applied coordinate device made it possible to transfer hot-wire probe along the x-coordinate with accuracy 0.5, $z = 0.2$, $y = 0.01$ mm. Diameter of the probe wire was 6 μm, length was 1 mm. Streamwise component of fluctuation velocity (u') and mean velocity (U) at different points in space x, y, z were determined. Free stream velocity in the test section of the wind tunnel was measured by Pitot — Prandtle probe connected with the inclined liquid micromanometer. Hot-wire probe was calibrated in a free stream opposite Pitot — Prandtle probe at flow velocity in the range 3 – 20 m/s so that the error of mean velocity was less than 2 %. More detailed description of calibration and the applied experimental equipment are presented in paper [14].

Hot-wire probe calibration, data acquisition, accumulation and processing of the measured information were conducted by personal computer connected with the anemometer bridge by analogue-digital converter (ADC). Signal from hot-wire probe was transmitted to ADC inlet and the signal from the low frequency source (short pulses with frequency 0.5 – 1 Hz) was transmitted to its trigged inlet to preserve phase information of the investigated disturbances. Single traces of the disturbance development in space and time were introduced into computer, averaged by ensemble to improve the relation signal/noise. It allows one to extract useful signal from background noises. Averaging was conducted by 10 – 40 single traces depending on the level of extracted signal as well as noise. The results of measurements were processed by computer by the program of space-time Fourier analysis. The technique of processing is given in detail in [19].

Measurements of the disturbances development along the transverse z-coordinate were conducted in maximum of their intensity by normal y to the plate surface.

3. MEASUREMENT RESULTS

As it was mentioned, membrane was vibrated by the loudspeaker which provided blowing of gas into chamber under membrane and its suction from it. That is why by analogy with the previous works on the study of "puff"-structures the transformation of membrane into convex state relative to the plate surface (Fig. 1, *b*) when membrane moved "down-up" was called "blowing" and its transformation into concave state (Fig. 1, *c*) when it moved "up-down" was called "suction".

During experiment two types of membrane vibration were investigated: for "small" and "large" amplitudes; besides, measurements were conducted in flow for stationary convex and concave membrane. In case of "small" amplitudes of vibrations (Fig. 2, *a*) membrane from one state smoothly came into equilibrium and then came to the opposite state. For that a damped element was introduced into experimental set-up (resetting hole) which provided resetting air from the chamber under membrane and frequency of surface oscillations f was 0.5 Hz. The second type of membrane vibrations (Fig. 2, *b*) was realized at closed resetting hole. The law of oscillations of the vibrating surface in time coordinates had the form of rectangular pulses, i. e., membrane came almost immediately from the state "blowing" into the state "suction" and vice versa; in this case the effective amplitude of oscillations increased more than two times. Frequency of oscillations was 1 Hz.

