Features of the interaction of localized free-stream disturbances with the straight and swept wing boundary layer

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Abstract. Under the conditions of a model experiment, the features of the appearance and spatial development the boundary layer disturbances – wave packets (precursors) and longitudinal localized structures were studied. Localized disturbances were created artificially upon local exposure of an external source to the boundary layer of the straight and swept wing with a low turbulence level of incoming flow. Wave packets formed near the fronts of longitudinal localized structures. The studies were carried out in a subsonic low-turbulent wind tunnel. Flow perturbations were recorded using a constant-temperature hot-wire anemometer.

1. Introduction
Laminar-turbulent transition in the boundary layer at a moderate or elevated level of free-stream turbulence is associated with disturbances created by external turbulence. The effect of free stream disturbances on the boundary layer leads to the formation of longitudinal localized structures or streaks, which are areas with an excess and deficit of longitudinal velocity [1, 2]. Longitudinal structures provide the basic conditions for the development of high-frequency wave disturbances, such as secondary instability and wave packets [3]. Under favorable conditions, wave disturbances turn into turbulent spots. According to recent experimental studies [4–6], a localized effect on the boundary layer can lead to the appearance of wave packets along with banded structures.

In this work, under controlled conditions, we study the occurrence and spatial development of perturbations of the boundary layer – wave packets (precursors) and longitudinal banded structures. Wave packets are formed near the fronts of longitudinal localized structures due to a sharp local change in the longitudinal flow velocity inside the boundary layer.

2. Experimental technique
The studies were carried out in a subsonic low-turbulent wind tunnel MT-324 of ITAM SB RAS. The free-stream velocity was \( U_{\infty} = 6.8 \) m/s. The freestream turbulence level \( T_u \) was 0.18% \( U_{\infty} \). Localized disturbances were created artificially by local exposure of the source to the boundary layer under a low turbulence level of incoming flow. The source of disturbances was located in the incoming flow near the model, see figure 1. The source of disturbances was a tube with an inner diameter of 2.5 mm through which air flowed out with a short pulse of 200 or 300 ms duration. Pulsed air blowing was provided by an electromagnetic valve. Pulses were repeated every 0.5 seconds. The method of introducing controlled perturbations was used, in which the moment of introducing disturbances and the moment of their registration always coincides, which makes possible a detailed study of the characteristics of the
boundary layer disturbances. It also ensures the preservation of phase information and allows tracking the dynamics of the development of the created disturbances at all stages of their development. Disturbances in the incoming flow and in the boundary layer were recorded using a constant-temperature hot-wire anemometer. In the paper an isocontours of velocity fluctuations used, representing the so-called hot-wire visualization of disturbances.

![Figure 1. Scheme of experiment.](image)

3. Results

3.1. Straight wing

Initially, the experiment was carried out on a straight wing model with a chord $C_1 = 290$ mm, installed in the closed wind tunnel test section at zero angle of attack. Pulse air blown out under a small excess pressure from the tube and interact with the boundary layer of the model in the region of the leading edge, which has a large curvature radius about 7 mm. Figure 2 presents the pictures of hot-wire anemometric visualization of this process. The cross sections of disturbances are shown in the region of their middle in the Y-Z plane for different longitudinal coordinates $X$. The first cross section at $X/C_1 = -0.04$ shows a disturbance in the incoming flow. The transverse size of the air jet flowing out of the tube remains almost unchanged (about 2.7 mm), while slightly compressing in the vertical direction, apparently due to interaction with the associated main flow. Faced with the leading edge of the model, the jet core generates a disturbance in the boundary layer, which has a much larger transverse dimension. Only the red region with excess of velocity has a transverse dimension in 4.6 times larger than the initial disturbance (12.5 and 2.7 mm, respectively). In this case, regions with a velocity defect (blue color) appear symmetrically on both sides. The disturbance generated on the model (including all regions of the defect and velocity excess) has a transverse dimension in 10 times larger than the boundary layer thickness $\delta$. Here, the $\delta$ can be estimated from the height of the disturbance (along the $Y$ coordinate). Moving downstream, the disturbance slightly diffuses, in proportion to the increase of the boundary layer thickness, which was noted in a number of previous studies [2, 3], when disturbances were introduced from the model wall [4, 5]. In [2], at a similar incoming flow velocity, the transverse size of the disturbance in the boundary layer approximately corresponded to the initial one, however, the radius of the leading edge in this experiment was much smaller, $0.5$–$0.7$ mm. It is likely that the air jet in the present experiment, interacting with a strongly blunted leading edge, behaves like an impact jet, which is not observed in [2], where the leading edge is quite sharp.
Figure 2. Isocontours of the longitudinal component of velocity fluctuations in different positions along the chord C1 of the straight wing in Y-Z plane in the region of the middle of the longitudinal localized disturbance.

Below is the evolution of the disturbance in the Z-t plane. Figure 3 shows typical visualization patterns for various coordinates along the flow direction. At X/C1 = 0.76 and further downstream, the formation and growth of the wave packet near the leading edge of the longitudinal localized disturbance are seen.

