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CONTROL OF SPANWISE FLOW INSTABILITY OF A SWEPT WING BY SUCTION*

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The experimental results on control by disturbances development in a swept wing boundary layer by means of localized and distributed suction are presented. The control by spanwise flow stationary vortices and secondary periodical disturbances generated at late stages of these vortices development was studied. It is shown that the distributed suction is a simple way to suppress the secondary vortex instability of a spanwise flow as compared with a localized suction. It was shown that the localized suction through a small diameter hole may cause generation of additional stationary vortices in the boundary layer. In this case complex nonlinear interactions between both controlled and controlling disturbances take place. The distributed suction effect through a group of holes is similar to the slot suction and it introduces much less disturbances of vorticity into the boundary layer.

Laminar-turbulent transition at low free stream turbulence in a 2D boundary layer can be conditionally presented in the form of separate stages: generation of the boundary layer waves, their amplification according to the linear theory, nonlinear breakdown of the laminar flow, and turbulization of the boundary layer. The recent studies showed that it is not a sole scenario of transition. For example, scenario of transition at high free stream turbulence fundamentally differs from the classical one at low free stream turbulence [1]. In this case a boundary layer is modulated in a transverse direction by streaky structures and the transition is related to the development of high-frequency wave packets localized in space and transforming into the turbulent spots downstream. The wave packets are generated because of spatial distortions of the mean velocity profiles that are unstable and the secondary high-frequency disturbances can grow on them. The packets of instability waves may be the examples of those above mentioned, however, their role in the transition process is secondary as compared with a classical transition scenario. The main role of the secondary high-frequency instability for the turbulisation of near-wall shear flows modulated by the longitudinal stationary vortices, such as the Goertler vortices, the crossflow vortices on a swept wing, and nonstationary vortices, such as the Λ-vortices, streaky structures at high free stream turbulence structures is confirmed both theoretically and experimentally by many researchers [1–4]. A primary instability of many shear flows is the generation of the longitudinal, localized in the transverse direction vortices and streaky structures in them by different reasons. Flow modulation by such structures gives rise to the unstable (inflexional) velocity profiles both in the transversal ($\partial u/\partial z$) and normal ($\partial u/\partial y$) directions that forms the

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conditions for generation of the secondary high-frequency disturbances on them. The instability of the velocity profile on a normal to the wall ($\partial u/\partial y$) becomes a condition for generation of so called varicose instability, and the transverse velocity profile ($\partial u/\partial z$) is for the sinusoidal one. The both types of the instabilities can be developed both separately and jointly that leads to the flow turbulisation.

The key role in studying of the secondary high-frequency instability is related to turbulization of the 3D swept-wing boundary layer. Understanding of physical mechanisms of turbulisation of such flow makes it possible to suggest different ways of controlling those processes. It is particularly important for technical applications, for example, for control by a boundary layer on plane swept wings, etc. The primary instability of the swept-wing boundary layer, as in a number of other cases, is related to its transverse modulation with longitudinal vortices initiated by the crossflow. The secondary high-frequency waves can be developed at these vortices that leads to a flow turbulisation.

Control of a laminar-turbulent transition by means of a gas suction from a boundary layer is studied, and in some cases it is already used for a long time. The example of successful use of the suction method for delay of transition demonstrates an application of control by transition on the swept wings. The experiment was performed in a real flight at the Mach number equal to 0.775 at approximate altitude of 9000 m and slip angle about 30° [5]. The experiment shows an efficiency of the distributed suction in domain of the leading wing edge prolonging the laminar flow right up to the first longeron (x/C = 0.13). Early suction on space is more efficient than the late one. An efficient system of the distributed suction through the narrow longitudinal slots located under each vortex of the longitudinal flow on the swept wing provides the delay in development of the secondary perturbations, and, on the whole, delays a transition [6]. The study results of the swept-wing boundary layer in controlled experiment showed that the suction through a mini-orifice is able to suppress significantly the secondary instability [7]. The suction led to suppression of the travelling waves developed on the stationary vortex structures. This effect is achieved by a local influence on the primary vortex system, and its maximum is directly under the vortex above which the secondary fluctuations are initiated. Another way to control the flow turbulisation in the swept-wing boundary layer is ribbing of the surface. The experimantal results [8] show that riblets significantly affect the efficiency of the stationary longitudinal vortices, and the flow becomes stable with regard to high-frequency travelling waves that leads to a laminar-turbulent transition in the absence of the riblets [8]. The wave inter-suppression in the region of their nonlinear development in the swept-wing boundary layer is considered in [7]. The secondary instability is the travelling waves developing at the initial vortex structure and are generated by acoustic perturbations, but the controlling fluctuations are generated by a periodic gas injection through a hole on the model surface. In the result, amplitude of the non-stationary disturbances within the vortex range located above the surface fluctuation source was decreased. Thus, the recent investigations showed a possibility to control the flow turbulisation in the swept-wing boundary layer by various ways including the suction method.

