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EXPERIMENTAL INVESTIGATION OF A STREAKY STRUCTURE VARICOSE INSTABILITY IN A SWEPT WING BOUNDARY LAYER*

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The investigation results of the controlled experiment of a streaky structure varicose instability in a swept wing boundary layer are presented. The picture of a streaky structure spatial evolution and secondary high-frequency disturbances generated on it is obtained using hot-wire measurements. It is shown that exactly a varicose instability is realized. It has been found that the secondary disturbance increases owing to instability of mean velocity distribution on normal to the wall caused by the streaky structure development. The following features of a varicose breakdown of a longitudinal stationary streaky structure are presented: structure modulation in the longitudinal direction by a secondary disturbance frequency, downstream excitation of new streaky structures, formation and development of nonstationary structures localized in space. In contrast to the boundary layer flow of the unswept wing models, where these structures resemble classical horseshoe structures or lambda-vortices, only one vortex remains on a swept wing from the two making the vortex structure because of the crossflow.

INTRODUCTION

The flow visualization modulated by the Goertler vortices [1] shows that the laminar-turbulent transition of such a flow is determined by the secondary mechanisms produced the instability waves on each vortex pair independently, so that neighbouring vortex pairs can intensify different types of the secondary motions, either in the form of periodic “meandering motions” of the vortices in spanwise direction or in the form of horseshoe-shaped braids in region of a strong cross shear layer. These disturbances are called as sinuous and varicose modes, respectively. Many investigators compare them with odd and even modes known form the analytical and numerical analysis of the secondary instability of the Goertler vortices.

An inviscid local mechanism is considered as a ground of instability stipulated by the instant velocity profile inflections both on normal (a varicose mode) and in transversal direction (sinuous mode). Choice of the instability mode generated first and growing more rapidly depends on certain initial conditions, in particular, on distance between the points of disturbance excitation. For example, the authors of [2, 3] numerically found that for long-wave vortices a varicose mode is dominating and for short-wave ones (more frequently occurring) a sinuous mode is prevailing. It is related to that the long-wave vortices provide a weak cross-shear, and the short-wave vortices cause a large shear. The 3D shear layer instability related to the

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near-wall low-velocity streaks is experimentally studied in a flat plate boundary layer in [4]. On a single streaky structure the separately symmetric (varicose) and antisymmetric (sinuous) modes are excited. When the streaky structure transversal size is larger than the shear layer thickness, a varicose instability growth is observed. When it is comparable or less than the shear layer thickness, the streaky structure becomes more unstable to the axisymmetrical modes than to the symmetrical ones. It is clearly seen from experiment [4] that an increase in the symmetrical mode leads to formation of hairpin-shaped vortices representing a pair of counter-rotating longitudinal vortices closed with a head. Therewith, the antisymmetrical mode is developed into the train of quasi-longitudinal waves with the vorticity of alternating sign.

A direct numerical simulation of the varicose instability in the turbulent boundary layer [5] shows a similarity of the horseshoe vortices generated both in the laminar and turbulent boundary layers. At the same time it is stated that a generation mechanism of the horseshoe vortices in turbulent boundary layers is related to inflectional instability of the streaky structures ($\partial U/\partial y$). The horseshoe vortices can cause excitation of new streaky structures in the turbulent boundary layer [6]. On the other hand, a sinusoidal instability related to the transverse inflectional velocity profile ($\partial U/\partial z$) is verified by several investigators [7–9]. It can be assumed that the both types of instability are the important mechanisms of turbulence self-sustaining in the turbulent boundary layer: a sinusoidal type is used for regeneration of the near-wall turbulence [10], and a varicose type is for generation of horseshoe vortices occupying the regions further from the wall [6]. Recently, a large volume of knowledge on the mechanism of turbulence development and self-sustaining in near-wall turbulent flows at small Reynolds numbers and on simple 2D models (flat plate, smooth surface, etc.) is accumulated. A question on applying those knowledge for description of turbulence in more complex gradient and 3D flows (straight and swept wings, roughness surfaces, large Reynolds numbers, etc.) and the turbulence development features in such flows is still open. This problem need to be further studied [11].

