5th International Conference on Experimental Fluid Mechanics – ICEFM 2018 Munich
Munich, Germany, July 2-4, 2018

Experimental investigations of the straight wing boundary layer disturbances, generated by finite surface vibrations

Mikhail Katasonov[1]*, Alexandr Pavlenko[1], Victor Kozlov[1,2]

[1] Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Novosibirsk, Russia
[2] Novosibirsk State University, Novosibirsk, Russia
*mikhail@itam.nsc.ru

Abstract

The development of controlled disturbances in the straight wing boundary layer by means of hot-wire anemometry technic is studied. Oscillations of a three-dimensional surface region of the model with large amplitude generate two types of perturbations: localized longitudinal structures and wave packets. Downstream, the intensity of localized longitudinal structures decreases. The wave packets appear in the region of an unfavorable pressure gradient near the fronts of a longitudinal localized structure. In the region of flow separation, an exponential growth of the amplitude of the wave packets is observed.

Introduction

Recently, to investigate a boundary layer laminar-turbulent transition, the method of introducing controlled disturbances is widely used. Yatskikh et al. (2015), Vaganov et al. (2016), and Westin et al. (1998), Katasonov et al. (2005) carried out investigations on the excitation of controlled longitudinal structures and wave packets in the boundary layer in conditions of supersonic and subsonic velocities of the oncoming flow. The advantage of this approach is the ability to study in detail the characteristics of artificially introduced perturbations with the phase information preservation, that is, to quantitatively track the dynamics of the development of a particular perturbation at all it stages. Boiko et al. (2002) and Katasonov et al. (2005) have used the blowing-suction technique to simulate the perturbations arising in the boundary layer under the influence of an enhanced free stream turbulence level. Another method of introducing perturbations, by means of pulsed oscillations of the three-dimensional surface, was used for investigations in the Blasius boundary layer by Chernorai et al. (2000), and on the straight wing by Chernorai et al. (2001). It was established in these experiments that longitudinal localized (streaky) structures are generated in the boundary layer. It was found out that, the high-frequency wave packets begin to appear in the unfavorable pressure gradient region, and then they grow downstream (Chernorai et al. 2001). This study had a qualitative nature, so it demanded continuation. The present paper is aimed the modeling of perturbations that arise in the boundary layer under the action of vortices from the oncoming flow and is extension of the study of Chernorai et al. (2001). Boundary layer disturbances were modeled by the impulse action of a limited surface area. In the present experiment, the development of longitudinal localized structure and wave packets in the regions of a favorable and unfavorable pressure gradient, as well as in the separation region, was quantitatively studied.

Experimental technique

Present investigations were carried out in a low-turbulent wind tunnel T-324 of ITAM SB RAS. The wind tunnel test section size was 4×1×1 m. The flow around of the straight wing with chord of C = 476 mm and span of L = 1000 mm was studied. The wing was mounted at the angle of attack α= 1°. The free stream velocity was U_∞ = 7.5 m/s. Free stream turbulence level did not exceed T*u* = 0.04% U_∞. The source of controlled disturbances was a square form flexible membrane with size of 14×14 mm, glued to the wing surface in the region of a favorable pressure gradient, see Figure 1. The membrane was driven by pressure pulsations created by a loudspeaker, which was hermetically connected to it by a pipe line. Square signal with duration t= 200 ms and period T=500 ms was sent to the loudspeaker. As a result, the membrane was cyclically deviated from the surface by 0.35 mm.

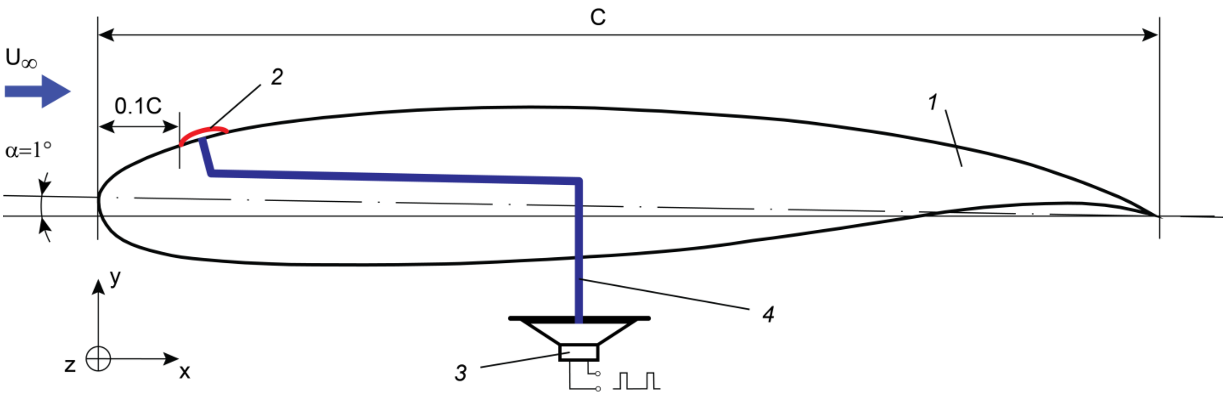

Figure 1: Experimental setup. 1 – straight wing, 2 – membrane, 3 – loudspeaker, 4 – pipeline.