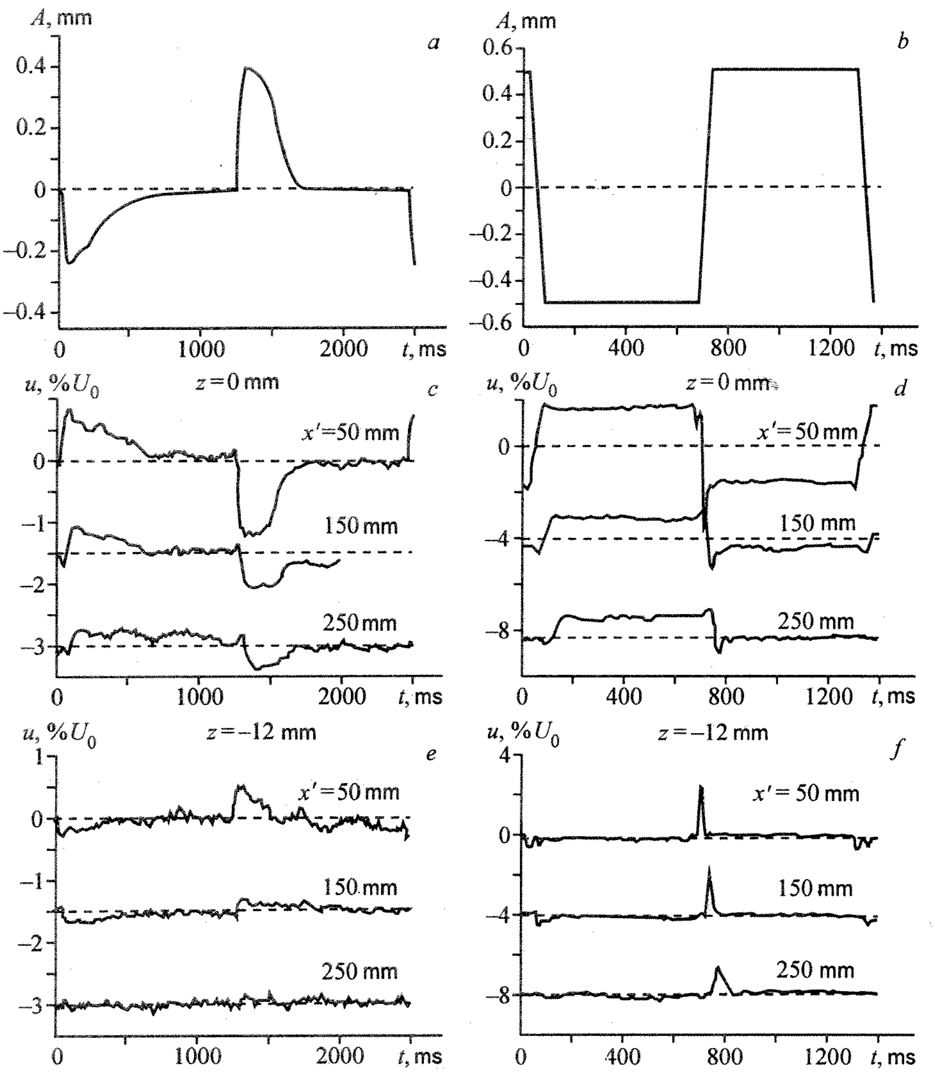

Fig. 2. Law of membrane oscillations at "small" (*a*) and "large" amplitudes of vibraions; oscilloscope traces of disturbances generated by membrane in the boundary layer for various distances downstream.

c, *d* — for the case of "small" amplitudes in the center and at membrane edge, respectively, *e*, *f* — the same for "large" amplitudes.

In Fig. 2, *c* – *e* shown oscillograms of fluctuation component of streamwise velocity at different distances downstream from the trailing edge of membrane $x' = x - x_0$: 50, 150, 250 mm in the membrane center (see Fig. 2, *c*, *d*) and at membrane edge (see Fig. 2, *e*, *f*). It is seen that in case of "small" and "large" amplitudes of oscillations (see Fig. 2, *d*) the disturbances appear in the boundary layer which are different by their structure.

Both half-periods of disturbance in case of "small" amplitudes of oscillations are presented in detail in Fig. 3 as isolines of fluctuation component of streamwise velocity in the plane z — t at $y = y_{U'_{\max}}$ for two values x'. It is seen that at the membrane edges regions are generated in which fluctuation component of velocity has a sign opposite to the velocity component in the region over membrane. Maximum amplitude of disturbance in these regions is approximately two times smaller