The goal of the present experimental work is to investigate the streaky structure varicose instability in the swept wing boundary layer. Such an investigation is important because the given type of instability occurs both in the laminar boundary layer modeled by the longitudinal structures and in the turbulent one, where coherent vortex structures of different types are observed; besides, a complex 3D flow is considered on a swept wing.

1. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The experiments were conducted in a subsonic low-turbulent wind tunnel of the Chalmer's Technological University (Goeteborg, Sweden). The turbulence level does not exceed $0.001U_0$ in the test section at freestream velocity equal to $U_\infty = 6$ m/s. A straight wing mounted in the test section under angles of attack is $\alpha \approx 0°$ and sweep angle is $\chi = 45°$ was used as the model (Fig. 1, *a*). For convenience the measurement results are presented in two coordinate systems (Fig. 1, *b*): the laboratory frame (the x-axis is parallel to the velocity vector of the undisturbed flow) and the wing coordinate system (the "c" subscript), the y-axis in both coordinate systems is directed normally to the model surface. Owing to the measurement results the x-coordinate is presented as dimensionilzed on the wing chord length c, which has the length 500 mm in the system of x, z coordinates and 707 mm in the system of x_c, z_c coordinates (see Fig. 1, *à*). To generate a streaky structure the disturbance was introduced through the hole with 1 mm in diameter drilled on the model surface at distance within 176 mm to the model leading edge at $z = 0$ mm. To generate the stationary streaky structure the disturbance was entered by a continuous air blowing. The

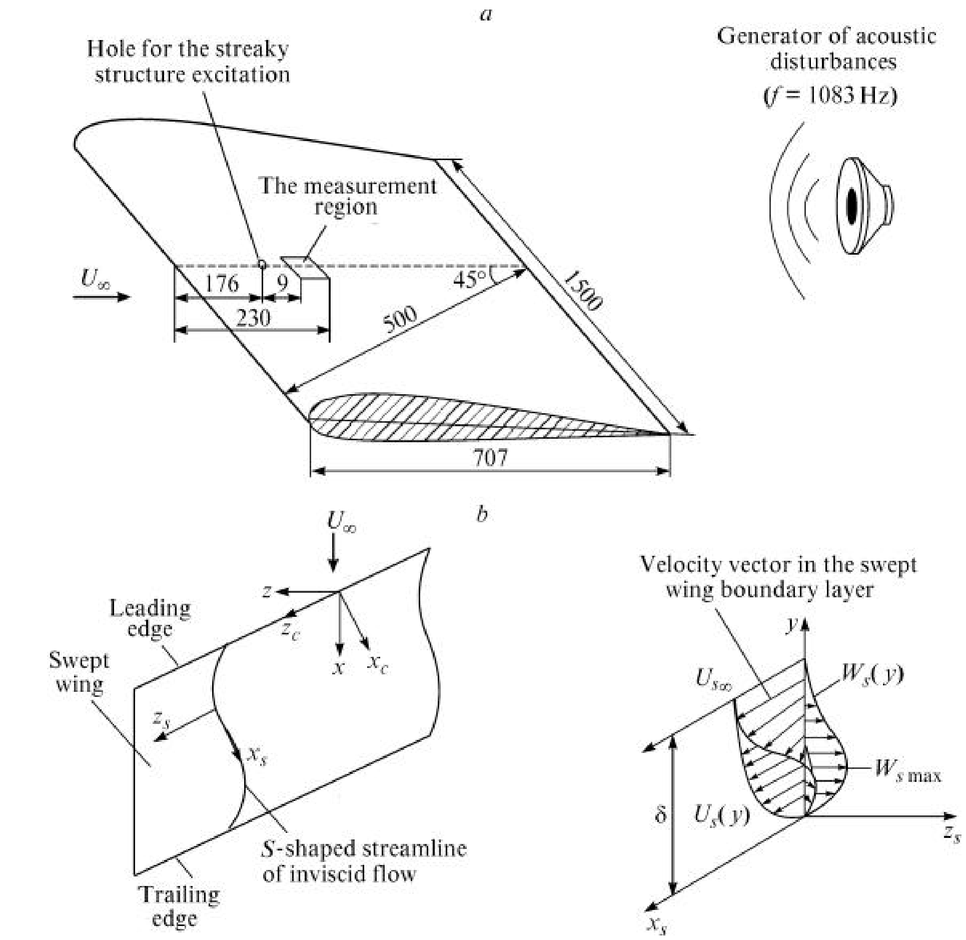

Fig. 1. Experimental setup (*à*), the coordinate systems (laboratory system and the wing system with subscript "*ñ*") and the velocity components in 3D boundary layer (*b*). (Demensions in mm).

