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Generation of disturbances in a swept wing boundary layer by localized surface vibrations

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Abstract

In the wind tunnel of small subsonic velocities, simulation of hydrodynamic perturbations in the boundary layer of the swept wing by means of vibrations of a localized surface region and investigation of their development under conditions of low turbulence of the incoming flow were carried out. The results are obtained using the method of hot-wire anemometry. It is found that the vibrator's work generates a disturbance consisting of a localized longitudinal structure and wave packets on its fronts. The influence of the secondary flow, which arises in the presence of a glide angle of the wing, on the development of the generated perturbations in the boundary layer of the model is studied. It is shown that the longitudinal structures observed in the disturbed flow change the trajectory of their motion and deform.

Introduction

The understanding of the laminar-turbulent transition mechanism is closely related to the physical processes that arise in the boundary layer. In recent years, researchers have paid special attention to the study of longitudinal localized perturbations in the boundary layer, denoted by the term "streaky structures." Disturbances in the incoming flow act on the boundary layer, as a result of which stream-oriented structures are formed that include flow regions with a high and low longitudinal velocity component. The amplitude of these structures increases as they propagate downstream, which leads to the emergence of turbulent spots, and as a result of the destruction of spots, the flow in the boundary layer changes from a laminar state to a turbulent one (Boiko et al. 2002, Westin et al. 1994). The non-modal enhancement of hydrodynamic perturbations leads to the formation of streaky structures, which goes beyond the traditional model of instability of flows with a velocity shift with respect to elementary waves (Dovgal et al. 2017). Streaky structures are quasi-stationary deformations of the shear layer oriented along the flow and limited in a transverse direction.

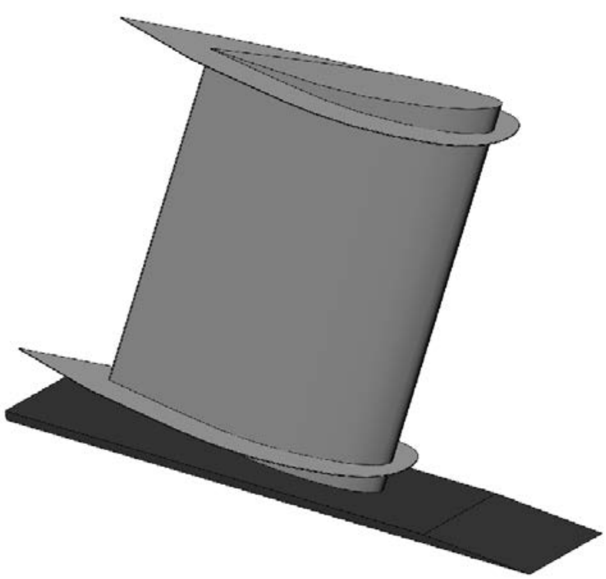
The origin and development of packets were studied in detail in previous experimental studies in the modeling of streaky structures of the boundary layer in various ways. Such methods include the generation of structures by blowing-in by air through the slits in the streamlined surface, its localized vibrations, and perturbation of the vorticity of the incoming flow in gradient and gradient flows (Kozlov et al. 2017, Chernorai et. al. 2001, Katasonov et. al. 2017).

It is known that when flowing over a swept wing, the streamlines on the outer boundary of the boundary layer acquire an S-shaped shape under the action of a transverse pressure gradient. As you dive into the boundary layer, the curvature of the streamlines increases, resulting in the formation of a so-called transverse or secondary flow. In works of Gorev (2006) and Gorev (2007), the modeling of streaky structures by the blow-in-suction method on the swept wing model is described in detail. This work was entirely devoted to the study of the origin and development of localized perturbations (streaky structures) in the boundary layer of the swept wing. Vibrations of the localized surface region generated hydrodynamic perturbations in the boundary layer of the model.

