About Stability Experiments of Supersonic Boundary Layer on Swept Wing

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Abstract: - The paper is devoted to an experimental study of stability and laminar-turbulent transition a three-dimensional supersonic boundary layer on swept wing. The wave characteristics of traveling disturbances in controlled conditions were determined. Results of experiments are qualitatively agreed with researches at subsonic speeds. The detailed data of natural disturbances development are obtained for the first time. Characteristic zones of disturbances evolution are determined. A position of instability region of secondary flow is experimentally defined. Some features of disturbances evolution, characteristic only for a supersonic boundary layer are revealed. It was shown experimentally that secondary cross-flow instability plays the main role in laminar-turbulent transition in 3-D supersonic boundary layers.

Key-Words: - swept wing, supersonic boundary layer, stability, cross-flow.

1 Introduction

The attention of researchers in various countries is focused on the problem of transition to turbulence in spatial boundary layers. This interest arises from the practical applications of this phenomenon, in particular, similar boundary layers (BL) are observed in the flow around a swept wing of an airplane. On the other hand the problem of laminar turbulent transition in 3−D BL is very complicated. In a 3−D case exist along with the well−known Tollmien−Schlichting waves, which development results to the turbulent transition in the 2−D boundary layers, stationary vortexes and some traveling waves (not T−S waves). Development of all instability disturbances and their relative role in transition strongly depend on the environmental conditions.

Most theoretical and experimental results on stability of a three-dimensional boundary layer were obtained for subsonic flow. Some recent studies in this field are discussed in reviews [1-2]. Obtained, that crossflow instability is the most important kinds of the instability responsible for early origin of turbulence on a swept wing. Theoretical research of stability of a compressible three-dimensional boundary layer was started in [3, 4]. Influence of thermal external waves on the flow structure in the boundary layer is much weaker.

However, very few theoretical and experimental investigations of supersonic 3−D boundary layer stability have been fulfilled up to date. Malik et al. [5] studied secondary instability on stationary crossflow disturbances in swept cylinder boundary layer at Mach number M=3.5. The secondary analysis yields three unstable modes with the peak growth rate at frequencies about 100 kHz, 1.05 kHz, and 970 kHz. The most unstable traveling crossflow disturbance has a peak frequency of about 50 kHz; therefore, the unstable frequency for secondary instability is an order of magnitude higher than that of the traveling crossflow disturbance. Mielke & Kleiser [6] studied laminar-turbulent transition in a 3-D supersonic boundary layer by mean DNS using the temporal model. Linear stability analysis shows the dominance of crossflow instability. The secondary instability analysis reveals a broad band of secondary unstable modes traveling in streamwise direction. Catafesta et al. [7] experimentally and theoretically studied transition on a swept wing model at M=3.5. Using the envelope $e_N$ method for linear stability calculation obtained the $N$−factor and compared results with the observed transition locations. Traveling disturbances with $N=13$ provide a good correlation with the transition data over a range of unit Reynolds numbers and angles of attack. Traveling disturbances with frequencies 40-60 kHz have the largest $N$ factors, and it is assumed that the transition is more likely caused by them. Attempt of transition prediction with accounts for all major stages was made theoretically by Choudhary et.al. [8]. The 3-D boundary layer stability to the stationary disturbances in a linear formulation was investigated in [9]. It was obtained that the boundary layer became unsteady to the stationary mode, when the cross flow reached a sufficiently small value, which is less than 1 % of an external flow.

Linear stage of cross-flow instability in relation to stationary and unsteady disturbances was investigated theoretically by Gaponov & Smorodsky [10]. Direct quantitative comparison of theory with our experiments [11] was presented. A good agreement of
the theory with measurements performed in T-325 has been obtained only for spanwise scales of cross-flow vortices. However, computed growth rates differ significantly from measurements. Principal cause of such discrepancy of theoretical and experimental data was nonlinearity.

In this paper some results of experimental study of stability of supersonic boundary layer on swept wing are presented.

