STATISTICAL FEATURES AND LEVELS OF NATURAL DISTURBANCES AT TRANSITION IN SUPERSONIC BOUNDARY LAYER

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Summary The natural disturbance experiments are executed in the flat plate boundary layer at Mach 2. Modified diagram technique is applied for pulsation decomposition in compressible flow. The method is more suitable for measurement by constant temperature anemometer and increases accuracy of estimations. Mass flow and temperature fluctuations and their relation are obtained in transition region of the supersonic boundary layer. Statistical diagram of pulsations from laminar to turbulent stage is obtained.

INTRODUCTION

The investigations of laminar-turbulent transition in supersonic boundary layer are usually carried out in conditions of controlled and natural fluctuations. The experimental researches of stability of shear flows with the help of controlled disturbances allow to compare the obtained data to calculations and to develop theoretical models. To study late stages of laminar-turbulent transition it is necessary to use the joint approach, in parallel conducting researches of development of natural and controlled disturbances. In this case for detection of character of nonlinear interaction of natural disturbances use a high-order spectrum analysis [1, 2], and simulate mechanism of this nonlinear interaction in controlled experiments [3]. At usage of the bispectral analysis the quadratic nonlinearity is allocated, and with the help of the trispectral analysis it is possible to allocate cubic nonlinearity. In case of a supersonic boundary layer this method never was applied. Motivation of usage of this method at research of late stages of laminar-turbulent transition in a supersonic boundary layer is the absence of theoretical models of nonlinear interaction of waves and necessity of the substantiation of experiments with controlled disturbances. In the paper the experiments on natural disturbance development in flat plate boundary layer are executed at Mach 2. A modified diagram technique (Kovasznay's method) in relation to constant temperature anemometer is proposed and applied for pulsation decomposition in compressible flow. The study of the statistical characteristics of natural pulsations in supersonic boundary layer is carried out.

SET-UP OF THE EXPERIMENTS

The experiments were conducted in a T-325 supersonic wind tunnel of ITAM SB RAS at Mach 2. The wind tunnel has noise level in test section at M=2 about 0.1% of pressure pulsations. Constant temperature anemometer (CTA) and 5µm hot-wire was used for the disturbances and the mean flow parameters measurements in a free stream and boundary layer on a flat plate with a sharp leading edge. The registration of flow parameters was conducted by the automated measuring system. The system consists from measuring instruments in the CAMAC standard under the control of the transputer T-800 and Pentium III. The pulsation signal from a hot-wire anemometer is registered by 12-bit 750 kHz analog-to-digital converter. Length of digital traces was from 2^{14} to 2^{21} points. The mean voltage from the hot-wire anemometer was measured by the digital voltmeter. Modified Kovasznay's method is applied for pulsation decomposition in compressible flow. Becoherence was determined by splitting of the initial oscillograms on 256 points [1, 2].

RESULTS

1. Statistical features of natural disturbances causing transition.

The experiments on natural disturbances evolution in a boundary layer on a flat plate were conducted both on longitudinal and on normal coordinate with the purpose to detail a picture of transition in the boundary layer. In this section data obtained at $Re_1=12.5\times10^6$ m^{-1} are described. At the first stage of fulfillment of experiments a methodical problem on an interpretation of statistical distributions of the measured oscillograms of natural disturbances was solved. It was necessary to prove by measurements that the CTA can be considered as the linear operator. It managed to be made due to the obtained normal distributions of fluctuations in a free flow of a test section of T-325. (Generally check of linearity consists in definition of smallness of the third and above order cumulants [1].

As follows from made experiments, in a boundary layer there is an extended enough area streamwise, where the normal distribution of fluctuations is saved and consequently the development of disturbances is linear. Then there is a deviation of distributions from normal one that indicates on nonlinear development and interaction of fluctuations. In transient area there is a segment, where this deviation is observed on all width of a boundary layer. When the layer becomes turbulent is observed normal (or equilibrium) distribution of fluctuations in its internal part and below and above there are the spikes and the distributions are not normal. Thus, in natural disturbances case pulsations pass from one equilibrium condition to another one. The experiments convincingly have shown, that most composite distributions of probability density of fluctuation amplitude are observed at the late nonlinear stage of transition and become simpler

in a turbulent layer a little. Here is discussed not about single sampling on longitudinal coordinate and about data of detail boundary layer measurements on a normal to a surface of a flat plate. The described here picture indicates also that in a turbulent boundary layer the transition goes as though continuously on a normal to a wall. ***Perhaps, that presence of a non-equilibrium in a free flow or its generation by different methods in a boundary layer accelerates transition at the expense of nonlinearity. It also hampers the solution of a problem of active transition control in shear layers.***
Mentioned above results are shown in Figs.1. The nonlinear region of disturbance development starts from Re ≈ 1100, deviation of a boundary layer thickness from theoretical for a laminar boundary layer becomes from Re ≈ 1300 that coincides with the beginning of transition.

