The experimental study of the weak shock wave action on the boundary layer of the sweep flat plate

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Abstract. The weak shock waves impact on the flow in the boundary layer of the sweep flat plate at Mach number 2 is studied experimentally. The model was installed at a zero angle of attack. Shock waves in the oncoming flow were generated by a two-dimensional roughness on the side wall of the wind tunnel test section. The data were obtained with a two-dimensional roughness on the wall of the wind tunnel and with a smooth wall at sweep angles (35 and 40 degrees) of the leading edge of the flat blunt plate. The measurements were carried out with a constant temperature anemometer.

1. Introduction
The turbulence developing in high-speed boundary layers is one of the least studied fundamental problems of fluid and gas mechanics. The study of the turbulence generated in supersonic boundary layers which are realized near the aircraft surface is necessary for the development of promising high-speed aircrafts. The process of laminar-turbulent transition in supersonic boundary layers significantly depends on the perturbations level in the free flow [1]. A turbulent boundary layer emitting acoustic pulsations into the free flow is one of the main sources of disturbances in supersonic wind tunnels [2–4]. In addition to acoustic pulsations, quasi-stationary perturbations, such as weak shock waves generated by roughness in the walls of the test section of the wind tunnel can impact on the flow around the models installed in wind tunnels.

A number of experimental [5–12] and numerical [13–14] works are devoted to analysis of the weak shock waves impact on the flow in model boundary layers. The case of an incident weak shock wave at a sweep leading edge at a small angle, when the wave “catches up” the model, is of fundamental and practical interest. In practice, this situation can occur when weak shock waves from the fuselage or other elements of the aircraft get onto a wing with a superonic leading edge. This paper is devoted to the experimental study of the weak shock waves effect on the flow in the boundary layer of the flat plate at the Mach number 2 and the leading edge sweep angles $\chi = 35^\circ$ and $\chi = 40^\circ$.

2. Experimental setup and data processing
The experiments were performed in the low-noise supersonic wind tunnel T-325 of ITAM SB RAS at the Mach number $M = 2$ and the unit Reynolds number $Re_1 = (8 \pm 0.1) \times 10^6 \text{m}^{-1}$. In the experiments, the model rotation mechanism was used; it allowed changing the sweep angle of the model leading edge.
during the experiment. The flat plate model had a blunting radius of the leading edge \( r = 2.5 \text{ mm} \) and was installed in the test section of the wind tunnel at the zero angle of attack.

The side wall surface roughness in the wind tunnel test section was used to generate the weak shock waves. An adhesive PVC tape was used as the two-dimensional roughness with a width (downstream) of 7 mm, a length (across the stream) of about 150 mm and a thickness of 0.13 mm. The schematic of the experiments is shown in figure 1, where 2D is a two-dimensional roughness, P is the trailing edge of a weak shock wave from the roughness, and \( L \) is the distance from the ledge to the leading edge of the plate. The distance \( L = 100 \text{ mm} \) was chosen so that the trailing edge of a weak shock wave from a two-dimensional roughness get on the leading edge of the plate for all sweep angles. The measurements were performed along the \( z \) coordinate perpendicular to the oncoming flow at the fixed value of the transverse coordinate \( y \approx 0.5 \text{ mm} \). To measure the pulsations and characteristics of the mean flow, the constant temperature hot-wire anemometer was used. The experimental setup, experimental equipment, and methods for measuring and processing experimental data are described in details in [9, 15–18].

3. Results
The measurements in the oncoming flow ahead of the leading edge of the model were performed. Figure 2 shows the distributions of the mass flow rate pulsations \(<m'>\) and the mean mass flow rate \( \rho U \) depending on the transverse coordinate \( z \) for two cases: with a sticker on the side wall of the test section ADT T-325 and with a smooth wall. In the first case, a perturbation in the form of an N-wave is detected in the oncoming flow. The area \( z > -12 \text{ mm} \) corresponds to an unperturbed oncoming flow. At \( z = -12 \div -15 \text{ mm} \), a significant transverse gradient of the mean flow is observed, which is accompanied by an increase in the pulsations distribution \(<m'>\). This area corresponds to the wave P1. In the area \( z = -15 \div -28 \text{ mm} \), a decrease in the mean mass flow rate is observed, which occurs unevenly in the area \( z = -20 \div -22 \text{ mm} \), the mean mass flow rate is constant and is accompanied by a change in the pulsations level. At \( z = -28 \div -36 \text{ mm} \), a sharp change in the mean mass flow corresponds to the wave P2 and is accompanied by a sharp change in the distribution of the level of pulsations of the oncoming flow. The distance between the waves P1 and P2 in the \( z \)-axis direction is approximately 16 mm. For the case of a smooth wall of the test section, in the oncoming flow the level of the mean mass flow rate and pulsations remains constant in the entire measured cross section.