2 Experimental Condition

The experiments were conducted at the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences in the M-325 supersonic wind tunnel with test-section dimensions 0.2×0.2×0.6 m at Mach numbers M=2.0. Two models of swept wings were used in experiments. First model was a symmetrical wing with a 40° sweep angle, a 7.7-percent-thick circular-arc airfoil. The model was mounted at zero incidences in the central section of the test section of the wind tunnel. The model length was 0.26 m, its width was 0.2 m, and the maximum thickness was 20 mm. A generator of localized artificial disturbances was used to introduce controlled oscillations in the boundary layer. The operation principle of the generator is based on a spark discharge in the chamber. Artificial disturbances were introduced into the boundary layer through an orifice in the working surface of the model, the orifice diameter was 0.42 m, and the frequency of discharge ignition was 20 kHz (which corresponds to disturbances at the fundamental frequency). The source of controlled disturbances was located at a distance x′ = (21.4±0.25) mm (x = 28 mm) from the leading edge of the model.

Second model was a symmetrical wing with a 45° sweep angle, a 3-percent-thick circular-arc airfoil. The model length was 0.4 m, its width was 0.2 m, and the maximum thickness was 12 mm.

The oscillations were measured by a constant-temperature hot-wire anemometer. Single-wire tungsten probes of diameter 5 µm (or 10 µm) and length 0.8 mm (1.2 mm) was used. The overheat ratio of the wire was 0.8, and the measured disturbances corresponded to mass-flow fluctuations. Disturbances were measured in the layer with y/δ = 0.6 (δ is the boundary-layer thickness). In this layer, the amplitude of disturbances reached the maximum value. The fluctuating and mean characteristics of the flow were measured by an automated data acquisition system. The fluctuation signal from the hot-wire anemometer was measured by a 12-bit A/D converter with a digitization on time 1.33 µs, and a mean voltage was fixed by a voltmeter. The length of each realization was 16384 or 65536 points. With the help of the discrete Fourier transform (DFT) on time t the amplitude-frequency spectra were determined:

\[ e_j'(x', z', y) = \sum_k \exp[i \omega_k t_k] \Delta t_k \]

where \( T \) - length of implementation on time, \( \Delta t_k = t_k - t_{k-1} \), and \( e_j(x', z', y, t_k) \) - digital oscillogram of a pulsation signal from a hot-wire anemometer. Absolute magnitudes of the mass flux fluctuations \( \rho U \) were determined by the method described in [12].

3 Results

3.1 Controlled disturbances

The experimental study of controlled disturbances evolution in boundary layer on swept wing were conducted at \( M=2 \) and \( Re=6.6 \times 10^6 \) m\(^{-1}\). The results of an experimental study of supersonic boundary layer stability on swept wing are described in detail in our experiments [11, 13]. The measurements were conducted in x’ cross sections by moving the hot-wire probe along the z’ coordinate, i.e., parallel to the leading edge of the model, in the layer of maximum fluctuations in the boundary layer for a constant value of the y coordinate. The origins of the coordinate systems x, y, z and x’, y’, z’ coincided with the position of the source of disturbances for the first model. For convenience, the value of the coordinate \( z’ = 0 \) was chosen coincident with \( z = 0 \). Oscillograms of mass-flow fluctuations along the spanwise coordinate \( z’ \) were obtained. We note that the averaging method used in the experiments allowed us to identify only fluctuations correlated with the source of disturbances.

As for the case of a flat plate, the disturbances are localized in a narrow region [14]. The wave train in the boundary layer on a flat plate was symmetric, whereas the wave train on a swept wing is asymmetric. The oscillograms near \( z’ = 0 \) have a tenon-shaped form, which was also observed in flat-plate experiments with high initial disturbances [14, 15].

