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SOME FEATURES OF DISTURBANCES EVOLUTION AND LAMINAR-TURBULENT TRANSITION OF A SUPERSONIC BOUNDARY LAYER ON A 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. Experimental study was carried out in two kinds of experiment. First kind – evolution of controlled traveling disturbances. Another – evolution of natural fluctuations, but stationary disturbances are excited by distributed roughness. These experiments make possible to study evolution of traveling and stationary disturbances and also their interaction from the region of a linear stage of development up to the transition region are presented for the first time for supersonic boundary layer on swept wing. Results of experiments are qualitatively agreed with researches at subsonic speeds. Some features of interaction of stationary and running disturbances, characteristic only for a supersonic boundary layer are revealed.

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 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 boundary layer 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 with axes directed along the outer streamlines 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[1-4]. Obtained, that crossflow instability is one of the most important kinds of the instability responsible for early origin of turbulence on a swept wing. 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 the them. Attempt of transition prediction with acounts for all major stages was made theoretically by Choudhary et.al.[8].

Linear stage of cross-flow instability in relation to stationary and unsteady disturbances was investigated theoretically by Gaponov & Smorodsky[8]. Direct quantitative comparison of theory with our experiments[9] 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.

Stability of supersonic boundary layer on swept wing was studied experimentally only in ITAM[10-12] . Evolution of natural fluctuations in the boundary layer on a swept wing was studied by Ermolaev et. al.[11]. It was shown that the character of distribution of the mean and fluctuating characteristics of the boundary layer is similar to the case of subsonic velocities. It was obtained at M=2, that the disturbances growth in three-dimensional boundary layer occurs much faster, than in the flat plate case. The results of an experimental study of evolution of controlled disturbances on a swept-wing model for Mach number M = 2 are presented Semionov et. al.[10,11]. The wave characteristics of traveling waves are obtained. The evolution of disturbances at frequencies of 10, 20, and 30 kHz is similar to the development of traveling waves for subsonic velocities. The angle of inclination of the wave vector for energy-carrying disturbances is directed across the flow, and the group-velocity vector is aligned with the steady cross-flow disturbance.

The objective of present work is an experimental study of nonlinear disturbances evolution on a swept wing supersonic boundary layer.

2. EXPERIMENTAL EQUIPMENT

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. A wing model with a 40^0 sweep angle of the leading edge and a lenticular profile was used in the experiments. 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[13]. The operation principle of the generator is based on a spark discharge in the chamber[14]. 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. The origins of the coordinate systems x, y, z and x', y', z' coincided with the position of the source of disturbances. For convenience, the value of the coordinate $z' = 0$ was chosen coincident with $z = 0$.

The oscillations were measured by a constant-temperature hot-wire anemometer with a 1:10 ratio of the bridge arms and a frequency range to 500 kHz. Single-wire tungsten probes of diameter 5 μm and length 0.8 mm was used. The overheat ratio of the wire was 0.8, and the measured disturbances corresponded to mass-flow fluctuations. Artificial disturbances were measured in the layer with y/δ =0.6 (δ is the boundary-layer thickness and y is the coordinate normal to the model surface). 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[15]. The fluctuating signal from the hot-wire anemometer was measured by a 10 digit analog-to-digital converter with a time step of 1 μsec, and the mean voltage in the bridge diagonal was measured by an voltmeter. To improve the signal-to-noise ratio, the signal was simultaneously summed over 500 realizations; the length of each realization was 400 μsec. The amplitude of the mean oscillograms of the fluctuating signal was controlled in the course of experiments. This allowed rather accurate determination of the boundaries of the introduced wave packet relative to the spanwise coordinate z'. The frequency spectra of disturbances were determined by the discrete Fourier transform

$$e'_{f\beta'}(x',y) = \frac{2}{T}\sum_{j,k} e'(x',z'_j,y,t_k)\exp\left[-i(\beta' z'_j - \omega t_k)\right],$$

where $e'(x', z'_j, y, t_k)$ is the digital oscillogram of the fluctuating signal from the hot-wire anemometer averaged over the rea1izations and T is the length of one realization in time. The amplitude and phase of disturbances were found after the discrete Fourier transform from the formulas

$$A_{f\beta'}(x',y) = \{\mathrm{Re}^2[e'_{f\beta'}(x',y)] + \mathrm{Im}^2[e'_{f\beta'}(x',y)]\}^{0,5},$$

$$\Phi_{f\beta'}(x',y) = \mathrm{arctg}\{\mathrm{Im}[e'_{f\beta'}(x',y)]/\mathrm{Re}[e'_{f\beta'}(x',y)]\}.$$

The absolute values of mass-flow fluctuations $(\rho U)'$ were determined by the method proposed by Kosinov et al.[15]. To measure a transition position the Preston tube or hot-wire sensor were used. A transition position was measured by varying unit Reynolds number at a fixed location of the probes.

