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The influence of small angle of attack on disturbances evolution and transition to turbulence in supersonic boundary layer on swept wing

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Abstract
The paper is devoted to an experimental and theoretical study of effect of small angle of attack on disturbances evolution and laminar-turbulent transition in a supersonic boundary layer on swept wing at Mach number M=2. Confirmed monotonous growth of the transition Reynolds numbers with increasing of angle of attack from -2° to 2.5°. The experimental data on the influence of the angle of attack on the disturbances evolution in the supersonic boundary layer on the swept wing model are obtained. Calculations on the effect of small angles of attack on the development of perturbations are made in the framework of the linear theory of stability. Obtained good qualitative correspondence of theoretical and experimental data.

1. Introduction

It is known that a small change in the angle of attack on sharp cones leads to a significant decrease of transition Reynolds numbers on the leeward side, and a smooth increase was observed on the windward side. An increase in the blunting of the sock of the cone leads to a decrease in the sensitivity of the Reynolds number of the transition to the angle of attack [1, 2]. There are only a few papers in which the influence of the angle of attack on the position of the laminar-turbulent transition on swept wings at trans- and supersonic flow velocities were considered. It was found in [3] that an increase of angle of attack α from -8° to + 8° resulted in a displacement of the transition point downstream. In [4] noted that the error of determination Re_{tr} was higher than the small displacement of transition location at the changing of angle of attack α in the range from -3° to 4. Only at M = 4.1 there was a small increase in laminar flow on the leeward side of the model compared to the windward one.
In [5] obtained a slight decrease in transition Reynolds number for angle of attack - 4 degrees in comparison with the α = 0. Effects of angle of attack on transition Reynolds numbers at 70% semispanwise station and at 30% semispanwise station at M = 2 are presented in [6]. Angle of attack varies from about -1.5° to 5.5°. Obtained monotonic increase of transition Reynolds number $Re_{tr}\approx 0,6\times 10^6$ to $Re_{tr}\approx 1,3\times 10^6$ with increasing angle of attack at 70% semispanwise probe station. The longest laminar region at the 30% semispanwise station is achieved at α = 1:73 deg, where the design pressure distributions realized. Even a slight deviation in the angle of attack from 1.73 deg moves the transition location significantly upstream.
The influence of the angle of attack on the laminar-turbulent transition position in the supersonic boundary layer on the swept wing remains open.

2. Experimental setup

The experiments are conducted at the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences in the T-325 low nose supersonic wind tunnel with test-section dimensions 0.2×0.2×0.6 m at Mach numbers M=2. Model is a symmetrical wing with a 45º sweep angle, a 3 percent-thick circular-arc airfoil with different leading edge bluntness. The model length is 0.4 m, its width is 0.2 m, and the maximum thickness is 12 mm.

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The disturbances are measured by constant temperature hot-wire anemometer. Single-wire tungsten probes of diameter 10 μm and length 1.5 mm is used. The overheat ratio of the wire is 0.8, and the measured disturbances correspond to mass-flow fluctuations. The constant voltage component "*E*" of the anemometer output are measured with an Agilent 34401A digital voltmeter. To recalculate "*E*", values of mass flux (ρU) in the supersonic part of the boundary layer, the known calibrating dependency for hot-wire anemometry, are applied: $E^2=L+K(\rho U)^n$, where L and K are dimensional calibration factors [7]. At the power coefficient $n=2S_{\rho U}$ ($S_{\rho U}$ – sensitivity of the hot-wire probe to mass flux pulsations), the equation is slightly simplified: $E^2= K(\rho U)^n$.
The fluctuating and mean characteristics of the flow are measured by an automated measurement system consisting of standard measurement devices and equipment in the CAMAC standard with a CC-32 controller and a basic computer. The fluctuation signal from the hot-wire anemometer is measured by a 12-bit A/D converter with a digitization on time 1.33 μs, and a mean voltage is fixed by a voltmeter. The length of each realization is 65536 points. System of measurements and data processing are described in detail in [7, 8]. Absolute values of the mass flux fluctuations $<m'>$ are determined by the method described in [7]. A method for determining the transition location with a help of hot-wire anemometer are used, when measurements are made at a fixed sensor position, and the value of unit Reynolds number $Re_1=U_\infty/\nu_\infty$ varies. Photo of the model in test section, installed at α=-2° is presented in Fig.1.