The objective of the present work is to consider an effect of localized and distributed suction on suppression of the secondary travelling disturbances generated on longitudinal streaky structures in the swept-wing boundary layer at the swept angle equal to 45° using a controlled experiment.

1. EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

The experiments were performed in the wind tunnel of the Chalmers Technological University in Goeteborg, Sweden. Sizes of the test section: the length is 3 m, the width is 1.8 m, and the height is 1.2 m. A turbulization level in the wind tunnel test section does not exceed 0.1 % from U_0 at the flow velocity U_0 = 8.2 m/s. A straight wing with chord 500 mm (Fig. 1) posed in the test section under swept angle equal to 45° was used as a model. The wing nose with a maximal thickness of 80 mm

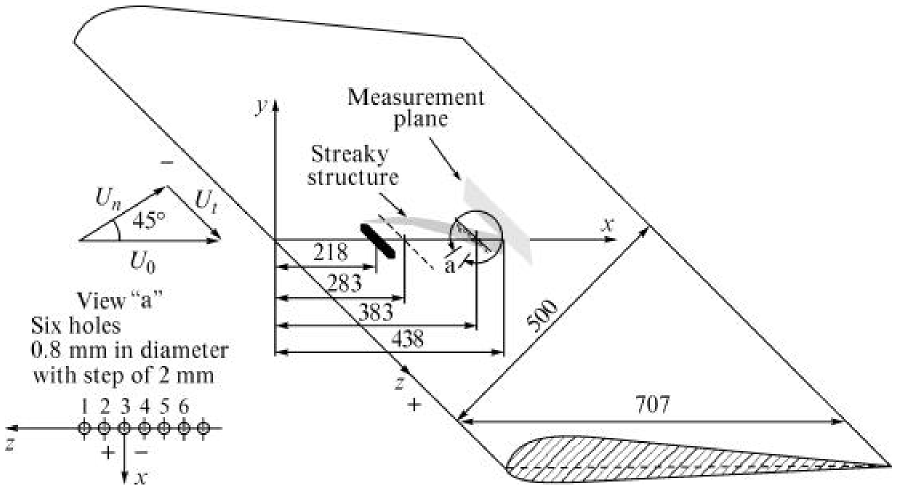

Fig. 1. The experimental set-up.
Sizes in mm.

has an ogival form smoothly transforming into two flat surfaces (see Fig. 1). The model was installed horizontally in the test section by means of a special carrier. To simplify the measurement procedure the angle of attack was chosen so that a flat surface of the wing was in parallel to the surface (x, z), which allowed one to move the probe retaining y = const. Such a position of the wing creates a weak unfavorable pressure gradient in the measurement region. The curve of spreading of the pressure gradient along the wing chord presented in Fig. 2 confirms this fact. It should be noted that a coordinate equipment allows one to move the probe in automated mode in three directions: downstream (x) with accuracy 0.01 mm; in a transverse direction (z) with accuracy 0.01 mm; along the normal to the wing surface (y) with accuracy 0.005 mm. A weak unfavorable pressure gradient (see Fig . 2) begins at $x/C = 0.2$. In the vicinity of $x/C = 0.4 – 0.8$ the pressure gradient $C_p/(x/C)$ is less than 0.25 and the pressure slightly increases with an approximately constant growth coefficient. Distribution of C_p does not point out any local boundary layer separations, and measurements of mean velocity profiles $U(y)$ show that the flow in the measurement region retains a laminar regime.

