EXCITATION OF TOLLMIEN–SCHLICHTING WAVES IN THE BOUNDARY LAYER ON A VIBRATING SURFACE

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The question of transforming external perturbations into a Tollmien–Schlichting wave in the boundary layer has been studied intensively lately since it is closely associated with the general problem of laminar to turbulent flow transition. A sufficiently complete survey of the literature devoted to this problem, i.e., the problem of boundary layer susceptibility to external perturbations, can be found in [1], where boundary layer response to spatially localized, time-periodic external perturbations is indicated.

Surface vibrations, which can turn out to be one of the most probable sources of instability wave generation in the boundary layer are characteristic for modern aviation engineering and aerodynamic installations. It has been shown in [2] that the excitation of a Tollmien–Schlichting wave in the boundary layer on a flat plate exposed to an external acoustic field will occur because of transverse vibration of the nose of the plate. A correlation between the transition Reynolds number and the vibration amplitude–frequency characteristics of the streamlined surface has been detected in [3]. The possibility, in principle, of exciting natural boundary-layer oscillations was indicated in theoretical papers [4, 5] devoted to the origin of Tollmien–Schlichting waves during surface vibrations when the localized vibration source is far from the plate leading edge.

The problem of subsonic flow around a flat plate with a triangular vibrator thereon performing harmonic oscillations is studied in [4]. The consideration was carried out within the framework of describing the flow by the equations of a boundary layer with self-induced pressure. It was shown there that the perturbations caused by the vibrator always damp out rapidly upstream, while rapid damping holds downstream for frequencies noticeably less than the critical, where the closer they are to the critical, the more slowly the damping will occur. It is found that at distances of several wavelengths downstream from the vibrator, perturbations with amplitude governed by the oscillator shape and size are generated in the Tollmien–Schlichting wave.

The resonance excitation mode, when the frequency and wavelength characterizing the vibrating surface agree with the corresponding instability wave parameters at the point of loss of stability, was investigated by the saddle-point method in [5]. It was established that the resonance interaction domain is concentrated in a narrow section of the streamlined surface. The Tollmien–Schlichting wave being formed is developed downstream according to laws of a solitary wave with initial amplitude governed by the vibrator shape and by the magnitude of the amplitude of its oscillations.

The purpose of this paper is an experimental confirmation of the possibility, in principle, of transforming small localized surface vibrations into a Tollmien–Schlichting wave and obtaining quantitative results describing this relation.

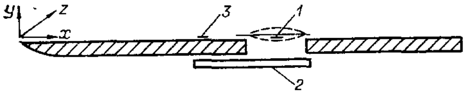

Fig. 1

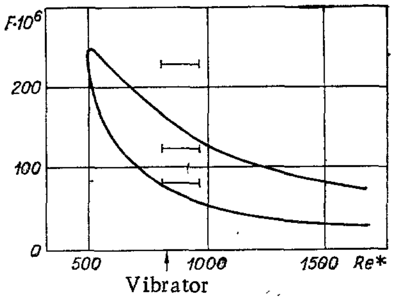

Fig. 2

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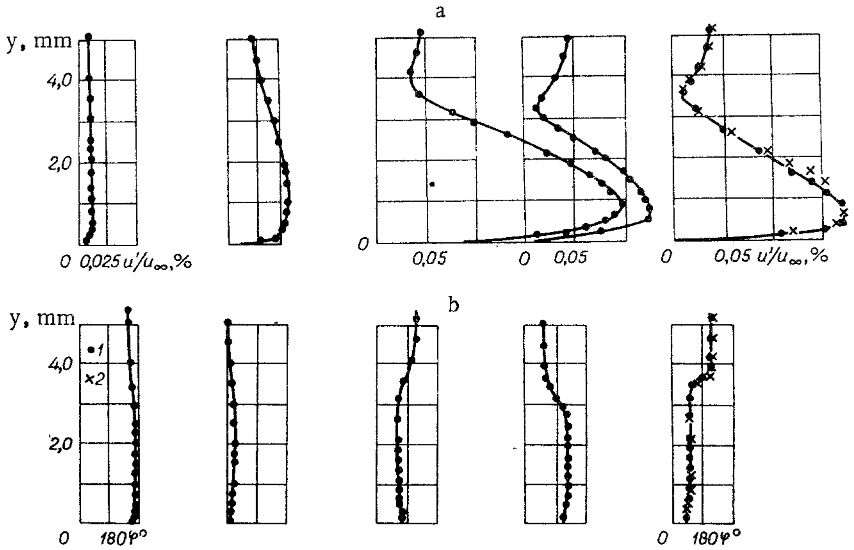

Fig. 3

The experiment was conducted in the low-turbulence T-324 wind tunnel (the spectrally integrated degree of turbulence is $\varepsilon \sim 0.04\%$) on an organic glass plate with elliptical nose mounted parallel to the stream. The ratio of the ellipse semiaxes is 1:66 on the working side and 4:66 on the opposite. The free stream velocity was $u_\infty = 7.25$ m/sec.

