MEAN FLOW DISTORTION EFFECT ON THE NONLINEAR WAVE INTERACTION AT THE TRANSITION IN SUPersonic BOUNDARY LAYER

Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 630090, Novosibirsk, Russia

Introduction

Usage of the controlled disturbances technique for the research of the nonlinear interaction mechanisms of unstable waves in a supersonic boundary layer still is a preferable method in contrast to the natural disturbance investigation. As the results of the linear stability theory are known in some cases, the deviation from linear wave development can be considered as nonlinearity. However, controlled disturbances can interact with random natural oscillations in nonlinear region of the supersonic boundary layer. As have shown by our experiments, this interaction leads to the essential amplification of random disturbances and to the earlier transition. So, the experiments become more complicated. Nevertheless, we were able already detected by this method: (1) the parametric subharmonic amplification of strongly inclined waves [1]; (2) the abnormal growth of quasi two dimensional disturbances of large amplitude [2]. There is also third wave interaction mechanism named as oblique breakdown and predicted by DNS [3, 4]. For the last mechanism are essential as well as the wave amplitude and spanwise non-uniformity of flow. It is appear in the amplification of strongly inclined waves of fundamental frequency. We guess that this mechanism will play the important role in laminar - turbulent transition at the presence of a periodic spanwise modulation of flow. We would like to check the oblique breakdown role in transition of 2D supersonic boundary layer in the paper.

Experiments set-up. The experiments were conducted in T-325 low noise supersonic wind tunnel of ITAM SB RAS on a flat plate with the sharp leading edge at Mach number 2 and unit Reynolds number Re_1=(6.73±0.04) × 10^6 m⁻¹. Figure 1 shows the flat plat installation in T-325 test section.

Fig. 1. Flat plate, traversing gear and hot-wire

The rectangular stickers from a scotch tape about 60 microns in thickness, approximately 1 mm in width and 5 mm in length were applied to induce the spanwise modulation of mean flow in the boundary layer. Twenty stickers were spanwise located on a distance of 25 mm from the leading edge. They are taped before an aperture of the disturbances source (38 mm) with spanwise step about 4 mm. Figure 2 (a) presents the details of this installation.

The experiments were executed for the single model installation (and fixed source intensity) in three phases. First phase of the experiments was the initial amplitude selection of controlled disturbances for a smooth surface (see Fig.2 (b)). Next step of the experiments was the measurements of wave train evolution in the artificially modulated boundary layer (Fig.2 (a)) and the last was the experiment without stickers in the boundary layer (see Fig.2 (b) again).

The development of controlled disturbances was measured by constant temperature anemometer (CTA) in the boundary layer. The tungsten hot-wires of 10 micron in diameter and of 1.5 mm in length was used. We use an automated measuring system which T-325 is equipped. It consists from equipments in CAMAC standard with CC-32 fast controller and PC computer. AC and DC signal from the hot-wire anemometer were written in computer using of 12-bit analog-to-digital converter (ADC) with sampling rate 750 kHz and by DC voltmeter (multimeter Agilent 34401A). Time traces in length of 1024 points were synchronized with glow discharge which was ignited with fundamental frequency of 20 kHz. 256 time traces were measured and averaged in each space position of hot-wire.

Mean and pulsation characteristics of the flow were obtained after hot-wire data processing using a standard technique.

Results. Mainly the obtained results give a direction for the further investigations, but some of them is interesting and will be discussed. We should change the experiment a little bit in order to test another stickers’ locations as well. The spanwise measurements for each X position were made at the fixed normal distance from the model surface and at \( y/\delta \approx \text{const} \).

Stationary disturbances. The mean mass flow deviations in spanwise direction for the smooth model surface are shown in Fig. 3. Localized stationary disturbance of 2-3% peak-to-peak amplitude is definitely observed at the centre line downstream from the source aperture behind X = 100 mm. Fig. 4 presents the flow modulation in spanwise direction at X=60, 100 and 120 mm which can be observed during measurements due to the periodicity in the mean voltage distributions of hot-wire output. The stagnation temperature decreasing of the flow was observed for the data at
X=120 mm. As Re$_t$ was approximately constant and the stagnation temperature decreased the mean mass flow also reduced. So it may be the explanation for the mean voltage value difference at the edges of distribution. The reason of stronger distortion of the mean flow in center of the distribution is the probably influence of the source hole in the model surface.

