Experimental and numerical investigation of excitation of artificial disturbances in the supersonic boundary layer

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Abstract. The influence of the parameters of the impulse action on the laminar supersonic flat-plate boundary layer on the excited localized perturbations is investigated at Mach 2. The influence of the duration of a pulsed discharge on the generated disturbances is studied experimentally. Also, a direct numerical simulation of the influence of the parameters of pulse injection on generated perturbations is carried out. It is obtained that as the duration of the action on the supersonic boundary layer increases, the amplitude of the generated disturbance increases. The velocity of the propagation downstream of localized disturbances in Mach 2 supersonic flat-plate boundary layer is estimated.

1 Introduction

One of the most informative methods of experimental investigation of the laminar-turbulent transition in boundary layers is the study of the evolution of artificial perturbations localized in time and space. Localized controlled pulsations have a wide spectral composition, which allows one to study the natural scenario of transition to turbulence. Artificial localized disturbances can be excited in the boundary layer by means of impulse action. In the case of supersonic flows, localized disturbances can be excited by a pulsed electric discharge [1, 2]. It was shown in [2] that the energy and duration of the pulsed discharge affect on the localized perturbations generated in the supersonic boundary layer. To develop methods for investigating the laminar-turbulent transition in supersonic boundary layers with the help of controlled perturbations, detailed data on the influence of the parameters of the action on the generated perturbations are needed.

This paper is devoted to the study of the parameters of the impulse action on the flat-plate supersonic boundary layer on excited localized disturbances. The influence of the duration of the action on the excited localized disturbances is investigated. Experimentally a pulse glow discharge was used. In numerical studies the localized disturbance was created by a short-term change in the boundary conditions on the plate surface.

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2 Experiment and numerical setup

Experiments were performed in a T-325 low-noise supersonic wind tunnel, at the Institute of Theoretical and Applied Mechanics, Siberian Branch of the Russian Academy of Sciences, at Mach number M=2 and unit Reynolds number $Re_1=3.9\cdot10^6$ m^{-1}. A flat plate with a sharp leading edge and a source of controlled disturbances were used as an experimental model (fig. 1). The plate had the following dimensions: width – 200 mm, length – 440 mm, thickness – 10 mm. The bevel angle from the leading edge was 14.5°. The leading edge thickness did not exceed 0.1 mm. The model was installed with zero angle of attack.

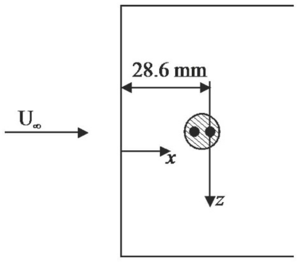

Fig. 1. Flat plate model with a source of controlled perturbations.

To initiate controlled localized disturbances an electric discharge was ignited between two copper electrodes, separated from each other and the model with an insulator. The electrode centers were located parallel to the direction of the flow (the *x* axis). The electrode diameter was 0.9 mm, while the minimum distance between them was approximately 0.9 mm. High-voltage pulses were supplied to the electrodes.

For detailed studies of the effect of the parameters of a pulsed discharge on the excited localized disturbances of a supersonic boundary layer, a pulsed glow discharge ignition circuit was developed. The developed circuit makes it possible to control the duration of a pulsed discharge, its current strength, and the frequency of ignition. The operation of the circuit is based on the modulation of a constant high voltage using a high-speed switch based on MOSFET transistors. The developed ignition circuit allows to generate high voltage pulses with amplitude up to 3 kV, duration from 5 μs. The control of the high-voltage switch was synchronized with the ADT-325 measuring complex.

Three value of duration of voltage pulses were examined: $\tau \approx 5$, 25 and 75 μs. The oscillograms of the discharge current in experiment are presented in figure 2. The peak of the current is observed at the moment of ignition of the discharge. After the discharge is set, the current is practically constant. When the signal is sent to the switch for closing, the discharge current is reduced to zero.

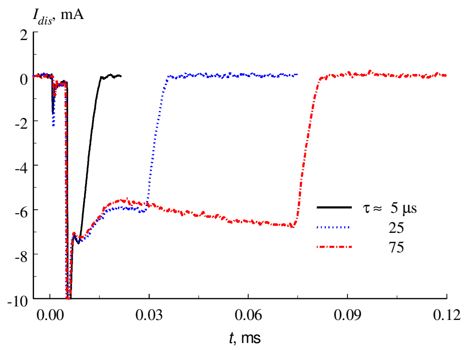

Fig. 2. Discharge current oscillograms.

Pulsations in a supersonic flow were measured using constant-temperature hot-wire anemometry (CTA-2016v2). A hot-wire probe, made of 10 μm diameter tungsten wire, was used. The anemometer full signal was digitalized with a 12-bit analogue-digital convertor (ADC). The ADC sampling frequency was 1250 kHz. The recorded signal was divided into a pulsating e' and a constant E component. Pulsations of mass flow m' normalized to the local mean flow were calculated as the ratio of the pulsation signal to the constant component considering the sensitivity coefficient.

