STREAKY STRUCTURES IN A WING BOUNDARY LAYER AT HIGH FREE STREAM TURBULENCE AND MODELLING OF THE TRANSITION IN SUCH FLOW

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1. Introduction

Raised interest of researchers to a problem of the laminar-turbulent transition at high free stream turbulence can be observed recently. The given interest is connected to a lot of reasons both of the scientific nature and requirements of the modern engineering with point of view its new opportunities. It is known, that laminar-turbulent transition at low free stream turbulence is occured caused by the process of generation and development of the instability waves, so-called, Tollmien – Schlichting (TS) waves. This type of transition was in details investigated by many researchers and continues to be studied in nowadays. A more complex way of understanding of the laminar flow breakdown mechanism into the turbulent state for the wall shear layers, where the boundary layer flow modulated by longitudinal, localized in spanwise direction structures. In this case, the classical scenario of transition due to the mechanism of spatial evolution of a TS wave ceases to work and it is necessary to understand what processes result in occurrence of longitudinal structures and what mechanism of their breakdown. By one of such transition mechanisms is the transition mechanism at high free stream turbulence. Experiments in the natural conditions [1-3] were shown, that the flat plate boundary layer at high free stream turbulence was modulated by streaky structures in spanwise direction. It was shown, that the spanwise scale of these structures correlated with a boundary layer thickness. On the other hand, all researchers observed the turbulent spots origination at last stages of transition. However, the more detailed development characteristics of the given structures, as well as the mechanism of their generation, development and breakdown was not investigated.

The next stage of the experimental studies of laminar-turbulent transition at high free stream turbulence was connected with investigation of this process not in natural but in controlled experiments [4]. The given technique has allowed to receive additional, and in some aspects and new information on this complex process. For the first time the streaky structures were modelled in the flat plate and straight/swept wings boundary layers by means of the localized in space and time disturbances generated both from a free stream and on a model surface. The development characteristics of the forced streaky structures correlated with the characteristics of the localized disturbances observed and investigated in the natural experiments. One of possible mechanism of the turbulent spot generation caused by interaction between forced streaky structure and high-frequency wave was detail investigated in work [5]. Disturbaces interaction resulted in generation of a high-frequency wave packet, which transformed into the turbulent spot downstream. On the basis of the studies carried out in the controlled experiments, for the first time the laminar-turbulent transition at high free stream turbulence scenario was suggested in work [4]. Different methods of control by disturbances development in such situations were suggested in work [6,7]. It is necessary to note, that the majority of studies considered above were carried out on a flat plate because it is more simple model with zero pressure gradient. Nevertheless, from the practical point of view it is very important to understand features of the pressure gradient boundary layers such, as for instance, the wing boundary layer. The majority of the real hydrodynamical devices, such as blades of the turbines, compressors, fans etc. are various airfoil profiles.

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Abstract

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The main purpose of this work is study of the laminar-turbulent transition at high free stream turbulence on the wing model both in the natural and controlled experiments. It is necessary to find out general regularities of the transition in such conditions on a flat plate and wing, and also features at last.

2. Experiments in the natural conditions

Smoke visualization of a straight wing boundary layer was carry out at low ($Tu \leq 0.04\%$ of U_∞) and at high ($Tu = 1.75\%$ of U_∞) free stream turbulence. For the first time, it is shown, that streaky structures at high free stream turbulence can exist and in a pressure gradient flow, in particular, on model with airfoil profile [8] because before the streaky structures were observed only in a flat plate boundary layer under zero pressure gradient at high free stream turbulence [4]. Streaky structures are not observed at low free stream turbulence. Thus, the gradient boundary layer is modulated by streaky structures, as well as in a situation for the gradientless boundary layer of a flat plate at high free stream turbulence. Smoke visualization of an interaction between natural streaky structures and forced two-dimensional TS wave in a boundary layer of the same model is shown, that the wave interacts with the natural streaky structures and this process results in turbulent spots generation [8]. The given result also correlates with visualization of the interaction between natural streaky structures and forced two-dimensional TS wave in a flat plate boundary layer [4].

