Modelling of the boundary layer disturbances by localized effect of the round membrane

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Abstract. The spatial development of the flat plate boundary layer disturbances by the hot-wire anemometry is experimentally investigated. Controlled disturbances were introduced into the laminar flow by means of a round membrane located on the surface of the model. The impulse motion of a round membrane leads to the formation of longitudinal localized structures and wave packets in the boundary layer. Wave packets consist of a set of straight and oblique waves, differing in their propagation characteristics. The development of wave packets downstream is consistent with the linear theory of hydrodynamic stability.

1. Introduction

In tasks, related to reducing an aerodynamic resistance of objects streamlined by the ambient medium and calculating their aerodynamic characteristics, an integrated approach is important in the study of all factors that may affect the laminar-turbulent transition process in the boundary layer. The laminar-turbulent transition scenario with a low degree of free-stream turbulence (less than 0.8% $U_\infty$) has been studied thoroughly [1] and the transition stages are described by the linear theory of hydrodynamic stability. The description of the transition with an enhanced or high level of the free stream turbulence requires experimental studies. Unfortunately, detailed studies of the effects occurring in the boundary layer in “natural” conditions are difficult and sometimes impossible due to the random nature of the occurrence of such phenomena. The paper [2] contains experimental data describing the boundary layer subjected to free stream turbulence in the range of 1 - 6%. The authors recognized the longitudinal structures: local areas of excess and defect of velocity, which prevail in the boundary layer flow at the high level of free-stream turbulence. One of the methods of studying these structures is to model them under controlled conditions. That is, injection of a perturbation into the boundary layer with a low degree of turbulence, study of its behavior, evolution, and flow response to it. Such a perturbation in the boundary layer can be injected by the method of deflection of the local surface area. As shown in previous works, pulsed oscillations of a surface area generate a wide range of disturbances. The experimental study of excitation of disturbances in the boundary layer by surface vibration was carried out in [3], in which the simplest case of a two-dimensional vibrator on a flat plate was considered. A comparison with the theoretical results [4] showed that the linear theory of hydrodynamic stability and susceptibility in the two-dimensional case correctly describes this process with small amplitudes of such vibrations. In a supersonic flow, artificially injected high-frequency perturbations were investigated in [5]. It was found that the wave packets obtained in this work can interact with natural disturbances. Their spatial-wave structure was also studied.
The purpose of this work is to study the occurrence and development of disturbances generated by the action of low-frequency motion of a limited surface area-round membrane in the flat plate boundary layer at high Reynolds numbers and high deflection amplitude of the membrane.

2. Methods

Experiment was carried out in the T-324 subsonic wind tunnel of the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences. The size of the test section was 1000 × 1000 × 4000 mm³. The degree of the oncoming flow turbulence Tu did not exceed 0.04%. A flat plate of 1000 mm width and 1500 mm length was used as a model, figure 1 (a). A source of artificial disturbances specially designed for this model was installed in the plate at a distance of 150 mm from the leading edge. The method of injecting perturbations by the membrane was chosen because of its pinpoint effect. At this method the deflecting surface does not introduce additional distortions into the flow (as in the blowing-suction method). It is clear setup to simulate numerically and, as a result, subsequent computer simulations of this experiment are possible. There were several reasons why it was decided to abandon the usual gluing of the membrane on the plate. First, because of the sticking of the membrane, an artificial unevenness was created, which at high speeds introduced disturbances that could no longer be neglected. Second, it was necessary to standardize the experiment in order to be able to repeat it in the future with another setup.

Figure 1. Scheme of the model (a) and device for holding the membrane (b).

