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EXPERIMENTAL STUDY OF MECHANISM OF HIGH-FREQUENCY BREAKDOWN OF Λ-STRUCTURE

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The paper presents the results of the experimental research of characteristics of Λ-structures development and mechanism of their transformation into the turbulent spots. It was shown that isolated Λ-structure can damp as well as increase downstream and transform into a turbulent spot. According to their structure these types of disturbances are two counter-rotating vortices ("legs" of disturbances) closed by the "head" in the leading edge. The difference of these two types is that Λ-structure that damps is a kind of a hairpin vortex and it does not cross the upper boundary layer edge; the "head" of the increasing Λ-structure crosses the upper boundary layer edge and disturbance obtains the form of the Greek letter Λ. It was defined that Λ-structure increase is connected with the development of the secondary high frequency disturbances on the "legs" of the structure. The reason of it is probably local transverse velocity gradient $\partial u / \partial z$ on the "legs" of Λ-structure which creates conditions for the secondary disturbances development in it. It was shown that frequency of the secondary disturbance decreases because of continuous extending of a localized disturbance under its propagating downstream. Secondary high frequency breakdown of structures is also observed at their periodical generation.

INTRODUCTION

As is known a laminar-turbulent transition in the boundary layer at low free stream turbulence takes place with appearing and developing of instability waves so called Tollmien — Schlichting waves (TS). At a non-linear transition stage when two-dimensional TS wave reaches high amplitudes it transforms into typical three-dimensional structures resembling Greek letter Λ at visualization of flow [2]. When these structures develop downstream they cause turbulization of a flow. Mechanism of development and breakdown of Λ-structures is not clear yet. At classic transition whose linear stage is described by the linear theory of stability there are known two scenarios of Λ-structures appearing at non-linear stage: harmonic or Klebanoff transition, *K*-mode [3, 4] when at visualization of a flow structures are placed one after another [2] and sub-harmonic or *N*-mode [7, 8] when the structures are set as on a chess-board [2]. On the other hand Λ-structures are observed at visualization of flows modeling other types of transition [5] and under natural conditions [6].

Thus, the role of the longitudinal vortex structures (Λ-structures) in the transition process is important therefore it is necessary to study them. Numerous theoretical and experimental research explaining non-linear stage of the classic transition makes it possible to understand this mechanism. In particular it was found that *N*-mode of a transition is performed by non-linear resonance interaction of the basic and two oblique waves with sub-harmonic frequency [7, 8]. *K*-mode of transition is more difficult to explain. Typical high frequency bursts so called "spikes" on the oscillograms were explained by the development of the secondary high frequency disturbances on the local distortions of the profile of mean velocity caused by non-linear development of a disturbance [3]. This fact was confirmed by a physical experiment [9]. However, later on the so called resonance-wave concept [10] was suggested in which the appearance of spikes was explained not by the secondary high frequency instability but by solitons generated in the upper boundary layer edge. Turbulization of the flow was performed by four wave parametrical resonance which generated solitons. This concept was confirmed by the numerical experiment [11]. It should be mentioned that this flow turbulization was experimentally confirmed only at the initial stages of non-linear development of disturbances which can be described theoretically. The mentioned concept is to be proved experimentally and theoretically for the later stages of transition of a flow into a turbulent state.

Modeling of classic transition was mainly connected with the generation of the periodic disturbances in the boundary layer, i. e. introducing a harmonic wave. At non-linear transition stage a wave was transformed into three-dimensional Λ-structures which propagating downstream created turbulence. It is known that in research of a "natural" transition it was found that in the majority of cases a transition occured through the stage of the formation and development of turbulent spots, i. e. structures localized in time and space. If localized Λ-structures can be transformed into turbulent spots as in the mentioned above experiments it is impossible to distinguish the given structures because of their close packing and their influence on each other on this reason. The study of turbulent spots formation is very important because it helps to understand a transition in shear layers. Usually a turbulent spot was excited by powerful impulses in a boundary layer [12] therefore the possibility of appearing a turbulent spot in the process of development of vortex disturbance was not studied. In [13] a separated Λ-structure was first modeled and it was shown that it was transformed into a isolated turbulent spot downstream. When amplitude of a disturbance source decreased a disturbance damped but when amplitude or flow velocity increased or at superimposing high frequency periodic disturbance the turbulent spot appeared again. In papers [14, 15] a hairpin vortex was investigated which was the same Λ-structure but more extended streamwise. It was shown that it is two counter-rotating vortices ("legs" of the structure) ended with the "head" which crosses the upper boundary layer edge. As structure propagating downstream secondary vortices are generated on its "head" and "legs" and it transforms into a turbulent spot.

The purpose of this work was to study in detail a transformation of isolated Λ-structure into a turbulent spot and obtain qualitative and quantitative information of this mechanism.

2. EXPERIMENTAL EQUIPMENT AND METHOD OF RESEARCH

The research was performed in a low free stream turbulence wind tunnel T-324 of the Institute of Theoretical and Applied Mechanics SB RAS. This tunnel has a transverse section of the test part 1000 × 1000 and the length of 4000 mm. A flat plate (*1*) made of acrylic plastic which is 1500 mm long, 1000 mm wide and 10 mm thick and vertically installed in the test part of the tunnel was used as a model. Disturbances were introduced in the boundary layer of a model through a slot (*2*) of 18 mm length, 0.4 mm width and set at a distance of 200 mm from the leading edge of the model (Fig. 1). The slot was formed to create unequal distribution of intensity of the introduced disturbance along it (see [13]). Disturbances were introduced by a dynamic loudspeaker (*3*, *4*). To generate high frequency disturbance a sinusoidal electric signal with frequency of 200 – 250 Hz was transmitted to the loudspeaker (*3*) from the outlet of a special generator. Pulsed localized disturbance to generate isolated Λ-structure was formed by the loudspeaker (*4*) to which short electric pulses of frequency 0.5 – 1 Hz were sent. To generate periodic Λ-structures the frequency of these pulses was 60 Hz. Periodic and pulse signals were synchronized as one and the same generator was their source. In this experiment a flow velocity

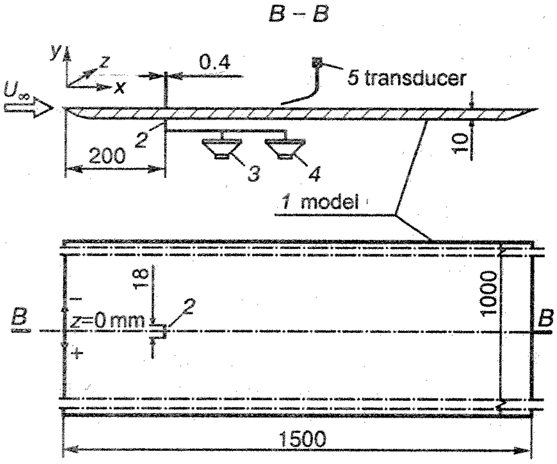


Fig. 1. Experimental setup.
Dimensions in mm.

was 5.6 m/s, the free stream turbulence of a free flow was not more than 0.04 %. Distribution of velocity in a boundary layer corresponded to Blasius flow.

