EXPERIMENTAL STUDY OF 3D LOCALIZED BOUNDARY-LAYER RECEPTIVITY TO FREE-STREAM VORTICES BY MEANS OF TWO-SOURCE METHOD

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1. Introduction

The investigation of mechanisms of excitation of the boundary-layer instability waves by various external perturbations represents an important aspect of the laminar-turbulent transition problem and has a crucial significance for both basic research of transition and practical applications. A review of recent studies in this field, related to 3D receptivity problems for 2D and 3D boundary layers, can be found in [1]. Most of previous experimental investigations were devoted to the receptivity to surface perturbations (roughness and vibrations) and to acoustic waves. Meanwhile, the excitation of instability waves by free-stream turbulence can also play a very important role and influence the transition process. The present paper is devoted to an experimental investigation of the 3D receptivity of Blasius boundary layer to non-stationary vortical free-stream disturbances due to their scattering on localized (in streamwise and spanwise directions) surface vibrations. There is only one available quantitative experimental study of a similar receptivity problem performed in [2] for *unsteady* free-stream vortices. A scattering of a weak vortex street (with 2D spanwise vorticity) on a localized two-dimensional surface roughness has been studied in this work in the Blasius flow. The results of this experiment were found to be in a good agreement with the 2D receptivity theory [3]. *Three-dimensional* receptivity to non-stationary free-stream vortices has not been studied in previous experiments at all. The scattering of free-stream vortices on surface *vibrations* was not studied even for purely two-dimensional case.

2. Procedures of Measurements and Data Processing

The experiments were conducted in the low-turbulence subsonic wind tunnel T-324 of the ITAM at the free-stream velocity U_e = 9.18 m/s and turbulence level less than 0.02 % (in the frequency range above 1 Hz). The wind tunnel has a 4 m long test section with a 1 m $\times$ 1 m cross-section. A sketch of the experimental setup is shown in Fig. 1. The laminar boundary layer under investigation was developed over a flat plate mounted in the test section at the zero angle of attack. The measurements were carried out by means of a hot-wire anemometer. The basic flow was shown to correspond almost exactly to the Blasius one with the virtual position of the plate leading edge shifted upstream by $\Delta x = -79$ mm from the physical one.

The experiment was conducted at controlled excitation of both perturbations: (*i*) the free-stream vortices and (*ii*) the surface vibrations. A low-amplitude 2D vortex street was excited in the free stream by means of a newly developed disturbance source (the source number 1) described below. The surface vibrations were simulated by means of a modified membrane vibrator (the source number 2), which was similar to that used in our previous experiments (see e.g. [4]) but had a smaller diameter (of 10 mm) and a more flexible membrane to provide larger amplitudes of vibrations and a broader spanwise-wavenumber spectrum of them. The vibrator was mounted flush with the wall at a distance x_s = 437 mm downstream the plate leading edge (Reynolds number $Re_s = U_e\delta_{1s}/\nu = 972$, where $\nu = 1.488 \cdot 10^{-5}$ m^2/s is the air kinematic viscosity).

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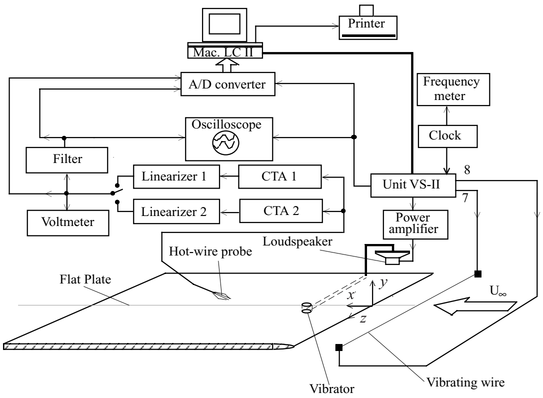

Fig. 1. Sketch of experimental setup.

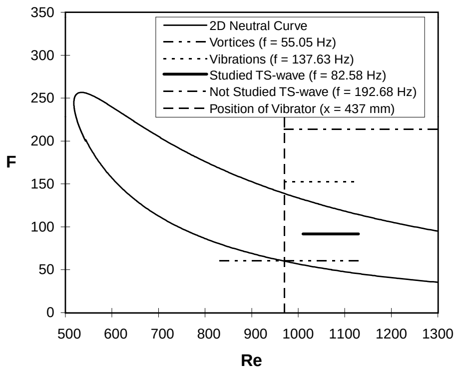

Fig. 2. Regions of measurements on stability diagram.