3. RESULTS

The results on disturbances evolution in supersonic boundary layer on a swept-wing model were obtained in two sets of experiments. First set - the experimental study of controlled disturbances evolution. 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. Second set - the experimental study of “natural” disturbances evolution in boundary layer on swept wing with distributed roughness[16,17]. So, the experimental data on interaction stationary and traveling disturbances in supersonic boundary layer on swept wing are considered in this paper.

The first set of experiments were conducted at M=2.0, unit Reynolds number $Re_1=U/\nu$ $=6.6\times10^6$ m^{-1}. The measurements were made in x' cross sections by moving the hot-wire probe along the z' coordinate, i.e., parallel to the leading edge of the wing, in the layer of maximum fluctuations in the boundary layer (y =const). These results of an experimental study of controlled disturbances evolution in supersonic boundary layer on swept wing are described in detail by Semionov et.al.[10,12]. In this paper we exemine disturbances evolution in nonlinear stage. Oscillograms of mass-flow fluctuations along the spanwise coordinate z' were obtained for x' =32.2, 36.1, 39.9 mm (where x' – distance from the source of controlled disturbances).

As for the case of a flat plate[18], the disturbances are localized in a narrow region. The wave train in the boundary layer on a flat plate is 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[18]. Introduction of artificial disturbances distorted the mean flow in the boundary layer. The distributions of the mass-flow rate ρU over the spanwise coordinate z', which are normalized to the maximum flow-rate value, are plotted in Fig. 1. In distributions of $\rho U(z')$ a minimum was observed, caused by stationary crossflow disturbances. Existence of stationary vortices is characterized for three-dimensional boundary layer. In contrast, the size of a steady perturbation obtained in our experiments is greater than the scale of cross-flow steady vortices[17]. In the last section (x' =39.9 mm), where practically take place transition, a destruction of stationary disturbances is observed.

For the linear stage of disturbances evolution was obtained, that the amplitude and phase distributions of disturbances along z', and the amplitude-phase spectra along β' are reminiscent of similar distributions obtained for a subsonic flow at a significant distance from the source[18]. The angle of inclination of the wave vector for energy-carrying disturbances is directed across the flow, and the group-velocity vector is aligned with the steady cross-flow disturbance. This result is in good quantitative agreement with calculations by Gaponov & Smorodsky[9].

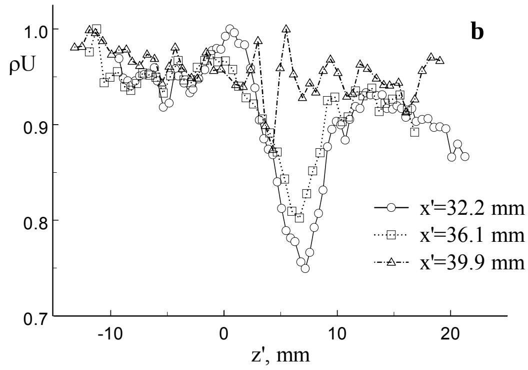

Figure 1: The distributions of the mass-flow rate ρU over the spanwise coordinate z'.

Another character of disturbances evolution is observed in nonlinear stage. Figure 2 shows the amplitude-phase β' spectra of disturbances for *f* = 10 (a) and 20 kHz (b). The amplitude and phase distributions at the basic frequency remain about same, as well as at earlier stage of evolution. The main differences are observed at subharmonic frequency. The primarily three-dimensional disturbances at the subharmonic frequency are transformed in "two-dimensional". The disturbances amplitude at subharmonic frequency surpasses amplitude of disturbances at base frequency. In the last section at *x*' =36.1 mm happen fast destruction of traveling disturbances and stationary structure. The strong growth of subharmonic disturbances, on all visibility, is connected to interaction with stationary disturbances. This data allow to assume, that there are the same processes, observed in nonlinear stage of controlled disturbances development in supersonic boundary layer on the flat plate at large initial amplitudes[18]. The obtained data are in quality correspondence with theoretical results by Mielke & Kleiser[6].