Research Methodology

Experimental studies were carried out in a low-turbulent wind tunnel T-324 ITAM named after SA Khristianovich SB RAS (Novosibirsk). This closed circuit type wind tunnel has a closed working section of a square section of 1 × 1 m and a length of 4 m. The level of turbulence is 0.04% of the incoming flow U_∞. The wind tunnel is designed for experiments at low subsonic flow velocities up to 70 m/s. The experiments were carried out on the swept wing model, which was installed in the working section at zero angle of attack relative to the incoming flow (see figure 1). The wingspan was 980 mm, the chord *C* was 890 mm, and the slip angle was 30 °. The speed of the oncoming stream was U_∞= 6.5 m/s and did not change later. The Reynolds number was Re_c=3.8*10^5. Perturbations in the boundary layer were generated by low-frequency controlled oscillations of an elastic lavsan membrane of square shape with a side of 16 mm. The membrane was installed at a distance of 50 mm from the leading edge of the wing model. The dynamic loudspeaker brought the membrane into motion, which was hermetically connected to it by a pipeline. Rectangular electric pulses with a frequency of 1 Hz and a duration of 0.3 s were fed to the loudspeaker through a low-frequency amplifier, resulting in the reciprocating motion of the membrane. The maximum deviation of the membrane was 0.6 mm.

Measurements of the time-average U and pulsation u components of the longitudinal component of the flow velocity were measured by the method of thermoanemometry using a single-wire sensor. In this work we used a constant temperature thermometer of A. A. Lab. Systems Ltd, model AN1003. The programmable traversing system carried out a spatial displacement of the sensor in the measurement region with an accuracy of 0.02 mm in the longitudinal, transversal directions and 0.005 mm along the normal to the model surface. The velocity of the oncoming flow in the working section of the wind tunnel was measured by the pneumometric method, using a Pitot-Prandtl nozzle connected to an electronic micromanometer. The thermo-anemometer sensor was calibrated in a free flow opposite the Pitot-Prandtl tube at flow velocities rate of 3-20 m/s, so that the error was less than 2%. The signal from the thermo-anemometer sensor, digitized via an analog-to-digital converter with a sampling frequency of 10 kHz, was stored in the memory of the personal computer with averaging of the oscillograms over the ensemble to improve the signal-to-noise ratio. Averaging was performed for 5-10 individual implementations, depending on the levels of the signal and noise. The experimental data were a set of oscillograms recorded



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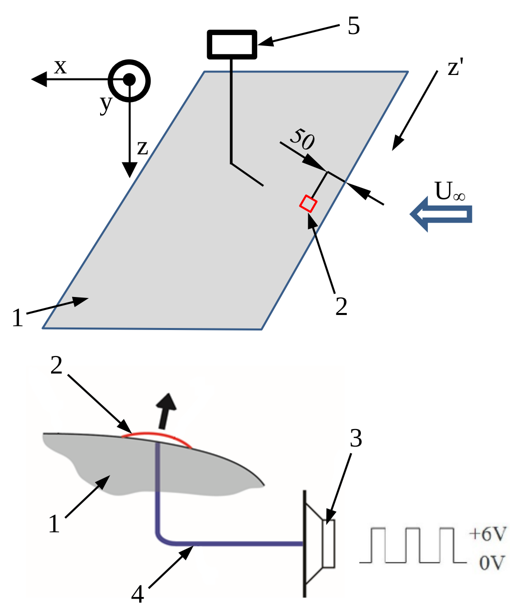

b

Figure 1: a. Experimental model of swept wing. b. Scheme of set-up: 1- wing, 2- membrane (16 x 16mm), 3- loudspeaker, 4- pipeline, 5- traversing system and hot-wire sensor.

at various measurement points near the surface of the model. The duration of a single oscillogram was 1 second. The processing of measurement results, filtering of the signal were carried out using programs for space-time Fourier analysis in the selected frequency range. Using the direct Fourier transformation of the oscillograms of the original signal from the thermo-anemometer sensor, the spectral composition of the pulsations was obtained. Next, the frequency range corresponding to the perturbation under study, neglecting other spectral components, was set. The inverse Fourier transform of the frequency spectrum thus modified allowed the signal to be reconstructed in the amplitude-time coordinates.

Results

Velocity profiles of undisturbed flow near the wing surface inside the boundary layer are presented in figure 2. There is detached laminar boundary layer in the region from x=100mm to x=450mm and separation area from x 450mm to 530mm. Longitudinal localized structure and wave packets are presented in the figure 3.