Initial amplitudes of wave trains. Figures 5 and 6 presents the initial mass flux distributions at X=60 mm for different frequencies. As it is follow from figure 5 we introduce mainly the fundamental disturbances for smooth flat plate and wide spectrum of pulsations is generated for artificially modulated boundary layer. Note that the electrical power of the glow discharge is the same in both cases. So this difference for the excited pulsations may be explained only by receptivity. This result was so unexpected and only subsequent measurements without stickers have confirmed that the disturbance source has earlier selected initial intensity.

More definitely the big difference in the initial amplitude of artificial disturbances is possibly to see from the wave number spectra presented in figures 7 and 8. We can conclude that 2D disturbances are mostly excited in the modulated boundary layer in contrast to typical 3D fluctuation generation by local source that takes place in 2D supersonic boundary layer and figure 7
demonstrates it. Such a behavior we were already observed only for the enough high power of controlled disturbance source [2].

**Relative receptivity.** Here we only present preliminary results regarding the receptivity of modulated boundary layer flow to disturbances from the local source used in the experiments by comparing the wave spectra at X=60 mm. Let's mark, that the modulated boundary layer has one order more receptivity to the controlled oscillations of subharmonic frequency (10 kHz) in comparison with the case of smooth surface. It is possibly to see from figure 9, where the ratio of amplitude wave spectra at X=60 mm are shown. Some peaks for subharmonic data are perhaps due to small intensity pulsations for smooth surface and it is necessary to do additional data processing for the data accuracy estimation.

It seems to be the data for fundamental frequency are more accurate and they have smooth dependence via wave number with maximum for 2D pulsations. We obtain the phase shift on about 90° in the phase wave spectra for fundamental disturbances shown in figure 10 for modulated flow in the comparison with a uniform stream in the boundary layer. Probably the fundamental wave train has waves with shorter wave length in modulated boundary layer.
Nonlinear wave train development. Figures 11-13 show the influence of mean flow modulation on the controlled disturbance evolution in streamwise direction. We can observe the subharmonic resonance at X=120 mm (see figure 12, 14) for the flat plate boundary layer on the smooth surface that was obtained before in [1] too. The spanwise flow modulation changes the nonlinear development of wave trains. 3D subharmonic resonance still take place (see figures 11 and 13), but 2D waves grows very rapidly as it is shown in figures 13 and 15. The development of pulsations is looked similar to the anomalous nonlinear propagation of high amplitude wave trains, mentioned above.

If the oblique breakdown mechanism takes place we have to see a fast growth of high beta part of the amplitude spectra for fundamental or subharmonic frequency. We can find such a behavior for the results presented in figure 15 and 16. The effect is not so big in comparison with subharmonic resonance or 2D wave growth. Nevertheless, perhaps the mean flow modulation creates the real competition between mentioned here mechanisms and oblique breakdown in the transition process of supersonic boundary layer.
Fig. 15. Relative growth factors for fundamental and subharmonic disturbances in modulated boundary layer.

Fig. 16. Comparison of wave amplitude and phase spectra for fundamental frequency. X=120 mm
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Conclusions

The comparative preliminary experimental investigation of wave train development in the supersonic flat plate boundary layer are conducted in spanwise modulated flow and without modulation. It is found that the spanwise flow modulation increase the receptivity features of supersonic boundary layer to the pulsations exciting from the surface. Generally, at least three nonlinear mechanisms of breakdown are visibly i.e. (1) asymmetric 3D subharmonic resonance; (2) anomalous growth of 2D pulsations; and (3) oblique breakdown. Following investigations has to be conducted in more fine conditions, which will clarify the competition of the breakdown mechanisms in detail.

REFERENCES