To separate perturbations generated by discharge from the background natural fluctuations of the boundary layer, the measurements were synchronized with discharge ignition. 320 traces were recorded at each measurement. Data processing included ensemble-averaging 320 traces. The same technique was used in [1, 2].

The measurements were made in the central region of the perturbations excited by the discharge (z = 0 mm). For all measurements the hot-wire probe was installed in the layer of the boundary layer, in which the mean flow remained constant - $\rho U \approx 0.7 \cdot (\rho U)_\infty$, where $(\rho U)_\infty$ is the mass flow over the boundary layer. In this region of boundary layer, the maximum level of natural pulsations was observed. Measurements were made at x = 60 and 100 mm. Note that for the given model and the selected flow parameters, the boundary layer remained laminar at the measured points.

Also, the *numerical* investigation of excitation and evolution of the localized disturbances in a flat-plat supersonic boundary layer was provided. The direct numerical simulation (DNS) of the compressible Navier-Stokes equations was carried out. The calculated domain is the plate with the disturbance source. Length of a plate equaled 140 mm, before a plate the area of 5 mm was set. On a plate conditions of an adiabatic wall were set. The calculations were provided for the close to the experimental flow parameters. The problem was solved in two stages. At first stationary problem was solved. At the second phase the task was solved in the presence of a localized disturbance, which was created by a short-term change in the boundary conditions on the plate surface with a diameter of 1 mm, and which is located on the center of the plate at a distance of 30 mm from the front edge. A normal speed component of 25 m/s was specified. This boundary condition was put on time at τ = 5, 25 or 75 microseconds and then the sticking condition returned again. The mass flow pulsations are examined. Note, that we consider data recorded in the boundary layer in the same region as in the experiment. More details about the calculations are presented in [3].

3 Results

The results of numerical and experimental investigations of impulse action with different duration on the supersonic flat-plate boundary layer are presented in figure 3. The mass flow pulsations obtained at x= 60 and 100 mm are shown. In fig. 3a the results of numerical simulation of generating by impulse blowing with different duration and evolution of the localized disturbances are shown. In fig. 3b the experimental data are presented.

The influence of the duration of the impulse action on the boundary layer on the time scales of the localized disturbance is revealed. As the duration of the action on the supersonic boundary layer increase, the amplitude of the generated disturbance increases. This result differs from the case of subsonic flow, where only an increase in the time scale of the perturbations is observed. The estimation is carried out on the maximum deviation from the mean flow. Both in DNS and experimental studies the velocity of perturbation propagation downstream is about 0.6 U_∞. Also, a packet of unstable waves forms on the leading edge of a localized disturbance in case of the DNS studies. Wave analysis showed that the development of a wave packet downstream corresponds to a linear stability theory [3]. However, in the experiment such structures are not observed, which may be due to their small amplitude. Note, that in experiments at subsonic velocities, a similar phenomenon was observed in [4].

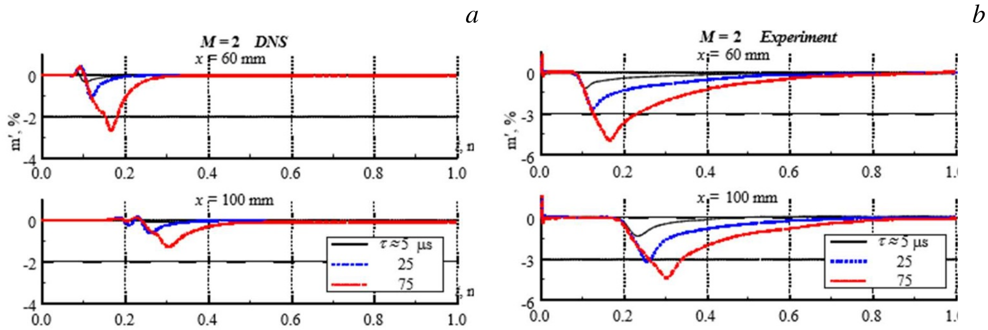

Fig. 3. Localized disturbances generated by impulse action with different duration. (a) – DNS, (b) – experiment.

4 Conclusion

The experimental and numerical investigation of the influence of the parameters of the impulse action on the excited localized perturbations in the laminar flat-plate supersonic boundary layer has been investigated. It has been obtained that as the duration of the action on the supersonic boundary layer increases, the amplitude of the generated disturbance increases. The velocity of the propagation downstream of the localized disturbances in the supersonic boundary at M=2 has been estimated. Both in DNS and experiments the velocity of perturbation propagation downstream is about 0.6 U_∞.

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