Figure 3 shows the distributions of the root-mean-square pulsations and the mean mass flow rate normalized to the free flow depending on the transverse coordinate \( z \) in the boundary layer of the sweep plate for the sweep angle of the leading edge \( \chi = 35^\circ \). For the case without two-dimensional roughness on the wall of the test section, the mean mass flow rate decreases monotonically with a decrease in the transverse coordinate \( z \). In the case with 2d roughness, the flow pattern in the boundary layer changes
over the entire measured cross section. The red lines in the figure indicate the longitudinal vortex generation region after the interaction of the wave from a two-dimensional roughness with the leading edge of the plate. In this part of the boundary layer, when the incident wave generated from the recess edge of the two-dimensional roughness, the mean mass flow rate changes along with the rising level of pulsations.

**Figure 2.** The mean mass flow rate and pulsations in the oncoming flow as functions of the transverse coordinate $z$.

**Figure 3.** The mean mass flow rate and pulsations in the boundary layer as functions of the transverse coordinate $z$ at the leading edge sweep angle $\chi = 35^\circ$.

**Figure 4.** The mean mass flow rate and pulsations in the boundary layer as functions of the transverse coordinate $z$ at the leading edge sweep angle $\chi = 40^\circ$.

The similar flow pattern in the boundary layer is observed at $\chi = 40^\circ$ (figure 4). In the case of 2D roughness on the wall of the test section of the wind tunnel, the flow pattern in the boundary layer changes over the entire measured cross section. In the area of longitudinal vortex generation after the interaction of the wave from the two-dimensional roughness with the leading edge of the plate, the mean mass flow rate and the level of pulsations change dramatically.

**4. Conclusion**

An experimental study of the impact of weak shock waves (which are introduced into the oncoming flow by roughness on the wall of the test section of the wind tunnel T-325) on the flow in the boundary layer of a blunt flat plate with the leading edge sweep angles $\chi = 35^\circ$ and $\chi = 40^\circ$ was carried out at the Mach number 2.
The perturbation in the form of an N-wave was detected by the measurements in the oncoming flow ahead of the leading edge of the model in the case of a roughness on the wall. The distance between the waves in the z axis direction was approximately 16 mm. For the case of a smooth wall of the test section, in the oncoming flow, the level of the mean mass flow rate and pulsations remains constant in the entire measured cross section.

At the sweep angles of the leading edge $\chi = 35^\circ$ and $\chi = 40^\circ$, the generation of a longitudinal vortex was detected in the boundary layer after the interaction of a wave from the two-dimensional roughness with the leading edge of the plate, accompanied by a change in the level of the mean mass flow rate and pulsations.

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References
[1] Gaponov S A and Maslov A A 1980 Development of Disturbances in Compressible Flows (Nauka, Novosibirsk)
[2] Kendall J M 1975 AIAA J. 13 290-9
[3] Laufer J 1961 J. Aerospace Sci. 28 685-92
[4] Gaponov S A and Semenov A N 2018 Fluid Dynamics 53 795-804
[5] Kocharyn V L, Kosinov A D, Yermolaev Yu G and Semionov N V 2019 EPJ Web of Conf. 196 00018
[6] Kosinov A D, Yatskikh A A, Yermolaev Yu G, Semionov N V, Kolosov G L and Piterimova M V 2017 AIP Conf. Proc. 1893 030072
[7] Kocharyn V L, Semionov N V, Kosinov A D, Yermolaev Yu G and Yatskikh A A 2018 AIP Conf. Proc. 2027 040026
[8] Kocharyn V L, Afanasev L V, Kosinov A D, Yatskikh A A, Semionov N V and Yermolaev Yu G 2019 AIP Conf. Proc. 2125 030104
[9] Ermolaev Yu G, Kosinov A D, Kocharyn V L, Semenov N V and Yatskikh A A 2019 Fluid Dynamics 54 257-63
[10] Kocharyn V L, Yatskikh A A, Kosinov A D, Yermolaev Yu G and Semionov N V 2019 Siberian J. of Physics 14 46-55 (in Russian)
[11] Vaganov A V, Kosinov A D, Noev A Yu, Radchenko V N and Skuratov A S 2018 AIP Conf. Proc. 2027 030112
[12] Yermolaev Yu G, Yatskikh A A, Kosinov A D, Semionov N V, Kolosov G L and Panina A V 2016 AIP Conf. Proc. 1770 020012
[13] Din Q H, Egorov I V and Fedorov A V 2017 Uch. Zap. TsAGI 48 10-9
[14] Din Q H, Egorov I V and Fedorov A V 2018 Fluid Dynamics 53 690-701
[15] Kosinov A D, Semionov N V, Ermolaev Yu G, Kolosov G L, Yatskikh A A and Kocharyn V L 2018 AIP Conf. Proc. 2027 040087
[16] Semionov N V, Yermolaev Yu G, Kocharyn V L, Kosinov A D, Semenov A N, Smorodsky B V and Yatskikh A A 2018 AIP Conf. Proc. 2027 030156
[17] Yatskikh A A, Ermolaev Y G, Kosinov A D and Semionov N V 2019 Tech. Phys. Lett. 45 242-5
[18] Kosinov A D, Semionov N V and Yermolaev Yu G 1999 Disturbances in test section of T-325 supersonic wind tunnel Preprint 6-99