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Observations on receptivity, stability, and transition of 2-D laminar boundary layers

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Abstract

Receptivity, stability, and transition of two-dimensional laminar boundary layers are studied under natural background disturbances, acoustical excitation, enhanced turbulence, their mixture, and different pressure distributions.

1. Introduction

At present two basic ideas are used to predict a laminar-turbulent transition in boundary layers. In accordance with *Tollmien-Schlichting* (TS) scenario supported by Schubauer and Skramstad experiments the transition is a result of an instability of basic flow. The scenario is usually observed in low-disturbed flow environments. The semi-empirical e^N criterion of transition exploiting this idea is still the standard tool in engineering practice, although it is known to ignore the receptivity of boundary layers with respect to external disturbances and late stages of transition. A term "*receptivity*" unites the physical processes which entail a forming of initial amplitudes of unstable boundary layer modes by freestream disturbances [1,2]. The second idea is due to *Taylor* [3]. Following to this theory, the cause of transition is the unsteady pressure gradients of external disturbances which produce local separations. Taylor's idea is also used in semi-empirical approaches to calculate the transition position in gradient and turbulent flows. This idea has no any direct experimental support.

In natural environments a few types of disturbances are known to influence on the location of laminar-turbulent transition in the boundary layers. There are freestream disturbances - sound, turbulence, and the disturbances due to the defects of surface and the surface vibrations. Present study is concerned with first three kinds of disturbances. One of goals of this study is to understand real physical mechanisms by which disturbances affect boundary layer transition. It is important for transition prediction and control.

The surface defects (roughness, unevenness, etc.) form a class of disturbances important for transition. They can create appropriate spatial scales to couple long-wavelength external disturbances with the shorter wavelength TS waves [4]. The energy of freestream disturbances may be transferred to unstable TS waves by localized [5,6,7] or non-localized receptivity [8]. Previous experimental studies [4,9] in localized sound receptivity of boundary layer modified by small rectangular strip fixed on surface have utilized indirect approach to get experimental estimations. The results may be affected by non-localized receptivity as well as by small variations in boundary layer stability [10]. The intent of this study is to obtain *a direct experimental estimation* of localized receptivity as well for pure acoustical excitation as for elevated freestream turbulence.

One of the goals is also to study the physical mechanisms responsible for laminar-turbulent transition at high Reynolds numbers and with extremely small initial amplitude of TS wave simulating boundary layer of *the natural laminar flow* (NLF) airfoils.

2. Experimental equipment

The experiments are conducted in the ITAM SB RAS wind tunnel T-324 (Novosibirsk). This facility is a low-turbulence close-circuit wind tunnel with the 1m x 1m x 4 m test section well suited for stability and receptivity experiments. Two flat plates used in the experiments are 0.996 m wide and 2.0 m long. Each of these plates is manufactured from the 6-mm aluminum alloy sheet. The leading edge shape is a semicylinder machined directly on flat plate model with radius r = 1 mm or 1.5 mm. The thickness of leading edge is constant along 60 mm from the nose of model and equal to 2 or 3 mm accordingly. The polished working surfaces of flat plates have slightly different *natural undulations which have been documented.* Each plate contains a row of 25 static pressure orifices of 0.35-mm diameter. The tail part of model is supplied by a flap to adjust the stagnation line position. A false ceiling is applied to create the pressure distributions over the flat plate.

A constant-temperature hot-wire anemometer (DANTEC 55M System) and acoustical measuring system are applied to get the freestream and boundary layer characteristics. The onset of transition is determined as the rise in skin friction by means of Preston tube. The freestream turbulence is generated by the screens placed upstream from model near the test section inlet or inside of contraction cone. The freestream acoustical disturbances are introduced by a loudspeaker placed downstream from the flat plate. Small rectangular strip attached to the flat plate surface served as a source of the localized receptivity.

3. Domain and boundary conditions

The limits of domain under study are selected to include the zones of receptivity, instability, and onset of transition in each experimental situation.

Pressure distributions used in tests are shown in Figure 1. One of these distributions (PD1) is created to

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simulate a boundary layer development over NLF airfoil. A minimum of the pressure coefficient distribution is located far downstream from the leading edge. Modified pressure distribution (PD2) has its minimum nearer to the leading edge. In localized receptivity experiments the pressure distribution over the 3-mm leading edge flat plate is fitted to create "zero" streamwise gradients.