Figure 3. Isocontours of the longitudinal velocity component fluctuations in different positions along the chord C1 of the straight wing in Z-t plane.
With a low Reynolds number, in our case $ReC1 = 131000$, flow separation occurs in the rear part of the wing. As was shown earlier, the region of the unfavorable pressure gradient, and in particular the flow separation, strongly destabilize the wave packet, which in the present experiment manifests itself in the region near the leading front of the localized disturbance. In the present experiment, the development of the wave packet led to the appearance of the $\Lambda$-structure. A similar result was observed upon introducing perturbations from the model surface [4].

3.2. Swept wing
Further experiment was carried out on a swept wing model of with a sweep angle of 45 degrees and a chord of $C2 = 410$ mm, also set at zero angle of attack. Figure 4 shows the visualization of the interaction of the disturbance generated by the tube with the boundary layer of the swept wing. Near the model nose at $X/C2 = 0.02$, the disturbance shifts upward from the axis of symmetry by 10 mm. Moreover, the internal structure of the disturbance differs from the case of a straight wing. There are only two areas - defect and excess of velocity. The total disturbance width turned out to be smaller than for the straight wing (7.5 and 12.5 mm). Due to the influence of the secondary flow directed along the leading edge of the wing, the perturbation becomes asymmetric. In the process of evolution downstream, the disturbance shifts first down and then up. Its width also increases in proportion to the increase of the boundary layer thickness. Figure 5 shows the disturbance cross section along the vertical coordinate $Y$ at $X/C2 = 0.61$. The velocity excess region is located above the velocity defect region, which means that, unlike the straight wing, see figure 2, the secondary flow spins the disturbance in main flow direction. In the region of an unfavorable pressure gradient, at $X/C2 = 0.85$, due to the secondary flow, new region is formed with excess of the velocity. Here, as in the case of a straight wing, a high-frequency disturbance (wave packet) comes out. The symmetry of the wave packet is also broken by the influence of the secondary flow, which was previously noted in [7].

The general view of the movement of longitudinal localized disturbance along the wing, made on the basis of real-scale visualization patterns (figure 4), shows its S-shaped trajectory, see figure 6, which coincides with basic ideas about the flow structure on a swept wing [8].

![Figure 4](image-url)  
**Figure 4.** Isocontours of the longitudinal velocity component fluctuations in different positions along the chord $C2$ of the swept wing in $Z$-$t$ plane.
A study of the dynamics of the downstream development of the generated disturbances on the straight and swept wings showed that the amplitude of the longitudinal localized disturbances damps. Moreover, their main characteristics coincide with the boundary layer disturbances generated by increased or high external turbulence [3]. The amplitude grow of the wave packets, which are also excited by the interaction of disturbances from the incoming flow and the boundary layer of the model, occurs in the region of an unfavorable pressure gradient and flow separation.

Figure 5. Isocontours of the longitudinal velocity component fluctuations in different positions along the chord C2 of the swept wing in Y-t plane, X/C2=0.61, Z1=1 mm.

Figure 6. Downstream evolution of the regions of the defect (blue) and velocity exceed (red color) of the longitudinal localized disturbance in the swept wing boundary layer.

4. Conclusions
It was found that longitudinal localized disturbances are arose in all considered cases. These disturbances were classified as longitudinal localized structures, in their characteristics identical to disturbances arising in the boundary layer under the influence of an increased level of free-stream turbulence. It was noted that the intensity of the longitudinal localized structures decreases in the downstream direction. High-frequency wave packets also appear by the interaction of the artificial external flow disturbances with the boundary layer. Wave packets rapidly increase in the presence of an unfavorable pressure gradient and in the flow separation area. During the interaction of free stream disturbances with a thin boundary layer in the region of the model nose, the disturbance expands in the transverse direction. The presence of a secondary flow on a swept wing influences strongly the structure of both longitudinal localized structures and wave packets. The longitudinal structures twist in the direction of flow, and their motion path takes an S-shape. Wave packets become asymmetrical.
Acknowledgments
This work was supported by the project of Russian Science Foundation 16-19-10330 and was partly carried out within the framework of the Program of Fundamental Scientific Research of the state academies of sciences in 2013-2020 (project No. AAAA-A17-117030610128-8).

References
[1] Morkovin M V 1984 *NASA-CP-2386*
[2] Westin K J A, Bakchinov A A, Kozlov V and Alfredsson P H 1998 *Eur J Mech-B/Fluids* 17 823-46
[3] Boiko A V, Grek G R, Dovgal A V and Kozlov V V 2002 *The Origin of Turbulence in Near-Wall Flows* (Berlin: Springer)
[4] Gorev V N and Katasonov M M 2004 *Thermophysics and Aeromechanics* 11 391-403
[5] Chernorai V G, Spiridonov A N, Katasonov M M and Kozlov V V 2001 *J. Appl. Mech. Tech. Phys.* 42 765-72
[6] Matsubara M, Takaichi K and Kenchi T 2009 *Proc. IUTAM Symp Laminar-Turbulent Transition* Ed Schlatter P, Henningson D S (Sweden: Springer-Verlag) pp 277-82
[7] Gorev V N, Katasonov M M and Kozlov V V 2007 *Fluid Dynamics* 42 732-39
[8] Schlichting H and Gersten K 2000 *Boundary layer theory* (Berlin Heidelberg New York: Springer)