The longitudinal component of the mean velocity U and velocity fluctuations u were measured by the constant temperature anemometer (CTA) AN-1003 with a single-wire sensor. The CTA sensor was relocated in the measurement area by automatic traverse system. The movement accuracy was 20 µm for the x and z coordinates and 5 µm for the Y coordinate. The free stream velocity was measured by a Pitot-Prandtl tube connected to electronic pressure transducer. The analog signal from the CTA was collected in the personal computer by means of analog-to-digital converter NI-6023. The desired signal was synchronized with the pulse generator supplied the loudspeaker. The methods of results collecting and processing were described in detail by Katasonov et al. (2012, 2014).

Results

Flow investigation outside the boundary layer of the model identified specific regions on the wing, Figure 2. The region from x/C = 0 to x/C = 0.4 of favorable pressure gradient (accelerating flow) was observed. On the other hand, there was a region of unfavorable pressure gradient (deceleration flow) from x/C = 0.4 and later. In the region of the deceleration flow, from x/C = 0.7, a horizontal segment in the distribution of mean velocity was observed, which was characterize the flow separation.
Figure 3 shows the mean velocity distribution along the normal to the surface coordinate (y) inside the boundary layer for different coordinates x. It is seen that for x/C = 0.71, the velocity profile has an inflection point, which also confirms the presence of the flow separation. Velocity profiles at x/C = 0.64-0.85 demonstrate the separation flow region. The presence of the separation area is characteristic for flow around of a wing at a small attack angles and low Reynolds numbers. Actual Reynolds number for the presented study is $Re_c = 2.3 \times 10^5$.

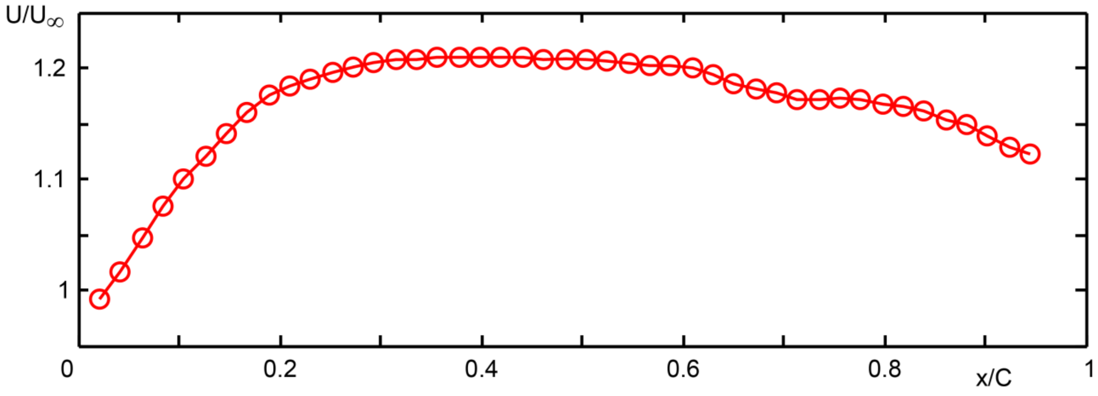

Figure 2: Distribution of the mean velocity along the wing chord.
Measurements were made outside the boundary layer.