secondary disturbance is excited by superposition on a stationary streaky structure of additional periodic in time the blowing-suction modulated a primary structure in the longitudinal direction, as in [5]. Velocity distribution above the wing outside the boundary layer, reflecting a pressure distribution along the model in the x-direction is shown in Fig. 2. It is seen that the downstream measurement domain is at joint of the favorable and unfavorable pressure gradients that represents a narrow area (45 mm) of a practically gradientless flow. The measurement domain in the transverse direction z is over the range from 14 mm to +2 mm, where z = 0 mm corresponds to position of the point of a disturbance excitation. All measurements are carried out by means of constant temperature hot-wire anemometer and a single

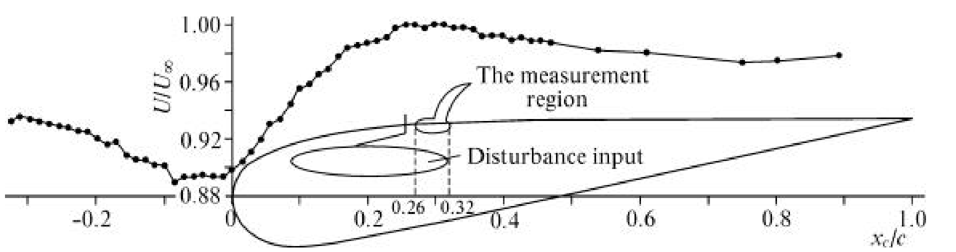

Fig. 2. Distribution of the flow velocity outside the swept wing boundary layer measured along the flow, χ = 45°, U_∞ = 6 m/s.

wire probe with a sensor element from gild tungsten wire with 5 *m*m in diameter and 1 mm in length. A coordinate mechanism allows one to conduct the measurements in an automatic regime on three coordinates *x*, *y*, and *z* with accuracy not less then 2 *m*m on each. The longitudinal mean velocity components ($\bar{u}$) and velocity fluctuations (u'_f) in a narrow band of frequences (f = 1083 Hz) of the disturbance excited by acoustic on the given coordinates were measured. The measurement results were processed by a special program (MatLab) that allows one to obtain the spatial pa t-terns in the form of contour diagrams of isolines of mean velocity distortions ($\Delta\bar{u}$) and its fluctua tions (u'_f) in (yz) plane and (xyz) space.

2. THE FLOW CHARACTERISTICS IN THE BOUNDARY LAYER IN THE ABSENCE OF DISTURBANCE GENERATION

It is known that the flow in the swept wing boundary layer is significantly three-dimensional that is related to the presence of the cross flow. Owing to this the inviscid flow streamlines in the boundary layer are distorted and have a typical *S*-form (see Fig. 1, *b*). The velocity vector over the boundary layer thickness is continuously turning at its moving to the wall, that arranges the conditions for generation of the crossflow vortices in the vicinity of the swept wing leading edge. Stability of such flows has been widely investigated for a long time by many researches in theoretical and experimental works. It is studied both under natural conditions, when the crossflow vortices are generated naturally on the swept wing and in the controlled experiment, where they are generated artificially by different methods. In the given case the controlled experiment method is used that allows one to study in detail this or that process of the disturbances development dynamics due to retaining of the phase information and caused by synchronization of their spatial development with an excitation source. Figure 2 points the measurement domain and position of disturbance excitation with respect to the streamlines. The mean velocity

