Evolution of mass flow and total temperature pulsations in flat-plate and swept-wing boundary layers at Mach 2 and 2.5

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Abstract. The experimental data on the development of natural disturbances during the laminar-turbulent transition in the boundary layers of a flat plate and a swept wing with a supersonic leading edge at Mach 2 and 2.5 are analyzed. Data are obtained using a hot-wire anemometer in the automatic scanning mode for overheating of the probe. The levels of pulsations of mass flow and disturbances of total temperature are determined using the modified diagrammatic method of Kovasznay taking into account the coefficient of correlation. It was found that at all stages of the laminar-turbulent transition of the flow in the boundary layer, the ratio of the levels of pulsations of the total temperature and pulsations of the mass flow and the correlation coefficient remain almost constant.

1. Introduction
The development of engineering methods for predicting the position of the laminar-turbulent transition in supersonic boundary layers is difficult due to the lack of knowledge about the laws of the transition and its sensitivity to changes in various flow conditions. To develop new models and numerical methods for predicting the laminar-turbulent transition, detailed experimental data on the levels and composition of pulsations of high-speed flows are necessary.

The most informative method of studying the development of disturbances in supersonic boundary layers is a hot-wire measurement. The hot-wire probe has a suitable high-frequency response and a sufficient spatial resolution. The hot-wire anemometer is sensitive to pulsations of mass flow and the stagnation temperature [1-4]. To separate the initial pulsation signal of the hot-wire anemometer into mass flow pulsations and total temperature fluctuations, measurements should be made at different values of the hot-wire probe overheating. The hot-wire anemometer created in 2016 in ITAM SB RAS enables measurements in the scanning mode for probe overheating at all stages of the laminar-turbulent transition in supersonic boundary layers. In our previous works [5-10], we measured the evolution of natural disturbances in the boundary layer on different models with different surface properties. In these studies, at splitting of the signal of the hot-wire anemometer it was assumed that the pulsations of the mass flow rate and the total temperature completely correlated.

In this work, the results of the separation of the hot-wire signal using the modified diagrammatic method of Kovasznay taking into account the coefficient of correlation are discussed. The experimental data on the mass flow pulsations and disturbances of total temperature at different stages of the laminar-turbulent transition in boundary layers of flat-plate and swept-wing at Mach 2 and 2.5 are presented.
2. Experimental set-up and data processing
The experiments were conducted in supersonic wind tunnel T-325 ITAM SB RAS. The flow Mach number was 2.0 and 2.5. In the experiments presented here, the value of the unit Reynolds number of the oncoming flow was Re'=11.5\times10^6 \text{ m}^{-1}. A flat plate with a sharp leading edge and a 3 percent-thick circular-arc swept wing with a sweep angle of the leading edge of 45° were used. Models were installed at zero angle of attack. More details on the swept wing model are presented in [11, 12].

The constant-temperature hot-wire anemometer with automatic scanning function for probe overheating was used. At each point measurements are carried out at 10 different probe overheats in the automatic mode.

The procedure for determining the pulsations of the mass flow <m'> and the total temperature <\theta'> is based on the modified Kovasznay diagram method [2]. The pulsating signal of the hot-wire anemometer and pulsations of the mass flow and total temperature are normalized on mean values and are determined as follows:

\[ e' = \frac{e}{E} \cdot 100\% \]  
\[ m' = \frac{(\rho U)'}{(\rho U)_{loc}} \cdot 100\% \]  
\[ \theta' = \frac{T_0'}{T_{0loc}} \cdot 100\% \]

where E is the mean voltage of the hot-wire anemometer, the loc index indicates the mean local values.

The pulsation signal of a hot-wire anemometer can be represented as follows:

\[ e' = Q \cdot m' - G \cdot \theta' \]  

where Q is coefficient of sensitivity to mass flow pulsations, and G is the coefficient of sensitivity to the total temperature fluctuations. These coefficients are determined by calibrating the hot-wire anemometer probe. Calibration is presented in the work [8]. Note that the coefficient of sensitivity to mass flow pulsations is practically independent of the temperature load on the sensor, while the coefficient of sensitivity to temperature fluctuations significantly depends on the temperature load.

Virtual pulsations are introduced in a modified form:

\[ \vartheta^* = \frac{e'}{Q} \]  

Also, a modified sensitivity ratio is set as:

\[ r^* = \frac{G(\tau)}{Q(\tau)} \]

Since in experiments, in fact, measurements occur at different points in time, averaging is necessary. The square of RMS level of virtual pulsations in the modified form can be presented as follows:

\[ \langle \vartheta^* \rangle^2 = \langle m' \rangle^2 - 2 \cdot r^* \langle m' \rangle \cdot \langle \theta' \rangle \cdot R_{\rho U,T0} + r^{*2} \cdot \langle \theta' \rangle^2 \]

where \( R_{\rho U,T0} \) is the correlation coefficient between pulsations of mass flow and total temperature.

For each value of the temperature load, the RMS level of virtual pulsations is determined from the experimental data and then the dependence on sensitivity ratio is built. An example of this is shown in Figure 1. RMS levels of the mass flow and the total temperature fluctuations and the correlation
coefficient can be determined by approximating this data by a polynomial of the second degree and determining the polynomial coefficients.

Figure 1. Distribution of the level of virtual pulsations from the sensitivity ratio.

3. Results
The level of the hot-wire anemometer signal in the boundary layer varies for different values of the temperature load, which is associated with a significant change in the sensitivity to the total temperature pulsations $G$. Figures 2 and 3 show the results of decomposition of the hot-wire anemometer signal on the mass flow and total temperature pulsations. The data obtained on the model of the flat plate (figure 2) and the swept wing (figure 3) are presented.

Measurements were provided along the coordinate normal to the surface at Mach 2. There are mass-flow pulsations, total temperature pulsations, and correlation coefficient. Also, the relationship of the level of total temperature perturbations to the level of mass flow pulsations is presented. As can be seen, this ratio and the correlation coefficient practically do not change from the normal coordinate in the region of the boundary layer with a large level of pulsations.
The data on the growth of disturbances downstream in the boundary layer at Mach number 2 are presented in figures 4 (flat plat) and 5 (swept wing). Similar data obtained at Mach number 2.5 are presented in Figures 6 and 7. For each probe position along the longitudinal coordinate, the probe was installed in the region of maximum boundary layer disturbances, while the mean mass flow was constant.

Figure 4. Results of the anemometer signal decomposition. Downstream growth of pulsations. Flat plate. M=2.

Figure 5. Results of the anemometer signal decomposition. Downstream growth of pulsations. Swept wing. M=2.

Figure 6. Results of the anemometer signal decomposition. Downstream growth of pulsations. Flat plate. M=2.5.

Figure 7. Results of the anemometer signal decomposition. Downstream growth of pulsations. Swept wing. M=2.5.

The pulsations of the total temperature and mass flow fluctuations increase during the laminar-turbulent transition. The ratio of the levels of pulsations of the mass flow rate and the total temperature remains almost constant at all stages of laminar-turbulent transition of boundary layers of swept-wing and flat plate. The correlation coefficient practically does not change at all stages of laminar-turbulent transition too. Similar results were obtained at Mach number of 2.5 on models of the flat plate and the swept wing.

Conclusions
The laminar-turbulent transition of the boundary layers of a flat plate and a swept-wing has been experimentally studied by the hot-wire measurements at various values of the probe overheating. Using the diagrammatic method, the hot-wire signal was decomposed into mass flow and total temperature pulsations, their levels and ratio have been determined. In addition, the correlation coefficient of mass flow and total temperature pulsations has been determined.
Both pulsations of the total temperature and mass flow fluctuations increase during the laminar-turbulent transition. Withal, the ratio of the RMS levels of pulsations of the mass flow rate and the total temperature remain almost constant at all stages of laminar-turbulent transition of supersonic boundary layers of swept-wing and flat plate. The correlation coefficient practically does not change at all stages of laminar-turbulent transition too.

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