Experimental study of perturbations modeled by a membrane in 2D and 3D boundary layers

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Abstract. The work is devoted to experimental studies of the dynamics of the development of perturbations introduced by a membrane under various conditions. The studies were carried out under conditions of a low and moderate degree of free-flow turbulence. It is shown that the impulsive motion of the membrane generates a localized longitudinal structure in the boundary layer, as well as wave packets at its fronts. A circular membrane generates wave packets consisting of forward and oblique waves, while a rectangular membrane generates predominantly forward waves. A moderate degree of turbulence inhibits the development of wave packets at the linear stage and intensifies at the nonlinear stage. The separation of the boundary layer stimulates an increase in the amplitude of the wave packets.

1. Introduction

The beginning of work on the problem of laminar-turbulent transition is indicated by the experiments of Osborne Reynolds in 1883. Since then, many important steps have been taken to address this problem. In 1924, Werner Heisenberg initiated the creation of the linear theory of hydrodynamic stability. Within the framework of this theory, the first calculations of the stability of the boundary layer were made by Walter Tollmiien and Hermann Schlichting in the early 1930s. Schubauer and Scramsted in a low-noise wind tunnel first experimentally discovered the intrinsic perturbations of the boundary layer and described their decisive role in the process of the laminar-turbulent transition in 1948. It is now clear that the transition to turbulence at a low and relatively low degree of intensity of external disturbances occurs due to the development of instability of the initial laminar flow to certain disturbances that develop into turbulent spots and low-frequency pulsations of large amplitude. The laminar-turbulent transition at a low degree of free-stream turbulence in the boundary flow is described in [1]. With an increase in the Reynolds number in the two-dimensional boundary layer, two-dimensional Tollmiien-Schlichting waves first of all grow, from which it can be assumed that they have a great chance of causing the transition to turbulence. Typical stages in the development of a laminar-turbulent transition at a low degree of turbulence of the external flow include the linear amplification of Tollmiien-Schlichting waves, their transformation into three-dimensional lambda-vortices, the formation of longitudinal vortex structures, the appearance of strong shear layers, the formation of turbulent spots and their merging, which leads to flow turbulization. At the same time, at a high degree of turbulence of the external flow, two main phenomena are usually identified that underlie turbulization: the generation of traveling waves with characteristics determined by the local properties of flow stability, and the appearance of quasi-stationary longitudinal structures formed under the impact of external vortex disturbances and pressure fluctuations. The streaky structures,
which received their name from the results of flow visualization [2], are observed in the form of quasi-stationary three-dimensional deformations of the laminar boundary layer, whose intensity and spatial extent increase downstream.

Past studies make it clear what kind of disturbances are present in natural conditions in the boundary layer in the case of an increased degree of turbulence of the flow around the body. At present, it is of interest to study experimentally such perturbations artificially introduced into the boundary layer. This research method makes it possible to solve the technical problem of the random nature of the appearance of the phenomena of interest and thoroughly study the dynamics and evolution of the phenomena that arise in the boundary layer with an increased degree of turbulence. One of the methods for introducing disturbances is the impulse action of a limited area of the surface. A membrane fixed to the surface acts as a surface area. A convex membrane can be regarded as a macroroughness, which makes it possible to compare the results of experiments with research conducted in this area. The membranes used in these experiments were secured in a special way - using a specially designed retention device. This device was obtained using 3D modeling and printing, which helped to set the membrane in such a way that, in an inactive state, it did not protrude above the surface and did not introduce uncontrolled distortions into the flow. It should be noted that a rectangular or square membrane allows obtaining a pseudo-two-dimensional perturbation, and a circular one - three-dimensional. This paper reveals the potential of using a membrane to introduce controlled disturbances into the boundary layer under the conditions of low and moderate degrees of free-flow turbulence.

2. Methods

All experiments considered in this work were carried out in an MT-324 subsonic wind tunnel of the ITAM SB RAS, with a test section of 200x200x800 mm³. The membrane integrated into the model was set in motion by pressure pulsations in the volume below its surface, which were created by a closed speaker, to which a rectangular signal with an amplitude of about 14.6 V was applied. The membrane was turning from the initial position to the deflected one, was in it for 100 ms, then moved back to the original position according to the harmonic law. This made it possible to measure once every half a second. In all the experiments under consideration, the average velocity $U$ and the velocity pulsations $u$ were measured using a constant temperature hot-wire anemometer. An important part of the experimental methodology is the synchronization of the introduction of a disturbance into the boundary layer and the beginning of its registration. This allowed many implementations to be carried out and then averaged over the ensemble to exclude non-deterministic noise (especially in conditions of an increased degree of flow turbulence) and to isolate a useful signal. The number of averaging in the experiments varied from 10 to 60.

3. Results

In the first experiment, a flat plate 200 mm wide, 675 mm long, and 10 mm thick was installed in the test section with a circular membrane with a diameter of 18.6 mm, installed at a distance of 100 mm from the leading edge. At the rear edge of the plate, a flap 200 mm wide and 50 mm long was fixed, which was raised above the plate surface by one mm and provided the necessary compression of the flow. The studies were carried out under conditions at which the oncoming flow velocity $U_\infty$ was 8 m/s and 20 m/s. The degree of flow turbulence $T_u$ did not exceed 0.2%.