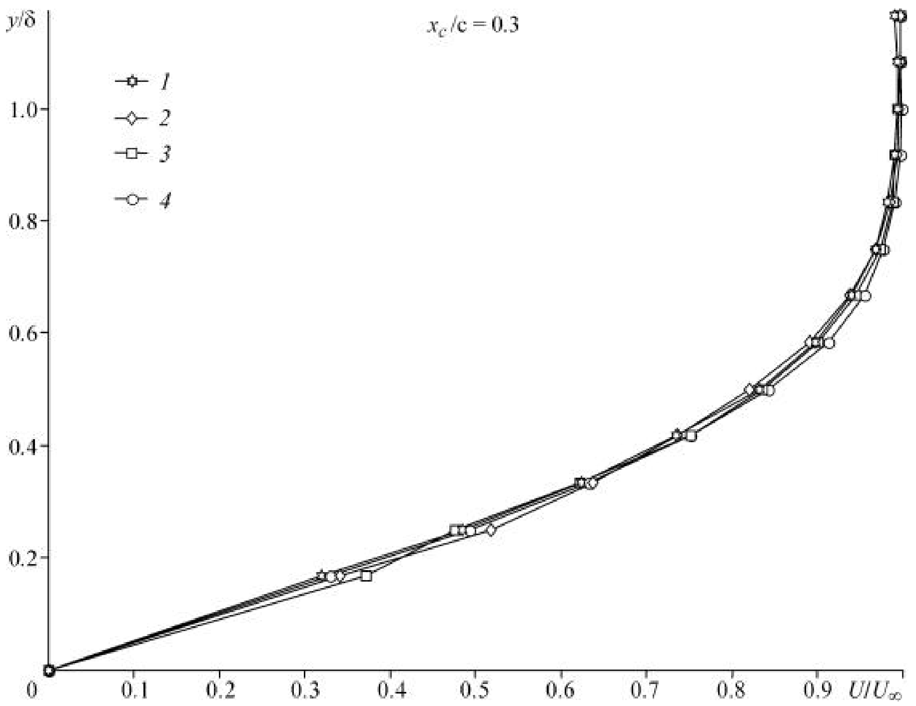

Fig. 3. A mean velocity profile in the swept wing boundary layer in the absence of disturbances for different *z* positions: 1.4 (*1*), −1.4 (*2*), −4.24 (*3*), −7 mm (*4*).

profile in the swept wing boundary layer in the absence of the disturbance excitation is presented in Fig. 3 at $x_c/c = 0.3$, over the range of z coordinate within 1.4 and −7 mm. It is evident that the profile reflects a laminar state of the flow, and the boundary layer thickness δ ($0.99U_0$) is approximately equal to 3 mm. So, it may be noted that in the given region it varies slightly.

3. THE VARICOSE STREAKY STRUCTURE INSTABILITY AT ACOUSTIC GENERATION OF THE SECONDARY DISTURBANCES

Figure 4 presents the volume pattern of streaky structure development with the secondary high-frequency disturbance and the contour diagrams of the corresponding sections, the mean-velocity defect ($\Delta\bar{u}$) and its fluctuations (u'_f) in the swept wing boundary layer in the (*yz*) plane. A general view is presented in the wing coordinate system for its possible comparison with the sections.