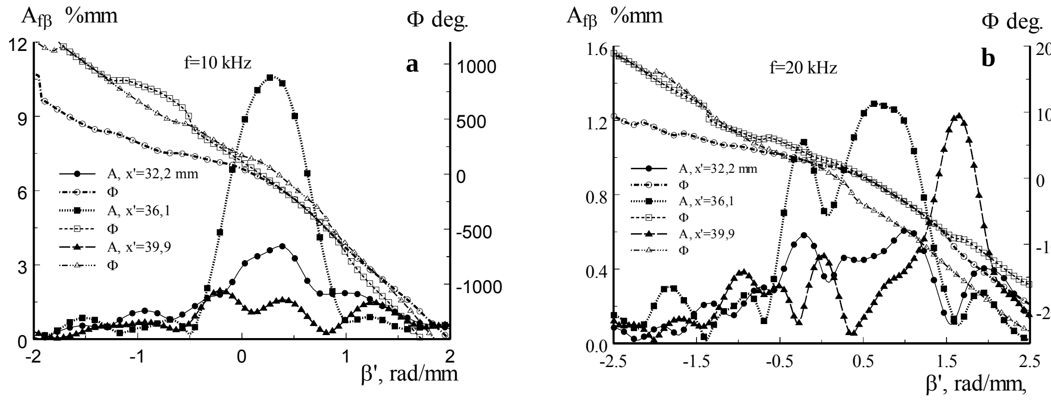

Figure 2: Amplitude-phase β' spectra of disturbances for second set of measurements; *f* = 10 (a) and 20 kHz (b).

Stationary crossflow disturbances are not well detected in 3-D supersonic boundary layer on polished surface at the natural conditions. Small roughness induces stationary flow distortion. Using periodical microroughness we can control transition in 3-D boundary layer assumed the leading crossflow instability in transition. However than TS waves can play important role in transition process. Perhaps the existence of stationary disturbances is not favorable for transition delay. As presented by Semionov & Kosinov[16], on the smooth wing surface laminar-turbulent transition takes place at $Re_{tr} \approx 0.95\times10^6$, using longitudinal roughness with *l*=2 mm 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 second set of experiments. Measurements were made in parallel to the leading edge sections for values of coordinate *x*=45, 60, 75, 90 mm and unit Reynolds number $Re_1=12{,}2\times10^6$ m^{-1} and at *x*=90 mm and $Re_1=14{,}4\times10^6$m^{-1}. That corresponds to five sections for Reynolds numbers Re=0.55×10^6, 0.73×10^6, 0.92×10^6, 1.1×10^6, 1.3×10^6 accordingly. The coordinate *x* was measured from the leading edge of the swept wing in stream direction. Measurements were spent in a layer of a maximum of pulsations in the boundary layer at *y*=const by moving the hot-wire probe along coordinate *z'* parallel to the leading edge. The distributions of the mass-flow rate *ρU* and mass flux <*m'*> over the spanwise coordinate *z'* for several sections are presented in figure 3. Thus, on these plots evolution of traveling and stationary disturbances and also their interaction from the region of a linear stage of development up to the transition region are presented.