Stationary perturbations were generated by means of the roughness element pasted on the wing surface (Fig. 1). The roughness was installed in parallel to the leading edge of the model at distance equal to $x/C = 0.3$ in the region of unfavorable pressure gradient. The roughness element generated the longitudinal stationary vortices at each of its transverse ends. A transverse size of the roughness (35 mm) allows the both vortices to be developed independently of each other, at least in the region of the measurements performed. Owing to that the measurements were performed in the region of a stationary vortex generated at the roughness element end located upstream due to the swept angle presence (see Fig. 1). The travelling waves were initiated by a periodical gas injection-suction through the hole 0.8 mm in diameter

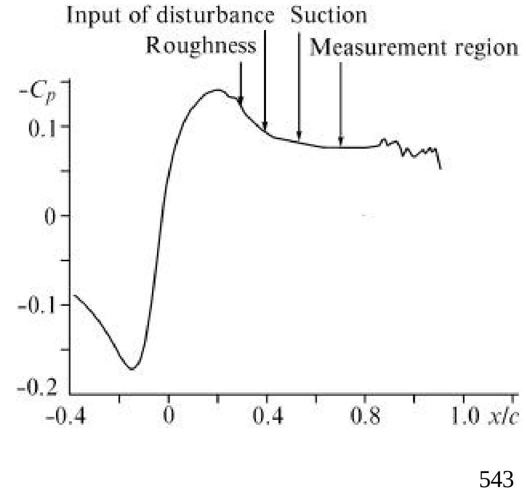

Fig. 2. Distribution of the pressure coefficient along the wing chord.

located at a distance of 283 mm to the wing leading edge. A hole position on a transverse coordinate correlates with a region of the stationary vortex development. A dynamic loudspeaker was used for injection-suction. A sinusoidal electrical signal with frequency 210 Hz was given from a sound generator to a loudspeaker. Control by the vortex development in the boundary layer was carried out by a gas suction through six holes 0.8 mm in diameter located in the vicinity of the stationary vortex development at distance 383 mm to the wing leading edge (see Fig. 1). The suction was carried out either continuously through a group of holes or individually through each of the six holes, but the suction rate is the same in every case. To optimize the influence efficiency on the controlled process the suction activity can be governed.

A hot-wire probe of a constant resistance was used as a measurement equipment. Streamwise component of mean ($\bar{u}$) and fluctuating (u') velocity in space (x, y, z) were measured. The probe was calibrated in an undisturbed flow in the velocity range from 2 to 9 m/s with accuracy up to 1 %. A calibrated function was determined as

$$U = k_1\left(E^2 - E_0^2\right)^{1/n} + k_2\left(E - E_0\right)^{1/2},$$

where E and $E0$ are the output voltages from the hot-wire probe at velocity U and zero flow velocity, respectively; $k1$, $k2$, and n are the constants determined empirically. The first term corresponds to the well-known King law, the second one is added for accounting of a free convection at low flow velocities. Value $1/n$ is close to 0.5.

The measurement results were automatically written to a hard disk of the computer and then were processed by special programs in a computational system MatLab.

2. MEASUREMENT RESULTS

As it was noticed above, behind the roughness element a stationary vortex is generated which development in space is shown in Fig. 3. In the given case the coordinates x_S = 100 mm and z = 0 mm correspond to position of the point of a