All measurements were performed by single wire probe of hot-wire anemometer with constant temperature (*5*). Thickness of the probe wire was 6 mkm, the length was about 1 mm. The streamwise component of velocity fluctuations (u') and mean velocity ($\bar{u}$) were measured in various points in a space of x, y, z (see Fig. 1). A free stream velocity in the test part of the wind tunnel was measured by Pito — Prandtl probe connected with a bent liquid micromanometer. Hot-wire anemometer probe was calibrated in a free flow opposite Pitot — Prandtl tube at free stream velocity in the range of 2 – 20 m/s in such a way that the error of the mean velocity was less than 3 %. Calibration function is described by formula

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

where E and E_0 are output voltages of the anemometer at flow velocity U and in rest, k_1, k_2 and $1/n$ are constants determined empirically. The first term corresponds to the known King expression, the second one is added to consider free convection at small flow velocities [16].

Calibration of the probe of hot-wire anemometer, collection, storing and processing of measured information were performed by PC "Macintosh LC II" connected with the bridge of DISA 55M01 hot-wire anemometer of by analog-to-digital converter MacADIOS-ADIO (GW instruments company). A measured signal from hot-wire anemometer probe comes to one inlet of analog-to-digital converter and to its trigger inlet a signal from a low frequency source (short pulses with frequency of 0.5 – 1 Hz) was transmitted to preserve phase information of the investigated disturbances. Introduced into computer single realizations of disturbances development in space and time were ensemble-averaged to improve a relation signal/noise. It made it possible to distinguish a weak measured signal from undetermined noise. From 5 to 100 of single realizations were averaged depending on the level both of a distinguished signal and noise. Development of disturbances along the transverse coordinate z was measured in a region of their maximum intensity by normal y to a plate surface.

3. PROCESSING OF MEASUREMENT RESULTS

Measurement results were processed by a computer according to the program of space-time Fourier analysis. Space-time distribution of streamwise component of velocity u' was subject to Fourier-transformation by space coordinate z:

$$u'(t,\beta) = 1/z_0 \int_{-z_0/2}^{z_0/2} e^{-i\beta z} u'(t,z)dz\,. \qquad (2)$$

For various coordinates x normalization was performed by the same quantity $z_0 = 128$ mm which led to one and the same number of β-harmonics for various sections along the longitudinal coordinate x (step of the transverse coordinate z was constant and equal to 1 mm). If the domains of measurements along z were less than + 64 mm then on the left and (or) on the right zero points were added in order to obtain the same quantity z_0. Since function $u'(z, t)$ is real amplitude part $u'(t, \beta)$ is symmetrical in relation to $\beta = 0$.

The results of calculations were presented in the form of contour diagrams of isolines of velocity fluctuations in the planes $z - t$; $y - t$; $y - z$ for various coordinates x. Solid isolines reflected velocity excess, the dashed ones showed its defect. Deviations from the mean velocity shown by isolines are indicated by percent in relation to the free stream velocity (min is a velocity defect, max is a velocity excess, step is a step of isolines); coordinate z is given in mm, time axis t is graduated in ms. Isolines are plotted with constant as well as varied step by amplitude. In some cases experimental information was presented as distributions along the transverse and normal coordinates of the maximum amplitudes of velocity pulses $A = f(z)$, $A = f(y)$.

4. RESULTS OF MEASUREMENT

4.1. Quality characteristics of development and transformation of Λ-structure in a turbulent spot

In the introduction it was said that the first results of the isolated Λ-structure transformation in a turbulent spot were presented in [13]. In Fig. 2, *a* visualization picture of this process in the plane $z - x$ taken from this work is shown. It is seen that Λ-structure as well as a turbulent spot are well identified. At decrease of the disturbance amplitude in a source a turbulent spot did not appear and disturbance damped downstream. In Fig. 3 taken from [14] oscillograms are measured in the plane of symmetry of a localized disturbance depending on the streamwise coordinate x for two flow velocities. At $U_\infty = 6.6$ m/s near the source of disturbances at $x = 240$ mm ($x_{slot} = 200$ mm) an oscillogram shows a defect of velocity and the presence of high frequency natural disturbance with frequency $f \approx 170$ Hz connected with Λ-structure formation at the leading edge. Oscillograms show that a disturbance damps downstream. At an increase of a flow velocity up to $U_\infty = 11$ m/s disturbance changes radically downstream. First, the amplitude of a high frequency component of disturbance increases sharply near the source ($x = 240$ mm), secondly, its development downstream transforms previously damped localized disturbance into a turbulent spot. An increase of the amplitude of the introduced disturbance in a source without increasing flow velocity has the same result. A conclusion can be made that a high frequency "natural seed" (connected probably with tilting effect of an isolated wave in a shear flow) at the leading front of a localized disturbance under certain conditions may increase and lead to a transformation of a