Thus, the boundary layer with a pressure gradient on a straight wing at high free stream turbulence is modulated in a spanwise direction by streaky structures as well as the flat plate boundary layer. One of possible mechanism of the turbulent spots generation in both cases can be connected with interaction high-frequency disturbances and streaky structures.

3. Experiments in the controlled conditions

3.1. Modelling of the streaky structures

Next stage of studies is connected to modelling of the forced streaky structures in a boundary layer of the straight wing [9]. The given modelling is similar to modelling of the streaky structures (or puffs, as we them have named earlier) in a flat plate boundary layer [4]. The localized, vortical disturbances were introduced into the model boundary layer from free stream by means of the dynamic loudspeaker technique. It is necessary to note, that the direction of the disturbances input and free stream velocity were coincided. Structure of the “puff” in a straight wing boundary layer is qualitatively similar on structure of the “puff” in a flat plate boundary layer [4]. It represents by region of the velocity excess/defect located in a disturbance plane of symmetry and two regions of the velocity defect/excess located on both sides from central region depending on suction/blowing respectively. In the given situation the structure is symmetrical in spanwise direction. The difference of solitary “puff” (streaky structure) developed in the wing and flat plate boundary layers is connected to that the oblique waves generated by “puff” at its spanwise edges are developed in case of a zero pressure gradient on a flat plate [4] and are suppressed by a favorable pressure gradient in case of its development on a wing. The essential changes in structure of localized disturbance are observed in a swept wing boundary layer. First, it becomes asymmetrical, and secondly, its spanwise scale becomes almost twice more in comparison with similar scale of the same disturbance on a straight wing. With it, it is necessary to notice, that the leading edges shape, thickness of the models and other experimental conditions in both cases were identical, except for a swept angle at the second model. The reason of such changes is crossflow in a boundary layer of the swept wing [10].

3.2. Interaction between forced streaky structure and high-frequency secondary disturbance

As already was noted above, one of possible mechanism of the turbulent spots generation at high free stream turbulence is interaction between streaky structures and high-frequency, secondary disturbances, possible of existence of which in the given conditions was confirmed by the controlled experiments mentioned in introduction [4]. The studies of the given interaction mechanism in the controlled experiments on a flat plate were shown its reality. Detailed characteristics of the disturbances development and their interaction were obtained for this case in work [5]. Study of the streaky structure development and its interaction with high-frequency, secondary disturbance on a straight wing model of 950 mm length, 480 mm chord length and 60 mm thickness (see Fig. 1(a)) located vertically in a working section of the low turbulence wind tunnel was carried out.

Low-frequency (f=0.5 Hz) and high-frequency (f=280 Hz) disturbances were introduced into the wing boundary layer through the narrow slot (3.5 × 0.5 mm) located on distance 35 mm from the wing leading edge by means of two dynamic loudspeakers. Disturbances were introduced into the boundary layer both simultaneously and separately. The wing model was located under zero attack angle and with it the velocity distribution outside of the boundary layer on a greater part of upper airfoil surface along its chord is demonstrated the existence of a favorable pressure gradient in this region (67% of chord length) (see Fig. 1(b)). The growth rates of disturbances are demonstrated the following features (see Fig. 2): the high-frequency wave (1) quickly decreases downstream, on distance 100 mm from a source its amplitude is 0.01% of U_∞, that is connected to influence of a favorable pressure gradient on the wave; localized disturbance (streaky structure) (2) also decreases dowstream practically with the same decrement, as in case of a flat plate, that indicate on weak influence of a favorable pressure gradient on the localized disturbance intensity at its downstream propagation; interaction of the decreasing disturbances (3) results in growth arising with this high-frequency wave packet and its transformation into the turbulent spot.