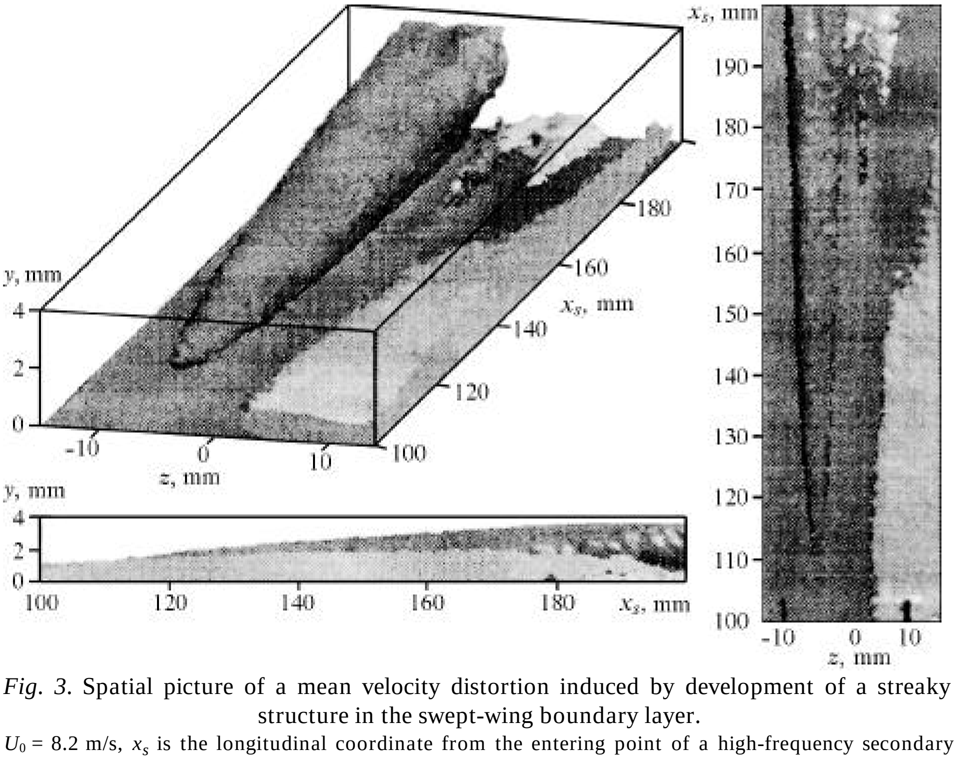

Fig. 3. Spatial picture of a mean velocity distortion induced by development of a streaky structure in the swept-wing boundary layer.

U_0 = 8.2 m/s, x_s is the longitudinal coordinate from the entering point of a high-frequency secondary disturbance.

high-frequency disturbance exciting (x = 283 mm to the leading wing edge (see Fig. 1). The vortex forms two alternating regions of an excess velocity and its defect on the transverse coordinate z to which the light and dark contours correspond. One can observe downstream the vortex transverse extension up to width of 20 mm at the longitudinal coordinate x_S = 200 mm that is the consequence of interaction between the secondary high-frequency disturbance and the stationary vortex. The contour diagrams of isolines of distortion of the mean and fluctuating velocities in the (y, z) plane for the given case without suction control at x = 438 mm are presented in Figs. 4, *à* and 4, *b*, respectively. The region of the velocity defect is seen on the left (12 % U_0) and its excess on the right (8 % U_0) in Fig. 4, *à* that makes an inflected transverse velocity profile $U(z)$ typical for development of structures of such kind. A similar profile is unstable with respect to high-frequency perturbations that can grow in this place. The given phenomenon is confirmed by Fig. 4, *b*, where an amplitude of the secondary disturbance is shown. It is seen that the intensity maximum (6 % U_0) position coincides with the inflection point in profile $U(t)$ presented in Fig. 4, *à*. The result of influence of the distributed suction through six holes is demonstrated at a contour diagram of a mean velocity in Fig. 5, *à*. It is noticed that the depth of the boundary-layer modulation is retained (amplitude $U_{\max} - U_{\min} \approx 20$ % in both cases) and disturbance maximums positions are displaced to the wing surface that is related with "pumping" of some gas volume that results to decrease in thickness of the boundary layer (y/d = 0.45 without suction and y/δ = 0.27 with suction). In the given case a distributed suction effect is very similar on a slot suction one. It results in introducing much less vorticity disturbances into a boundary layer.