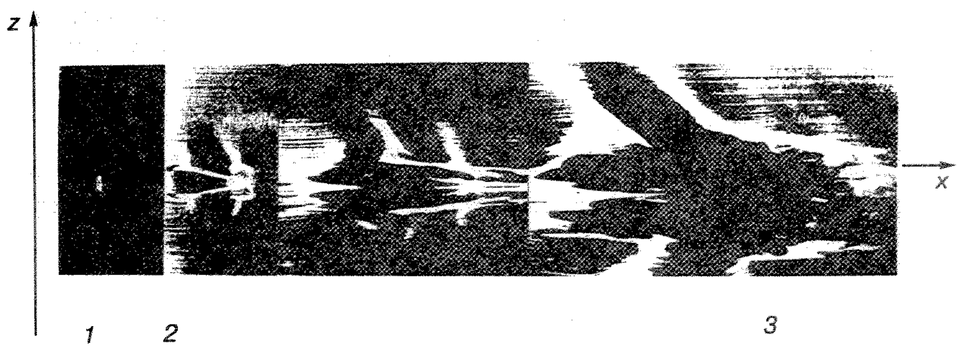
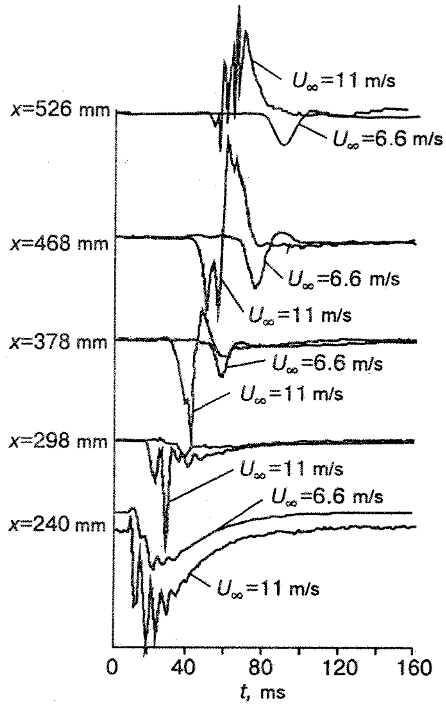


Fig. 2. Visualization picture of Λ-structure transformation in a turbulent spot [13].
1—a localized disturbance; *2*—Λ-vortex; *3*—a turbulent spot; the view in the plane $x - z$.

Fig. 3. Oscillograms of Λ-structure development at various free stream velocity at z = 0 mm.



damped localized disturbance in a turbulent spot as it is in Fig. 2. As the localized disturbance propagates downstream the frequency of the developed in it a high-frequency secondary disturbance decreases ($f \approx$ 130 Hz and x = 468 mm) probably due to a streamwise stretching of the first one [17]. The conditions providing an increase of a high-frequency natural disturbance in this structure and its characteristics of development will be considered in detail in the next section of this paper in which an artificial disturbance will be studied and phase information made it possible to obtain quantity data.

At this stage we estimated only main quality characteristics of Λ-structure transformation in a turbulent spot. Above the development of a natural high-frequency "seed" in the localized disturbance was considered, further the results of research of a damped localized disturbance interaction with artificially introduced high-frequency disturbance will be presented. The results of the similar research were published in [18] where it was shown that in interaction of two damped disturbances of Tollmien — Schlichting wave and Λ-structure an increasing wave packet appears with frequency by two times less than TS wave has which is transformed in a turbulent spot downstream (Fig. 4). Oscillograms in Fig. 5 (taken from [14]) demonstrate a development of a damped localized disturbance downstream as well as its interaction with TS wave (f = 290 Hz) ending in a formation of a turbulent spot. Qualitatively this process is similar to the process of development of a natural high-frequency "seed' presented above (see Fig. 2).

Thus, on the basis of the results of a research presented here we may state the following:

a isolated Λ-structure was modeled and various mechanisms of its transformation in a turbulent spot was qualitatively investigated;

it was shown that Λ-structure can damp downstream;

damped Λ-structure in case of a development of a "seed' or in interaction with a high-frequency wave can be transformed into a turbulent spot;

since Λ-structure stretchs continuously in a shear layer a frequency of high-frequency disturbance developing in it decreases.

4.2. Quantitative characteristics of Λ-structure development and transformation in a turbulent spot

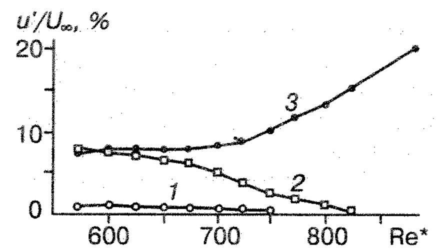


Fig. 4. Curves of increasing disturbances.
1 — Tollmien — Schlichting wave, *2* — a localized disturbance, *3* — interaction of T — S wave with a localized disturbance, $y = y(u_{max})$.

The next stage of research of Λ-structure transformation in a turbulent spot was to study quantitative characteristics of

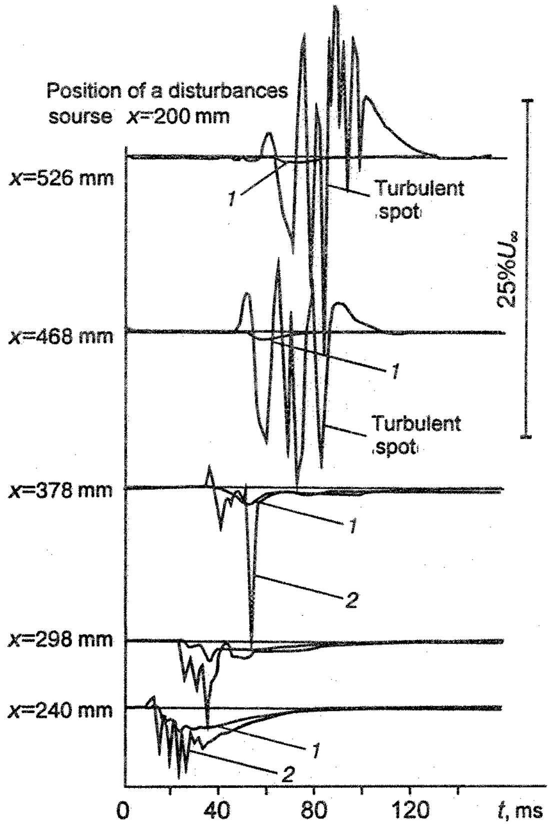


Fig. 5. Oscillograms of a damped Λ-structure (*1*) and Λ-structure interacting with a high-frequency disturbance (frequency f = 290 Hz) (*2*) at z = 0.

the process in detail. Experiments were performed under the same conditions as the visualization picture in Fig. 2 was. As it was mentioned in case of absence of disturbances in a boundary layer a laminar flow with a mean velocity profile close to the Blasius one was realized. The measured thickness of the boundary layer at distance x from the leading edge equal to 377, 480 and 587 mm was 5; 5.7 and 6.3 mm respectively. (It should be noted that the conditions of the given experiment and visualization experiment presented in Fig. 2 were the same).