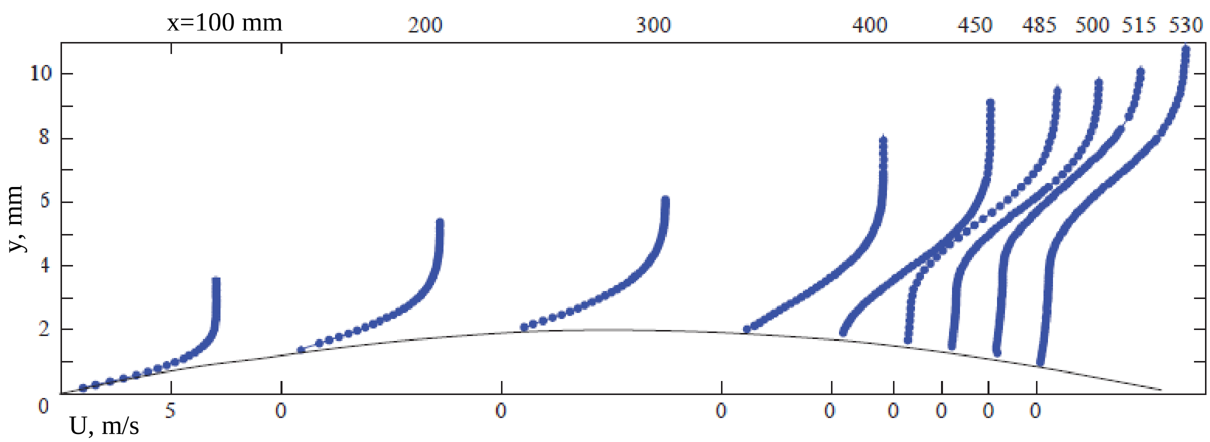

Figure 2: The profiles of the average velocity along the normal to the surface inside the boundary layer, along the chord of the swept wing for x = 100, 200, 300, 400, 450, 485, 500, 515, and 530 mm in unperturbed flow.

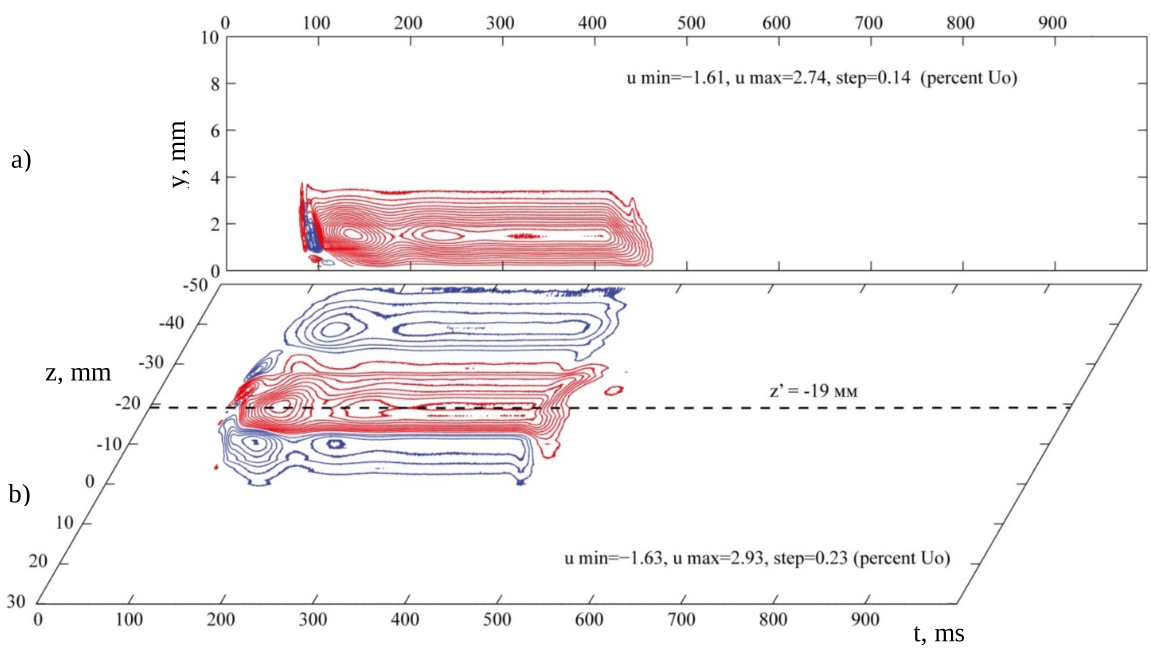

Figure 3: Contours of velocity fluctuations at the point x = 300 mm along the chord of the wing in the planes: a) y-t (z' = -19 mm); and b) z'-t. Red and blue lines- positive and negative deflection of the longitudinal velocity component respectively.