Due to the certain investigations a generation of streaky structures was found out by suction through the holes of a small diameter. In this case a transverse scale of the streaky structures generated is less than a transverse scale of a streaky structure which control is carried out at a long distance downstream (x = 383 mm) and where it reaches the value of 20 mm. Influence of the distributed suction on development of a high-frequency secondary disturbance is shown by isolines of the mean velocity fluctuations in Fig. 5, *b*. The decrease in the fluctuation level nearly twice from 6 % U_0 is observed in Fig. 4, *b* (without suction) up to 3 % U_0 in Fig. 5, *b* (with suction). At the same time the secondary-disturbance intensity maximum position is located closer to the wall (y/δ = 0.4 without suction and y/δ = 0.2 with suction) that is directly related to a displacement to the wall of the intensity maximums positions of velocity excess and defect (see Figs. 4, *a* and 5, *a*). It should be noted that

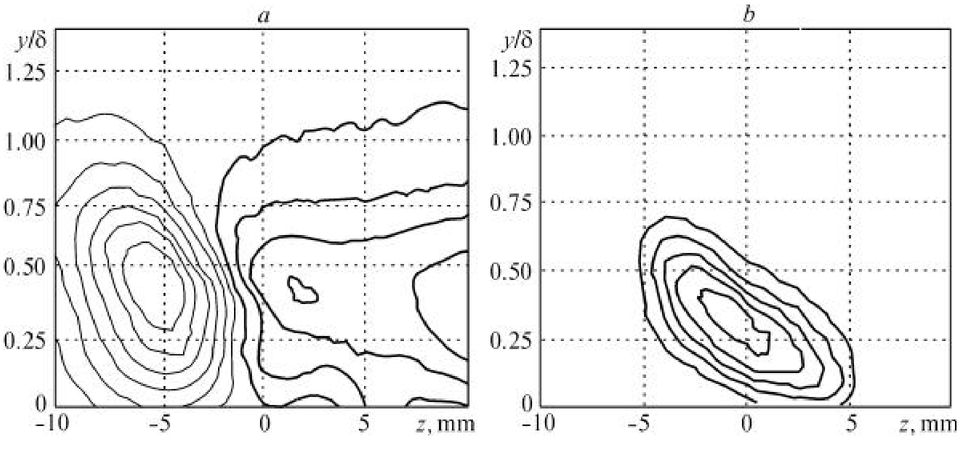

Fig. 4. Contour diagrams of the mean velocity isolines (*à*) and fluctuating velocity (*b*) of the disturbance developing in the swept-wing boundary layer in y – z plane without control.

U_0 = 8.2 m/s, x = 438 mm; thick isolines are the velocity excess, thin isolines are the velocity defect, isoline step is 2 % U_0 (*a*) and 1.2 % U_0 (*b*).

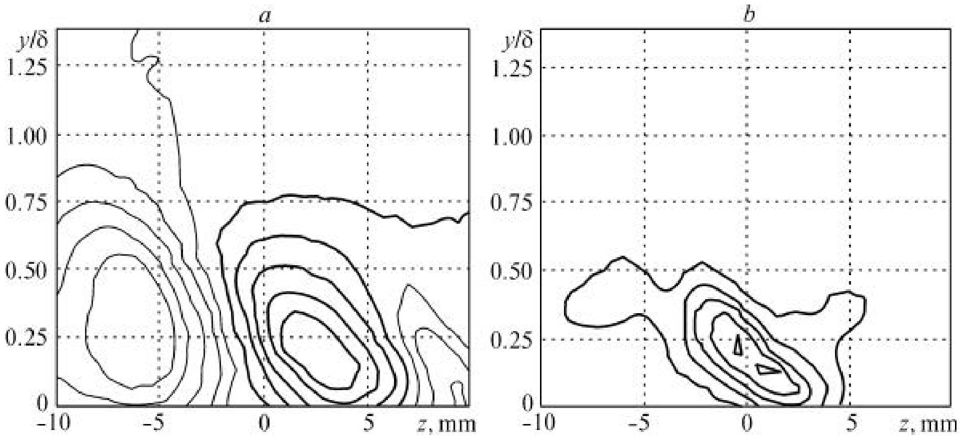

Fig. 5. Contour diagrams of mean velocity isolines (*à*) and fluctuating velocity (*b*) of disturbance development in the swept-wing boundary layer in the $y - z$ plane at control by means of a distributed suction.

