Experimental investigation of the natural and controlled disturbance development in a supersonic boundary layer on the swept wing

A V Panina¹, A D Kosonov¹², N V Semenov¹, Yu G Yermolaev¹, G L Kolosov¹ and A A Yatskikh¹²

¹Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Institutskaya str., 4/1, Novosibirsk, 630090, Russia
²Novosibirsk State University, Pirogova 2, Novosibirsk, 630090, Russia

E-mail: avpanina@itam.nsc.ru

Abstract. The results of investigation of the transverse flow inhomogeneity effect on the natural and controlled disturbance development in 3D supersonic boundary layer are considered. The transition curves were measured on a model of a smooth swept wing and on a swept wing with roughness elements of two configurations. The influence of periodic surface roughness on the growth of natural pulsations (without using a discharge) in the boundary layer is determined. In experiments with artificial disturbances it is found that the periodic modulation of mean flow can lead to stabilization of controlled disturbances in supersonic boundary layer on a swept wing. It was found out that the weak flow inhomogeneity can influence the effectiveness of the active/passive technology of supersonic boundary layer transition control, including the surface microroughness on a swept wing.

1. Introduction

Experimental studies of the laminar-turbulent transition mechanisms of a supersonic boundary layer have been conducted over fifty years but this issue does not lose its relevance [1-3]. To solve the problem of flow laminarization it is necessary to clarify the mechanisms of laminar-turbulent transition in detail [4-8]. In recent years, interest in the flow laminarisation has only increased. It is planned to use various methods of active and passive flow control to design the next generation of compact commercial supersonic aircraft. One of the promising methods of flow control is the using of surface roughness. In [5, 9], it was shown that periodic surface roughness near the leading edge of a swept-wing model may both stabilize the flow and make the laminar-turbulent transition closer to the leading edge of the model.

The goal of this work was to investigate the transverse flow inhomogeneity effect on the natural and controlled disturbance development in 3D supersonic boundary layer on a thin swept wing.

2. Experiments set-up

The experiments were carried out in the T-325 low-noise supersonic wind tunnel that is a part of the Joint Access Center “Mechanics” of ITAM SB RAS. In all series of experiments the Mach number M = 2.0 and unit Reynolds number Re₁ = 5.1 × 10⁶ m⁻¹.

The aluminum model of swept wing with swept angle χ = 45 degree and sharp leading edge was used in the experiments. The test surface of the swept wing has radius of curvature R = 4 m, the bottom surface was flat. This corresponds to 3% profile and the maximum thickness of the model is 12 mm.
The model was installed at zero angle of attack at the center of the test section. Source of artificial disturbances [10, 11] was built in the model and it was driven by the high frequency glow discharge in chamber similar to that presented in [10-12]. Controlled pulsations have been introduced into boundary layer through the surface aperture that is 0.4 mm in diameter.

Coordinate system is associated with the flow:

- the $x$-axis is directed downstream along the axis of the test section ($x = 0$ at the glow discharge);
- the $z$-axis is perpendicular to the free-stream ($z = 0$ at the center of model).

The coordinate system is associated with the model:

- the coordinate $z'$ is directed parallel to the leading edge;
- the coordinate $x'$ is perpendicular to it;
- the $y$-axis is normal to the surface model.

The origin is common to both systems.

Transverse modulation of the mean flow in the boundary layer was created using adhesive tape stickers. Roughness is located on the top surface of the model parallel to the leading edge. Stickers were square, its size was $a = 3$ mm and thickness $h = 60$ microns. Three configurations of the sticker location are discussed in the paper:

- spacing between roughnesses was $d = 6$ mm (see figure 1a);
- spacing between roughnesses was $d = 12$ mm (see figure 1b);
- swept wing with smooth surface.

![Figure 1. Swept wing: (a) Spacing between roughness elements is 6 mm. (b) Spacing between roughness elements is 12 mm.](image)

The spanwise measurements were made at the fixed normal distance from the model surface and at $y/\delta = \text{const}$ for each position. The accuracy of the amplitude wave spectra was within $\pm 5\%$ for the most energy part of wave spectra. Measurements of natural pulsations were performed at a fixed value of a unit Reynolds number with an increase in the longitudinal coordinate $x$ along the center line of the model ($z = 0$).