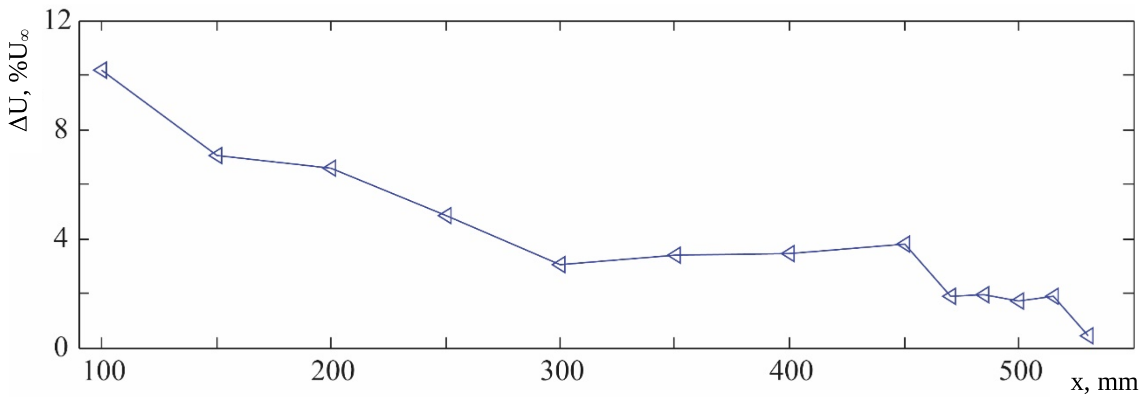

Figure 4: The deviation of the velocity from the undisturbed flow in the region of the localized longitudinal structure.

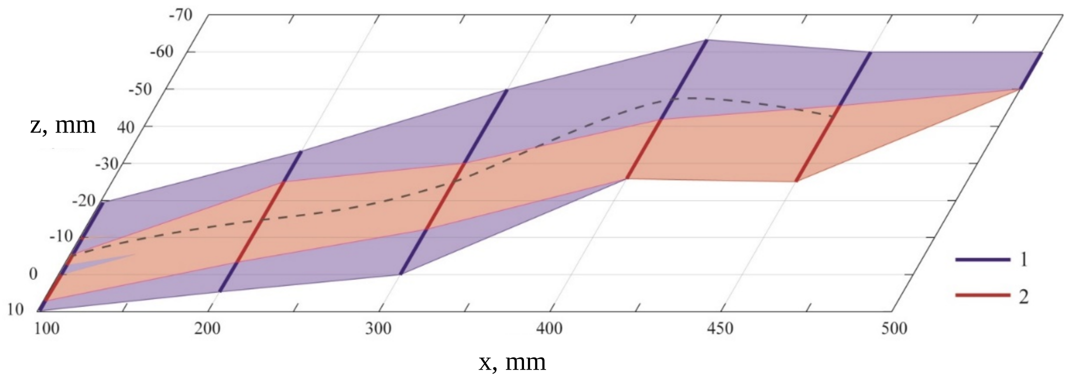

Figure 5: The development of a longitudinal localized structure in the boundary layer of the swept wing. 1 and 2 - negative and positive deflection of the longitudinal velocity component respectively.

The downstream behavior of the longitudinal localized structure (the distribution of it intensity along the x-axis) is shown in the figure 4 and figure 5. The amplitude of the longitudinal structure decreases at the distance from x = 100 to 530mm. The most interesting case is plotted at the figure 6, where the dependence of the r.m.s. oscillation amplitude on the longitudinal coordinate is presented. At the adverse pressure gradient area (x>300 mm) the wave packets amplitude starts grow at x=450 mm in the separation area. The disturbance growth at the leading and rear fronts of the streaky structure is near-exponential.

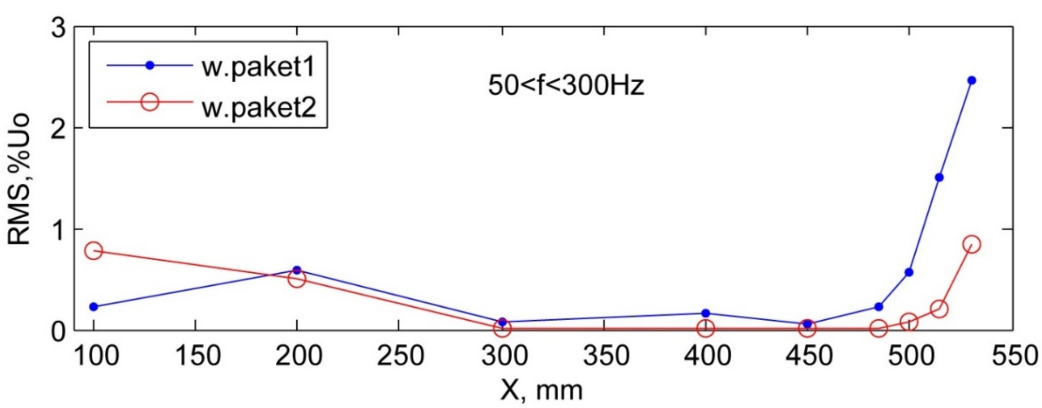

Figure 6: The perturbation amplitude (RMS) along the chord of swept wing for wave packets at the forward front (1) and rear front (2) of the longitudinal localized structure. The frequency range is 50-300 Hz.

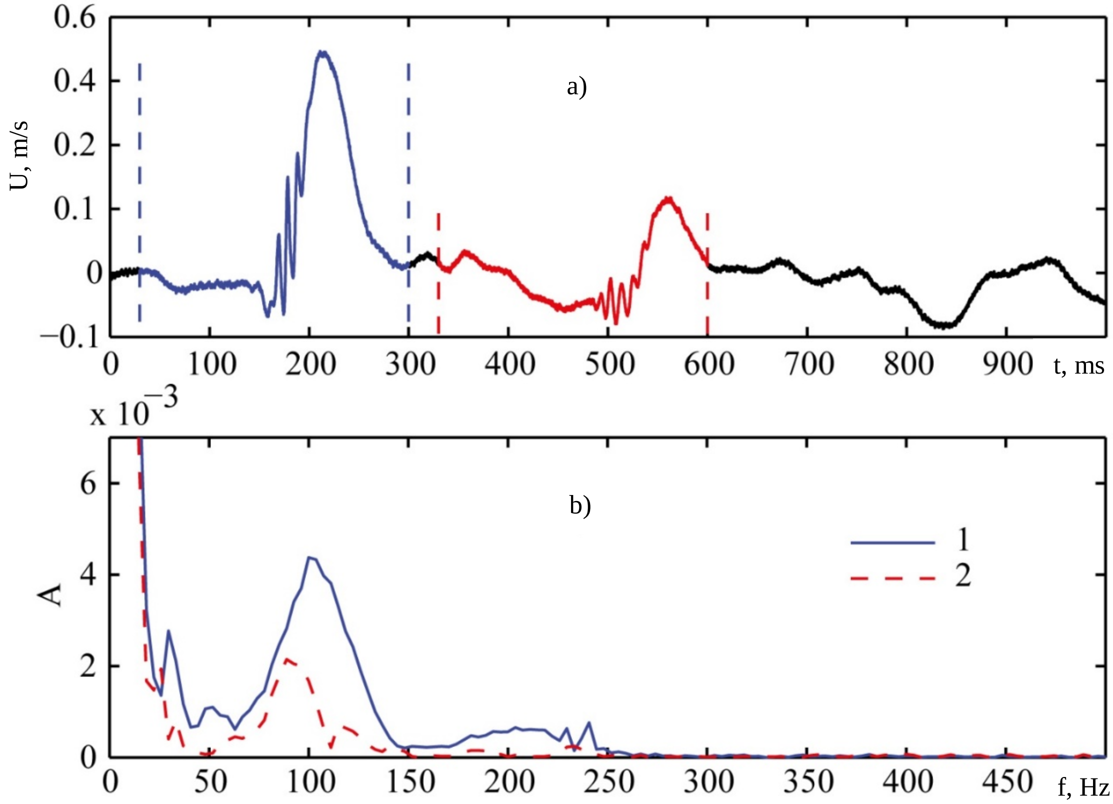

Figure 7: a) The characteristic oscillogram of the perturbed flow, and b) the amplitude spectrum in the region of forward front (1) and rear front (2) of the longitudinal structure at x = 500 mm.