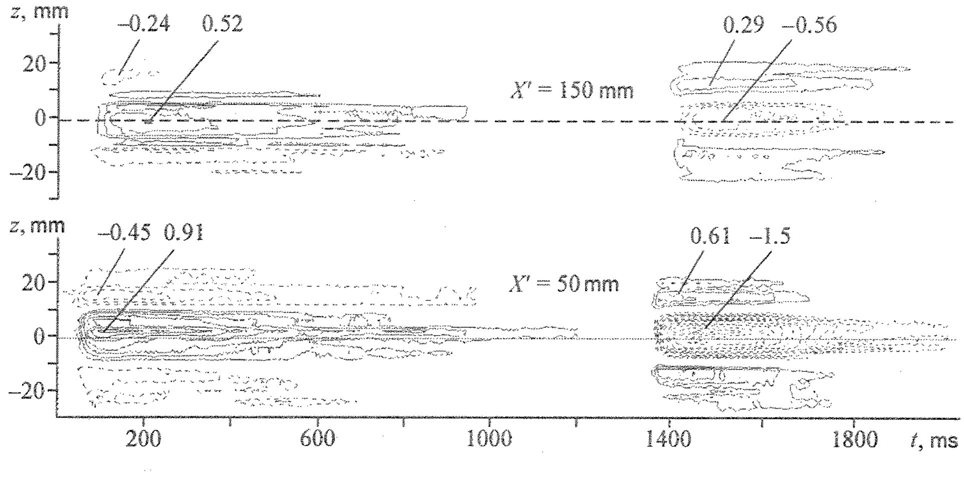

Fig. 3. Isolines of fluctuation component of velocity in the plane $z - t$ for "small" amplitudes.

Figures show the values in percent of free stream velocity. Isoline step is 0.075 %.

than in the center. It is also seen that at the leading edge of disturbances there are small regions where isolines are not parallel to the flow. When disturbance propagates downstream its shape is not changed, its localization is preserved but disturbance damps. Amplitude of disturbance at a distance of 100 mm downstream decreases almost two times. Its phase velocity is approximately $0.4U_0$. A conclusion can be made that this disturbance is a packet of T — Sch waves propagating downstream. To make it clear, Fourier transformation of the disturbance was conducted. In Fig. 4, *a* shown the distribution along the transverse coordinate dimensionalized by maximum of amplitude of the first (basic) harmonics and in Fig. 4, *b* — its phases for various coordinates downstream. The disturbances phase shift by 180° at the membrane edges is clearly seen. The presented plots show that disturbance preserves its localization and amplitude of disturbance at edges is approximately two times smaller than in the center of membrane. These results coincide with data of paper [23]. In Fig. 4, *c*, *d* shown the distribution of velocity fluctuation component in case of convex and concave membrane. Distribution of amplitude shows that there are no streamwise stationary vortices at membrane edges. The law of distribution of velocity fluctuation component along the transverse coordinate is the same as for "small" amplitudes of oscillations. These plots also show that in the stationary case the disturbances of shear from the convex and and concave membrane coincide till sign, i. e., membrane was made with good accuracy. Besides, disturbances generated at this amplitude of membrane oscillation are still close to linear (probably, to weak non-linear).

From the mentioned above we can make the conclusion that in case of "small" amplitudes of membrane oscillations 3-D localized damping wave packet T — Sch is generated in the boundary layer, its phase velocity being $0.4U_0$. At membrane edges there is phase shift by 180° and localization of disturbance in the transverse direction is preserved at propagation downstream. In the problem with the initial data this wave packet can be presented as a set of sinesoidal harmonics with a variable amplitude by the transverse coordinate of the type shown in Fig. 4, *c*, *d*.

Isolines of velocity fluctuations in the plane $z - t$ for $y = y_{U'_{\max}}$ (Fig. 5) show the stages of development of disturbance generated by membrane oscillations with "large" amplitude. It should be mentioned that not the whole disturbance is presented here, as it is shown in Fig. 2, *d*, *f*, but only the leading edge of its second half-period