Disturbances in the flow were measured with a constant-temperature hot-wire anemometer (CTA). Probes with tungsten wire of 10 microns in diameter and 1.5 mm long were used. The value of overheat loading of the wire was set equal to 0.8, and then 90% of the measured disturbances corresponded to mass-flow fluctuations [13, 14]. To move the probe along the $x$, $y$, and $z$ coordinates, a traverse gear was used.

In experiments with artificial disturbances the pulsation measurements were synchronized with glow discharge which was ignited with fundamental frequency of 20 kHz. AC and DC signals from CTA were written to the PC by using the 12–bit ADC with sampling rate of 750 kHz and by DC voltmeter, correspondingly. Four time traces of 65536 points in length were measured and written to file in each space position of hot-wire. Measurements on the smooth swept wing and on the wing with roughness were performed at a fixed electrical source power of artificial disturbances.

The mean and pulsating characteristics of the flow were obtained after data processing using the standard technique [15-18].
3. Results

3.1. Natural disturbance measurements

Measurements of natural pulsations (without ignition of the discharge) allow us to determine the structure of the flow in the boundary layer on the model, as well as to obtain transition curves.

Figure 2 shows a comparison of the mean flow modulation in the spanwise direction in the initial section \( (x' = 14.14 \text{ mm}) \) for the case of a smooth wing and swept wing with periodic stickers. Period of mean flow modulation corresponds to the period of roughness on the model surface. For the case of roughness with period of 6 mm we managed to create the heterogeneity of mean flow of almost "sine" type in some area. The presence of disturbance source aperture in the model surface introduces an additional mean flow distortion (near \( z' \approx 2 \text{ mm} \)). Measurements in other sections in \( x' \) show that the mean flow distortion does not change downstream.

Figure 3 shows a comparison of the obtained transition curves for three cases of roughness arrangement. The transition start position is the same for all cases. The end of the transition was not fixed. However, it can be noted that the growth rate of pulsations in the boundary layer for the case of a swept wing with roughness exceeds the growth rate of pulsations on a smooth wing for these experimental conditions. The highest growth rate of disturbances is observed for the case of a swept wing with roughness with a spacing between roughness elements \( d = 6 \text{ mm} \).

3.2. Artificial disturbance measurements

Next, we consider the results of experiments using artificial pulsations.

Figure 4 shows a comparison of wave amplitude spectra over \( \beta' \) at the fundamental frequency of 20 kHz in the initial section \( (x' = 14.14 \text{ mm}) \). Let us note that electrical power of disturbance source was the same in all series of the experiments. However, the obtained data show that the relative receptivity of the boundary layer to the nonstationary disturbances differs significantly.
Figure 4. Comparison of wave amplitude spectra over $\beta'$ at the frequency of 20 kHz in the initial section.

Figure 5. The normalized wave amplitude spectra over $\beta'$ at different distance from glow discharge source for fundamental wave train at $f = 20$ kHz.
(a) Smooth surface of swept wing.
(b) Swept wing with roughness, $d = 6$ mm.
(c) Swept wing with roughness, $d = 12$ mm.

Figure 5 demonstrates the amplitude wave spectra of pulsations at different distances from the glow discharge normalized to the maximum value of the pulsations amplitude in the initial section. These data allow us to estimate the growth rate of disturbances (transfer factor). In figure 5a the results are given for the case a smooth surface of swept wing, in figure 5b, they are presented for the swept wing with roughness, $d = 6$ mm, and in figure 5c, they are shown for the swept wing with roughness, $d = 12$ mm.
The results show that the most growing perturbations correspond to $\beta' \approx 1$ rad/mm wave number in all cases.

Figure 6 shows the transfer factor dependences on transverse wave number $\beta'$ for the fundamental frequency $f = 20$ kHz. The results presented in figure 6a show that at the initial stage the growth rates of disturbances for the most amplified waves ($\beta' = 1$ rad/mm) in cases of the swept wing with the roughness spacing of 6 mm and a smooth wing are less than the growth rate of disturbances in case of the swept wing with roughness spacing of 12 mm. However, at position $x' = 35.36$ mm from the disturbance source aperture the growth rate of perturbations in cases of the smooth wing is greater by about 1.5 times than the growth rate in cases of the swept wing with roughness (figure 6b). Due to this we can conclude that using the microroughness it is possible to stabilize the disturbance development at the fundamental frequency in boundary layer on a swept wing.