The source of vortices (number 1) consisted of a thing tungsten wire (of 100 μm in diameter) fixed under tension in the flow (see Fig. 1). The wire was positioned upstream the plate leading edge (at $x = -138$ mm) parallel to it. The wire oscillated in the plane normal to the free-stream direction under the influence of two shakers manufactured on the base of stepping motors. The frequency of oscillations was close to the first eigen mode of the wire as a string. The disturbance excited in the flow represented a kind of an anti-symmetric vortex street, which was similar to well-known Karman-street but had rather small amplitude (about 0.6% for the rms intensity of streamwise velocity fluctuations). The wire y-coordinate was adjusted to provide propagation of the vortex street slightly above the external edge of the flat-plate boundary layer.

Both perturbations were harmonic in time but had different frequencies. The free-stream *vortex* frequency was f_v = 55.05 Hz, while the frequency of the *surface* vibrations was f_s = 137.63 Hz. The excitation of the Tollmien-Schlichting (TS) waves occurred at two combination frequencies $f_{TS1,2} = f_s \pm f_v$. However, the excited instability waves had large enough (i.e., accurately measurable) amplitudes only at 'left' combination frequency $f_{TS1} = f_s - f_v$ = 82.58 Hz, which was studied in detail. It is important to note that all spectral modes were coherent with each other and had integer number N of their periods per the length of the signal realization T_r = 908.33 ms. Namely: N = 50, 125, 75, and 175 periods for modes f_v, f_s, f_{TS1}, and f_{TS2} respectively. Therefore, the amplitudes and phases of all important spectral modes were obtained by means of Fourier decomposition as Fourier series coefficients for the ensemble averaged time-traces. The electric signals, which fed the stepping motors of the source number 1 and the loudspeaker driving the vibrator (the source number 2), were generated by an electronic unit VS-II described in [5]. The signals were formed by a computer program and downloaded into the unit RAM. Then, they were played periodically (with period T_r) under the guidance of an external clock. A reference signal was generated every period T_r and used for ensemble averaging of the hot-wire signals, which were linearized and introduced into an Apple computer via an A/D converter.

The frequencies f_v, f_s, f_{TS1}, and f_{TS2} correspond to the frequency parameters $F = 2\pi f \nu / U_e^2 \cdot 10^6$= 61.1, 152.7, 91.6, and 213.8 respectively. The positions of the regions of main measurements are shown in Fig. 2 on the linear stability diagram for the 2D TS-waves (where $\mathrm{Re} = U_e \delta_1/\nu$ is the local Reynolds number). The stability calculations were performed by R. Hanifi (private communication, 1996) using the 'non-parallel' PSE approach.

The main measurements of the excited TS-wave train were carried out inside the boundary layer at a fixed non-dimensional distance from the wall $y/\delta_1 = 0.75$ ($U/U_e = 0.42$) that is close to the wall-normal position of the 3D TS-wave amplitude maxima. A set of spanwise profiles was measured in a fare-field of the vibrator at x = 480, 500, 520, and 540 mm (Re = 1010, 1028, 1046, and 1063 respectively). The wall-normal profiles were also taken in addition at several streamwise positions. The shape of the vibrator oscillations was carefully measured by a micro displacement measuring system "OptoNCDT 1605". The linearity of the investigating receptivity problem was checked by means of variation of the disturbance amplitudes. It has been found that the amplitudes of the excited TS-waves are constant within an experimental accuracy when they are normalized by the amplitudes of vibrations and free-stream vortices. The TS-wave phase distributions were also independent of the external disturbance amplitudes.

The obtained experimental data were subjected to a deep processing, which included the decomposition of the instability waves and the surface vibrations into normal oblique modes (harmonic in time and space) inclined at various angles to the mean flow direction. The amplitudes of the excited normal TS modes were then extrapolated upstream to the location of the surface vibrator to obtain the initial TS-wave spectrum. As the result, the coefficients of the vibration-vortex boundary-layer receptivity have been obtained experimentally for every studied value of the spanwise wavenumber. These coefficients were defined in the following way:

$$G_{\text{vib-vor}}(\beta) = \frac{B_{\text{TS1o}}(f_{\text{TS1}}, \tilde{\alpha}_{\text{rTS1}}, \beta)}{C_{\text{s}}(f_{\text{s}}, \hat{\alpha}_{\text{rs}}, \beta) A_{\text{v}}(f_{\text{v}}, \tilde{\alpha}_{\text{rv}})}, \tag{1}$$

where B_{TS1o} is the spectral amplitude in the initial spanwise-wavenumber spectrum of the excited TS-wave, C_{s} is the resonant amplitude spectrum of the surface vibrations, and A_{v} is the vortex street amplitude measured at the boundary layer edge at $y = \delta$. Spanwise wavenumber β, as well as the frequencies f_{s} and f_{v}, are free variables (the parameters of the problem), while the streamwise wavenumbers $\tilde{\alpha}_{\text{rTS1}}$ and $\tilde{\alpha}_{\text{rv}}$ are eigen values, which correspond to dispersion relationships of for the TS-waves and the free-stream vortices respectively. The 2D spectrum of the surface vibrations contains all values of the streamwise wavenumber α_{rs} for every given value of the spanwise wavenumber β. However, only 'resonant' modes are able to excite the TS-waves due to the vibration-vortex interaction. The resonant streamwise wavenumbers $\hat{\alpha}_{\text{rs}}$ in the spectrum of surface vibrations was determined for the 'left' combination mode $(f_{\text{TS1}}, \tilde{\alpha}_{\text{rTS1}}, \beta) = (f_{\text{s}}, \hat{\alpha}_{\text{rs}}, \beta) - (f_{\text{v}}, \tilde{\alpha}_{\text{rv}}, 0)$ as

$$\hat{\alpha}_{\text{rs}}(\beta) = \tilde{\alpha}_{\text{rTS1}}(\beta) + \tilde{\alpha}_{\text{rv}}. \tag{2}$$

It was also found that $\tilde{\alpha}_{\text{rv}} = 2\pi f_{\text{v}} / U_{\text{e}}$ with high accuracy.

3. Experimental Results

In order to exclude a mechanism of rescattering of the previously generated TS-wave (at the vortex frequency f_{v}) on the surface vibrator, special measurements have been performed upstream the vibrator. In a preliminary regime of measurements the vortex frequency was chosen to be equal to $f_{\text{v}}' = 109.09$ Hz, i.e., close to the upper branch of the neutral stability curve (see Fig. 2). In this case the vortex street was found to excite a 2D TS-wave (with frequency f_{v}') *upstream the vibrator* (probably near the plate leading edge). This excitation is illustrated in Fig. 3 and leads to spatial beatings with period $\lambda_{\text{xb}} \approx 40$ mm that corresponds to superposition of a "tail" of the free-stream vortex street (which average streamwise wavenumber is $\tilde{\alpha}_{\text{rv}}(f_{\text{v}}') =$ 0.0951 rad/mm and phase speed $C_{\text{xv}}/U_{\text{e}} = 0.79$) and the TS-wave excited upstream by vortices. Indeed, assuming that the characteristic streamwise phase speed of the TS-wave is $C_{\text{xTS}}/U_{\text{e}} \approx 0.3$ (see e.g. Fig. 5 below), i.e., $\tilde{\alpha}_{\text{rTS}}(f_{\text{v}}') = 2\pi f_{\text{v}}' / C_{\text{xTS}} \approx 0.249$ rad/mm, the period of beatings can be estimated as $\lambda_{\text{xb}}(f_{\text{v}}') = 2\pi / [\tilde{\alpha}_{\text{rTS}}(f_{\text{v}}') - \tilde{\alpha}_{\text{rv}}(f_{\text{v}}')] \approx 40.8$ mm in agreement with Fig. 3.

In such regime the correct measurements of the vibration-vortex receptivity are impossible. Therefore, the vortex frequency had been reduced to $f_{\text{v}} = 55.05$ Hz to provide attenuation of the TS-wave generated by vortices near the leading edge. In this new regime

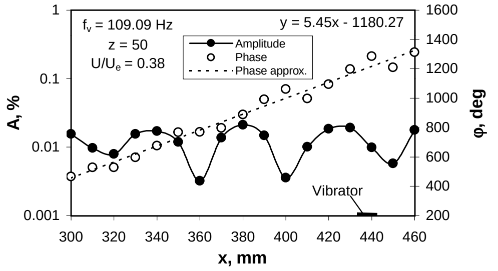

Fig. 3. Excitation of TS-wave upstream the vibrator at vibration frequency in a preliminary regime.