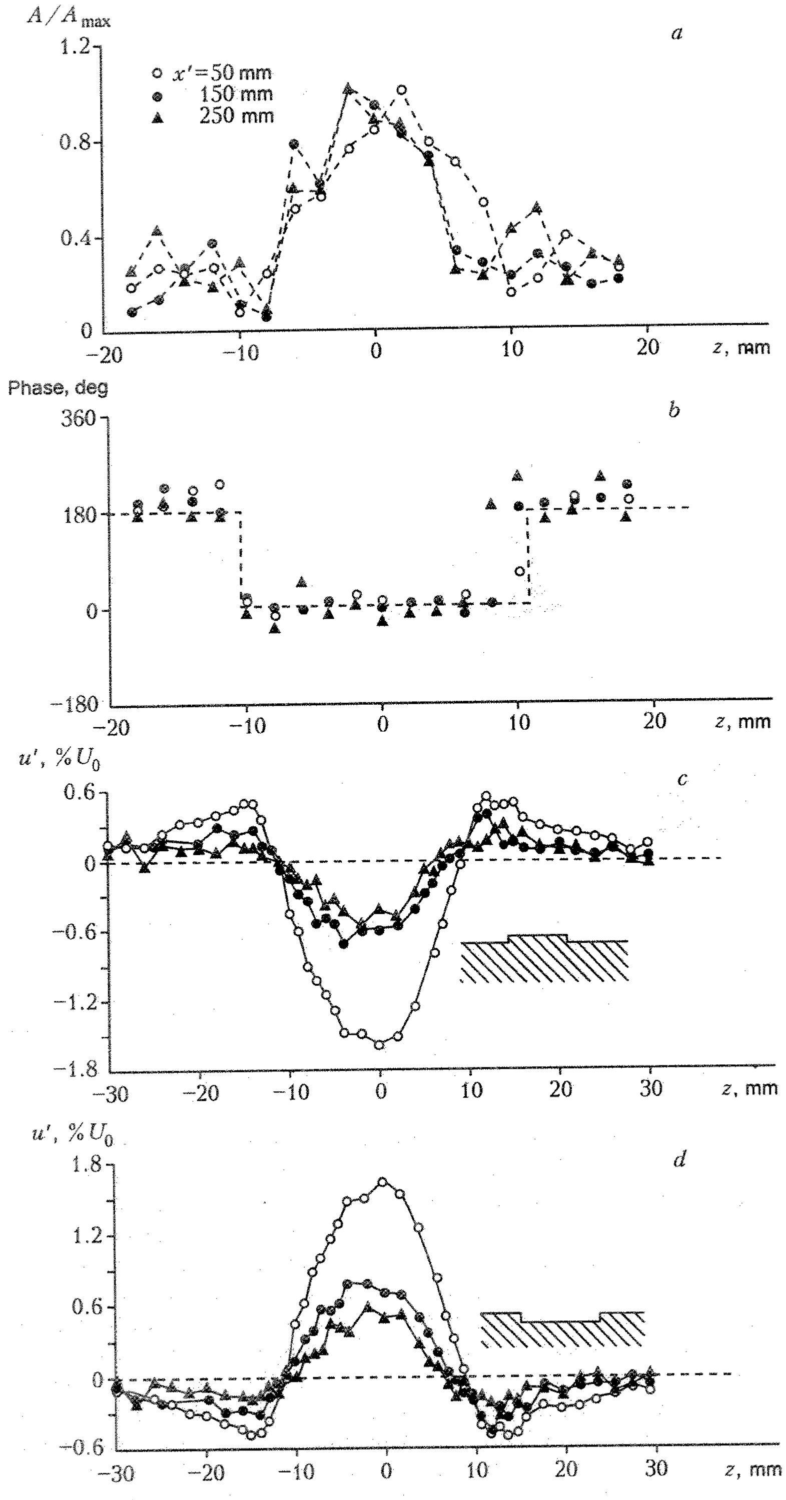

Fig. 4. Distributions along the transverse coordinate of amplitude (*a*) and phase (*b*) of the basic harmonic of velocity fluctuation component for "small" amplitudes of oscillations for various distances downstream and velocity fluctuation component for stationary convex (*c*) and concave (*d*) membrane.

