Experiments on the wave train development in 3D boundary layer at Mach 2

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Abstract. Stability experiments of controlled disturbances in 3D supersonic boundary layer on the thin swept wing at low unit Reynolds numbers are considered in the paper. The results of the linear evolution of stationary and traveling disturbances in supersonic boundary layer on swept wing at controlled conditions are presented. Wave characteristics of traveling disturbances are obtained. Stabilizing effect on the wave train evolution due to periodic micro roughnesses is demonstrated.

1. Introduction

Problem of transition origin in supersonic boundary layer on swept wing is in focus for researchers more than 50 years. Such attention to this object is conditioned both practical applications and difficulty of the problem. Up to now the main result for 3D boundary layer were obtained for subsonic flows, see (Saric W. S., Reed H. L., White E. B., 2003; Gaponenko V. R, Ivanov A. V., Kachanov Y. S., Crouch J. D., 2002; Chernoray V. G., Dovgal A. V., Kozlov V. V., Leofdahl L., 2005). We should state that experiments on the linear development of controlled disturbances in a 3D supersonic boundary layer were not successfully perhaps due to nonlinearity (Semionov N. V. Ermolaev Yu. G. Kosinov A. D., Levchenko V. Ya., 2003) as the linearity of pulsation development was not checked in those experiments. 7.7% airfoil has been used in the previous measurement so that the linear pulsation growth region was located only within the leading edge at the conditions of the experiments. Therefore we have been conducted a new stability experiments testing the thin swept wings (3% airfoil) at low unit Reynolds numbers. It has allowed investigating the linear disturbance evolution in supersonic boundary layer on swept wing for natural and controlled disturbances in smooth surface conditions of the models. The paper presents the experiments on the wave train development at the linear stage of transition in 3D supersonic boundary layer.

2. Experiments set-up

The experiments were conducted in T-325 low noise supersonic wind tunnel of ITAM SB RAS at Mach 2 and unit Reynolds number $R_\text{e1} = 5.2 \times 10^{-6} \text{ m}^{-1}$. The swept wing with swept angle of the leading edge of 45° was used (see Fig.1). The model was specially designed for controlled disturbance experiments. The test surface of the model has radius of curvature
R=4 m, the bottom surface is flat (3% profile, maximum thickness is 12 mm). Source of artificial disturbances was built in the model. Controlled pulsations penetrated into boundary layer through an aperture of 0.4 mm in diameter and they were excited by high frequency glow discharge in chamber. Two set-ups of micro roughnesses on the model surface were used as it is shown in fig.1. Pulsations in the boundary layer were measured with the help of constant temperature hot-wire anemometer. Hot-wire probe from tungsten with 10 micron in diameter and 1.6 mm in length was used. The measurements were synchronized with glow discharge which was ignited with fundamental frequency of 20 kHz. AC and DC signals from CTA were written to the PC by using of 12-bit ADC with sampling rate 750 kHz and by DC voltmeter correspondingly. The measurements were synchronized with glow discharge which was ignited with fundamental frequency of 20 kHz. Four time traces of 65536 points in length were measured and written to file in each space position of hot-wire. Mean and pulsation characteristics of the flow were obtained after data processing using a standard technique. The spanwise measurements were made at the fixed normal distance from the model surface and at y/d const for each position. First step of data processing consisted in averaging of time traces and then Fourier transform of the data:

\[ A_{f\beta} = \frac{2}{T} \sum_{n=1}^{T} \sum_{j=1}^{\infty} A(t_n, z_j)e^{-i(\beta z_j - wt_n)} \Delta t_n \Delta z_j \]  

(1)

where T - length of digital time trace, \( \Delta t_n = t_{n-1} - t_n \), and \( A(t_n, z_j) \) - time trace of the normalized pulsation amplitude from the hot-wire anemometer. We have used DFT procedure and optimized length of time traces for different frequencies.

![Figure 1. Experimental set-up: Case 1 (left), Case 2 (right)](image)

3. Results

Two part of the paper are presented here. First is concerned to the linear wave train development in 3D boundary layer on smooth surface of swept wing. At least seven experiments were conducted at slightly differ initial amplitude of pulsations for the last three years. Second part of the paper is devoted to study of the controlled pulsation evolution in 3D supersonic boundary layer flow behind of the distributed roughness on the model surface.