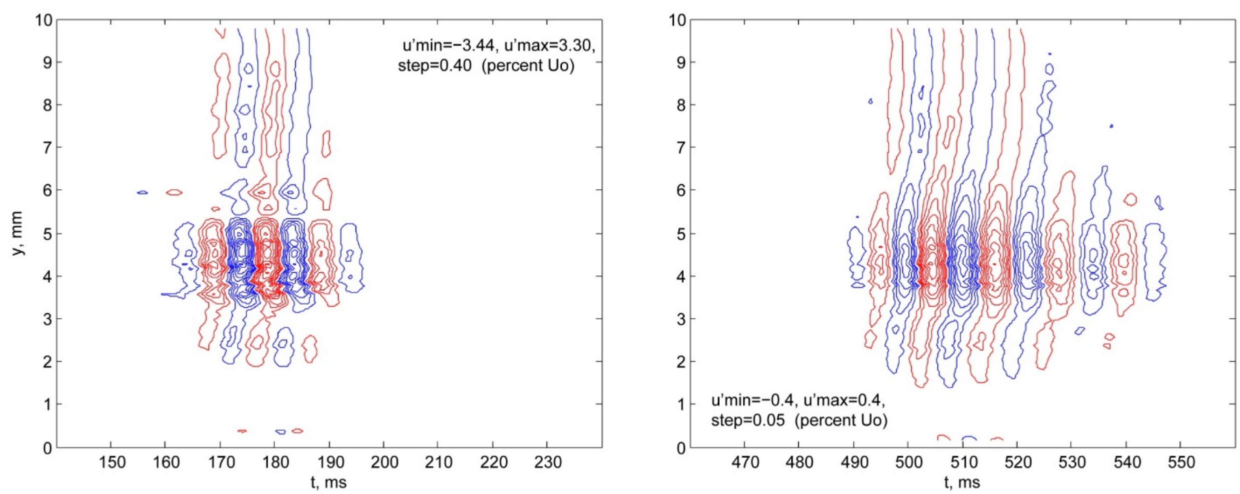

Figure 8: Contours of velocity fluctuations along the normal to the model surface for the wave packet on the forward and rear fronts of the localized longitudinal perturbation. Red and blue lines- positive and negative deflection of the longitudinal velocity component respectively. The frequency range is 50 - 300 Hz. x=500mm. z' = - 45 mm.

The time trace at the maximum of disturbance in normal coordinate (y) together with it power spectra in section x=500mm is presented in figure 7. Wave packets in the section x=500mm were obtained by means of filtration procedure, consisting in the forward and backward Fourier transform (see figure 8). Those wave packets are positioned exactly near the forward and rear fronts of the streaky structure.

Conclusion

It was found that low-frequency oscillations of the three-dimensional surface lead to the formation of two types of perturbations in the boundary layer of the swept wing with a low degree of turbulence of the incoming flow: quasistationary longitudinal localized structures and wave packets. As you move downstream, the longitudinal structure is damped. The wave packets are damped in the region of the favorable pressure gradient. In the region of a weak unfavorable pressure gradient, the attenuation ceases. Starting from the region of separation of the boundary layer, the amplitude of the wave packet increases by a factor of 10 for the rear front and 25 times for the forward front. Due to the rapid growth of the amplitude of wave packets, the flow goes from laminar to turbulent flow. Investigations of streaky structures generated by vibrations of a localized surface area on a plate, a straight and a swept wings, have shown that longitudinal structures and wave packets on their fronts are formed and develop in a similar way. It can be concluded that general physical laws can be traced in all three cases.

Acknowledgements

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