The distribution of intensity of the localized disturbance A_{min}, A_{max} introduced into the boundary layer along a spanwise coordinate is given in Fig. 6, *a*. The diagram shows that it is presented by a peak of velocity defect in the plane of a disturbance symmetry and two peaks of the excess of velocity placed symmetrically in relation to the peak of velocity defect. This distribution is typical of disturbances with two counter rotating vortices (Goertler vortices, hairpin-shape and Λ-shape vortices etc). The distributions show that disturbance damps downstream. The structure of the given damped localized disturbance is clearly presented by isolines of velocity fluctuations in the plane $z - t$ at $y = y\left(u'_{max}\right)$ in Fig. 6, *b* – *d* in which the dashed lines show the region of velocity defect in the plane of symmetry, solid lines show two regions of velocity excess on both sides of it. One can observe oblique waves on the edges of disturbances in a form of the curved at certain angle isolines (the dashed lines). Propagating downstream disturbance damps. It is shown by a change of its maximum amplitude from 14 % at x = 377 mm (see Fig. 6, *b*) to 6 % at x = 587 mm (see Fig. 6, *d*).

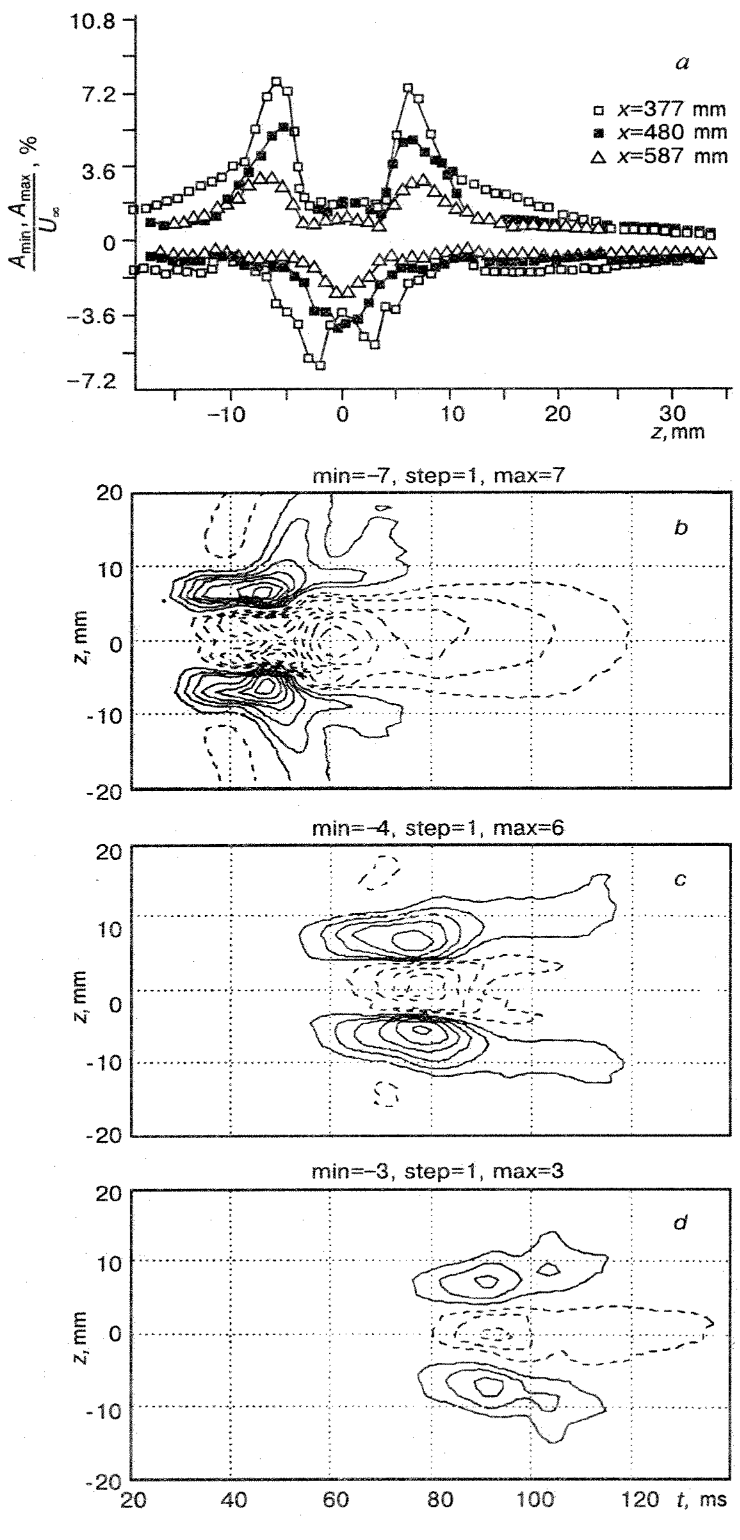


Fig. 6. Distribution of intensity of a localized disturbance (Λ-vortex) by transverse coordinate for various values x (*a*) and isolines of fluctuations of a streamwise component of velocity in the plane $z - t$ at x = = 377 mm (*b*), 480 mm (*c*) 587 mm (*d*); U_∞ = 5.6 m/s, $y = y(u'_{max})$.

At superimposing high-frequency periodic disturbance (a wave with frequency f = 200 Hz and amplitude A_{RMS} less than 1 %) it interacts with a localized disturbance which leads to growth of the latter, especially on the "legs" region, i. e. in the counter-rotating vortices. It is shown by intensity distribution of the localized disturbance and its interaction with a wave along the spanwise coordinate x = 377 mm (Fig. 7, *a*) and in the figures of isolines of velocity fluctuations of interacting disturbances in the plane $z - t$ at $y = y\left(u'_{max}\right)$ in Fig. 7, *b* – *d*. Amplitude of the localized disturbance at interaction with a wave increased by 4 times on the "legs" of the structure (see Fig. 7, *a*, at $z \pm 5$ mm) as compared to the amplitude of a disturbance without wave. Structure of the "legs" of a disturbance acquired a horseshoe shape with some periods of high frequency disturbance in them (see Fig. 7, *b* – *d*). Amplitude of disturbance (which is defined as difference of max and min in each figure) rises downstream from 45 % at x = 337 mm to 56 % at x = 480 mm (see Fig. 7, *b*, *c*) till that time when it is transformed in a turbulent spot at x = 587 mm (Fig. 7, *d*). "Legs" of the localized disturbance stretch during its propagation downstream that is why frequency of the secondary high-frequency disturbance developing in them decreases continuously.