3.1. Natural disturbances evolution

Natural pulsation development was tested in order to verify the linear region of transition process in boundary layer of the model. To define the region statistical approach is used. The typical way to see the linear disturbance development is to consist in verification of the distribution normality for pulsation amplitude. It was defined that there is the linear disturbance development region up to 130-140 mm. In the linear region we detect low frequency pulsation growth as well as amplification of disturbances at 10-30 kHz. The amplitude-frequency spectra of disturbances
for different values of x coordinate shows the data and presented in Fig.2. Follow the results we decided to use 10 kHz frequency from sine wave generator for ignition of glow discharge in chamber to excite 20 kHz fundamental disturbance in 3D boundary layer. Similar natural pulsation evolution in 3D supersonic boundary layer was demonstrated by (Semionov N. V. Ermolaev Yu. G. Kosinov A. D., Levchenko V. Ya., 2003). From fig. 2 is possible to see that the maximum of high frequency electronic noise of constant temperature anemometer (CTA) is located at about 300 kHz. The data were obtained in centerline of the swept wings when hot-wire probe is placed in maxima of pulsation profile at each of the positions. The results indicate that second swept wing is possible to use for artificial perturbation testing as disturbances has similar evolution in both swept wing models.

Figure 2. Evolution of the amplitude frequency spectra for natural disturbances.

3.2. On the linear wave trains development

The technique that is used in the experiments is more complicated than we used before for flat plate at controlled disturbance experiments (Panina A. V., Kosinov A. D., Ermolaev Yu. G., Semionov N. V., 2010; Kosinov A. D., Maslov A. A., Shevelkov S. G., 1990). As the probe moving was in parallel to the leading edge we got time increasing that was necessary for the measurements. Coincident with the swept wing leading edge the coordinate system are presented in fig. 3. Here it is as usual mean flow direction in test section correspond X-coordinate.

Figure 3. Coordinate system coincident with the leading edge and disturbance source

Almost harmonic wave train with fundamental frequency of 20 kHz was excited in the boundary layer only at low electrical power of glow discharge and low initial amplitude of disturbances. Periodic wave trains evolutions are observed at increasing of source power that it may be coincident with asymmetric design of the electrodes. Nevertheless, growth of the
controlled disturbances was detected at linear development of the natural background pulsations for all tested initial amplitude of controlled pulsations. Mean flow distortion in spanwise direction was observed within measurement accuracy only at increasing of source power. Nonlinearity was not observed for natural pulsations as well as for controlled disturbances. Isolines of time traces amplitude of controlled disturbances portion of total pulsations in spanwise direction at initial and downstream sections of measurements are shown in Fig. 4. The data correspond to the minimal power of glow discharge. Similar results are obtained for another electrical power of pulsation source at fundamental frequency. Let’s note that the position X=0 correspond to the disturbance source. It is experimentally confirmed, that downstream disturbances evolution on a swept wing considerably differs from the case of flat plate. Wave trains are asymmetrical in space as usually for 3D boundary layer see for example (Semionov N. V. Ermolaev Yu. G. Kosinov A. D., Levchenko V. Ya., 2003).

Figure 4. Time traces in spanwise direction. X position is defined from disturbance source

Initial disturbance amplitude of mass flux in (Y, Z’) section for fundamental (left) and subharmonic (right) waves are shown in Fig. 5. As follow from the data maxima of both pulsations are located at about same Y coordinate. The results are very useful as we usually can the possibility to measure pulsation field at fixed Y coordinate.

Figure 5. Isolines of RMS amplitude in normal to the model surface direction for fundamental and subharmonic disturbances for initial X coordinate

Experimentally obtained, that disturbance profile for beta’ - mode of fluctuations have
maxima also at about same Y coordinate. The results are possible to see in Fig. 6.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{profiles.png}
\caption{Profiles of RMS amplitude of beta’ - mode in normal to the model surface direction for fundamental and subharmonic disturbances for initial X coordinate}
\end{figure}

The more precisely changes in the amplitude of artificial disturbances during downstream evolution can be seen from the wave number spectra presented in Fig. 7. We can conclude that 3D boundary layer almost precisely select the disturbances at beta’= 1.1 - 1.2 rad/mm and amplify them downstream at the linear stage of transition. Similar behavior we have already observed only for 2D boundary layer but at symmetrical amplitude spectra over wave number of controlled disturbance (Kosinov A. D., Maslov A. A., Shevelkov S. G., 1990).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectra.png}
\caption{Downstream evolution of the amplitude beta spectra for fundamental and subharmonic disturbances}
\end{figure}

The presentation of the amplitude beta’ spectra is not enough to understand of the features of disturbance downstream evolution. Phase spectra evolution of controlled pulsations over wave number beta demonstrate the typical shape of phase spectra for fundamental waves in 3D supersonic boundary layer and indicate where accuracy was enough for the determination of them. As the fact we have phase distributions better at increasing power of local disturbances source. We should also remark on the relative of data on phase beta’ spectra. They strongly depends from position definition of Z=0. So full processing of the data is more complicated task in comparison with 2D boundary layer data. What is concerned these experiments we will get
wave characteristics of controlled disturbances from the data as phase downstream evolution looks as linear growth at fixed beta’. Perhaps it is an indicator that there is only one mode evolution and this mode may coincide with traveling wave of 3D supersonic boundary layer.