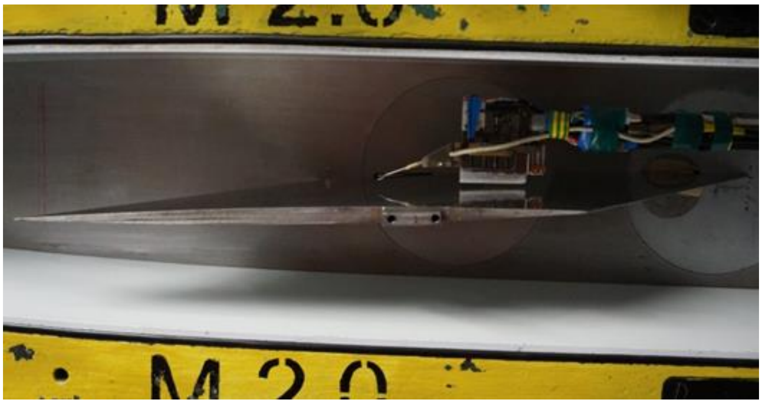

Figure 1. Photo of the model.

3. Results

An experimental investigation of the influence of the angle of attack on a laminar-turbulent transition in a three-dimensional supersonic boundary layer on the swept-wing model is performed. Measurements are made at a fixed position of hot wire probe *x*=150 mm, where *x* is longitudinal coordinate from the leading edge. Measurements of the curves of disturbances growth in the boundary layer on a swept wing model for different angles of attack at Mach number M = 2 are fulfilled. The results of the measurement are shown in Fig. 2. The location of laminar-turbulent transition corresponds to a maximum of amplitude disturbances. As can be seen from the presented data, the change in the angle of attack has a strong effect on the transition Reynolds number Re_{tr}. When the angle of attack was changed from approximately -2° to 2.5°, a monotonic increase of transition Reynolds number from $Re_{tr}\approx1.4\times10^6$ to $Re_{tr}\approx2.4\times10^6$ are confirmed with increasing of angle of attack. The obtained data are consistent with the results of measurements [6] at the 70% semispanwise probe position.
According to the experimental data presented in Fig. 1, an analysis of flow stability on the swept-wing model is carried out. The calculations are performed within the framework of the linear stability theory of compressible three-dimensional boundary layers in the approximation of the local self-similarity of the mean flow. The system of equations and the approach realized in the calculations are described in detail in [9]. The location of the laminar-turbulent transition in the framework of the linear theory was determined approximately by the method of $e^{\mathbf{N}}$. A comparison of unit Reynolds numbers Re_1, corresponding to the maxima in the growth curves for different values of the angle of attack of the model and the calculated dependences of Re_1 obtained for different values of the **N** factor and corresponding to the transition are made in Fig. 3. As in experiments obtained that transition Reynolds number increases with the growth of angle of attack. It is seen that laminar-turbulent transition occurs at the value of the **N**-factor **N**=8. Calculations are carried out at $Re_1=16\times10^6$ m^{-1}. In this case, the most intensifying (dominating in the spectrum to the transition position) are perturbations with frequencies $20 < f < 25$ kHz. The obtained results of calculations on the linear stability theory are in a good qualitative agreement with experimental data.

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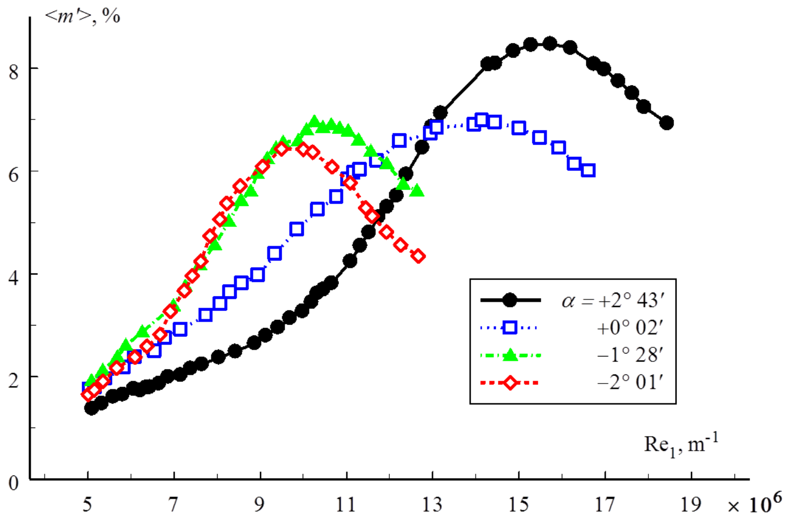