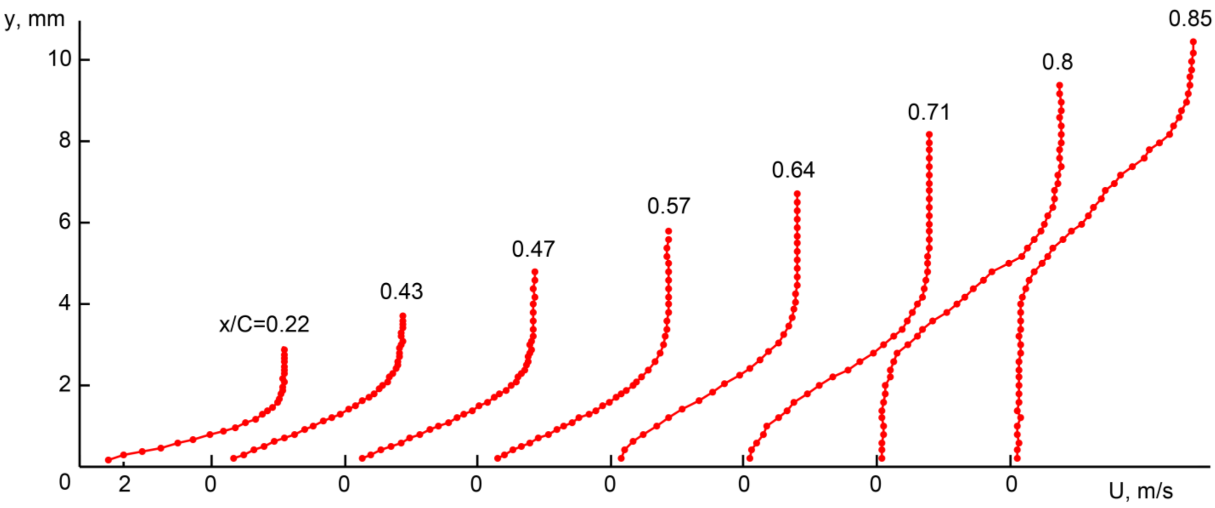

Figure 3: Mean velocity profiles.

Deviating from the model surface, the membrane took effect on the boundary layer. Result of this influence is shown in Fig. 4 as contours of the equal velocity fluctuations in z-t and y-t planes for x/C = 0.22. The local action of the membrane leads to the formation of a characteristic disturbance in the boundary layer. The duration of the disturbance corresponds to the length of the pulse controlling the membrane (200 ms). The parameters of this disturbance correspond to longitudinal localized structures or so-called "streaky" structures, which were investigated in more detail by Westin et al. (1998). These perturbations were observed in visualization patterns illustrating the flow within the boundary layer under conditions of enhanced or high free stream turbulence level. Figure 5 shows the distribution of the intensity of the longitudinal localized structure while it develops downstream. It can be seen that the amplitude of the longitudinal structure decreases in the investigated region (from x/C = 0.22 to 0.57) from 3.2% to 1.8% U_∞. Alfredsson at al. (2001) and Katasonov et al. (2014) also noted the fact in previous studies, that the amplitude of artificial longitudinal localized structure is fade.

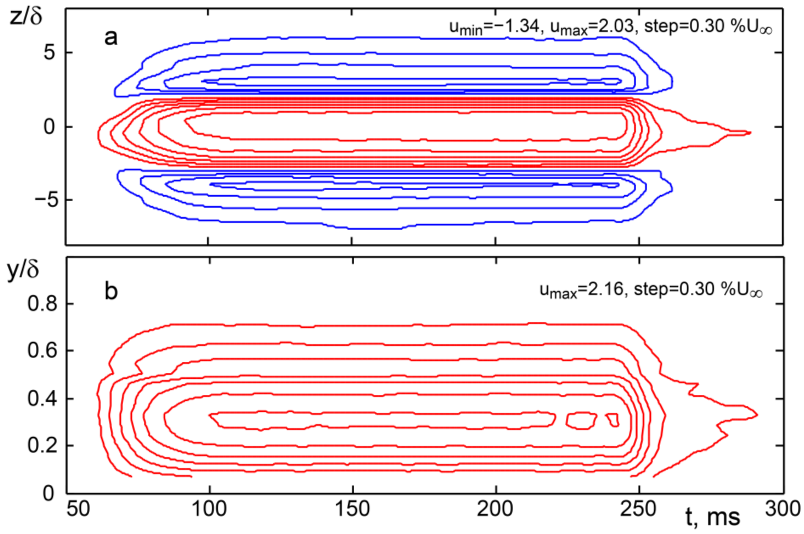

Figure 4: Contours of equal velocity fluctuations at x/C=0.22.
(a) in z-t plane at $y=y_{umax}$; (b) in y-t plane at z/δ=0.

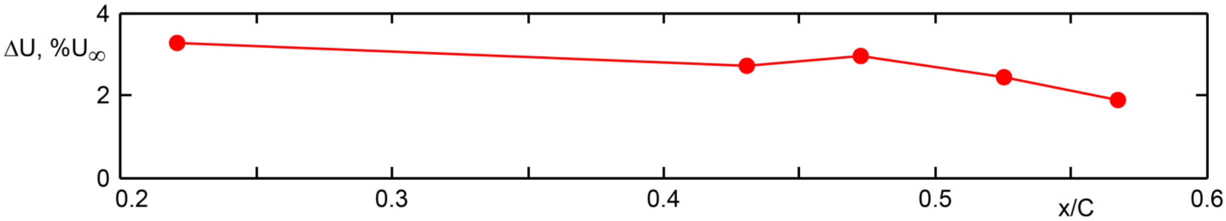

Figure 5: Downstream distribution of the amplitude of localized streak at $y = y_{umax}$.

In previous experiments by Chernorai et al. (2001) and Katasonov et al. (2014), it was observed that the wave packets appeared near the fronts of longitudinal localized structures while they introduced into the boundary layer. At present study, wave packets began to appear from x/C = 0.7. In Figure 6 (a) and (b) they are shown as contours of equal velocity fluctuations after applying of a filtration procedure, which consists in forward and inverse Fourier transform in the frequency range of 70 <f <350 Hz, see Katasonov et al. (2012). It can be seen that the wave packets are time-separated corresponding to the length of the longitudinal disturbance (200 ms) and are located near the leading (120 <t <160 ms) and the rear (300 <t <340 ms) front of the longitudinal localized structure. Gorev and Katasonov (2004) identified such high-frequency disturbances as Tollmien-Schlichting wave packets in experiment. Figure 6 (c) shows the distributions velocity fluctuations (rms) for wave packets along the normal to the surface coordinate. It can be seen that the amplitude of the wave packet near the leading edge is in 10 times weaker than at trailing. Three distinct maxima are distinguishable in rms distributions. The first maximum is positioned at the boundary of the circulation region in the boundary layer separation area, near the surface, at y/δ = 0.2. The second maximum is located in the region of the largest velocity gradient at y/δ = 0.6 and exceeds the other maxima in amplitude. The third maximum is near the outer border of the separated boundary layer at y/δ = 1.1-1.3. These extremes are clearly distinguishable for both wave packets. This distribution of fluctuations in the boundary layer coincides with the results of work of Boiko et al. (2002) in which development of the Tollmina-Schlichting wave in separated flow was studies.

The characteristic power spectra of the disturbances are shown in Figure 7 (a). Peak at f≈160 Hz corresponds to wave packets near the leading and trailing fronts. Peak near f = 0 corresponds to low-frequency oscillations in the separated boundary layer.
Figure 7 (b) shows the distribution of the wave packets amplitude along the wing chord. The wave packets amplitude begins to increase sharply in the region of the unfavorable pressure gradient, starting from the beginning of the separation region (x/C = 0.7). Comparison of the growth rate of the packets with each other indicates that the amplitude of the wave packet on the leading front begins to increase at x/C = 0.7 and for the trailing at x/C = 0.76.

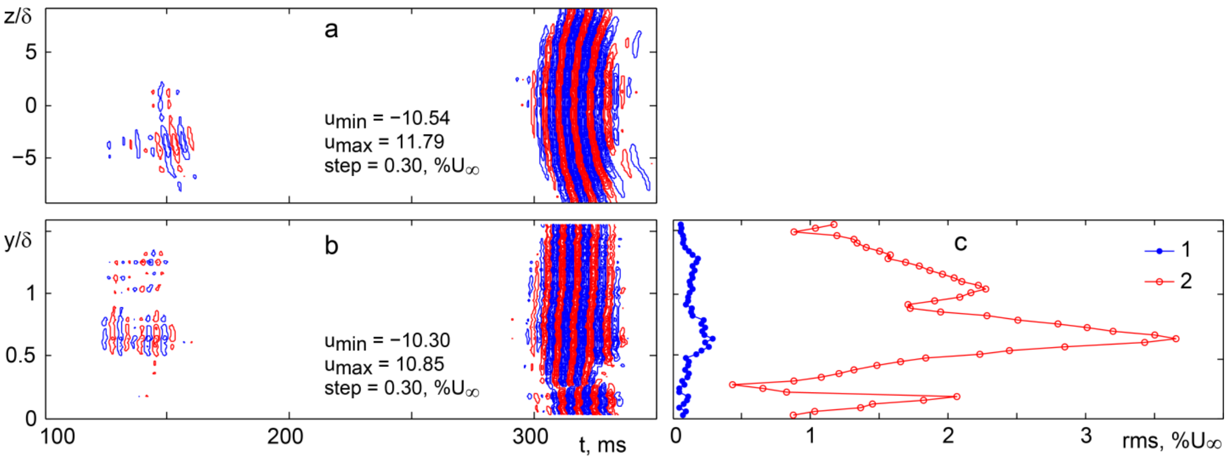

Figure 6: x/C=0.8, frequency range 70<f<350 Hz. (a) – contours of equal velocity fluctuations in z-t plane at $y=y_{umax}$, (b) – in y-t plane at z/δ=0, (c) – rms distribution of the velocity fluctuations along the normal coordinate, (1) wave packet at the leading (1) and trailing (2) front.