3.3. Mean flow distortion effect on the linear wave trains development

The influence of trip tape location and its number on the initial amplitude of generated pulsations at fixed electrical power of glow discharge as well as at its changing is studied in this part of the paper. Optimal operational conditions for controlled disturbance excitation have been found. The stationary disturbance amplitude in 3D boundary layer flow due to usage of roughness elements and actual aperture of disturbances source as well as RMS pulsation amplitude of mass flow in linear region of disturbance development was determined at Mach 2.

However first results will be concerned to the comparison of mean flow distortion in 2D and 3D boundary layers. The same single roughness is used in flat plate and swept wing boundary layer. The experiments set-up is presented in Fig. 8. The roughness element is located at about equal boundary thickness conditions.

![Figure 8. Experimental set-up: three (left), and five (right) roughnesses](image)

We would like to estimate mean flow distortion due to such a roughness. The results are presented in Fig. 9. Here it is compared maximums mean flow distortion in both cases. As it is follow from the data 3D boundary layer is more sensitive to the stationary disturbance from the model surface than 2D boundary layer. Pick-to-pick stationary disturbance amplitude in 3D boundary layer is about 1.5 times more than in 2D boundary layer. Spanwise scale of the stationary disturbances is comparable as Z’=1.4 Z.

Set-up of experiments concerning to investigation mean flow distortion effect on artificial disturbance excitation in 3D boundary layer are presented in Fig. 10. First of all we will consider a comparison of mean flow data in spanwise direction for different conditions i.e.: smooth case (3), three roughnesses case (2) and five roughnesses case (1) are shown in Fig. 11. Almost sine wave distortion we got for case (1), but when roughness is located in line with source aperture, than an additional distortion is appeared, that is similar to 2D boundary layer case (Panina A. V., Kosinov A. D., Ermolaev Yu. G., Semionov N. V., 2010).

It has been found out the influence of trip tape location and its number on the value of generated pulsations at fixed electrical power of glow discharge as well as at its changing. Comparative experimental data regarding receptivity of supersonic swept wing boundary layer to controlled disturbances for smooth and rough surface were obtained. Here we will consider...
initial wave spectra for different surface conditions. These data are shown in Fig. 12 (left). As follow from this figure initial amplitude depends on surface roughness conditions. Maximal
initial amplitude is observed in case (2) when three roughness elements are located on the model surface. Minimal initial amplitude is detected in case (1) when five roughness elements are located on the model surface and smooth surface case is between them. However, the initial amplitude spectra are quite similar each other. The amplitude spectra shape is dramatically changed downstream due to spanwise modulation of mean flow only in case (2) see Fig. 12 (right). Let’s remark that amplitude wave train in case (1) grows but less than in another tested cases.

![Figure 12. Comparison amplitude wave spectra from initial (left) and downstream (right) spanwise distributions](image)

In order to see this behavior more in detail consider ratio the amplitude beta' spectra. The data are presented in Fig. 13. It was obtained that damping effect of spatial wave packet by using micro roughness elements located in swept wing boundary layer can be appeared in near field of disturbances source.

![Figure 13. Transfer factors distribution for wave normalized on initial wave spectra](image)

The effect is visible for most amplified waves, but it is really less than in flat plate boundary layer as recently shown by (Panina A. V., Kosinov A. D., Ermolaev Yu. G., Semionov N. V., 2010).
4. Conclusion

Linear stage of evolution of natural and controlled disturbances in supersonic boundary layer of swept wing was investigated at Mach 2 in detail. A location of instability region is experimentally defined. Quality and some quantity correspondence of natural and controlled experiments were obtained. In controlled experiment it was possible to create a quasi-harmonic wave train with frequency of controlled pulsation of 20 kHz. Downstream growth of the disturbance amplitude was detected. Excitations of disturbances at other frequencies were found in the investigated region of the wave train evolution at increasing of source power. Nonlinearity was not detected. Pulsation profiles over spanwise wave numbers were determined for the first time. 3D boundary layer is more sensitive to the stationary disturbance from the model surface than 2D boundary layer. Damping effect on development of spatial wave packet by using micro roughness elements located in swept wing boundary layer can be appeared in near field of disturbances source.

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