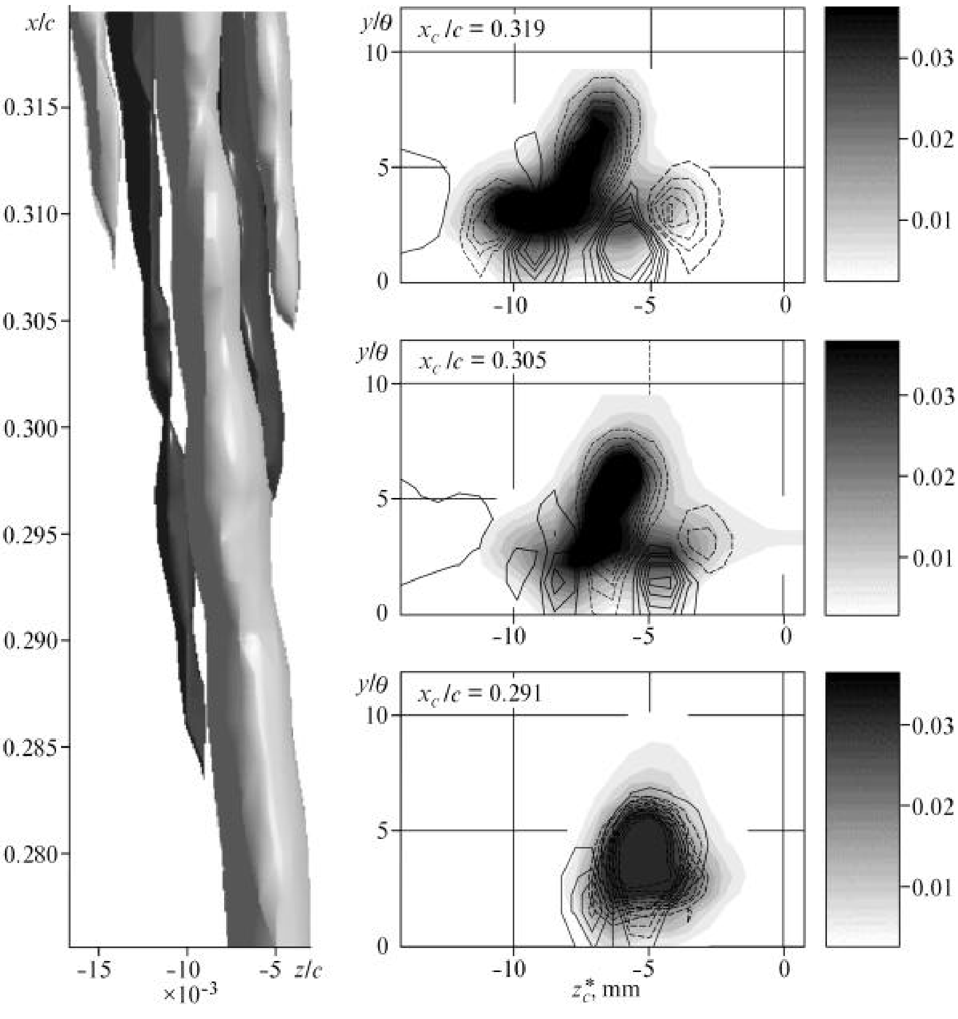

Fig. 4. The 3D picture of the streaky structure development and the secondary high-frequency disturbance with frequency of 1083 Hz, $U_\infty = 6$ m/s.

Left: for some t_0 the instant velocity distortions isosurfaces are shown in the coordinate system of the wing. Right: the contour diagrams of the corresponding sections, the solid lines — $+\Delta\bar{u}$, the dotted lines — $-\Delta\bar{u}$, half-tones — mean-velocity fluctuations u'_f. (From the results of hot-wire measurements).

It is seen that the isolines of the mean velocity profiles demonstrate the regions of a velocity defect, and the regions of its excess are located symmetrically concerning their transversal direction. The given distribution is typical of development in a shear layer of a longitudinal vortex localized in the transverse direction or the streaky structure. Two circumstances observed in the given distribution should be noted. The first circumstance is the longitudinal structure, which is continuously displaced in direction of negative *z* with its downstream motion, the second one is that new regions with the velocity defects appear that point to arising new longitudinal structures placed symmetrically on *z* with respect to the first. It is distinctly seen in the spatial pattern of the streaky structure development $\Delta\overline{u} = f(x, z)$ (see Fig. 4). The velocity defect localized on *z* at $x_c/c = 0.29$ is transformed downstream into several regions. It is drifted towards the negative *z* under angle 6° with regard to the *x*-axis and, evidently, is related to the crossflow on the swept wing (see Fig. 1, *b*, the streamline turn is in the given wing area). It should be noted at once that a longitudinal structure multiplication on its evolution downstream is related to the artificially excited secondary disturbance developing on it. In case of absence of such, under the same experimental conditions (the flow velocities, model geometry, and its spatial position) the longitudinal structure is dissipated downstream.