Figure 2. Dependences of mass flux pulsation <*m*′> versus unit Reynolds number Re_1 for different angles of attack.

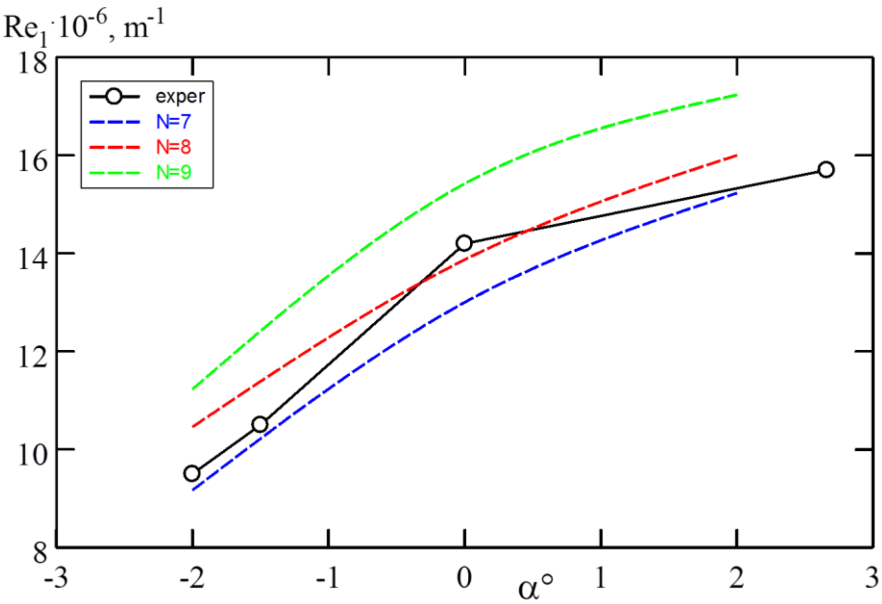

Figure 3. Dependences of unit Reynolds number of the transition versus of angle of attack α of the swept wing model. Comparison of experimental data (symbols) and calculations of the transition position by the e^N method for various values of the **N**-factor (dashed lines).

Oscillograms and amplitude–frequency spectra were obtained at each measurement point. Figure 4 shows the amplitude–frequency spectra obtained by processing of oscillations of the measurement data of curves of disturbances growth at angle of attack α =-2°. The same data are obtained for other angles of attack.
At M=2 with increasing of Reynolds number there is an intensive excitation and growth of pulsations in a range of frequencies from 10 up to 35 kHz on an initial stage of disturbances development. This obtained experimental data are in a good agreement with calculations based on the linear stability theory [9] and in our experiments at M = 2 on different models [8, 10, 11]. The growth of pulsations in a range of frequencies from 10 up to 80 kHz was observed near to transition location. The calculations of evolution of instability disturbances are performed within the framework of the linear stability theory at the following parameters: our model, M=2, $Re_1=5\times10^6$ m^{-1}, Pr=0.72, γ=1.4, α=-2°, 0, 2°, 4°. Example of obtained results is presented in Fig.5. Figure 5 shows the calculated diagrams of stability of the boundary layer on the model of the swept wing. The isolines of the spatial growth rates of instability

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perturbations of cross-flow are shown on the plane by transversal wave number *β'* ¬ frequency *f*. The obtained theoretical results on the linear stability theory are in a qualitative agreement with experimental data.

