Evolution of artificial disturbances in swept wing supersonic boundary layer

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Abstract. Experimental data on the evolution of artificial controlled travelling disturbances in a three-dimensional supersonic boundary layer on a 45° swept wing at Mach number 2.0 is presented. Artificial disturbances were introduced in the boundary layer using a periodical glow discharge with a frequency of 20 kHz. Pulsations of the boundary layer were measured with a constant-temperature hot-wire anemometer and the probe moved parallel and not parallel to the leading edge of the model. In both cases spatial-temporal and spectral-wave characteristics of the wave train development were obtained and quantitatively compared with each other. This paper discusses the suitability of the method for measuring fluctuations fields when the probe is moving not parallel to the leading edge of the model.

1. Introduction
The problem of predicting the laminar-turbulent transition onset in three-dimensional (3D) boundary layers has been studied for more than one decade [1, 2]. The practical significance is obvious, since the same boundary layers are realized on the wings of aircraft. But the task is complicated by the fact that in the case of 3D boundary layer, additional factors appear that affect the laminar-turbulent transition process. Thus, a distinctive feature of the boundary layer of the swept wing is the presence of a crossflow, which is responsible for the emergence of new types of instabilities. As a rule, four main types of flow instability are distinguished in 3D boundary layer: attachment line instability on the leading edge, stationary crossflow instability, cross-flow instability to the travelling disturbances, instability of the Tollmien-Schlichting waves. What type of instability will be the key and determine the laminar-turbulent transition strongly depends on environmental conditions, such as Mach number, surface quality, etc.

As for the supersonic boundary layer, it is somewhat more complicated than the case of an incompressible boundary layer. Differences between incompressible and compressible flows are already observed at the linear stage of development of unstable disturbances. Several studies were devoted to the evolution of traveling pulsations in 3D supersonic boundary layer [3-5], where it was found that the laminar-turbulent transition is determined by this type of disturbance. To excite controlled travelling pulsations in a supersonic boundary layer, a periodic discharge in the chamber is used at the ITAM SB RAS [6-8]. This approach made it possible to study in detail the linear development of a wave train on a swept wing (sweep angle of 45 degrees) with a Mach number of 2.0 for disturbance frequencies of 10 and 20 kHz [9, 10].
In the above works, measurements with the hot-wire probe were performed parallel to the leading edge of the model. Since in previous experiments \cite{10} it was found that the maximum of the pulsations for all waves is approximately in one place along the boundary layer, it is of interest to measure the wave characteristics in the coordinate system associated with the incident flow. In this approach, the probe does not move parallel to the leading edge of the wing, but perpendicular to the incident flow – as in the case of a flat plate. This approach has its advantages and disadvantages. Of the benefits – a simplification in the processing of experimental data, namely in the Fourier transform and the estimation of the longitudinal wave numbers. On the minus side – the movement of the probe in experiment occurs along a curved path with a change in the normal coordinate, since the upper surface of the wing model is not flat, but convex. The results of the experiments at Mach 2 and their comparison, performed in two approaches – when the probe is moving in parallel and not parallel to the leading edge, are presented below.

2. Experimental setup and data processing
The experiments were performed in a T-325 low-noise supersonic wind tunnel of ITAM SB RAS, at Mach number $M = 2.0$ and unit Reynolds number $Re_1 = 5 \times 10^6 \text{ m}^{-1}$. Disturbances in the flow were measured with a constant-temperature hot-wire anemometer. A tungsten wire with a diameter of 10 microns and a length of 1.7 mm was used. Using a coordinate device, the hot-wire anemometer probe could move in all three directions in space.