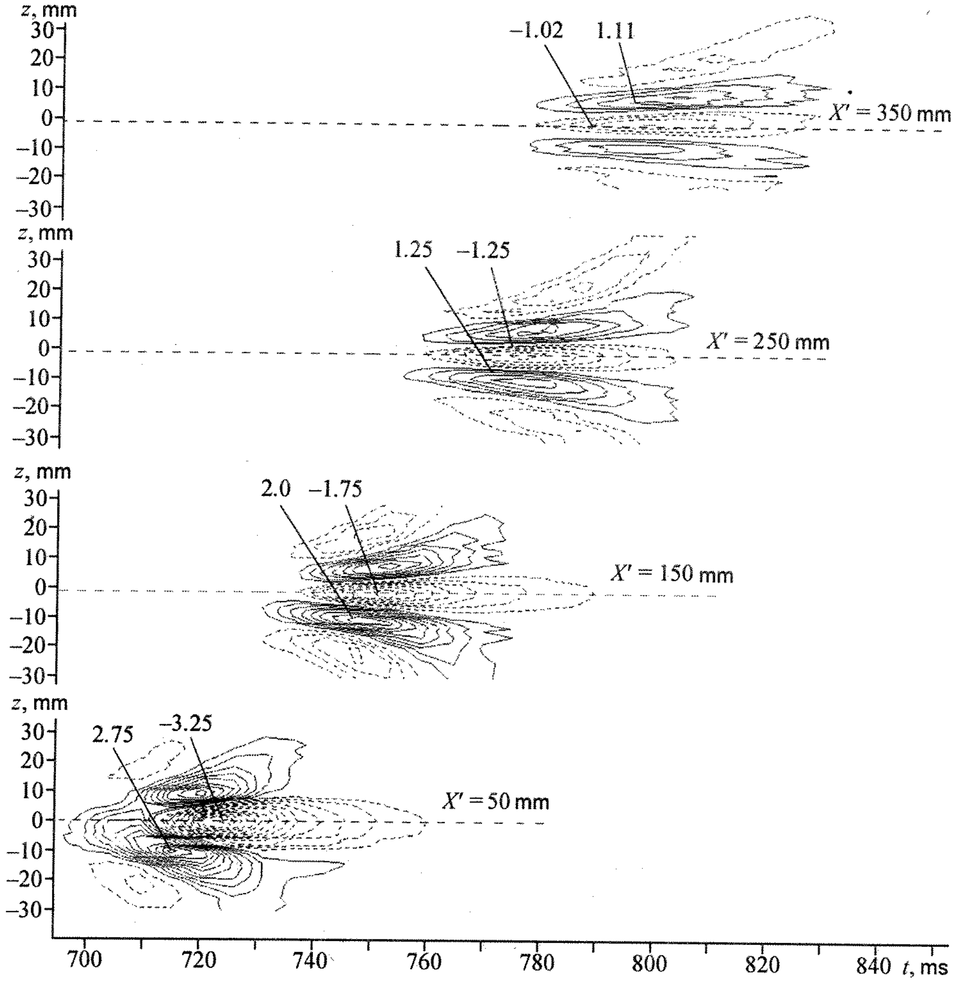

Fig. 5. Isolines of velocity fluctuation component in the plane $z - t$ which show development of disturbance generated by vibrations on the surface for "large" amplitudes ("blowing").

Figures show amplitude values in percent of free stream velocity. Isoline step is 0.25 %.