Let us consider the contour diagrams of the velocity fluctuation isolines, i. e. the secondary high-frequency disturbance induced by acoustics (see Fig. 4). It is seen at its initial development stage (at $x_c/c = 0.29$) that the secondary disturbance maximum coincides with the maximum of the velocity defect region in distribution $\Delta\overline{u} = f(z)$. Figure 5 shows the mean velocity profiles for different x_c/c, where the secondary disturbance develops at the inflection point of the mean velocity profile,

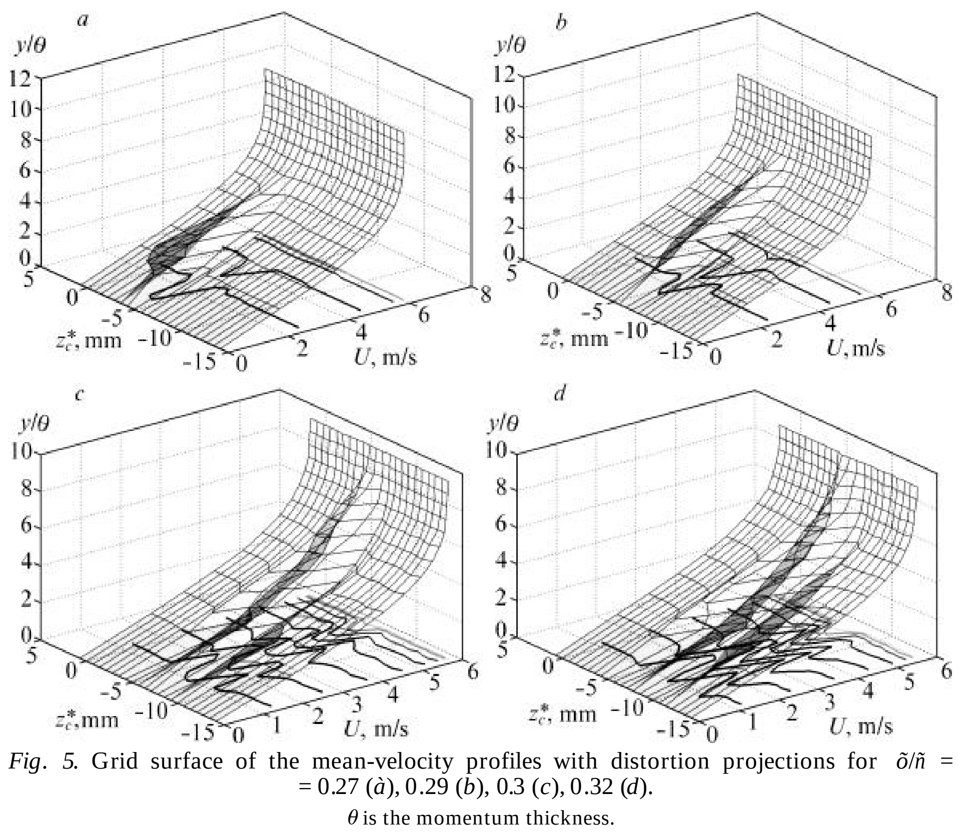

Fig. 5. Grid surface of the mean-velocity profiles with distortion projections for õ/ñ = = 0.27 (*à*), 0.29 (*b*), 0.3 (*c*), 0.32 (*d*).
θ is the momentum thickness.

i. e., an inviscid instability of the velocity profile takes place, that coincides with the linear theory of stability. Further downstream a secondary disturbance intensity remains constant, and its maximum gradually moves upwards from the wall that is related to inflection point displacement of the $\Delta\overline{u} = f(y)$ profiles (see Fig. 5). This fact points to development of the streaky structure varicose instability that is related to an unstable distribution of mean velocity normally to the wall $\Delta\overline{u} = f(y)$ [6] in contrast to the sinusoidal instability depending on the transverse velocity profile $\Delta\overline{u} = f(z)$ [7–9]. The following features can be distinguished during downstream evolution of the secondary disturbance: a multiplication of the high-frequency structure in transverse direction, where the maximums in intensity of new structures coincide with the velocity gradients in $\Delta\overline{u} = f(z)$ distributions, that it is seen in Fig. 4; the disturbance intensity firstly rapidly grows from 1 % at $x_c/c = 0.274$ up to 3.5 % at $x_c/c = 0.286$ and then it achieves the level of 3.5 % downstream. Further, downstream, the flow becomes turbulent.