A swept-wing model was used in the experiments (see figure 1). The model had a sweep angle of $45^\circ$ and a slightly blunted leading edge of radius 0.2 mm. The swept wing had a 2.6% lens-shape airfoil on the upper side and a flat surface on the bottom side, with a maximum thickness of 12 mm. The curvature radius of the upper side of the model was approximately 4000 mm. Inside the model, a source of localized artificial disturbances was located, similar to that described in \cite{6}. Controlled pulsations from the periodic discharge were introduced into the boundary layer through the hole with a diameter of 0.4 mm on the upper surface of the model. The point source was located at a distance of $x_0 = 56.6 \pm 0.3$ mm from the leading edge of the model. The discharge was ignited at a frequency of 20 kHz and introduced disturbances into the boundary layer at the same frequency, while the measurements were synchronized with the operation of the discharge. In each position of the probe, time traces were recorded containing the AC component of the signal. Two coordinate systems associated with the flow and with the leading edge of the wing are shown in figure 1. Note that the position $x = 0$ was chosen at the source aperture.

![Figure 1. A swept wing model and coordinate systems used.](image)

As already mentioned, this paper presents the results of experiments in two approaches: when the hot-wire probe moves parallel to the leading edge of the model and not parallel. Approximate trajectories
of movement of the probe are shown in figure 2. The value $x_s$ corresponds to the distance from the discharge to the measuring section along the central line of symmetry of the model.

![Figure 2. The trajectory of movement of the hot-wire probe: parallel to the leading edge (up), not parallel to the leading edge (down).](image)

The hot-wire anemometer measures the pulsation of the mass flow in the longitudinal direction $m(x,z,t)$ [10]. After that, the frequency-wave disturbance spectra were calculated using the discrete Fourier transform (see formula (1) in [10]).

To obtain $\alpha_r$, we used the estimation:

$$\alpha_r = \frac{\Delta \Phi_f}{\Delta x_s},$$

where $\Delta x_s$ is the distance between the measured sections in the $x$-direction. Since with a different motion of the probe, after the Fourier transform, the wave and phase spectra $A_{\beta f}, \Phi_{\beta f}$ and $A_{\beta f}', \Phi_{\beta f}'$ are obtained (in the case of parallel and not parallel to the leading edge motion of the probe, respectively), for the comparison of the dispersion relations $\alpha(\beta)$ the connection of two coordinate systems was used:

$$\beta = \beta' \cos(45^\circ) - \alpha_r' \sin(45^\circ),$$

where $45^\circ$ is the wing sweep angle.

3. Results

Measurements of the controlled disturbance evolution were performed at three different $x_s$-coordinate values for the case of movement of the probe parallel to the leading edge of the model, and at five $x_s$-coordinate for the case of not parallel movement. These measurements were carried out in a layer of maximum fluctuations, which corresponds to the condition $y/\delta \approx 0.6$, where $\delta$ is the thickness of the boundary layer. Note, that in the first case, the measurements in each section took place at a constant value of the $y$-coordinate, whereas in the second case it was necessary to change the $y$-coordinate when
the probe moving perpendicular to the oncoming flow. In both experiments, the source of controlled disturbances introduced pulsations at frequency $f = 20$ kHz in the supersonic boundary layer. The evolution of disturbances at this frequency downstream is discussed below.

The amplitude distributions of disturbances at frequency 20 kHz in the spanwise direction are shown in figure 3. We can note the increase in the wave train amplitude downstream, the expansion of its boundaries, and the shift of the center of the wave packet to the region of positive values of the $z'$- and $z$-coordinate. Asymmetry is also observed with respect to the central line where discharge is ($z' = 0$ mm). This fact is associated with the presence of the crossflow in the boundary layer of the swept wing, which is not observed in the amplitude distributions for the case of a flat plate [6]. On the whole, the obtained picture of the spatial development of the wave train corresponds to the results of [9, 10].

![Figure 3](image-url1)

**Figure 3.** Amplitude distributions of disturbances in the spanwise direction when hot-wire probe moves parallel (left) and not parallel (right) to the leading edge.

![Figure 4](image-url2)

**Figure 4.** Amplitude $\beta$-spectra of disturbances when hot-wire probe moves parallel (left) and not parallel (right) to the leading edge.