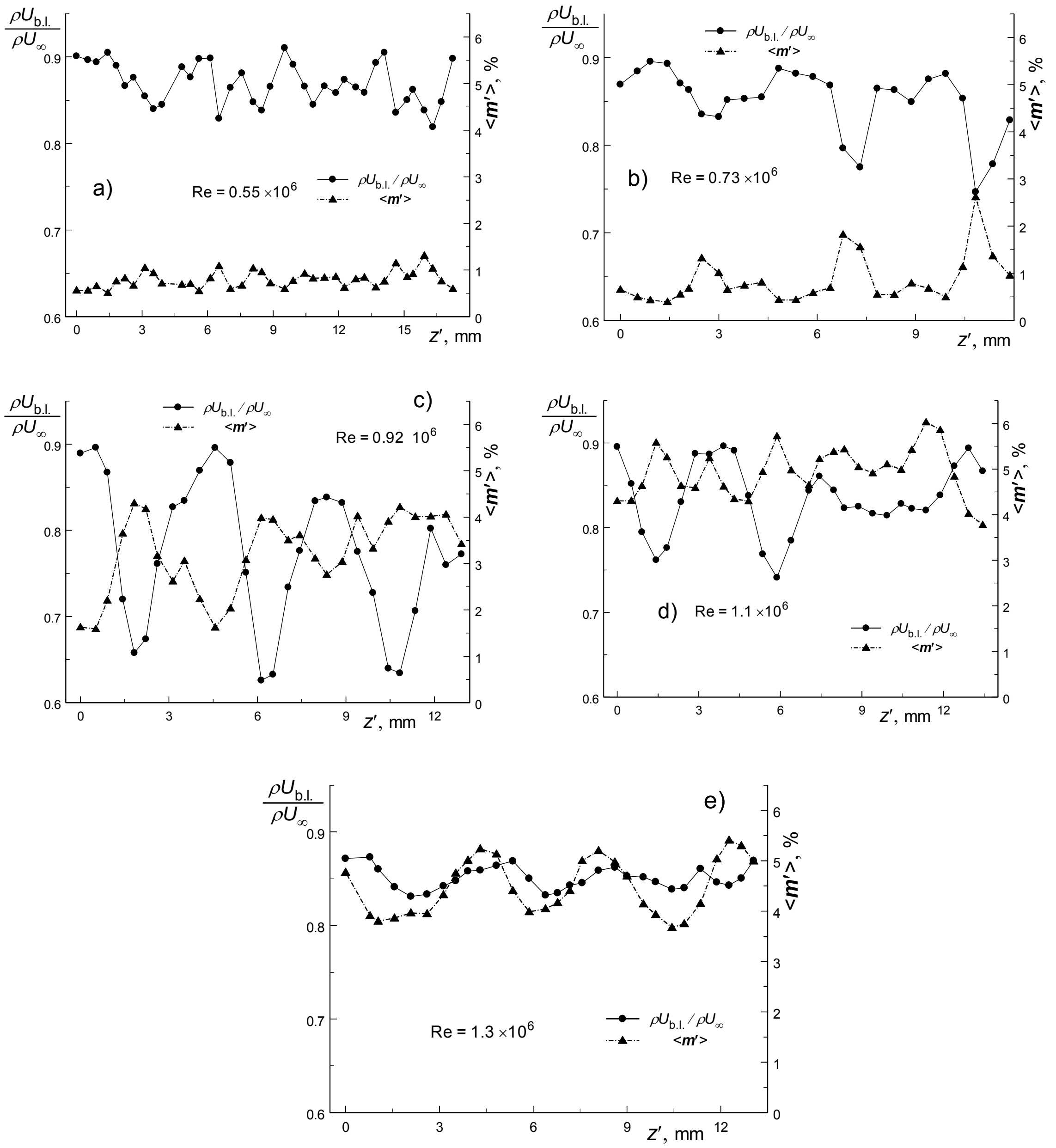

Figure 3. The distributions of the mass-flow rate ρU and mass flux $<m'>$ over the spanwise coordinate z'.

For the first section it is received, that stationary disturbances, exited by the distributed roughness, only start to be allocated from the background. The tendency to an establishment of some periodicity is visible. Though distance from the end of the distributed roughness up to the first section enough big (25 mm), but obviously periodicity along spanwise direction yet was not allocated. We shall note that for the case of the smooth surface also it was impossible to allocate periodicity along scope of a wing though the certain tendency was observed by Ermolaev et.al.[11]. In the subsequent sections the periodicity in distributions has the sharply expressed form. In this case it is possible precisely to determine a step between stationary structures in the spanwise direction. The step of stationary disturbances periodicity in parallel to the leading edge direction makes approximately 4 mm, which well correlates with the distributed roughness spacing. Similar results for mass flux distributions where periodicity of maxima and minima also are received. Maxima in distribution of stationary disturbances strictly corresponds minima of fluctuation distributions in a boundary layer for the second and third section. In last two sections corresponding to the region of nonlinear disturbances evolution, fast reorganization of flow is observed. In section at Re=1.1×10^6 periodicity under the stationary disturbances remains, and on pulsations there is a change of periodicity. It is possible even to tell, that there was a doubling number of the periods. In last section at Re=1.3×10^6 already the maximum in distribution of the mass-flow rate ρU strictly corresponds to the maximum of mass flux <*m'*> in the boundary layer. Similar processes were observed in experiments at subsonic speeds[18] where it has noted been, that in a region of linear disturbances evolution their maximum is just in the field of shift of mean velocity, and in the region of nonlinear development of such conformity was not observed. Fast change of structure of traveling disturbances in the region of nonlinear development also has noted been in first set of experiments where evolution of controlled disturbances was studied at M=2 on the same wing model. From the data presented in fig.3 it is visible, that amplitude both traveling, and stationary disturbances increased at first, but to the end of transition region began to decrease. The similar result has been received and in first set of experiments.

4. CONCLUSIONS

Evolution of traveling and stationary disturbances in supersonic boundary layer on swept wing was studied. Obtained, that existence of several instability modes lead to the fast reorganization of structure of disturbances. Such fast reorganization of structure of traveling disturbances in case of subsonic speeds it was not observed. It is possible to tell, that features, characteristic only for a supersonic boundary layer are observed basically near to the transition region. And it is a reason of some discrepancy of experimental and theoretical data.

5. ACKNOWLEDGEMENTS

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