Figure 6 shows the pattern of a spatial visualization of a streaky structure evolution with the secondary disturbances developed on it in the laboratory frame x, y, z performed by hot-wire measurements. It is seen that the structure has a longitudinal modulation caused by development on it of a high-frequency disturbance, that is typical of the varicose instability. Step of modulation correlates with the wavelength λ of the secondary disturbance, that is 4–5 mm in the given experiment at frequency $f = 1083$ Hz and flow velocity equal to $U_\infty = 6$ m/s. Downstream multiplication and generation of new streaky structures are observed. As it was noted in introduction, the varicose instability development leads to appearance of peculiar vortex structures represented by two counter-rotating vortices closed with a head (on type of the lamda-, horse- or hairpin-shaped vortices). Figure 7 demonstrates the picture of a spatial visualization of the secondary high-frequency disturbance in the coordinates x, y, and z performed with hot-wire measurements, as in Fig. 6. Typical nonstationary formations multiply in transverse direction in accordance with the pattern observed in Fig. 6. However, in the given case we observe only the development of a high-frequency component of the streaky structure breakdown mechanism. Exactly secondary instability development leads to a laminar-turbulent transition, and the varicose instability mode is observed at the nonlinear stage of its development in the form of horse-, hairpin-shaped, and other vortices. However, in the given case, the localized formations of a slightly different type are observed, that is, evidently, related to that we study a streaky structure varicose instability in the swept wing boundary layer. In [12] it was shown that the lamda-structures in the swept wing boundary layer become axisymmetrical due to effect of a crossflow, and

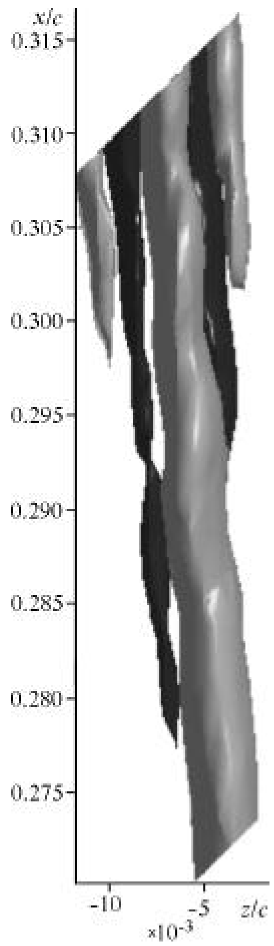

Fig. 6. Spatial picture of the streaky structure development in the swept wing boundary layer.

Black — excess of $\Delta\overline{u}$, grey — defect of $\Delta\overline{u}$ (from the hot-wire measurements in the laboratory coordinate system).

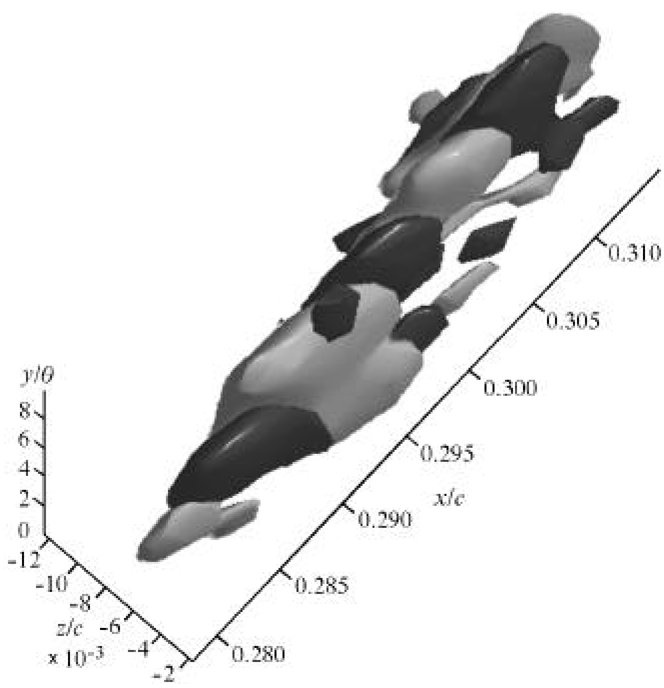

Fig. 7. Spatial picture of development of a high-frequency secondary disturbance developing on a streaky structure in the swept wing boundary layer (from the hot-wire measurements in the laboratory coordinate system).