(i. e. "blowing") constant component of signal is deducted. Duration of this disturbance is about 60 ms at the formation stage ($x' = 50$mm), the region of length 27 ms is clearly distinguished in disturbance (which in space coordinate makes up 90 mm, i. e., membrane's length). It can be said that this disturbance is formed by "throwing out" of membrane's liquid into the boundary layer. The region with the velocity defect is formed over membrane, which is the volume of low velocity liquid thrown out by membrane, and two regions with accelerated velocity are formed at membrane edges which is the result of displacement of upper accelerated layers of liquid into this layer. In other words, there is so-called the "tilting effect" of the boundary layer [16] at membrane edges. Propagating downstream disturbance is localized spanwise and stretched downstream. Dimensional value of transverse scale of disturbance varies from 22 to 18 mm and non-dimensional — from 5.6 to 3.2 of the boundary layer thickness, i. e., we can speak about some selection of scales and about the fact that spanwise scale of disturbance approaches 2δ which corresponds to non-dimensional spanwise wavenumber 0.5. This value is marked in many papers as typical of streamwise structures at the plate [9, 19]. Regions of velocity defect at disturbance edges are oblique waves which are generated due to the fact that velocity of its propagation is higher than T — Sch wave has. At the initial stage of development ($x' = 50 - 150$ mm) disturbance velocity is approximately $0.55U_0$, when it propagates downstream it is equal to $0.75U_0$. From Fig. 6 where cross-sections of disturbances by the normal coordinate, at $z' = 10$ mm are presented, it is seen that disturbance intensity is approximately at the height of displacement thickness. At the formation stage (Fig. 6, *a*, $x' = 50$ mm) disturbance intensity maximum is lower than the coordinate of displacement thickness, when it propagates downstream (Fig. 6, *b*, $x' = 250$ mm) it comes up from the wall. It can be concluded from this figure that propagation velocity of disturbance leading edge which is near the upper edge of the boundary layer is $0.8U_0$ and the trailing one, near the wall, is $0.4U_0$. Because of that disturbance is continuously stretched when it propagates downstream. A comparison with the results of papers [3, 19] shows that characteristics of the development of this disturbance and "puffs" are similar: alternation of narrow regions with accelerated and decelerated velocity in the transverse direction, oblique waves at the edges, maximum of disturbance intensity is higher from the wall than T — Sch wave has, velocity of motion is approximately equal to local mean velocity in the boundary layer. At the initial stage the transverse scale of disturbance is the

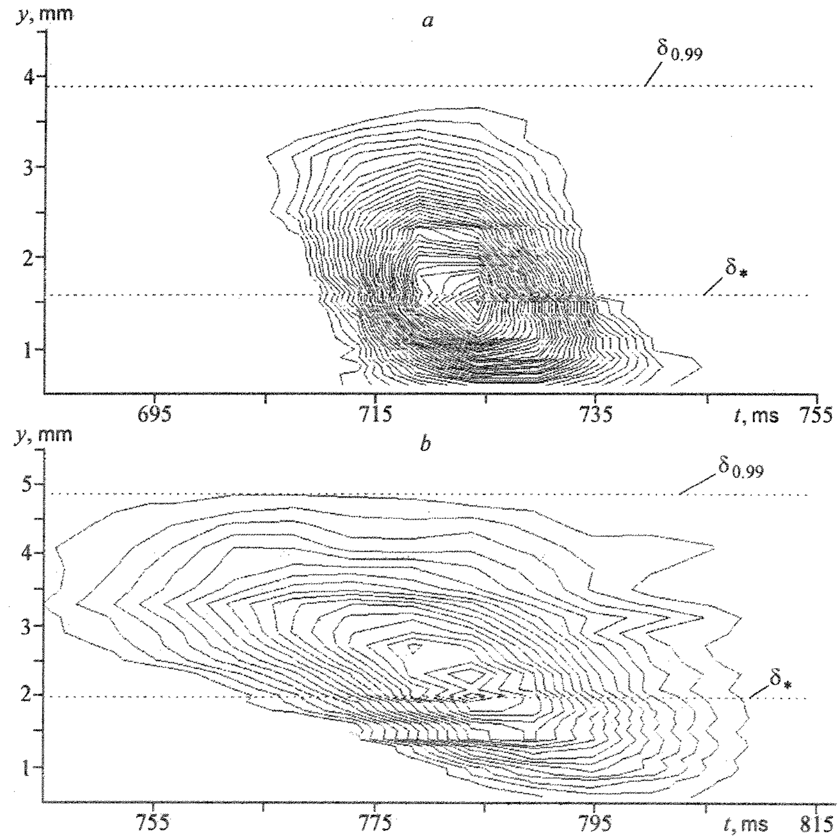

Fig. 6. Isolines of velocity fluctuation component in the plane $y - t$ for "large" amplitudes of vibrations ("blowing", $z = 10$ mm).