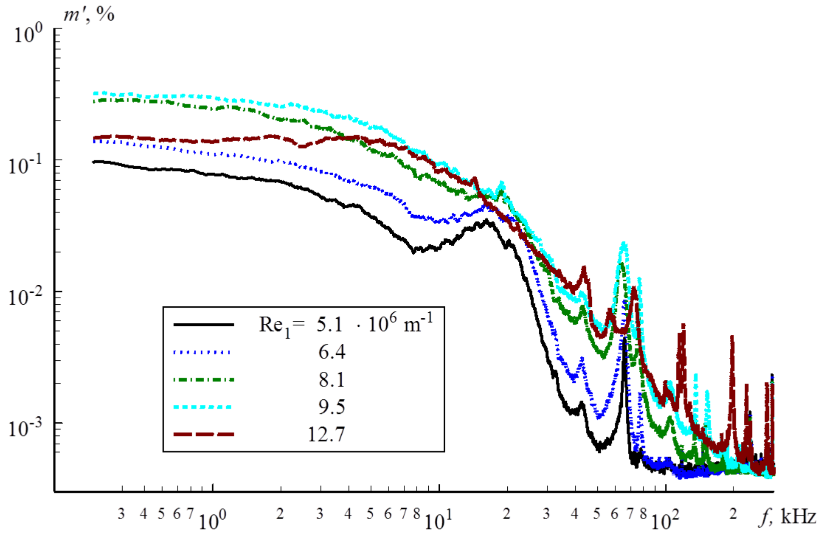

Figure 4. Evolution of amplitude-frequency spectra of disturbances at M=2, α=-2°.

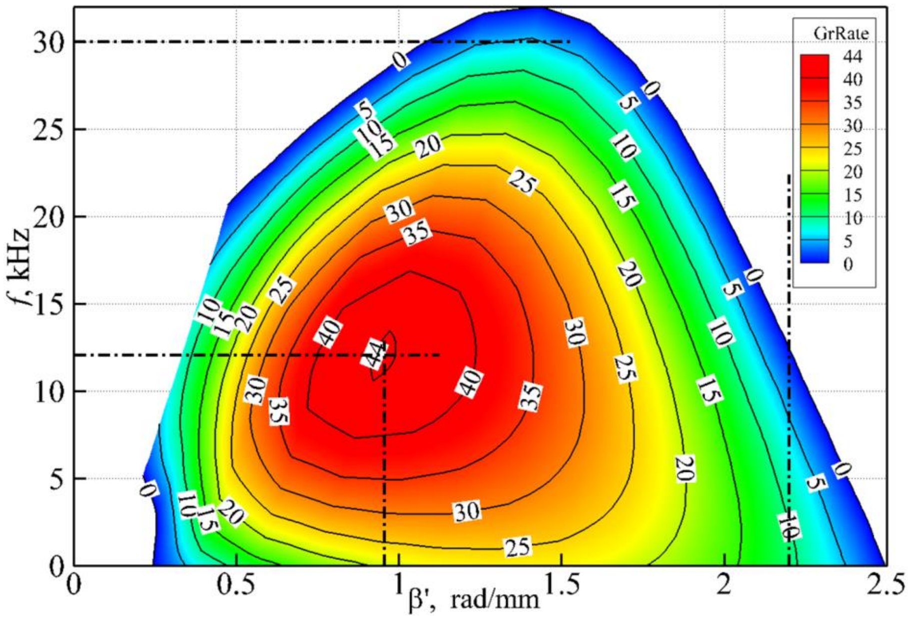

Figure 5. Diagram of stability of the boundary layer on swept-wing model at M=2, α=-2°.

4. Conclusion

An experimental study of the effect of small angles of attack on a laminar-turbulent transition in a supersonic boundary layer on a swept-wing model is performed. Obtained, that the changing of the angle of attack has a strong effect on the transition Reynolds number Re_{tr}. Confirmed monotonous growth of the transition Reynolds numbers with increasing of angle of attack from -2° to 2.5°.

Calculations on the effect of small angles of attack on the development of perturbations are made in the framework of the linear theory of stability. Obtained good qualitative correspondence of theoretical and experimental data.

It is planned to carry out experimental studies, the results of which can be, not only qualitatively, but quantitatively compared with calculations.

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