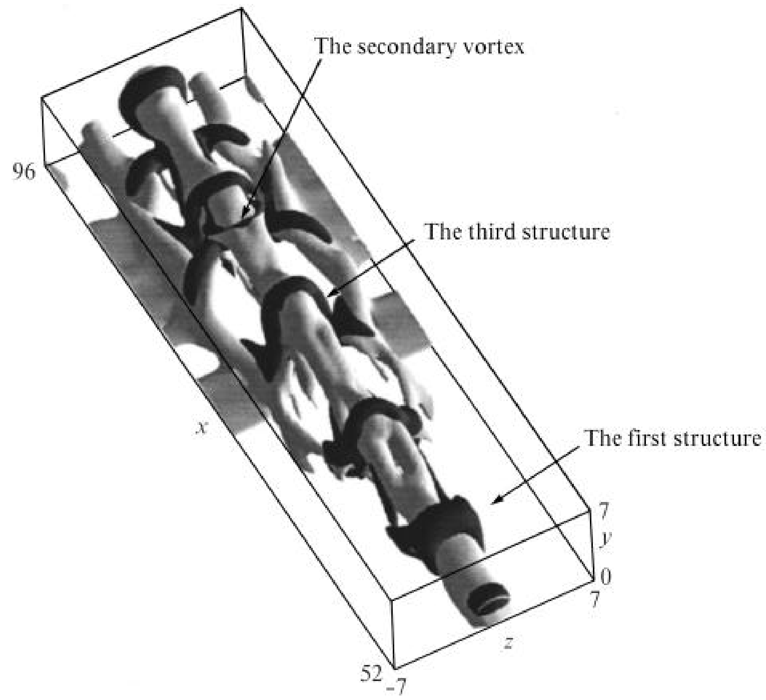

Fig. 8. Development of a varicose instability mode according to [5].
Light tint is a low-velocity structure, dark-grey tone is the low-pressure region.

at the sweep angle of 45° and higher from the two counter-rotating vortices of the lamda-structure only one longitudinal localized vortex remains. In this experiment the sweep angle is 45°, and single structures are observed remaining from symmetrical formations existing in the absence of the crossflow in the boundary layer. In conclusion, to verify that exactly the streaky structure varicose instability is investigated in the swept wing boundary layer, let us present the pattern of development of the streaky structure varicose instability in a swept wing boundary layer in a turbulent boundary layer on a flat plate studied by a direct numerical simulation in [5] (Fig. 8 taken from work [5]). Comparing the given picture with Figs. 6 and 7 several coincident qualitative characteristics of the varicose instability can be noted in both cases: 1) transverse modulation of a streaky structure caused by development of the secondary disturbance on it; 2) multiplication of the structure (excitation of new streaky structures) at its downstream development; 3) appearance of the horseshoe-shaped (see Fig. 8) and longitudinal vortices (see Fig. 7) localized in space.

4. CONCLUSIONS

Due to the experimental investigation of a streaky structure varicose instability on a swept wing the following is established.

1. The instability of a varicose type can take place in the given case.

2. Development and increase of the secondary disturbances on a streaky structure is found to be caused by unstable distribution of a mean velocity normally to the wall. The given fact corresponds with the basic criterion of a varicose instability.

3. The secondary high-frequency disturbance is shown to lead to the streaky structure longitudinal modulation and downstream excitation of the new streaky structures.

4. The structures localized in space appear due to development of the secondary disturbance. In contrast to similar formations (two counter-rotating symmetrical vortices closed with a head) in the absence of the crossflow in the boundary layer they represent an asymmetrical structure in the form of a localized vortex caused by a crossflow effect.

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