The design feature of the controlled disturbances source as a roughness on the bottom surface of a wing has resulted in formation of stationary disturbances. Existence of stationary vortices is characteristic for three-dimensional boundary layer [1, 7, 9]. In distributions of \( \rho U(z’) \) a minimum was observed, caused by stationary crossflow disturbances. The position of the minimum of \( \rho U(z’) \) shifts downstream (along x) at an angle of 3.0-3.5° to the x axis, which indicates the downstream entrainment of cross-flow vortices in the boundary layer in the region of the present measurements. The experimental value of the inclination angle of stationary disturbances to the free stream is close to the calculation results [9], where at \( M = 2 \) was obtained, that the angle between a wave vector and external flow...
characteristics of disturbances with relative to analysis of the array of fluctuation oscillograms was much greater. By means of a frequency-wave rate of disturbances that refer to the right maximum $z'$ carrying frequencies. The amplitude of disturbances for frequencies of 20 and 30 kHz had two maxima (the right maximum near $z' \sim 7$ mm and the left maximum near $z' \sim 0$). The growth rate of disturbances that refer to the right maximum was much greater. By means of a frequency-wave analysis of the array of fluctuation oscillograms relative to $z'$ and $x'$, we determined the wave characteristics of disturbances with $f = 10$, 20, and 30 kHz. Figure 1 shows the amplitude-phase $\beta'$ spectra of disturbances for $f = 10$ (a) and 20 kHz (b) for first set of measurements.

![Figure 1. Amplitude-phase $\beta'$ spectra of controlled disturbances](image)

By means of a frequency-wave analysis of the array of fluctuation oscillograms relative to $z'$ and $x'$, we determined the wave characteristics of disturbances with $f = 10$, 20, and 30 kHz. Note, that the amplitude and phase distributions of disturbances along $z'$, and the amplitude-phase spectra along $\beta'$ are reminiscent of similar distributions obtained for a subsonic flow at a significant distance from the source [17]. On the basis of the phase spectra of disturbances, we can conclude that there exists a range of wavenumbers where the streamwise phase growth is almost linear for $\beta' = \text{const}$, which allows us to determine the streamwise wavenumber. For each fixed value of $\beta'$, we determined first the stream-wise wavenumber $\alpha_r$ and then $\alpha'_r$ along the $x'$ axis: $\alpha'_r = (\alpha_r/\cos 40^\circ - \beta' \tan 40^\circ)$. The inclination angle of the wave vector $\chi'$ in the plane $(x', z')$ was found from the formula $\chi' = \arctan (\beta'/\alpha')$. The resultant dependences $\alpha_r'(\beta')$ and $\chi'(\beta')$ are plotted in fig. 2.

![Figure 2. Dependences $\alpha_r'(\beta')$ and $\chi'(\beta')$ over $\beta$; $f=10$ kHz, $\bigcirc - \alpha_r'$, $\bullet - \chi'$; $f=20$ kHz, $\square - \alpha_r'$, $\blacksquare - \chi'$; $f=30$ kHz, $\triangle - \alpha_r'$, $\blacktriangle - \chi'$](image)

It follows from these results that the disturbances with the highest amplitude for $f = 10$ kHz, like for $f = 20$ kHz, have an angle of inclination of the wave vector in the plane $(x', z')$ between 60 and 120°. The disturbances with frequency of 30 kHz did not increase in this flow region. The angle of the group-velocity vector obtained for the unstable disturbances was about 43° in the plane $(x', z')$, which coincides with the direction of downstream entrainment of the stationary disturbances with account of revolution of the coordinate system.

Another character of disturbance evolution is observed in the nonlinear stage (second set of measurements). The amplitude and phase distributions at the basic frequency remain about same, as well as at

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earlier stage of evolution. Though also they changes from section to section, what does not allow to determine the wave characteristics $\alpha'$ and $\chi'$. The main differences are observed at subharmonic frequency. Figure 3 shows the amplitude-phase $\beta'$-spectra of disturbances for 10 kHz for second set of measurements. The primarily three-dimensional disturbances at the subharmonic frequency are transformed in "two-dimensional". The amplitude of disturbances at subharmonic frequency surpasses amplitude of disturbances at base frequency. The strong growth of subharmonic disturbances, on all visibility, is connected to interaction with stationary disturbances. The same processes were observed at studying of nonlinear development of controlled disturbances in supersonic boundary layer on the flat plate at large initial amplitudes [13, 14]. In the last section (39.9 mm) happen fast destruction of traveling disturbances and stationary structure. The obtained experimental data are in qualitative correspondence with theoretical results [6].