U_0 = 8.2 m/s, x = 438 mm, thick isolines are the velocity excess, thin isolines are the velocity defect, isoline step is 2.4 % U_0 (*a*) and 0.6 % U_0 (*b*).

maximum of the secondary disturbance intensity on a transverse coordinate is located in the region of a maximal velocity gradient ($z \approx -1$ mm, Figs. 4, *à* and 5, *à*), i. e. in the inflection point in the mean velocity profile $U(z)$.

Figure 6, *à* demonstrates distribution of a mean velocity on z measured in the region of a disturbance maximum (that is determined without a suction controlling effect) on the normal to the surface at y/δ = 0.45 for the case of a localized suction through different holes and without it. On the whole, the localized suction does not significantly affect on the mean velocity distribution excluding the suction through hole 6 positioned in the vicinity of a velocity minimum, when the depth of a flow modulation appreciably decreases. The result of influence of the localized suction on development of the secondary high-frequency disturbance (see Fig. 6, *b*) is more interesting. The greatest decrease in the fluctuation intensity in the region of an inflection point in the mean velocity profile at $z = -2$ mm is obtained at suction through hole *5*. As compared with the case without suction, the maximum in fluctuation intensity decreases nearly by 1.8 times (from 5.5 % U_0 up to 3 % U_0). Suction through other holes is less efficient or it does not influence the secondary

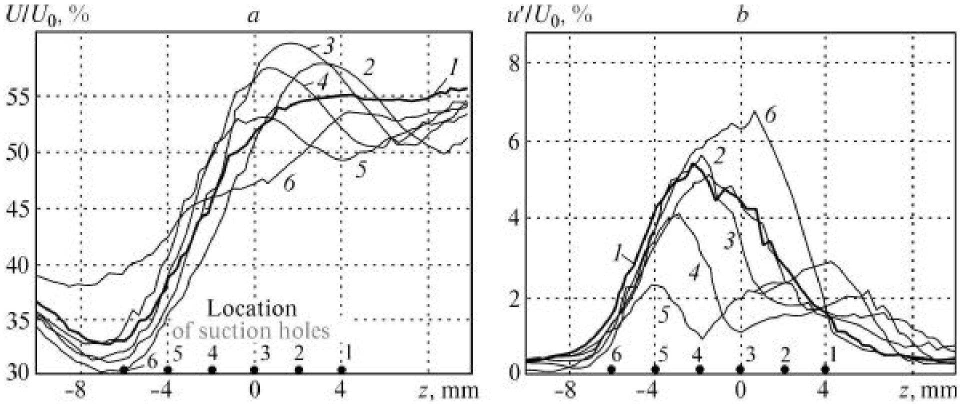

Fig. 6. Influence of a localized suction on distribution of mean velocity (*à*) and fluctuating velocity (*b*) for disturbance of the swept-wing boundary layer.

1 —without suction; *2 – 5*, and *6* is the suction through the holes *1 – 4*, and *5*, respectively.

disturbance amplitude. Increase in the fluctuation amplitude at suction through hole *6* somewhat goes beyond the whole picture, that significantly decreases in a transverse gradient of the mean velocity $(\partial U/\partial z)$ that shall delay a disturbance growth. This fact needs to be additionally analyzed.