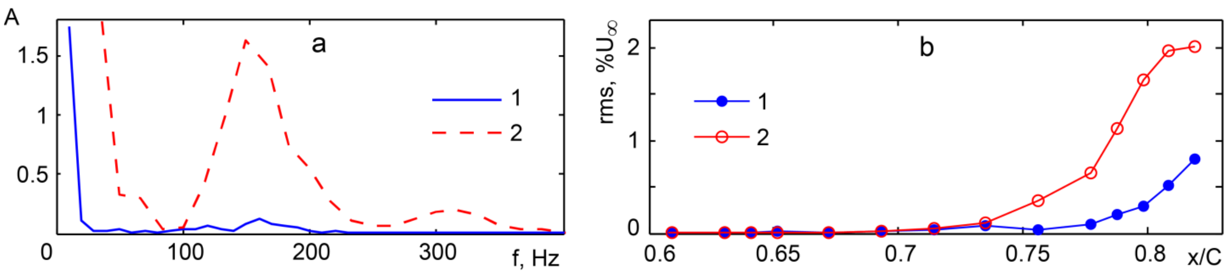

Figure 7: Power spectrum at x/C=0.8, z/δ=0, $y=y_{umax}$, (a) and downstream distribution of the wave packets amplitude near the maximum (b), at the leading (1) and trailing (2) front.

Conclusion

It is shown that the vibrations of a three-dimensional surface with a large amplitude lead to the formation of two types of disturbances in the boundary layer: longitudinal localized structures and wave packets located near their fronts.
It is shown that the intensity of longitudinal localized structures decreases downstream. On the contrary, the amplitude of the wave packets grows rapidly if they fall into the flow separation region. The spatial development of high-frequency disturbances coincides with the development of a Tollmien-Schlichting wave under the similar conditions.

Acknowledgements

The work was supported by the Russian Science Foundation (project No. 16-19-10330).

References

Alfredsson PH, Katasonov MM and Kozlov VV (2001) Generation and development of ‘‘passive’’disturbances in the blasius boundary layer. *Thermophysics and Aeromechanics* 8(3):337-344

Boiko AV, Grek GR, Dovgal AV, Kozlov VV (2002) The origination of turbulence in near-wall flows. *Springer, Berlin Heidelberg, New York*:268

Chernorai VG, Grek HR, Katasonov MM and Kozlov VV (2000) Generation of localized perturbations by a vibrating surface. *Thermophysics and Aeromechanics* 7(3) :339-351

Chernorai VG, Spiridonov AN, Katasonov MM, Kozlov VV (2001) Generation of perturbation by a localized vibrator in the boundary layer of a non-swept wing. *J. App.l Mech. Tech. Phys.* 42(5) :765-772

Gorev VN and Katasonov MM (2004) Origination and development of precursors on the fronts of streaky structures in the boundary layer on a nonswept wing. *Thermophysics and Aeromechanics* 11(3):391-403

Katasonov MM, Kozlov VV, Nikitin NV, Sboev DS (2014) The emergence and development of localized disturbances in a circular pipe and boundary layer. *Novosib. State Univ. Novosibirsk. RIC NSU*:222 (in Russian).

Katasonov MM, Motyrev PA, Sboev DS, Kozlov VV and Evers QB (2012) Development of the Wave Packets-Forerunners in the Straight Wing Boundary Layer. *Vestnik NSU, Series: Physics* 7(1):28-38

Katasonov MM, Park SH, Sung HJ and Kozlov VV (2005) Instability of streaky structure in a Blasius boundary layer. *Exp. Fluids* 38(3):363-371

Vaganov AV, Ermolaev YuG, Kolosov GL, Kosinov AD, Panina AV, Semionov NV and Yatskikh AA (2016) Impact of incident Mach wave on supersonic boundary layer. *Thermophysics and Aeromechanics* 23(1):43-48

Westin KJA, Bakchinov AA, Kozlov VV, and Alfredsson PH (1998) Experiments on localized disturbances in a flat plate boundary layer. Part I: The receptivity and evolution of a localized free stream disturbances. *Eur. J. Mech./Fluids* 17:823-846

Yatskikh AA, Ermolaev YuG, Kosinov AD, Semionov NV (2015) Evolution of wave packets in supersonic flat-plate boundary layer. *Thermophysics and Aeromechanics* 22(1):17-27