Measurements in the free stream and boundary layers are carried out with natural background disturbances as well as under acoustical excitation, enhanced turbulence, and their mixture at the freestream mean velocity of about 18 m/s. The transition is stimulated by the harmonic sound wave with frequencies f = 109 or 190.5Hz (dimensionless parameters $F = 33\cdot10^{-6}$ and $57.3\cdot10^{-6}$ accordingly). The frequencies were close the most amplified ones in experiments with natural disturbances. The sound pressure level at discrete frequencies is varied from about 59dB (natural case) up to 102dB at reference point. Boundary conditions in free stream under acoustical excitation were defined by linear superposition at least of two sound waves traveling in opposite directions. The turbulence intensities measured within $2\text{-}40\cdot10^{3}$ Hz frequency band were varied between values 0.0014 (natural case) and 0.0062. Sound and eddy components of freestream oscillations were separated as the uncorrelated values in this case.

4. Transition in flat plate boundary layer

Studying a problem of unstable TS waves origin and transition under the influence of an artificial sound field [11] it has been observed: a) *stable spatial modulation of total hot-wire signal inside laminar boundary layer* and b) *TS-wave amplitude* A_{TS} *is linear function of forcing sound wave amplitude*. The former may be interpreted as an independence of initial phases difference $\Delta\theta$ between sound and TS waves from amplitude of acoustical disturbance A_S and time. Revision of pervious data concerning of sound excitation TS wave supports this observation. The latter means that $A_{TS} = k_S \cdot A_S$, $k_S \approx$ const. for ω = const., where ω is a circle frequency. Remarkably also that an appearance of total hot-wire signal spatial oscillations could be recorded just in some closeness of neutral point.

These important observations permit to get an experimental estimation for the TS-wave amplitude using an analogy with simple linear superposition of two coherent harmonic processes. But physical mechanism responsible for a forming of initial TS-wave amplitudes was not disclosed at that time.

5. Method of sound receptivity study

A new method of sound receptivity study is developed in [12,13]. Its idea is briefly described below.

Usually a mixture of different modes of natural freestream disturbances generates *a primary* unstable TS waves with some initial phase inside laminar boundary layer. But what of modes (turbulence or sound) produces main contribution for initial TS-wave amplitude and which physical mechanism is a leading one are unclear. If additional *trial wave* is created by means of a source and *known* mode it will be superimposed with the primary one. As result the total oscillation amplitude measured at some location downstream in boundary layer will be changed. The value of the change may be used as *a measure* of contribution of this known mode.

It was shown in [4] that in a vicinity of small two-dimensional surface nonuniformity (e.g., thin strip) a linear generation of TS wave by external sound wave takes place. The result is utilized in new method. During first stage of tests *the measure* of acoustical contribution should be determined. For this purpose the measurements are conducted in pure sound field in boundary layer without and with small surface nonuniformity set at some location. The initial phase of the trial TS wave can be easily changed by means of small variation of nonuniformity position along streamwise direction. The total TS-wave amplitude alteration recorded somewhere downstream gives desirable *measure* of contribution. Then the tests are carried on in boundary layer subjected to action of the mode mixture (e.g., natural disturbances). If the same result will take place it is possible to deduce that the sound give rise to the TS wave. Below it will be also shown the turbulence does not change the localized sound receptivity. This observation supports the previous conclusion.

The method was applied in experiments with flat plate boundary layer (see above). The data obtained led to the conclusion that sound component of natural freestream disturbances created main contribution in initial TS wave amplitude. But the generation mechanism has not been still clarified

Obviously the trial TS wave may be used to control the boundary layer state. Depending on phase difference between *primary* and *trial* TS waves the auto destructive or constructive superposition of unstable oscillations will exist downstream in boundary layer. It should be emphasized the method of boundary layer control does not use any other energy than the energy of freestream disturbances.