![Figure 6](image-url)

**Figure 6.** The comparison of the transfer dependences on $\beta'$ at the frequency of 20 kHz.
(a) $x' = 28.28$ mm. (b) $x' = 35.36$ mm.

**Conclusions**

The paper are presented the results of investigation of the transverse flow inhomogeneity effect on the natural and controlled disturbance development in 3D supersonic boundary layer on a thin swept wing.

In experiments with natural disturbances the transition curves were measured on a model of a smooth swept wing and on a swept wing with roughness elements of two configurations. It was obtained that the growth rate of pulsations in the boundary layer for the case of a swept wing with roughness exceeds the growth rate of pulsations on a smooth wing for these experimental conditions. The highest growth rate of disturbances is observed for the case of a swept wing with roughness with a spacing between roughness elements $d = 6$ mm.

In experiments with artificial disturbances it is found that the periodic modulation of mean flow can lead to stabilization of controlled disturbances in supersonic boundary layer on a swept wing. It was found out that the weak flow inhomogeneity can influence the effectiveness of the active/passive technology of supersonic boundary layer transition control, including the surface microroughness on a swept wing.

**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] Laufer J and Vrebalovich T 1960 *J. Fluid Mech.* **9** 257
[2] Kendall J M 1975 *AIAA J.* **13** 290
[3] Kosinov A D, Maslov A A and Shevelkov S G 1990 *J. Fluid Mech.* **219** 621
[4] Radeztsky Jr R H, Reibert M S and Saric W S 1999 *AIAA J.* **37** 1371
[5] Saric W S and Reed H L 2002 *AIAA Paper* **2002-0147**
[6] Fransson J H M, Talamelli A, Brandt L and Cossu C 2006 *Phys. Rev. Lett.* **96** 064501
[7] Schneider S P 2008 *Journal of spacecraft and rockets* **45** 193
[8] Li F and Choudhari M M 2010 *Theor. Comput. Fluid Dyn.* DOI 10.1007/s00162-010-0190-x
[9] Semionov N V and Kosinov A D 2007 *Thermophysics and Aeromechanics* **14** 337
[10] Kosinov A D, Semionov N V and Shevelkov S G 1994 *Int. Conf. Of the methods of Aerophys.* *Research. Proc.* **2** 159
[11] Kosinov A D, Semionov N V and Yermolaev Yu G 1996 *Int. Conf. Of the methods of Aerophys.* *Research. Proc.* **2** 137
[12] Kosinov A D and Tumin A 1996 *Resonance interaction of wave trains in supersonic boundary layer, Nonlinear Instability and Transition in Three-Dimensional Boundary Layers* eds. Duck P W and Hall P (Kluwer: Academic Publishers) 379
[13] Kosinov A D, Yermolaev Yu G, Nikolaev N N, Semionov N V and Semisynov A I 2007 *Int. Conf. Of the methods of Aerophys.* *Research. Proc.* **5** 81
[14] Kosinov A D, Semionov N V and Yermolaev Yu G 1999 *Disturbances in test section of T-325 supersonic wind tunnel* Preprint **6-99** (Russian Academy of Sciences, Siberian Division, Institute of Theoretical and Applied Mechanics)
[15] Kosinov A D, Panina A V, Semionov N V, Yermolaev Yu G and Gaponov S A 2013 *Recent Advances in Fluid Mechanics and Heat & Mass Transfer: Proceedings of the 11th International Conference on Fluid Mechanics & Aerodynamics (FMA ’13)* 19
[16] Kosinov A D, Semionov N V, Ermolaev Yu G, Kolosov G L, Yatskikh A A and Kocharin V L 2018 *AIP Conference Proceedings* **2027** 040087
[17] Kosinov A D, Kolosov G L, Yatskikh A A, Semionov N V and Ermolaev Yu G and Panina A V 2018 *AIP Conference Proceedings* **2027** 020016
[18] Yatskikh A A, Kosinov A D, Semionov N V, Smorodsky B V, Ermolaev Yu G and Kolosov G L 2018 *AIP Conference Proceedings* **2027** 040041