Comparing the intensity distributions of the localized disturbance and its interaction with the wave by the normal to a surface for various coordinates downstream (Fig. 8) we may note the following features.

1. On the "legs" of "decreasing" localized disturbance and that one interacted with the wave the region of velocity excess prevails whose maximum of intensity is near the wall (more detailed information is in Fig. 25, 30 and in [19]).

2. In the plane of symmetry, on the contrary, the velocity defect region prevails whose maximum is near the upper boundary layer edge (Fig. 8, *a*, *c*, at x = = 377 mm). Downstream for localized disturbance having interacted with high-frequency wave this region propagates far across the upper edge of a boundary layer showing that the "head" of the structure comes out of a boundary layer (Fig. 8, *d*, at x = 480 mm). Damped disturbance remains inside the boundary layer (Fig. 8, *b*). Coming out of the "head" of increasing Λ-structure beyond the upper edge of the boundary layer was mentioned in [15] (Fig. 9).

Consider in detail the figure of isolines of velocity fluctuations in the plane $y - t$ at x = 377, 480 mm and spanwise coordinate z = 0 mm. The structure of the damped localized disturbance at x = 377 and 480 mm (see Fig. 8, *a*, *b*) does not change. Considerable changes take place when the localized disturbance is superimposed by a high frequency wave. The "head" of the structure comes close to the upper edge of the boundary layer, several closed regions of isolines appear with defect and velocity excess (see Fig. 8, *d*, at x = 480 mm).

Thus, we may state that the structure of the damped localized disturbance and its interaction with high frequency wave are two counter rotating vortices ("legs") ending with the "head". The difference is that in the first case a disturbance does not pass the boundary layer edges and damps downstream, in the second case a disturbance "head" passes the boundary layer and disturbance is transformed in a turbulent spot downstream.

To understand better the structure of these two disturbances measurements of the distribution of intensity and velocity fluctuations along the spanwise coordinate z for various positions by the normal to the surface y at x = 480 mm were performed. Contour isolines of the velocity fluctuations of the damped localized disturbance in the transverse coordinate (Fig. 10, *a*, *b*) confirm characteristics of the given disturbance mentioned above. The structure of the damped disturbance presents probably two counter rotating vortices ending with the "head". The "head" of the structure is inside a boundary layer, "legs" have a weak bend to the "head" therefor typologically a disturbance reminds of rather a "hairpin" vortex than Λ-vortex. Maximum width of the structure is approximately 25 mm.

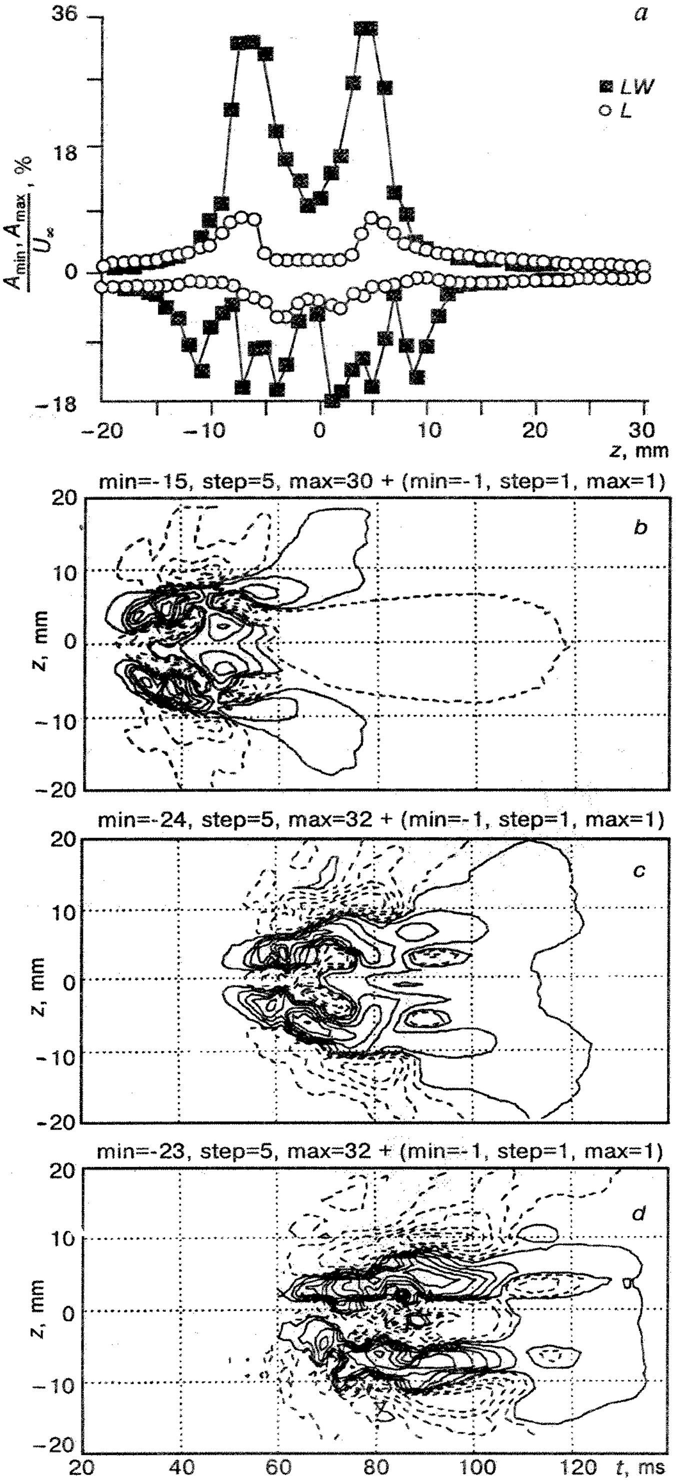


Fig. 7. Distribution of intensity of a localized disturbance L and its interaction with high frequency wave LW at $x = 377$ mm by a transverse coordinate (*a*) and isolines of fluctuations of streamwise component of velocity in the plane $z - t$ of Λ-vortex interacting with high frequency wave ($f = 290$ Hz) at $x = 277$ mm (*b*), 480 mm (*c*), 587 mm (*d*); $U_\infty = 5.6$ m/s, $y = y(u'_{max})$.