Observation of the development of perturbations was realized by using a thermoanemometer sensor. Signals were processed by a combination of "DISA" thermoanemometric apparatus and the frequency analyzer FAT-1. A rectangular through hole with dimensions 180 mm × 28 mm (Fig. 1) covered by a 20-μm-thick lavsan film, to whose lower surface a 0.05-mm-thick and 3-mm-wide metal tape 1 was glued, was selected at a distance of $x_0 = 490$ mm from the nose of the plate. The permanent magnet 2 was fastened below the plate. When a sinusoidal electrical current from the G3-34 generator passed through the tape, the metal tape vibrated in the magnetic field together with the film. This permitted obtaining two-dimensional surface vibrations with amplitudes of several to several tens of microns.

Measurement of the amplitude of the surface vibration during the experiment was by observation of the broadening of the spot from a laser beam incident on the vibrating surface and being reflected by the wall of the wind tunnel. In order to determine the amplitude of the vibrating surface in microns, an initial static calibration was performed by using a micrometer. This permitted measuring the surface vibration amplitudes with ∿30% accuracy.

Measurements of the vibrator oscillation amplitude over its whole surface showed that the surface vibration amplitude remained practically approximately constant on two-thirds of the surface (along the x axis).

To obtain the usual Tollmien–Schlichting wave, the method described in [6] was used. The tape 3 (see Fig. 1) was placed in the stream at a height of 0.15 mm from the plate surface at a distance of 400 mm from the nose, and was set in motion exactly as in the first case.

The range of variation of the frequency parameter $F = 2\pi f\nu/u_\infty^2$ and the Reynolds number Re* measured over the displacement thickness δ^* at which the experiment was performed is shown in Fig. 2. The measurements were conducted both within the neutral stability curve at the frequency f = 45 Hz ($F = 81 \cdot 10^{-6}$) and f = 70 Hz ($F = 121 \cdot 10^{-6}$) (in the growing perturbation domain) and outside (in the damping domain) at the frequency f = 120 Hz ($F = 225 \cdot 10^{-6}$). The distributions over the coordinate z as well as the growth curves of the amplitude and phase were here measured at the level of the inner maximum of the perturbations.

Perturbation amplitude and phase profiles, respectively, are presented in Fig. 3a and b for the longitudinal velocity component u' as a function of the transverse coordinate x ($x - x_0 = -20, 0, 20, 40, 60$) and the frequency f = 70 Hz ($F = 121 \cdot 10^{-6}$). It can be seen that the perturbation amplitude and phase across the boundary layer change slightly upstream of the vibrator, which is apparently related to the presence of just pressure pulsations. In the domain behind the vibrator, the perturbation amplitude and phase profiles (points 1) gradually acquire the shape typical for a Tollmien–Schlichting wave with movement downstream,

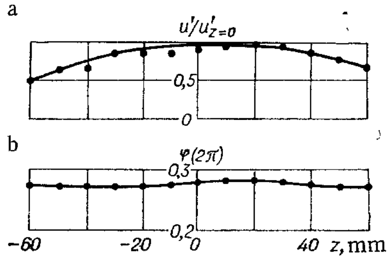

Fig. 4

i.e., two maximums are observed in the amplitude profile and a jump change in the phase by a quantity equal to π at the perturbation minimum point. For $x - x_0 = 60$ mm a comparison with the profiles obtained for the customary Tollmien–Schlichting wave (the points 2) shows their practically complete agreement.

Perturbation amplitude and phase distributions are presented, respectively, in Fig. 4a and b as a function of the coordinate z for $x - x_0 = 20$ mm for the frequency f = 70 Hz ($F = 121 \cdot 10^{-6}$). It is seen that the perturbation phase remains constant with high accuracy, while the amplitude varies approximately within the same limits as upon the insertion of perturbations by the tape according to a known method (see [7], say).

Perturbation amplitude growth curves given by the vibrator (points 1) and the tape (points 2) for a 45-Hz frequency are presented in Fig. 5a. It is seen that a pulsation maximum amplitude occurs at a distance of $x - x_0 = 20$ mm from the beginning of the vibrator, then the perturbations produced by the vibrator damp out abruptly with progress downstream, after which they grow. Further small periodic fluctuations in the perturbation amplitude along the longitudinal coordinate can be explained by the superposition of the pressure pulsations produced by the vibrator and the Tollmien–Schlichting wave.