Measurement of the average velocity inside the boundary layer showed that at the given flow velocities, the Blasius flow was implemented in the boundary layer. The results show that for a velocity of 8 m/s the form parameter is $H = 2.5$, which corresponds to a deviation of 0.09 from the theoretical solution. The velocity profile is more "full", such a flow is less

Figure 1. Wave packet at the trailing edge of the longitudinal structure. $U_\infty = 8$ m/s
susceptible to intrinsic perturbations. For a velocity of 20 m/s $H = 2.58$, which corresponds to negligible deviations from the Blasius profile.

The disturbance introduced into the boundary layer is a localized longitudinal structure, which consists of alternating streaky zones of excess and defect in velocity. High-frequency wave packets are formed at the leading and trailing edges of this structure. Figure 1 shows the isolines of the velocity pulsations of the wave packet at the trailing edge of the disturbance. Blue lines indicate a defect in velocity relative to average velocity, and red lines indicate overspeeding. In the pictures below, the color of the isolines denotes the same. The wave packet consists of straight and oblique waves. This picture of the disturbance is similar to the picture of a typical wave train obtained in [3] (Fig. 2). In this work, point gas injection through the hole was used as a source of disturbances.

![Figure 2. Isolines of the amplitude of the wave packet at the back front of the disturbance (a) and of the typical wave train in the boundary layer of a flat plate generated by a point source (The gradient indicates the degree to which the velocity deviates from the average) (b).](image)

The amplitude of the localized longitudinal perturbation in all the cases studied decayed downstream. The evolution of wave packets was consistent with the linear theory of hydrodynamic stability, starting to grow under conditions when the parameters of the experimental point fell into the instability zone. Direct waves grew stronger than oblique ones.

![Figure 3. Hot-wire visualization of disturbances in the boundary layer: isolines of the velocity pulsation in the plane $(Z-Z)$ at $Y = Y_{u_{\text{max}}}$ $X/C = 0.32$ (1) $0.56$ (2), $Tu = 0.18 \% U_{\infty}$ Longitudinal localized structure (a), wave packet after filtering in the frequency range $100 < f < 200$ Hz (b).](image)

The purpose of the second experiment was to study the effect of an increased (moderate) degree of turbulence on the disturbance generated by a square membrane in the boundary layer of a sliding wing. A swept-wing section with a chord $C = 410$ mm and a glide angle of $45^\circ$ was used as a model. The model was installed in the test section at an angle of attack $\alpha = -1^\circ$. A membrane in the form of a square with a side of 14 mm was fixed to the model at a distance of 110 mm $(X/C = 0.27)$ from the leading edge along the axis of symmetry of the model. The membrane could deviate 0.3 mm upward from the surface of the model. The membrane was controlled in the manner described earlier. The
studies were carried out under conditions at which the oncoming flow velocity $U_\infty$ was 7 m/s. To create an increased level of turbulence in the incoming flow, a set of turbulizing grids was used, by means of which the degree of flow turbulence $Tu = 0.18$ and $0.8\% U_\infty$ was achieved. The source of disturbances was located in the area of an unfavorable pressure gradient $X/C = 0.27$.

Hot-wire visualization of the disturbance introduced into the boundary layer shows the occurrence of a localized longitudinal disturbance with a duration of 100 ms. High-frequency wave packets are generated near the leading and trailing edges of the longitudinal disturbance (Fig. 3a). Shown here is the distribution of isolines of velocity pulsations along the wingspan behind the source of disturbances at $X/C = 0.32$ (1) and 0.56 (2) $Tu = 0.18\% U_\infty$. The size of the longitudinal structure along the transverse coordinate ($Z$) is determined by the size of the membrane and significantly exceeds the thickness of the boundary layer near the membrane at $X/C = 0.27$. At 150 $\lt t \lt 250$ ms, a relaxation region with a velocity defect is observed; its appearance is associated with the peculiarities of the source of the disturbance. Downstream, the localization of the longitudinal structure is preserved. The relaxation zone disappears.

The topology of the obtained disturbances is preserved with an increase in the degree of free-flow turbulence up to $Tu = 0.8\% U_\infty$. The qualitative difference between the pictures is manifested in an increased level of noise phenomena, which are caused by an increased degree of turbulence, which is of the same order of magnitude as the studied phenomena. An analysis of the distribution of the amplitudes of the velocity fluctuations in the boundary layer showed that in the region of a favorable pressure gradient ($0.31 < X/C < 0.42$), the wave packets at the leading and trailing edges of the disturbance in the case of low and increased degrees of free-flow turbulence practically did not change their amplitude. In the region of an unfavorable pressure gradient, all of the above high-frequency disturbances begin to grow; moreover, under the influence of an increased degree of turbulence, the beginning of the growth of the disturbance amplitude shifts downstream from $X/C = 0.5$ to 0.57. This can be explained by the fact that an increased degree of turbulence induces longitudinal structures in the boundary layer, which suppress the growth of wave packets at the linear stage of their development. A similar result was observed in the study of the straight wing in [4] for wave packets of small amplitude.