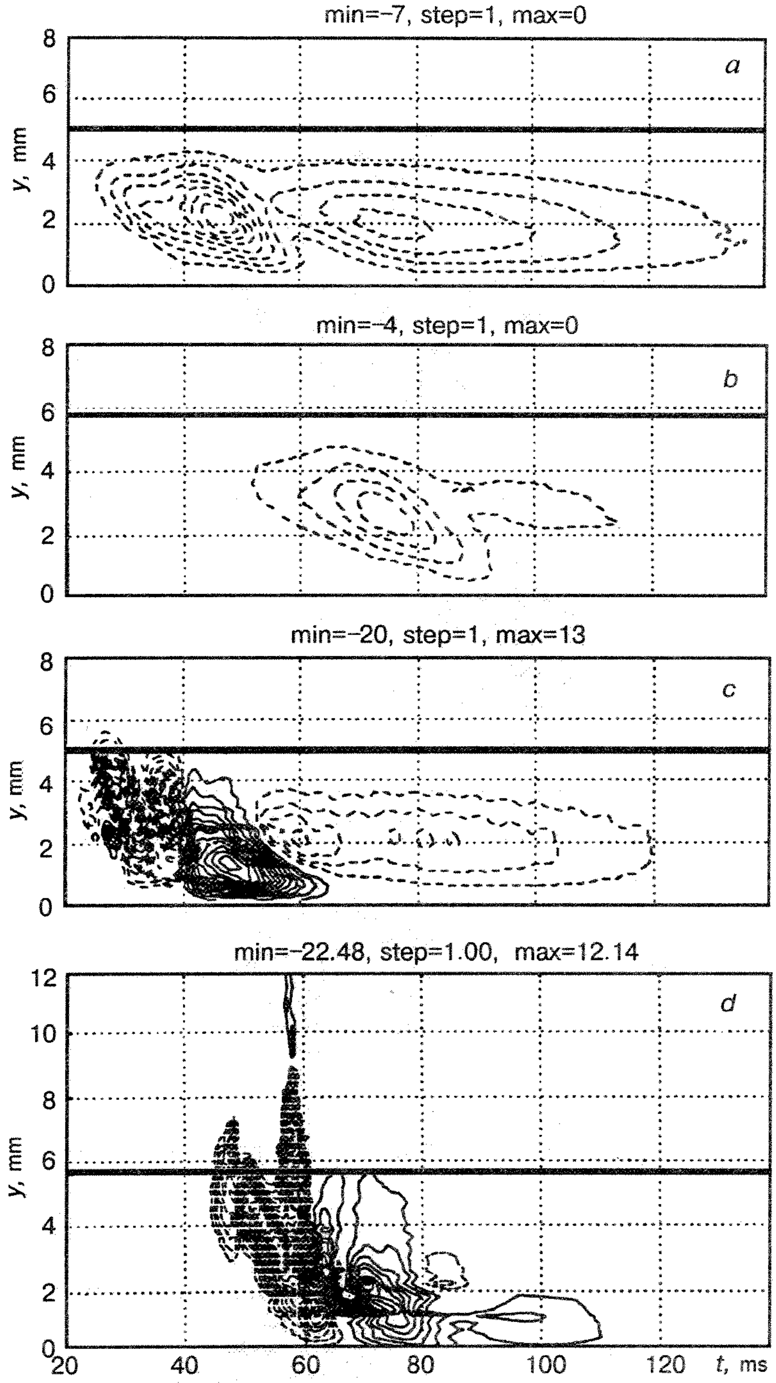


Fig. 8. Isolines of fluctuationsof streamwise component of velocity in the plane $y - t$ of a localized disturbance at x = 377 mm (*a*), 489 mm (*b*) and Λ-vortex interacting with high frequency wave (f = 200 Hz) at x = 377 mm (*c*), 480 mm (*d*), U_∞ = 5.6 m/s, z = 0 mm.

Horizontal line is upper boundary layer edge.

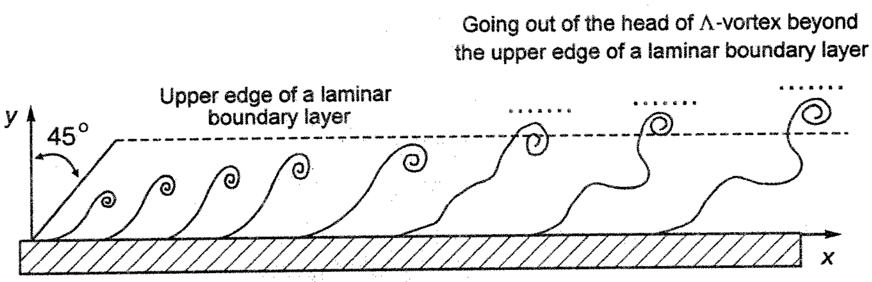


Fig. 9. Scheme of the development of an increasing Λ-vortex downstream in a laminar-boundary layer [15].

At the same distance from the leading edge (x = 480 mm) contour isolines of velocity fluctuations of the localized disturbance which has interacted with a high-frequency wave show (see Fig. 10, *c*, *d*) that at the periphery along the spanwise coordinate two peaks with velocity defect are formed. It means that the structure becomes wider on its "legs" (approximately up to 35 mm) which have a horseshoe shape, their intensity increases. One can observe the formation of the oblique waves at Λ-structure edges. Beyond boundary layer (see Fig. 10, *d*, at y = 8.5 mm) the structure becomes narrower (about 5 mm) with amplitude maximum in the plane of its symmetry. One can make a conclusion that typologically this disturbance reminds of rather a classic Λ-structure (see Fig. 2) than in the first case though a source of generation of both disturbances was the same. The difference is that in the latter case the localized damped disturbance is superimposed by a secondary high-frequency wave. Their interaction led to the fact that a development of the secondary disturbance on the "legs" of the structure which is similar to the development of secondary disturbances in stationary vortices [20] or streaky structures ("puffs") [14, 21] created conditions for a transfer of energy of a mean flow to counter rotating vortices (structure "legs"). As a result of this process disturbance intensity grows and the "head" passes across the edge of the boundary layer.