6. Leading edge and transition

The experiments are focused on the qualitative study of so-called "leading edge" receptivity of the smooth flat plate boundary layer with respect to free-stream sound. As a rule, there are simultaneously a few sources of receptivity in the wind tunnel experiments. Therefore a comparison of theoretical and experimental data and a separation of main receptivity process are difficult problems. It seems the best way in experimental work is an attempt to create a situation when some of sources are turned off. Thereupon it is needed to modify the situation and to investigate problem by means of the some turned on source of receptivity. For this purpose the semicircular leading edge of flat plate looks more preferential as compared with traditional semielliptical one. Strong nonhomogeneities of flow are located far upstream from a neutral point, and the influence of global surface curvature is eliminated. Now, if small surface nonhomogeneity (e.g., a strip) is set at variable distance

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X_h between leading edge and neutral point due to the autodestruction effect (see above) it will be possible to detect a boundary layer region which can produce some contribution in the initial TS-wave amplitude and affect transition. This experimental scheme has been tasted in [14]. Results are in Figure 2 and show a reaction of boundary layer oscillations on rough and tiny variations of strip position (or of *trial* TS wave initial phase). It can be seen that auto destruction/construction effect take place just for X_h> 150 mm approximately. Open square symbol corresponds to the TS wave amplitude without strip (smooth flat plate).

The main results are as follows:

a) The region of TS wave appearance under acoustic excitation is localized near to the lower neutral curve for "zero" pressure gradients boundary layer. A variation in definite range of global pressure gradients results to a weak shift of location of TS wave rising. The adverse pressure gradients lead to the amplification of initial TS wave amplitude, and the favourable pressure gradients attenuate it.

b). The boundary layer domain which could affect on the formation of initial TS wave amplitude and transition locates on some distance downstream from the leading edge. It is also correct when the boundary layer is subjected to the global adverse pressure gradients starting directly from the leading edge. Despite the unfavorable pressure gradients the TS wave could not be detected in nearest vicinity of smooth flat plate leading edge but due to them the domain of probable influence expands towards the leading edge.

These observations reduce problem of TS wave origin in boundary layer under acoustic excitation towards the influence of boundary conditions.

7. NLF pressure distribution and transition

Accounting above mentioned observations the natural surfaces undulation has been measured. Fourier analysis has shown that surfaces contain the spatial scales which corresponded to the wavelength of the most amplified TS waves under background disturbances. Strong boundary layer response is recorded for the same TS-wave frequencies under acoustic excitation. The forcing free-stream acoustic disturbances was proved to couple with the suitable scale of natural surface undulation giving rise to the TS waves by nonlocalized acoustic receptivity [15]. The region of coupling locates in the vicinity of neutral point. The initial TS wave amplitude is linear with the acoustic wave amplitude. In the case of the natural background disturbances (ε = 0.0014) the initial TS wave amplitude is mainly created by natural free-stream sound. The TS waves grow linearly up to the onset of transition followed by their nonlinear breakdown Fig.3. The onset of transition moves upstream with the sound pressure level increase. The N-factor corresponding to the onset of transition lowers with the increase of sound pressure level from 59dB (natural background sound) to 102dB at the discrete frequency. The data is in Figure 4. The narrowband or broadband freestream sound provokes in the boundary layer TS waves in the same frequency range like the natural wind tunnel noise. Their amplitudes are approximately proportional to the sound pressure levels. Nonlocalized sound receptivity together with linear amplification give a shape to the oscillation spectra measured downstream.

As it is well known, a hot wire is not sensitive with respect to the direction of flow and is working as a two-half-period detector circuit. When an amplitude of input harmonical signal is more than the mean value of voltage, the output oscillations will have a typical shape. Oscillograms of fluctuations in boundary layers subjected to adverse pressure gradients and acoustic excitation became typically distorted on some distance after strong amplification of unstable TS wave. Analysis of oscillograms permits to deduce there is some region placed very close to the wall where the signal deformation similar to that mentioned above exists. This means that the microseparations arise and evolve near the smooth rigid wall. The sizes of these lenses induced by TS wave do not exceed $0.15\delta_1$ in the normal to surface direction (δ_1 is the displacement thickness), and are less than one-half of the TS wavelength in the longitudinal direction. A number of lenses were two or three in dependence of time moment. The strong nonlinear processes started after an appearance of microseparation lenses. The microseparation lenses, induced by unsteady pressure gradients of the main TS wave, are found for the first time in [16]. The finding of the microseparations supports both current points of view (Tollmien-Schlichting and Taylor) on the physical mechanisms of transition to turbulence in boundary layers.