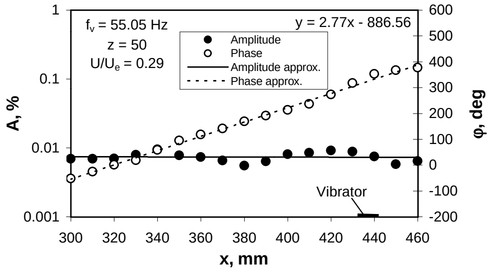

Fig. 4. Absence of excitation of TS-wave upstream the vibrator at vibration frequency in the main regime.

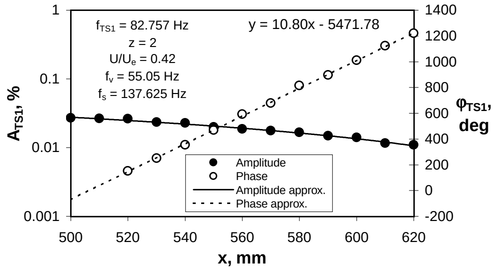

Fig. 5. Excitation of TS-wave downstream the vibrator at combination frequency f_v.

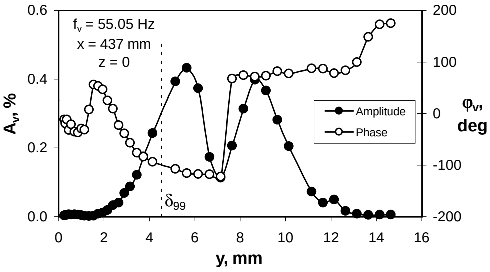

Fig. 6. Shape of the free-stream vortex street and its position with respect to the boundary layer edge.

(chosen as the main one), the TS-wave is practically absent at the position of the surface vibrator and almost no beatings is observed (Fig. 4, the vibrator is tuned off). The disturbances measured in the boundary layer at y/δ_1 =0.51 (U/U_e = 0.29) propagate with phase velocity C_{xv}/U_e = 0.78 and correspond to "tail" of the free-stream vortex street. Due to the vibration-vortex receptivity mechanism these disturbances scatter on the vibrator and the mode dominating at left combination frequency f_{TS1} downstream the vibrator represents a TS-wave-train with the characteristic phase speed $C_{xTS1}/U_e = 0.30$ (Fig. 5).

The shape of the free-stream vortex street, as well as its position with respect to the boundary layer, is illustrated in Fig. 6 where the amplitude and phase of the streamwise velocity fluctuations (at the vortex frequency f_v) are shown versus the wall-normal coordinate y. The measurement was performed over the center of the surface vibrator (x_s = 437 mm). The vortex disturbance is seen to be located near the boundary-layer edge and has two distinct maxima and a phase jump in the vortex-street center. The disturbance amplitude at $y = \delta_{99}$ is $A_v = 0.297\%$.

The shape of the surface vibrations is illustrated in Fig. 7, where contours of membrane oscillation amplitudes are shown in (x, z)-plane. The phase of vibrations is found to be constant within ±5° over the whole surface of the vibrator. The central section of the amplitude part of the 2D wavenumber spectrum of the shape of vibrations is presented in Fig. 8. This spectrum was obtained for the vibration amplitudes normalized by the amplitude in the membrane center. Similarly to the shape of vibrator, its spectrum is axisymmetric. The distribution presented in Fig. 8 was approximated by six-order polynomial (see curve and formula in Fig. 8). The resonant spectrum of vibrations determined according to (2) is also shown in this figure.

A set of spanwise-wavenumber spectra of the excited TS-waves is shown in Fig. 9 for four streamwise positions. Several typical streamwise distributions of the normal TS-amplitudes and phases are illustrated in Fig. 10 together with their approximation (exponential one for amplitudes and linear one for phases) and extrapolation to the position of the vibrator center. The approximation of the phase distributions gave us the TS-wave dispersion curves $\tilde{\alpha}_{rTS1} = \tilde{\alpha}_{rTS1}(\beta)$ presented in Fig. 11a and a unique dependence of the TS-wave propagation angle θ_{TS1} on the spanwise wavenumber β shown in Fig. 11b.