Contour diagrams of constant velocity fluctuations of the streaky structures depending on streamwise coordinate are shown, that the structure of streak is symmetric in spanwise direction, the disturbance intensity damps downstream, its absolute size in spanwise direction increases and, probably for this reason, appearance of additional streaks are observed at x = 245-315 mm. It is necessary to note, that on the initial stage of the streaky structure development at x = 105 mm can be observed a high-frequency signal near to disturbance leading edge caused by impulse influence on the boundary layer. However, this high-frequency signal disappears downstream due to its suppression by a favorable pressure gradient.

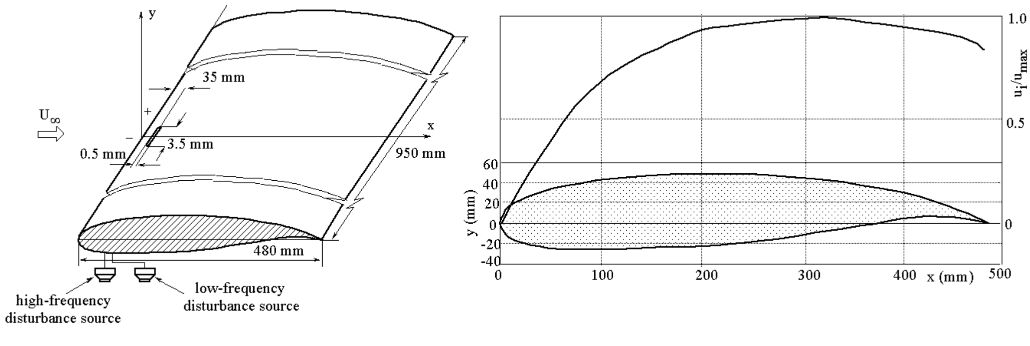

Fig. 1. Experimental set-up – (a) and velocity distribution in region out of the wing boundary layer downstream – (b), U_∞ = 8.4 m/s, z=0.

Oscilloscope traces of the streaky structure development and its interaction with the high-frequency disturbance obtained by measurements in a plane of symmetry of the disturbances at different positions downstream are shown in Fig. 3 (I). It is seen, that the amplitude of the streaky structure is decreased downstream but the intensity of the interacted disturbances grows. Interaction results in generation of a high-frequency wave packet, which transforms into the turbulent spot

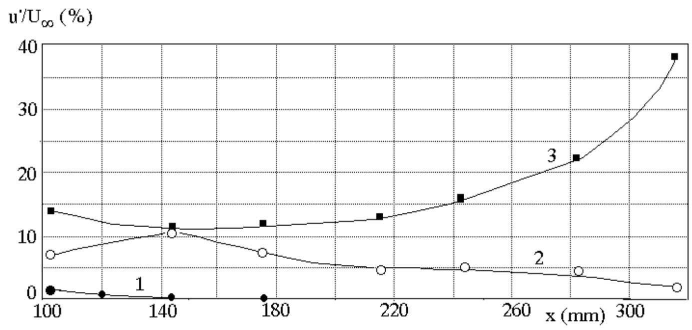

Fig. 2. Intensity disturbances distributions downstream in region of favorable pressure gradient in the wing boundary layer: 1 – high-frequency disturbance (f = 280 Hz); 2 – localized disturbance ("puff"); 3 – interaction between localized and high-frequency disturbances, $U_\infty = 8.4$ m/s, $y = y(u'_{max})$