The free-stream turbulence enhanced by means of a screen (ε = 0.0025 and 0.0062) has led to typical distortion of oscillation profiles inside the boundary layer. The scenario of transition is similar that is observed in low-disturbed free stream. The natural disturbances provoke the same frequency band of TS waves. With acoustic forcing there are the region of coupling of external disturbances with surface undulation, linear growth, and nonlinear breakdown of TS waves. In opposite to the action of free-stream sound the increase of turbulence due to the eddy mode from ε= 0.0014 to 0.0062 almost does not affect the position of transition under the same sound pressure level. Initial TS-wave amplitude stays linear with acoustic amplitude. Initial TS amplitude is independent from turbulence level. The receptivity coefficients stay approximately the same (ε = 0.0025). Though some effect likely exists for the 0.0062 turbulence intensity. The boundary layer stability weakly changes because of variations in the mean flow produced by free-stream turbulence. The N-factor corresponding to the onset of transition is about the same value for equal acoustic conditions. An interaction between TS wave excited by free-stream sound and the motion generated in the boundary layer by turbulence happens at the late nonlinear stage of transition.

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8. Modified pressure distribution and transition

For modified pressure distribution (the minimum of pressure locates nearer to leading edge) and the least free-stream turbulence the same basic results were observed, i.e. the acoustical forcing accelerates the boundary layer transition due to the receptivity and TS instability. But the increase of free-stream eddy mode has led to the decrease of transitional Reynolds number. At the same time the influence of sound intensity on transition has disappeared in spite of that the acoustical receptivity and stability of boundary layer are not altered as affected by free-stream turbulence. A complicated scenario of transition takes place.

9. Localized receptivity

The nearest vicinity of rectangle strips having the heights from 10 μm up to 146 μm is inspected to obtain the direct experimental estimations of boundary layer response and the size of TS-wave forming domain [15]. The strip width is chosen to be equal to a half of TS wavelength (about 25 mm). The strip is placed a little upstream from neutral point for a frequency under consideration to eliminate a superimposing with natural TS-wave generated by freestream disturbances [12,13]. The data obtained indicates that a roughness strip as small as 20 μm in height produces remarkable variations of basic flow within the boundary layer. A size of the mean flow distortion region in streamwise direction may be larger than a half of TS-wave length. The TS wave amplitudes as low as $O(10^{-6})$ *directly measured* inside this region have led to the *direct* experimental estimations of localized receptivity coefficients. The initial TS wave amplitude gains in the linear manner with the growth of the forcing freestream sound pressure level up to 102 dB. However the increase of roughness height leads to the nonlinear amplification of the excited TS wave, Fig.5. In point of fact the free-stream turbulence does not change the acoustical receptivity. The total coefficient of the localized receptivity is mainly determined by conversion of sound component of freestream disturbances under the elevated turbulence.

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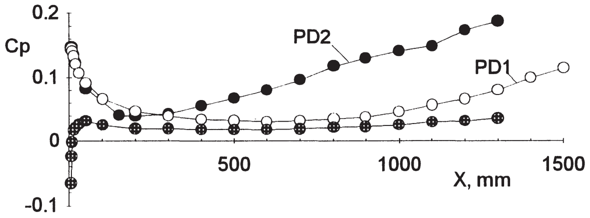

Fig.1. Pressure distributions

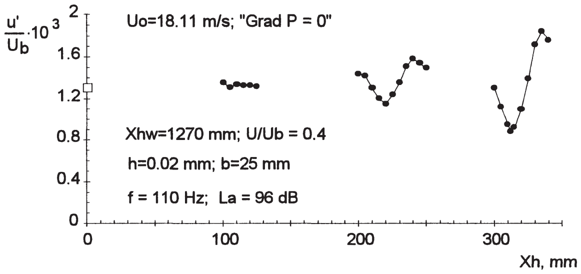

Fig.2. Total RMS velocity amplitudes in boundary layer

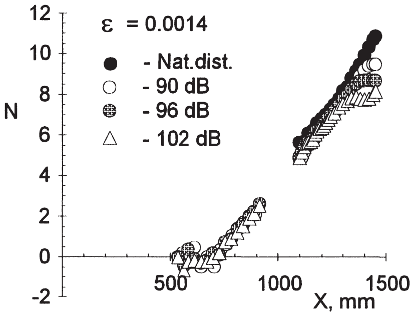

Fig.3. Amplification factor for wave with frequency f = 109 Hz

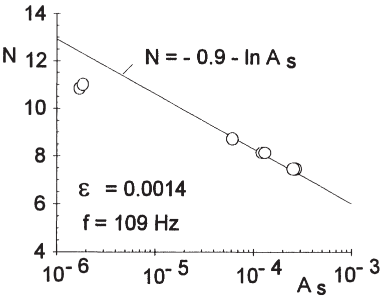

Fig.4. N-factor via freestream sound amplitude $A_S = u'_s/U_0$

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