2. On nonlinear interaction of natural pulsations in supersonic boundary layer
As follow from controlled disturbance experiments the resonance conditions for the unstable waves in supersonic boundary layer at Mach 2 can be realized in the wide range of wave numbers [3] due to the dispersion weakness. This feature can be clear shown below for natural disturbances too by enough big values of bicoherence. In this section data obtained at $Re_1=6.5\times10^6$ m^{-1} are described. The purpose data processing is to find out the cause of filling of spectra in high-frequency area (20 - 250 kHz). The bispectral analysis of the oscillograms of fluctuations has confirmed advantage of quadratic character of nonlinear interaction of disturbances in supersonic boundary layer. The phase coupling down to frequencies 200 kHz is observed. However, at the last stage of transition the role of quadratic nonlinearity weakens for most powerful of low-frequency disturbances (up to 30 kHz). Cubic nonlinearity for low-frequency disturbances probably appears. The phase coupling of high-frequency disturbances (from 40 up to 120 kHz) in controlled experiments can be understood using obtained data.

3. Modified diagram technique for pulsation decomposition in compressible flow
In order to interpret the pulsation measurements using hot-wire Kovasznay [4] has developed pulsation diagram technique introducing a "virtual temperature pulsations". However by the same manner we can define a "virtual mass flow pulsations". Perhaps the reason to choice first definition for Kovasznay was that $S_{\rho u}\approx0$ at $\tau\approx0$ for CCA method and so relative sensitivity is not well defined. For CTA $S_{\rho u} \approx$ *const* and we avoid this problem. To detect of the temperature pulsations it is necessary to use higher overheat ratio then as usual. Full description of the method and its motivation is not goal here and we only will demonstrate obtained results. Downstream distribution of mass flow and total temperature fluctuations in supersonic boundary layer is shown in Fig. 2. They relation is not changed significantly during transition at $\rho U\approx const$.

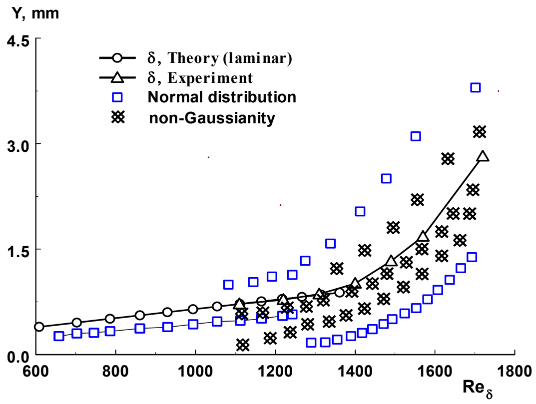

Figure 1. Statistical diagram of transition.

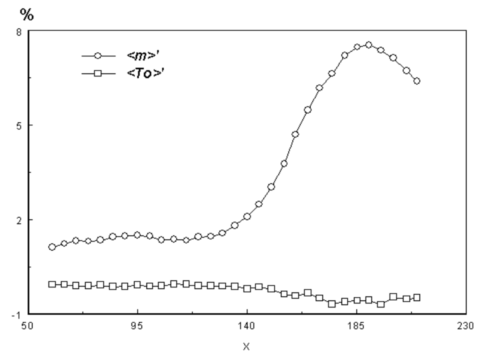

Figure 2. Transition curves versus different kind of pulsations

CONCLUSIONS

The study of the statistical characteristics of natural pulsations in supersonic boundary layer is carried out. Linear and nonlinear regime of transition is determined. It is obtained, that the increase of amplitudes of high-frequency disturbances is caused by phase coupling of pulsation with frequencies from 20 to 200 KHz. The data indicates on the weak disturbance interaction in some regions of turbulent boundary layer. Total temperature pulsations to mass flow pulsations ratio is not changed significantly during transition at $\rho U\approx const$.

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