It should be noted that visualization picture of transformation of a isolated structure into a turbulent spot given in Fig. 2 reflects the process of interaction of disturbances. Secondary disturbances developed on the "legs" of Λ-structure can be observed at visualization of its development in a water channel in [19] (see Fig. 40). Exemplary topological scheme of a damped and increased Λ-structure formed on the basis of present research and analysis is shown in Fig. 11.

4.3. Characteristics of development of periodic Λ-structures and their interaction with a high frequency wave

As it was shown above a isolated Λ-structure may damp or increase in the process of its interaction with a high frequency disturbance. The development of the latter downstream leads to a formation of a turbulent spot. It is a question if periodic Λ-structures, i: e. structures modeling *K*- or *N*- modes of transition can damp and in the interaction with a high frequency secondary disturbance turbulize the flow. To answer this question the experiment of the same model (see Fig. 1) and under the same conditions was performed. Periodic Λ-structures with frequency f = = 60 Hz and high frequency disturbances with frequency 240 Hz were generated. Fig. 12 shows oscillograms of the development of damped periodic Λ-structures downstream and their interaction with a high frequency disturbance. It is seen that when a high frequency disturbance with the amplitude lower than 1 % is introduced in a boundary layer it begins to interact with Λ-structures which then increase and are transformed into isolated in time turbulent formations. The same process is observed under "natural" conditions when high frequency oscillations are not introduced [22]. Thus, as it is in a previous case periodic Λ-structures can damp and

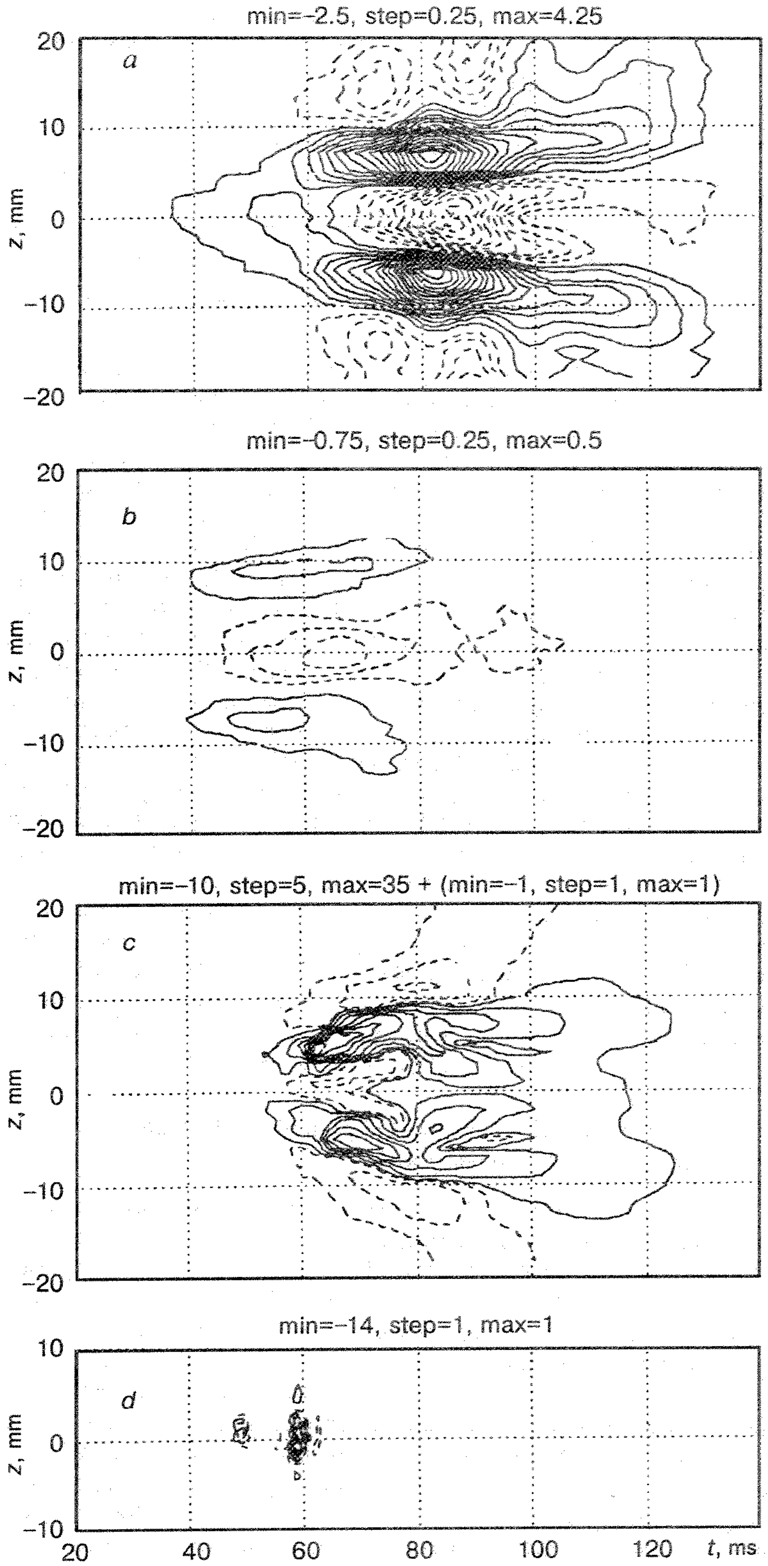


Fig. 10. Isolines of fluctuations of a streamwise component of velocity in the plane $z - t$ of a localized disturbance at y = 1.25 mm (*a*), 5.0 mm (*b*) and Λ-vortex interacting with high frequency wave (f = = 200 Hz) at y = 1.25 mm (*c*), y = 8.5 mm (*d*); U_∞ = 5.6 m/s, x = 480 mm.