Growth curves of the perturbation phase are presented in Fig. 5b for the same frequencies. It is seen that the wave phase produced by the vibrator is practically unchanged up to the domain $x - x_0 = 20$ mm, which is associated with the pressure pulsations emitted by the vibrator. Then phase growth starts, indicating the presence of a Tollmien–Schlichting wave.

The amplitude and phase growth curves were measured for different surface vibration amplitudes. It turns out that after normalization with the vibrator oscillation amplitude taken into account, the shape of the distributions of both the amplitudes and phases remains unchanged, indicating compliance with the superposition principle and linearity of the process.

A comparison of the perturbation amplitude growth curves given by the vibrator and the tape is shown in Fig. 6 for different frequencies [points 1-3 for f = 70 ($F = 121 \cdot 10^{-6}$), 45 ($F = 83 \cdot 10^{-6}$), and 120 Hz ($F = 225 \cdot 10^{-6}$), respectively]. The surface vibration amplitude is here 70, 50, 28 μm, respectively, while the maximum pulsation amplitude in the domain above the vibrator is 65, 47, 26 mV in dimensional units. It is seen that at a downstream distance of several wavelengths, all the growth curves presented are practically in agreement, the perturbation amplitude produced by the vibrator damps out rapidly upstream, as is verified by the results in [4]. It also follows from Fig. 6 that transformation of the surface vibrations into an equivalent Tollmien–Schlichting wave for different frequencies occurs identically for a constant surface vibrations amplitude (here the equivalent wave is understood to be a two-dimensional Tollmien–Schlichting wave produced by a localized vibrator). Further downstream development of the perturbations occurs differently, in conformity with linear stability theory.

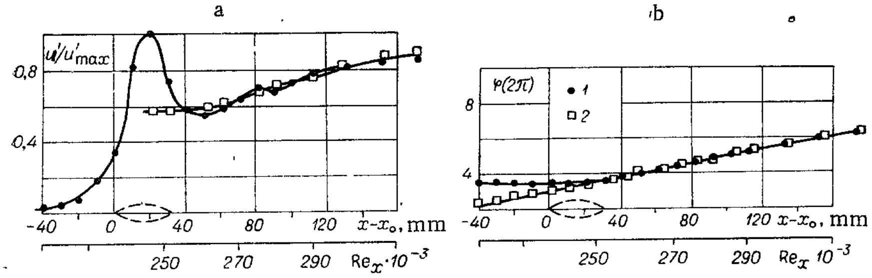

Fig. 5

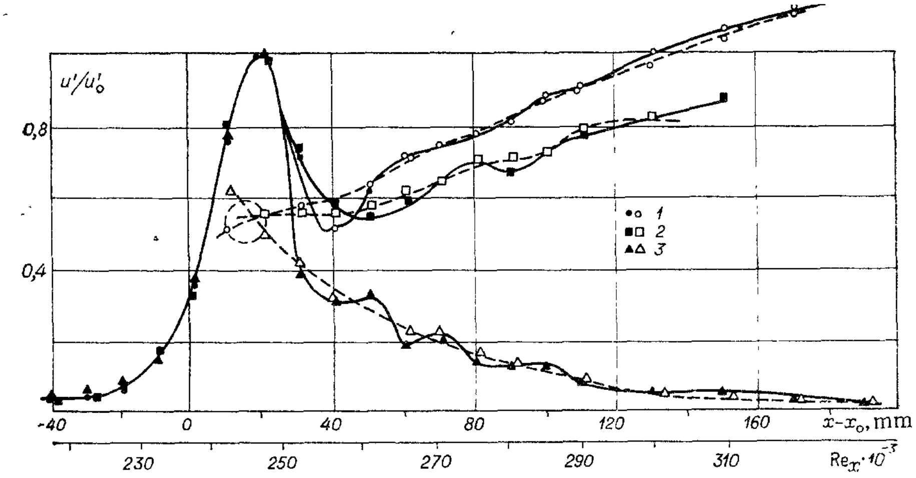

Fig. 6

Results of the experiment showed that the dimensionless amplitude of the equivalent Tollmien–Schlichting wave (u'/u_∞) in the domain above the vibrator is practically independent of the vibration frequency for a constant surface vibration amplitude in the frequency band under investigation, depends linearly on their amplitude, and is ∿0.07 ± 0.02% for a 10-μm surface vibration amplitude.

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