a — at $x' = 50$ mm value of maximum amplitude is 1.9 % U_0, *b* — at $x' = 250$ mm maximum value is 0.9 % U_0. Isoline step is 0.05 %. δ, δ^* — measured thickness of the boundary layer and displacement thickness, respectively.

same as Λ-structure has [14], when it propagates downstream it becomes smaller, up to 3.2 of the boundary layer thickness, i. e., it is close to the scale typical of "puffs". Thus, liquid thrown out by membrane into the boundary layer is turned at membrane edges into streamwise vortex with features typical of "puff"-structures. From this point of view the curvature of isolines at the leading edge of the wave packet in case of "small" amplitudes of oscillations can be interpreted as liquid "thrown out" by membrane which did not lead, however, to the formation of the streamwise structure. The reason is small intensity of vortices generated at membrane edges. Thus, it can be concluded that when frequency of membrane oscillations is or less than $U_0/2l$ (where l is membrane's length) under other similar conditions (effective amplitude, spanwise velocity of transition and the law of membrane oscillations, flow velocity) "puff" structures will be formed. When the frequency of oscillations increases, probably, the "tilting effect" will not take place but it should be confirmed by further investigations. It should be noted that the "suction" of membrane in the given experiment did not lead to the formation of "puff"-structure. It is explained by the fact that amplitude of disturbances is large, that is why at membrane oscillations the liquid layers which are at different height in the boundary layer take part. When modelling "puffs" by "blowing-suction" through the cross slot [19], it was noted that the characteristic spanwise size of disturbances from the slot at the initial stage of development at "blowing" is always smaller than at "suction". That is why at "suction" the intensity of the structures is smaller, i. e., receptivity of the boundary layer to disturbances with various signs is different, hence, we have the problem with various initial data. In paper [2] direct numerical simulation of streamwise structures was performed. The initial conditions for them were assigned as a pair of counter-rotating vortices. At the initial moment "blowing" and "suction" were simulated by the pair of vortices with equal amplitude and size but with different direction of their rotating. Non-linear effects led to the fact that when time increased the diturbances acquired various spanwise scale and disturbances amplitude at "suction" became smaller than at "blowing". In other words, receptivity of the boundary layer to this type of disturbances at their downstream propagation is different. Probably, these effects take place in our case, that is why disturbance at "suction" does not lead to the formation in the boundary layer of the localized streamwise structure and transformed downstream into T—Sch wave packet.

4. CONCLUSIONS

Thus, in case of "small" amplitudes of membrane oscillations 3-D localized decreasing T—Sch wave packet is formed and it propagates downstream. Its phase velocity is $0.4U_0$. The wave phase shift by 180° is observed at membrane edges. Localization of disturbances propagating downstream is preserved.

In case of "large" amplitudes of membrane oscillations a "blowing" generates disturbance with characteristics typical of "puff"-structure. At the initial stage velocity of its propagation in the layer of maximum amplitude of fluctuations is approximately $0.55U_0$ and when disturbance propagates downstream it grows up to $0.75U_0$. When it develops the disturbance is localized in the spanwise direction. Velocity of propagation of its leading edge which is near the upper edge of the boundary layer is $0.8U_0$ and of the trailing edge near the wall is $0.4U_0$, due to this fact disturbance is continuously stretched propagating downstream. Maximum of dicturbance intensity by the normal coordinate is located considerably higher from the wall than T—Sch wave has.

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