Variation of the mean velocity on z at a distributed suction through different groups of holes and without it is shown in Fig. 7, *à*. It may be seen that there is a decrease in the transverse velocity gradient $(\partial U/\partial z)$ approximately by 30 %, at suction through the groups of holes (*1*−*6*) and (*3*−*6*) as compared with the case without suction and the same increase at suction through the groups of holes (*1*−*4*). According to the local theory of stability an amplitude of high-frequency secondary disturbances has to be decreased in two first cases and be increased in the last one. However, it can be observed in Fig. 7, *b* that the travelling disturbances reduce in all cases of the distributed suction approximately by 3 times as compared with the cases without suction. The greatest decrease in maximum of intensity of velocity fluctuations (by 4 % U_0 from 5.5 % U_0 up to 1.5 % U_0) is observed at suction through the group of holes (*3*−*6*), by 2 % U_0 at suction (*1*−*6*) and by 2.5 % U_0 at suction (*1*−*4*). Thus, only decrease in amplitude of fluctuations at the distributed suction through groups of holes (*3*−*6*) and (*1*−*6*) to some extent correlates with the deductions of a local theory of stability. At suction through a group of holes (*1*−*4*) such a correlation is not observed. Owing to this it can be assumed that the main contribution in decrease in intensity of disturbance fluctuations travelling on a streaky structure is related to the generation of streaky structures on each hole, which, in its turn, in result of complex nonlinear interactions with controlling disturbance lead to the fact mentioned above. More detailed understanding of a mechanism of this effect needs further investigation.

The investigation results show on the whole that the distributed suction, as compared with a localized one, is more efficient method for intensity suppression of the secondary disturbances travelling on a stationary streaky structure in the swept-wing boundary layer. The following comment is necessary to this conclusion. In the experiments performed earlier on controlling by development of the travelling disturbances developing on stationary streaky structures in a swept-wing boundary layer [1, 7] it was observed that at the initial stage of development of the both the streaky structure and secondary disturbances travelling on it the localized suction suppressed the later right up to the complete flow laminarization. The given effect is mainly related to the influence of suction on the mean-velocity transverse gradient $(\partial U/\partial z)$ that increases the flow stability with respect to secondary disturbances. The

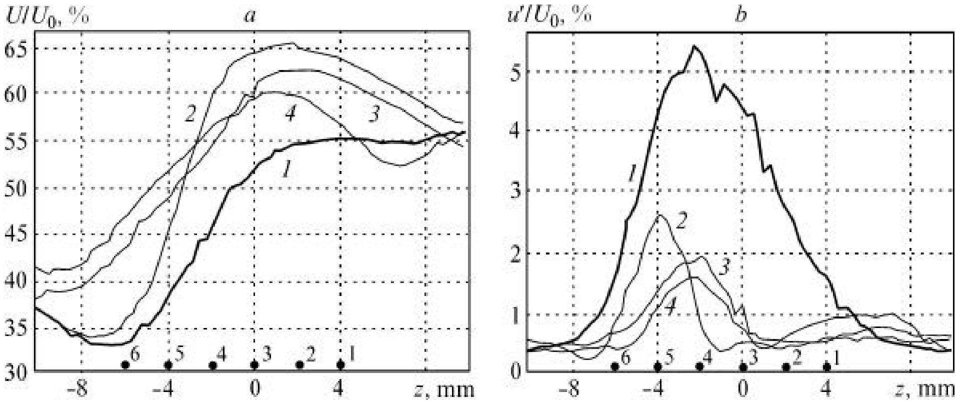

Fig. 7. Influence of the distributed suction on distribution of a mean velocity (*à*) and velocity fluctuations (*b*) for disturbance of the swept-wing boundary layer.

1 — without suction; *2* — suction through the holes *1* – *4*; *3* is the suction through holes *1* – *6*; *4* is the suction through holes *3* – *6*.

feature of the given experiment is that the controlling is performed in the region located much lower downstream, where a streaky structure and the secondary perturbation pass a significant development stage as against the experimental conditions [1, 7] that can affect the controlling results.

3. CONCLUSION

On the basis of experimental investigations of a possibility to control by perturbation development in the swept-wing boundary layer by means of a localized and distributed suction the following is found out.

1. A localized suction as a method of suppression of intensity of secondary disturbances is less efficient as compared with a distributed suction.

2. The distributed suction through holes located in a row in a transverse direction reduces the intensity of the secondary disturbances, and on the whole, at a fixed quantity of a gas sucked the controlling effect increases with increase in number of holes through which the suction is carried out.

3. It is shown that a distributed suction through a row of holes whose whole extension occupies all the transverse size of a streaky structure, suppresses the intensity of the secondary disturbance by 3 times and, thus, delays the flow turbulisation.

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