Figure 4 shows the amplitude $\beta$-spectra of the controlled disturbances at frequency 20 kHz. Again, as in figure 3, there is an asymmetry of the $\beta$-spectra for the boundary layer of the swept wing (in contrast to the case with a flat plate). The amplitude growth is observed in a wide range of spanwise wavenumbers, but the amplitude maximum is located at $\beta' = 1.11$ rad/mm for the case of parallel moving of the hot-wire probe and at $\beta = 1.17$ rad/mm for the case of not parallel moving. This values belong to the linear peak in downstream wave train development and correspond to $\beta'$-spectra in [9, 10].
Having amplitude and phase $\beta$-spectra, it is possible to evaluate other wave characteristics of the development of unstable disturbances, namely, the wave number of the longitudinal component of the wave vector $\alpha_r$ and the angles of inclination of the wave vectors. The estimated results for $\alpha_r$ for both cases of hot-wire probe movement are shown in figure 5 (left). The dependences $\alpha_r(\beta)$ are seen to be close to the linear ones and numerically coincide with each other and with estimates in [9, 10]. The directions of the wave vectors for two cases (see figure 5 (right)) also show the correspondence of the wave characteristics in the measurements parallel and not parallel to the leading edge. Note that other wave characteristics, such as the phase velocities, the wavelengths, and the amplification rates (increments) also coincide in two different approaches.

![Figure 5. Dispersion relations $\alpha_r(\beta)$ (left) and directions of wave vectors (right).](image)

4. Conclusion

The wave characteristics of the development of artificial traveling disturbances with a frequency of 20 kHz in a supersonic boundary layer on a swept wing with a Mach number of 2.0 are experimentally obtained. Two approaches were tested in the movement of the hot-wire anemometer probe: parallel and not parallel to the leading edge of the model. In both cases, it was shown that the distributions of spatial amplitudes and $\beta$-spectra are asymmetric. This fact is associated with the presence of the crossflow in 3D boundary layer. It was found that the amplitude maximum is located at $\beta' = 1.11$ rad/mm for the case of parallel moving of the hot-wire probe and at $\beta = 1.17$ rad/mm for the case of not parallel moving. Comparison of the results of two approaches to the movement of the probe shows the equivalence of data processing methods for determining the wave characteristics of controlled disturbances, which makes it possible to measure the fields of controlled disturbances in the boundary layer of the swept wing in the traditional way for flat plate models. Also, the obtained dispersion dependences $\alpha_r(\beta)$ will allow one to check the condition of wave phase synchronism to reveal the mechanism of nonlinear interaction.

Acknowledgments

This work was supported by the Grant of the President of the Russian Federation (MK-2491.2019.1). The study was conducted at the Joint Access Center “Mechanics” of ITAM SB RAS.

References

[1] Bippes H 1999 *Prog. Aerospace Sci.* **35** 363–412
[2] Saric W S, Reed H L and White E B 2003 *Annu. Rev. Fluid Mech.* **35** 413–40
[3] Cattafesta III L N, Iyer V, Masad J A, King R A and Dagenhart J R 1995 *AIAM J.* **33** 2032-37
[4] Li F and Choudhari M 2011 *Theor. Comput. Fluid Dyn.* **25** 65–84
[5] Yermolaev Y G, Kosinov A D and Semionov N V 2014 *Journal of Applied Mechanics and Technical Physics* **55** 764–72
[6] Kosinov A D, Maslov A A and Shevelkov S G 1990 *J. Fluid Mech.* **219** 621–33
[7] Yermolaev Y G, Kosinov A D, Semionov N V, Tagaev S N and Semisynov A I 2009 *FMA '09:*
Proceedings of the 7th IASME / WSEAS International Conference on Fluid Mechanics and Aerodynamics p 89

[8] Lysenko V I, Gaponov S A, Smorodsky B V, Yermolaev Y G, Kosinov A D and Semionov N V 2016 J. Fluid Mech. 798 751–73

[9] Ermolaev Y G, Kolosov G L, Kosinov A D and Semenov N V 2014 Fluid Dynamics 49 188–97

[10] Kosinov A D, Kolosov G L, Semionov N V and Yermolaev N V 2016 Phys. Fluids 28 064101