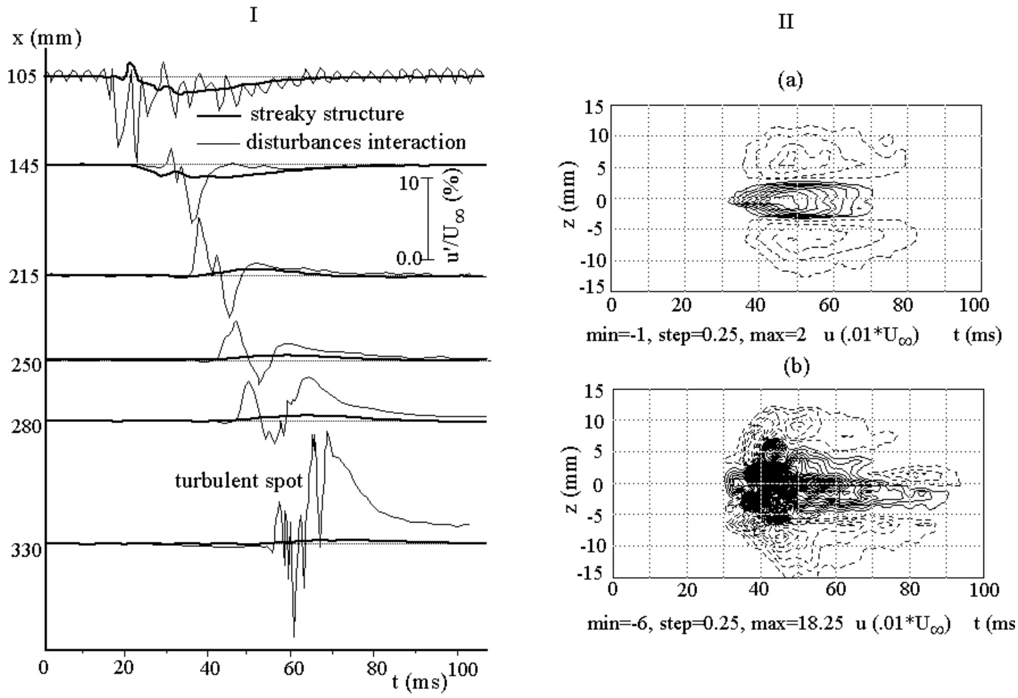

Fig. 3: (I) – Traces of the localized disturbance and its interaction with the high- frequency disturbance, z = 0 mm. (II)- Contours diagram of constant velocity fluctuations of thelocalized disturbance(a) and its interaction with the high-frequency disturbance (b) at x = 215 mm. The contours of velocity excess and defect are shown by solid and dashed lines respectively. Disturbances amplitude are shown in percents of free stream (max-velocity excess, min -velocity defect, step – isolines spacing), $U_\infty = 8.4$ m/s, $y = y(u'_{max})$

downstream. The contour diagrams of constant velocity fluctuations of the streaky structure (a) and its interaction with the high-frequency disturbance (b) at x=215 mm are shown in Fig. 3 (II). It is seen, that the interacted disturbances amplitude has increased more than in eight times (b) in comparison with the solitary streaky structure (a). It is possible to observe maxima of the disturbance intensity (b) located in the regions of the maximal velocity gradients in spanwise direction for the streaky structure (a) that point to the secondary, high-frequency instability of the flow locally modulated in spanwise direction by streaky structure travelling downstream. The given result correlates with the data on the disturbances interaction obtained in experiments on a flat plate [5]. In contrast with the flat plate, as it was already mentioned above, in this case we have not observe the oblique wave, which are suppressed by a favorable pressure gradient.

Thus, modelling of the mechanism of the turbulent spots generation due to the interaction between streaky structures and high-frequency disturbances at high free stream turbulence is shown, that this mechanism for the flat plate and wing boundary layers is qualitative identical.

4. Conclusions

– For the first time, existence of the streaky structures in a pressure gradient flow on the straight wing model at high free stream turbulence is found.

– It is shown, that the turbulent spots generation in a pressure gradient boundary layer at high free stream turbulence can take place due to the interaction between streaky structures and high-frequency, secondary disturbances.

– For the first time, the streaky structure was modeled in a pressure gradient boundary layer and it is shown, that the favorable pressure gradient weakly influence on its decreasing.

– For the first time, interaction between streaky structures and high-frequency, secondary disturbances in a pressure gradient boundary layer was modeled and qualitative identity of the given interaction mechanism for a flat plate and a wing boundary layers is shown.

– Stabilizing influence of a favorable pressure gradient on the waves development is once again confirmed, in instance, it influence on the oblique waves which were practically suppressed at an initial stage of the solitary streaky structure development.

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