The next experiment was undertaken as a continuation of the above-described studies and aimed at studying the effect of the separated flow on the disturbances generated by a circular membrane. It is known that the growth of disturbances in the separation zone, their subsequent destabilization, and transition to turbulence are characteristic. This is associated with the fact that the average velocity profiles in the separated flow have an inflection point and turn out to be more unstable to small oscillations [5]. At the same time, suppression of wave packets at the linear stage of development by an increased degree of flow turbulence is noted. In the case of the presence of a separated flow, these two factors will affect the introduced disturbances in a difficultly predictable way.

Figure 4. Contours of the velocity disturbance in the $z$ – $t$ plane at its maximum along the $y$ coordinate at $x = 215$ mm: a - without signal filtering, b - after filtering in the frequency band 100–700 Hz, c - enlarged image of the wave packet at the leading edge of the disturbance obtained at b.
manner. In this regard, there is interest in studying the effect of both the separated flow and the increased (moderate) degree of turbulence on the disturbances generated by the membrane in the boundary layer.

A flat plate was used as a model, with a projection 50 mm wide and 3 mm high with a smooth rise installed at a distance of 202 mm from the leading edge. At a distance of 100 mm from the leading edge, a circular membrane with a diameter of 18.6 mm was mounted, deviating from the initial position upwards by 0.35 mm. The oncoming flow velocity $U_\infty$ was 6.5 m/s. The oncoming flow was turbulized to the value $Tu = 0.8\% U_\infty$ (moderate turbulence) using a turbulizing grid installed in front of the inlet to the test section.

The experimentally obtained profiles of the average velocity show that before the step, the flow is laminar; in the flow behind the step, the profiles have a pattern characteristic of the separated flow. The membrane located in front of the separation region introduces into the boundary layer disturbances of two types – a longitudinal localized structure and wave packets at its fronts. Visualization of the flow using a hot-wire anemometer shows that at a low degree of free-flow turbulence, the wave packet at the leading edge after passing through the separation zone was transformed into an $\lambda$-structure, and the wave packet at the trailing edge was a turbulent spot (Fig. 4). The longitudinal structure retained its scale in the transverse direction.

With a moderate degree of freestream turbulence, the disturbances generated by the membrane retain their topology both before and after the separation zone. There is a good qualitative agreement of the visualization patterns at all stages of the development of the disturbance.

The intensity of the amplitude of the longitudinal structure generated by the impulse deflection of the membrane decreases monotonically, both in the case of a low degree of free-stream turbulence and an increased (moderate) one. An increased degree of turbulence enhances the attenuation process, from 19.7 to 7.8% $U_\infty$. An increased degree of free-flow turbulence affects the evolution of wave packets even more strongly. In the separation zone at a low degree of turbulence, a significant increase in the amplitude of the pulsation is observed for wave packets on both fronts of the disturbance. A similar result was obtained in [6] when generating spatially localized boundary layer perturbations on a straight wing in the region of an unfavorable pressure gradient. With an increased (moderate) degree of turbulence, suppression of the growth of the amplitude of pulsations is observed at the initial stage, when the considered disturbances are linear. However, further downstream of the separation zone, the growth rate turns out to be greater than in the case of low freestream turbulence. The amplitude of the longitudinal localized perturbation of the wave packet located at the trailing edge turns out to be smaller, which was also noted in other works. Apparently, this is due to the peculiarity of the membrane. Generally, the nature of the development of the wave packets under study corresponds to the existing ideas about the stability of separated flows. The destabilization of the flow mentioned at the beginning of the article upon separation of the boundary layer is manifested in an increase in the spatial increments of instability waves by an order of magnitude, as well as in the expansion of the range of growing oscillations in the frequency-wave spectrum. Such conditions are obviously favorable for the amplification of wave packets arising in the near-wall flow zone upon its low-frequency localized excitation.

### 4. Conclusion

The authors carried out an extensive experimental work consisting of three experiments in which the disturbances introduced by membranes of different shapes into the boundary layer were investigated. The studies were carried out in conditions of low and increased degrees of free-flow turbulence, as well as in a separated flow, to understand how this affects the development of disturbances.

The impulsive movement of the membrane generates a localized longitudinal structure in the boundary layer, as well as wave packets consisting of direct and oblique Tollmien-Schlichting waves in the case of a round membrane. The rectangular membrane predominantly excites direct waves. It was found that the spatial development of disturbances at the central frequency of wave packets is consistent with the linear theory of hydrodynamic stability. An increased degree of turbulence inhibits the
development of wave packets at the linear stage and enhances at the nonlinear stage, both in the case of a two-dimensional boundary layer and a three-dimensional one. The separation of the boundary layer stimulates the development of wave packets and their transformation into $\lambda$-structures and then into turbulent spots. Exposure to an increased degree of turbulence leads to attenuation of longitudinal structures before and after the separation zone. An increased degree of turbulence reduces the amplitude of wave packets at the linear stage of development, to the separation zone, and at the same time contributes to an intensive growth behind the step at the nonlinear stage.

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