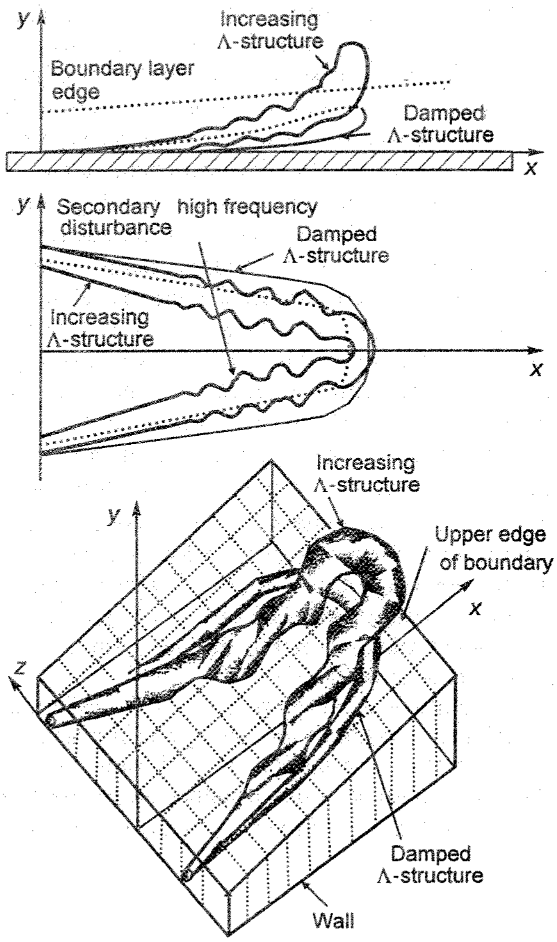


Fig. 11. Spatial scheme of a localized disturbance of Λ-structure type.

under certain conditions (when a high frequency disturbance is introduced) begin to increase and lead to a flow turbulization. The research data show that it is connected with the development of secondary high frequency disturbances on the "legs" of the damped Λ-structure. The reason of an increase of secondary disturbances may be a local transverse gradient of velocity $\partial u / \partial z$ on the "legs" of the structure. In the same way secondary high frequency disturbances are developed in the flows modulated in a transverse direction by streaky structures ("puffs") [21] and stationary vortices [19, 22] etc.

In conclusion we should mention the following. To control the process of a laminar-turbulent transition it is necessary to know its mechanism. In this respect research carried out in [14, 20, 21, 23 –

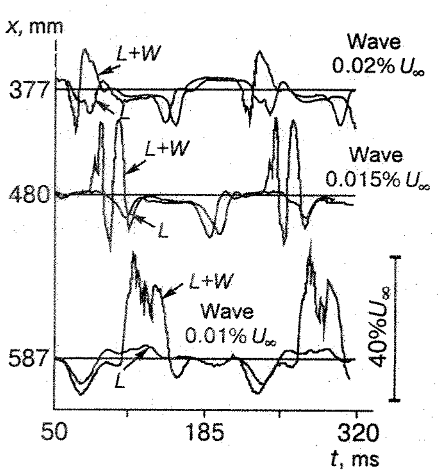


Fig. 12. Oscillograms of the development of periodic (f = 60 Hz) damped Λ-structures (L) and periodic Λ-structures ($L+W$) interacting with a high frequency disturbance (f = 240 Hz) ($L+W$) at U_∞ = = 5.6 m/s, x_{slot} = 200 mm, z = 0 mm.

25] which showed the role of a transverse velocity gradient $\partial u/\partial z$ for the development in it of secondary high frequency disturbances in various three-dimensional flows made a great contribution into the study of the methods of control connected with the effect on $\partial u/\partial z$ gradient. In three-dimensional flows modulated in a transverse direction by streamwise stationary vortices of Goertler type and "cross-flow" vortices the secondary high frequency travelling disturbances can appear, develop and lead to a transition depending on the value of $\partial u/\partial z$ gradient. Decrease of intensity of stationary vortices with riblets [26] or by local suction [27] led to a decrease of $\partial u/\partial z$ gradient, development of secondary disturbances are stopped or delayed and transition is prevented. On the other hand travelling localized disturbances of Λ-vortices, "puffs" (streaky structures) etc are streamwise vortices or streaks of the accelerated or slow fluid which as well as stationary vortices create spanwise modulation of a flow which is local in time and space. Gradient $\partial u/\partial z$ may also be a reason of the development of the secondary disturbances in it. Investigation of the control of Λ-vortices transformation into turbulent spots by riblets [28] showed that the intensity of Λ-structure "legs" decreased and as a result $\partial u/\partial z$ gradient decreased too, development of the secondary disturbances was slower or stopped. Generation of the secondary vortices over the "head" and on the "legs" ceased which led to delaying of Λ-vortices transformation into a turbulent spot. The same result was obtained in research of the influence of riblets, spanwise wall oscillations and the local suction on the development of secondary disturbances in "puffs" (streaky structures) [29, 30].

Thus, research of the control of development and transformation of various streamwise vortices in turbulence made it possible to confirm again one of the possible mechanisms of turbulization of a laminar flow through the process of development of the secondary high-frequency disturbances on the local gradients of velocity $\partial u/\partial z$ formed in the modulation of the flow in a transverse direction by these structures.

5. CONCLUSION

On the basis of research of Λ-structure transformation into a turbulent spot we can make the following conclusions.

1. Localized disturbances of Λ-vortices type may damp as well as increase. Topologically both are counter rotating vortices ("legs") closed by the "head" in the leading front. The difference is that the first one is close to a "hairpin" vortex and disturbance does not pass across the upper edge of the boundary layer, the second one has the form of a Greek letter Λ and a disturbance "head" comes far out of the upper edge of a boundary layer.

2. Λ-structure transformation into a turbulent spot is a result of the development of secondary high frequency disturbances on the "legs", i. e. in the region of maximum local velocity gradient $\partial u/\partial z$. This process may take place either in the development of a natural high frequency disturbance whose "seed" may be in similar localized disturbances or through the mechanism of disturbances interaction. The main condition of realization of this mechanism is a respective value of gradient $\partial u/\partial z$ which is connected with the level of intensity of a localized disturbance and periodicity of counter rotating vortices ("legs") in a spanwise coordinate.

3. Frequency of the secondary high frequency disturbance on the "legs" of a structure decreases because of the constant stretching of a localized disturbance in a shear layer.

4. When a secondary disturbance develops it promotes energy transfer of a mean flow to low frequency disturbances ("legs" of Λ-structure). The intensity of the "legs" increases which makes the "head" of Λ-structure come out across the upper edge of a boundary layer.

5. Mechanism of breakdown of periodic Λ-structures typical of *K*- and *N*- modes of transition as in the case of destruction of a separate Λ-structure or streaky structures is connected with the development of the secondary high frequency disturbances in them.

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