A special support device (see figure 1(b), made of ABS plastic, was designed and printed by means of 3D printer, then being inserted into the plate it held the membrane. This device flushes the surface of the membrane with the plate, without creating unnecessary irregularities. In addition, one more degree of freedom appears for the membrane. Device geometry allows its up and down deflection, forming a protrusion or recess on the surface of the plate. Using a modular-type disturbance source simplifies the experiment preparation. After these upgrades, the model was installed vertically in the wind tunnel test section at a zero angle of attack. The membrane was set in motion by pressure pulsations from the head of the loudspeaker, connected to the chamber of the membrane support device by means of a pipeline. An electric signal of a rectangular shape with an amplitude of 14.6 volts and duration of 0.2 sec was applied to the speaker from the generator, as a result of which the membrane made reciprocating deflection with a frequency of 2 Hz, moving from the rest position to
the raised position with an amplitude of 350 μm up and 90 μm down, so all flow pattern was repeated every 500 ms. The flow velocity $U_\infty$ in this experiment was 21.5 m/s, which corresponds to the number of Reynolds $Re_\delta > 1200$ at the measuring area. The spatial development of boundary layer disturbances was investigated using hot-wire constant temperature anemometry. The signal from hot-wire anemometer was synchronized with the generator of artificial disturbances.

3. Results
The localized effect of the membrane on the boundary layer leads to formation of two types of disturbances. In figure 2, there are the contour lines of velocity fluctuations plotted in the z-t coordinates, demonstrating those artificial disturbances. The localized longitudinal structure in the area of $z = [-10, 10]$ mm, $t = [50, 250]$ ms and wave packets on the leading and trailing edges are clearly segregated. The longitudinal structure arises due to the local deviation of the membrane surface upwards. Its length along the flow is determined by the time during which the membrane is in a deflected position (200 ms). It should be noted that in the experiment two longitudinal structures are distinguished: one "long", (200 ms of duration) and one "short" at the back part, 25 ms of duration.

![Figure 2. Contours of velocity fluctuations in z-t plane at $y_{\text{ymax}}$, x=600 mm.](image)

Moreover, the areas of deflected and exceeded speed of the longitudinal structure at the back are in antiphase with the rest. Short longitudinal structure resembles ones that were generated in previous experiments by a short pulse and were called as "puffs". The appearance of “short” longitudinal structure in the present experiment is apparently caused by the peculiarity of operation of the round membrane and it requires further research. Wave packets occur in a short period of time when the membrane makes its movement up and back, down. In order to study the high-frequency wave packets, a filtering procedure: the method of discrete direct and inverse Fourier transform was used. The result of this procedure, figure 3 (a, c) demonstrates that wave packets occur in the time when the membrane performs its movement. These data also give a qualitative picture of their form. The picture shows that the wave packet consists of straight sections $z = [-20, 20]$ mm inclined (oblique) on both sides. Each of those packets has individual maximum of velocity fluctuations in z-direction, see figure 3 (b, d).

Figure 4 shows the isocontours of the wave packet amplitude of present research in comparison with the isocontours of a typical wave train, obtained in [6]. The types of wave packets appeared as a result of the injection of perturbation by the blowing-suction method and the method of localized vibration of the surface are fundamentally similar. The amplitude distribution of the different parts of
disturbance is shown in figure 5. The behavior of amplitude downstream of the wave packets is differing for the straight and oblique waves. The intensity of straight wave packets increases constantly downstream, see figure 5 (a). At the same time, oblique wave packets grow sharply first and then their amplitude decreases, see figure 5 (b). The amplitude of the "short" localized longitudinal structure decreases downstream as well as the "long" streak, see figure 5 (c).

Figure 3. Contours of velocity fluctuations in z-t plane (a, c) at y_{max}, x=600 mm after applying the Fourier filter in the region of 120-400 Hz, and its value of std in z-direction (b, d).

Figure 4. Isolines of the amplitude of the wave packet at the back front of the disturbance (a) and of the typical wave train [6] in the boundary layer of a flat plate generated by point source (b).

Figure 5. The distribution of the amplitudes of the straight (a) and oblique (b) wave packets as well as the longitudinal structures (c) along the x coordinate. 1- the front edge wave packet, 2- the rear.
Conclusion
Pulse movement of the round membrane with high amplitude in the boundary layer results in formation of disturbances of two types: longitudinal localized structures and wave packets near their fronts. Creating a source of modular perturbations allowed us to obtain data for high Reynolds numbers, where the wave packets become growing. Wave packets generated in this case consist of straight and oblique waves. The nature of their development is consistent with previous studies (generation of perturbations by a point source).

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