3.3 Evolution of natural disturbances

Up to now stability of supersonic boundary layer on swept wing was studied experimentally only in ITAM. Some interesting data on evolution of natural and controlled disturbances were presented in [11, 13, 16]. But all these data were obtained for wing with 7.8 % profile, where transitional Reynolds number is equal $Re_x=10^6$. Complex structure of disturbances and very fast changing of structure of traveling and stationary disturbances was observed in [11, 13, 16]. All this strongly complicates research of stability of a three-dimensional boundary layer. On the other hand there is a problem of comparison theoretical and experimental data.

Therefore it has been decided to spend new experiments on a thin wing and at low unit Reynolds number. In this case the distance from a leading edge up to a point of transition becomes more in some times in comparison with the previous experiments [11, 13, 16]. It has allowed investigating in detail disturbances evolution in supersonic boundary layer on swept wing, especially at an initial linear stage.

Evolution of natural disturbances in supersonic boundary layer of swept wing was investigated in detail for the first time. Oscillograms, amplitude-frequency spectra, mean velocity profiles, pulsation profiles and statistical diagrams of natural fluctuations were obtained. Streamwise disturbances evolution is shown in fig.4. Characteristic regions of disturbances development were determined. Growth of disturbances was observed approximately from $x=100$ mm, that corresponds to $Re_x \geq 0.5 \times 10^6$. It is shown from fig.4 that laminar-turbulent transition took place approximately at $x/c \approx 0.7$ $(Re_x \approx 1.3 \times 10^6)$, where $c$ – chord of the wing, $x$ – longitudinal coordinate from the leading edge.

Measurements were spent in the field of stable fluctuations of supersonic boundary layer on swept wing (50 mm < $x$ < 100 mm, $Re_x=0.25 \times 10^6:0.5 \times 10^6$)
at this experimental set-up for the first time. Amplitude-frequency spectra are plotted in fig.5 at $Re_x=0.35 \times 10^6 \ (x=70 \ mm)$ and $Re_x=0.4 \times 10^6 \ (x=80 \ mm)$ for several meaning of normal coordinate. As a result of measurements it was revealed, that on an initial stage ($Re_x=0.25 \times 10^6 \div 0.35 \times 10^6$) spectra of disturbances remind a case of a flat plate. But some excitation of pulsations in a range of frequencies from 10 up to 30 kHz was detected at $x=80 \ mm$ at values of normal coordinate close to the critical layer ($y=0.53 \ mm$). These disturbances correspond to an instability mode of cross flow [6, 7, 10] and are observed at $Re_x \approx 0.35 \times 10^6$ for the first time. So it is possible to say that experimentally defined a position of instability region of cross flow. At $Re_x \geq 0.5 \times 10^6$ growth of traveling disturbances was observed near to the surface of the wing, and at $Re_x \geq 0.7 \times 10^6$ across all boundary layer.

### 4 Conclusion

An experimental study of disturbance development in a supersonic boundary layer on swept wing was carried out. The wave characteristics of traveling disturbances in controlled conditions were determined. It was obtained that the evolution of controlled disturbances is similar to development of travelling waves for subsonic speeds. It was shown experimentally that secondary cross-flow instability plays the main role in laminar-turbulent transition in 3-D supersonic boundary layers.

The detailed data of disturbances development up to transition location are obtained for the first time. Characteristic zones of disturbances evolution are determined. A position of instability region of secondary flow is experimentally defined. Some features of disturbances evolution, characteristic only for a supersonic boundary layer are revealed. It is confirmed, that the basic mechanism of occurrence of turbulence in a supersonic boundary layer on a swept wing - secondary instability of cross flow.

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### References:


