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Experimental Study of the Natural Disturbance Evolution in a Swept Wing Boundary Layer with Periodic Spanwise Roughness at Mach 2 and 2.5

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Abstract
Experiments on the disturbance evolution are conducted in boundary layer of 45-degrees swept-wing with periodic roughness elements at Mach 2 and 2.5. Flow characteristics are measured by constant temperature anemometer. For disturbance quantities definition by diagram technique the 10 values of hot-wire temperature loading in auto scanning mode is applied. It was found that the periodic roughness lead to small upstream moving of the transition in comparison of smooth surface. The disturbance decomposition shows that the relative values of stagnation temperature disturbances to the mass flow pulsations does not change significantly during transition process.

1. Introduction

The attention of researchers in various countries is focused on the problem of transition control in spatial boundary layers on swept wings. Advanced technology of passive control of the laminar-turbulent transition (flow laminarization) in boundary layer with the help of distributed roughness on the swept-wing surface near the leading edge is studied experimentally [1-6] and theoretically [7-11] in different countries. As is known from experiments at subsonic flow over swept wing, the distributed roughness is an effective way of control of crossflow instability [1, 2]. It was obtained, that spanwise spacing of circular roughness elements with $\lambda_{st}\approx0.5$-0.55, located in a neighborhood of a leading edge of a swept wing takes a significant effect on transition delay. This method of passive control with the help of distributed roughness was first used for of the transition delay in a supersonic boundary layer on a swept wing with subsonic leading edge in [3]. A positive result in exercising passive control over supersonic boundary layer in flight tests at M=1.85 were reported in [4]. The tests were carried out on a wing model with supersonic leading edge secured under the fuselage. The transition was identified by means of IR thermography. An original shape of microroughness elements in the form of streamwise structures distributed along the wing span was proposed in [5], which allowed the transition on a swept wing with a supersonic leading edge to be delayed by 40%. On the smooth wing surface laminar-turbulent transition takes place at $Re_{tr} \approx 0.95\times10^6$, using longitudinal roughness has resulted to flow laminarization and $Re_{tr} \approx 1.35\times10^6$. Precisely for this laminarized boundary layer results of experimental study of stationary and traveling disturbances evolution are presented in [12].
But the optimum parameters of the distributed roughness (shape, size, location) for the most effective transition control are completely unknown. To determine such parameters, it is necessary to study their effect not only on the position of the laminar-turbulent transition, but also on the development of unstable perturbations. Only hot-wire measurements allow to obtain information about spatial evolution of high-frequency disturbances. Such a modern approach of disturbances evolution experiments in 3-dimentional boundary layer with inhomogeneity on swept wing was applied at first in [13]. The measurements were made with the help of scanning constant temperature hot-wire anemometer (SCTA). As a result of pulsation decomposition, based on modified Kovasznay's diagram technique [14-16], evolution dimensionless pulsations of mass flow, total temperature and their relative value in the region of the laminar-turbulent transition of a supersonic boundary layer of swept wing with roughness elements were obtained for the first time [13]. Such an experimental approach is desirable for correct comparison with the results of calculations. These studies are a continuation of [13].

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2. Experimental setup and data process

Experiments are performed in the T-325 long-duration blowdown low-noise supersonic wind tunnel of the Khristianovich Institute of Theoretical and Applied Mechanics SB RAS at Mach 2 and 2.5 and unit Reynolds number $Re_1 = 11.5 \cdot 10^6$ m^{-1}. The T-325 test-section size is 0.2 × 0.2 × 0.6 m. Model is a symmetrical wing with a 45º sweep angle and 3 percent-thick circular-arc airfoil with a slightly blunted leading edge by radius of 0.4 mm. The model is 0.4 m in length and 0.2 m in width. The maximum thickness of the swept wing is 12 mm. Boundary layer inhomogeneity on swept wing is created by using the glued tape stickers. The square stickers by size of 2.5 mm × 2.5 mm with thickness of 60 microns were applied. They were located on the model surface in parallel to the leading edge by period of 5 mm on the distance of 55 mm downstream from the leading edge. Photo of the swept wing model with roughness elements, hot-wire and traversing gear is shown in Fig. 1. Sketch of roughness element installation is presented in [13].

FIGURE 1. Photo of the swept wing model with roughness elements, hot-wire and traversing gear

The flow characteristics in supersonic boundary layers were measured by a constant-temperature anemometer (CTA) operating in scanning mode. Probes from single tungsten wire by diameter of 10 μm and 1.5 mm in length are used. 4096 points of the DC signal and 65536 points of the AC signal were recorded in each space position for each from 10 values of the hot-wire temperature loading $\tau=(T_w-T_e)/T_0$, where Tw – heating wire temperature, Te – wire recovery temperature, $Te = 0.95 \cdot T_0$, T_0 – stagnation temperature of flow. The hot-wire temperature loading are changed from about 0.45 to 1.0. The pulsation decomposition to the mass flow and the total temperature disturbances was provided according to [14]. The sensitivity factors to the mass flow, the mass flow pulsations and to the total temperature fluctuations are determined by hot-wire calibrations in the free flow of the wind tunnel [14]. Calibration relationship of mean voltage from hot-wire anemometer E to mass flow ρU are shown in Fig.2. The distribution of the coefficients of sensitivity to pulsations of mass flow Q and to total temperature fluctuations G from the wire temperature loading τ for Mach numbers M=2 and 2.5 are presented in Fig 3. After that, to estimate the values of root-mean-square mass flow $<m'>$ and total temperature $<T_0'>$ fluctuations, the modified Kovazhny's linear diagrams of pulsations in modified for CTA manner were applied which is similar to described in [14].

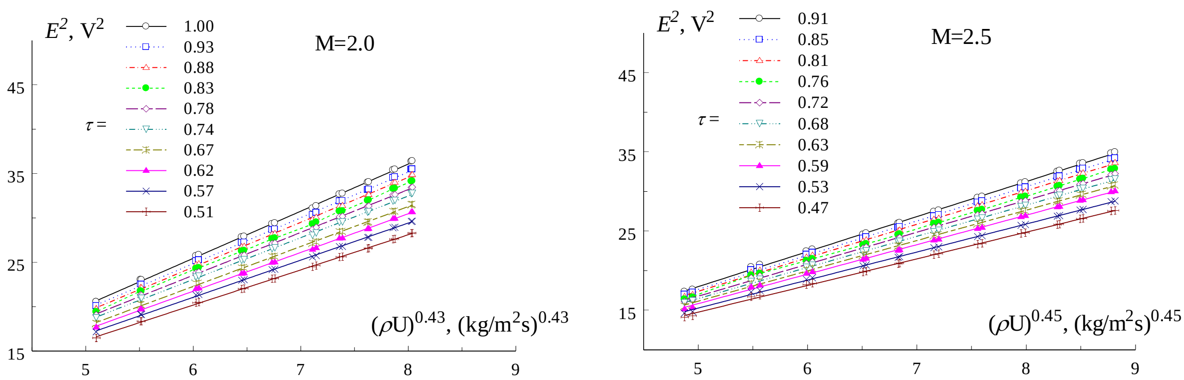

FIGURE 2. Calibration relationship of mean voltage from hot-wire anemometer E to mass flow ρU at Mach numbers 2 and 2.5

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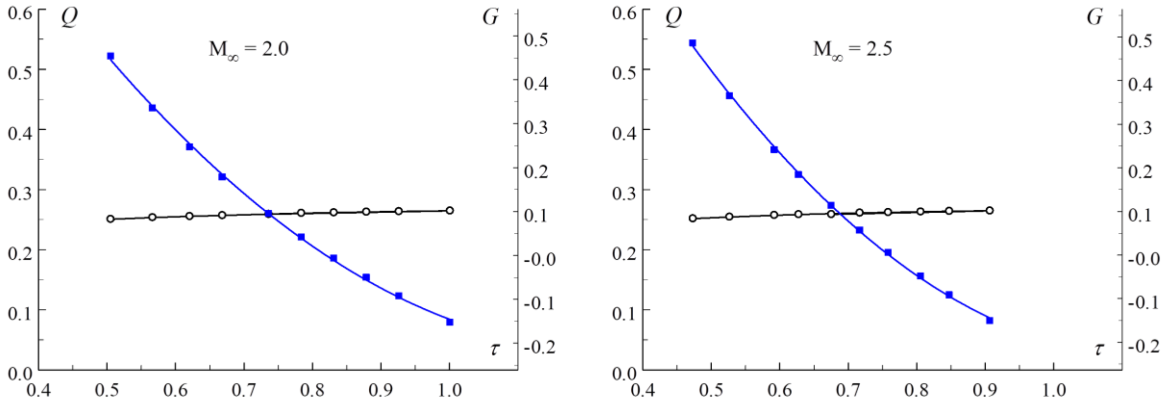

FIGURE 3. The distribution of the coefficients of sensitivity to pulsations of mass flow Q and total temperature fluctuations G from the wire temperature loading τ

The results of the experimental study of the free flow pulsation field in the test section of the T-325 wind tunnel at M = 2 and 2.5 are presented in [17]. Obtained, that level of mass flow pulsations is approximately 0.1% of the mean flow over a wide range of unit Reynolds numbers Re_1 at M = 2. In the range up to $Re_1 \approx 7 \times 10^6$ m^{-1}, the mass flow pulsations is higher at M = 2.5, compared to similar values at M = 2 and low-noise regime is observed at $Re_1 > 7 \times 10^6$ m^{-1}. Measurements are fulfilled at $Re_1 = 11.5 \cdot 10^6$ m^{-1}, hence all data is obtained for the low noise operation of the wind tunnel.

3. Results

Flow modulation in spanwise direction on the swept wing model with roughness elements (steakers) are show in Fig.4 for M=2 and M=2.5. Spanwise measurements are made parallel to the leading edge of the swept wing at a distance *x* = 80 mm and at normal coordinate *y=const*. Value of the *y*-coordinate corresponds to the layer of maximum pulsations across the boundary layer in no modulated region. The *x* coordinate was counted from the leading edge of the model in the streamwise direction. It is shown that the shape of the disturbances is close to sinusoidal and correlates well with the period of the distributed roughness elements. If at M=2 maximums in the distributions of disturbances in the mean flow rigorously correlate with the maximums of fluctuations in the boundary layer then then at M = 2.5, vice versa maximums in the distributions of disturbances in the mean flow rigorously correlate with the minimums of fluctuations in the boundary layer. The nature of this phenomenon is not clear and additional research is needed. Note that these two cases were also observed in experiments, but the case of coincidence of the positions of the maxima was obtained at the last stage of the laminar-turbulent transition.

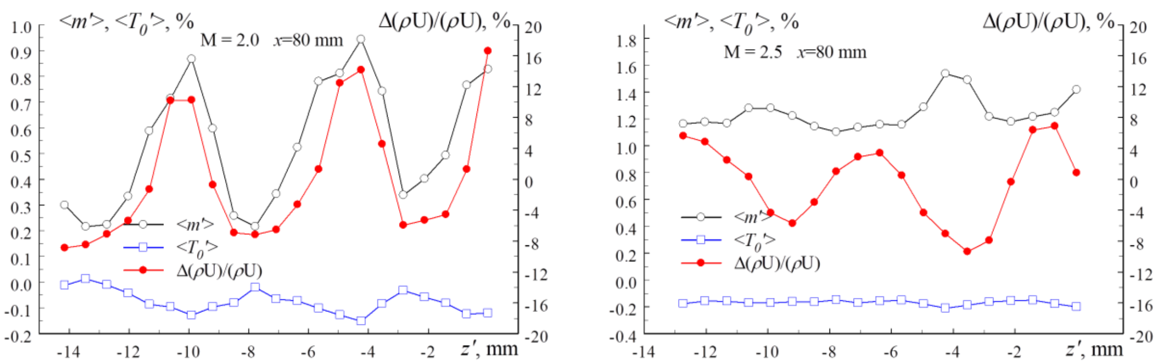

FIGURE 4. The distributions of root-mean-square mass flow <*m*′> and total temperature <T_0′> fluctuations and mass flow ρU at Mach numbers 2 and 2.5 on model with roughness element

Laminar-turbulent transition measurements are made in spanwise sensor position, when the mass flow pulsation have maximum, *z*'=-4.6 mm at M=2 and *z*'=-6.4 mm at M=2.5. The results of disturbances evolution in the swept-wing boundary layer are presented in Fig. 5. The downstream growth of mass flow pulsations, pulsations of total temperature and relative pulsation levels <T_0′>/<*m*′> for the case of a smooth model and a model with roughness

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elements at M= 2 and 2.5 is shown. The downstream measurements are carried out under the condition, that the sensor moves along the streamline (mean mass flow remained constant) inside the boundary layer. The maximum of the pulsations indicates to the end of the laminar-turbulent transition. It is obtained, that the presence of roughness elements leads to an earlier laminar-turbulent transition in supersonic boundary layer on swept wing. The transition Reynolds number $Re_{tr} = Re_1 \times x = 1.84\times10^6$ in the case of a smooth swept wing, while for the model with roughness elements $Re_{tr} = 1.69\times10^6$ at Mach number 2. The corresponding values of transition Reynolds number for the Mach number 2.5 are 1.51×10^6 and 1.46×10^6. The parameters of the roughness elements were chosen to obtain the transition delay. But, perhaps in our case, for the swept wing with thin 3% profile, the main role in the transition process is played not by stationary disturbances, but by nonlinear processes caused by mean flow modulation [7]. The ratio of the mass flow and total temperature pulsations, when the measurements of the transition are carried out under the condition $\rho U=const$, remains about constant.

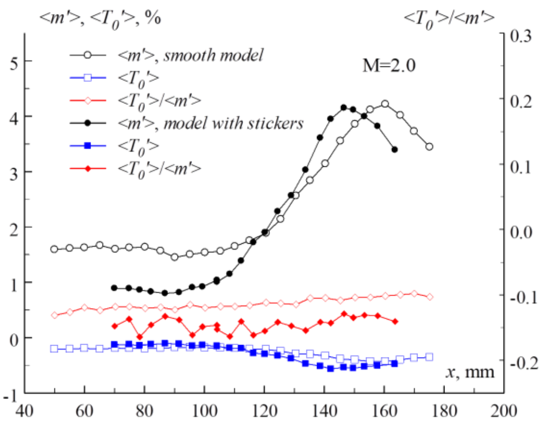

FIGURE 5. The development of root-mean-square mass flow <*m*′> and total temperature <T_0′> fluctuations and relative pulsation levels <T_0′>/<*m*′> on smooth model and model with roughness elements at Mach numbers 2 and 2.5

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