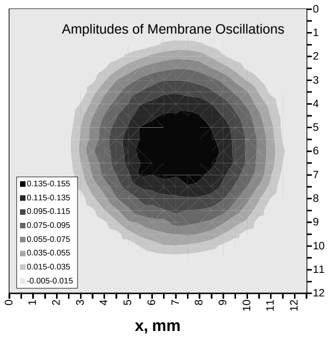

Fig. 7. Amplitude of surface vibrations in (*x*,*z*)-plane.

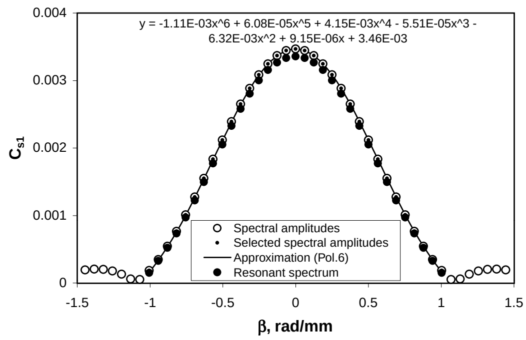

Fig. 8. Central section of 2D wavenumber spectrum of vibrations and the resonant spectrum of vibrations.

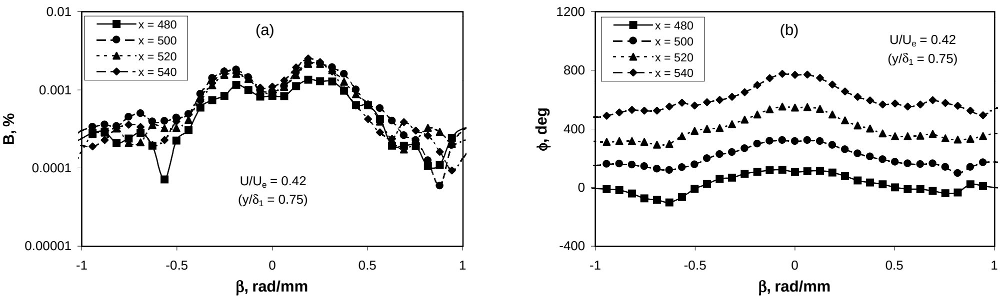

Fig. 9. Amplitude (*a*) and phase (*b*) parts of the TS-wave spanwise-wavenumber spectra at four downstream positions.

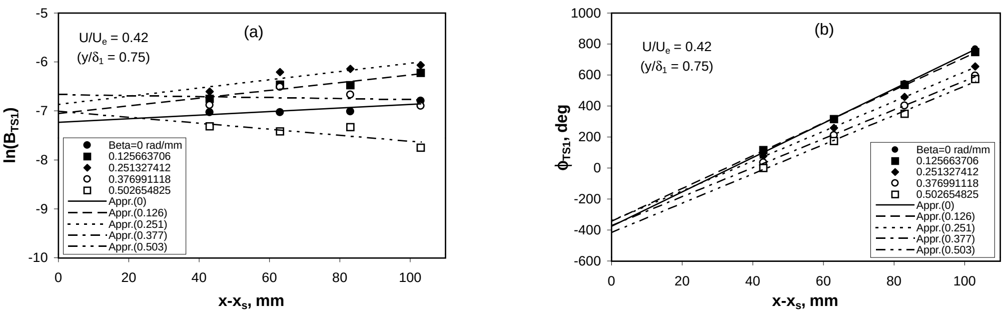

Fig. 10. Downstream evolution of normal TS-mode amplitudes (*a*) and phases (*b*) and their upstream extrapolation.

Finally, the vibration-vortex receptivity coefficients were determined according to (1) as functions of the spanwise wavenumber β (Fig. 12*a*) and the TS-wave propagation angle θ_{TS1} (Fig. 12*b*). First, the comparison of the directly measured and symmetrized receptivity coefficients indicates that the accuracy of their determination is reasonably good in the studied range of the TS-wave propagation angles θ_{TS1} (from zero to 70º). Second, it is seen that the vibration-vortex receptivity is the lowest for 2D TS-waves and increases with the wave propagation angle. In other words, the transformation of the 2D free-stream vortices on 3D vibrational waves is more efficient compared to that occurred on 2D surface vibrations. Finally, the values of the vibration-vortex receptivity coefficients turned out to be very similar to those found in previous experiments and DNS [6,7] for the vibration-acoustic and roughness-acoustic receptivity mechanisms in spite of rather different experimental conditions.

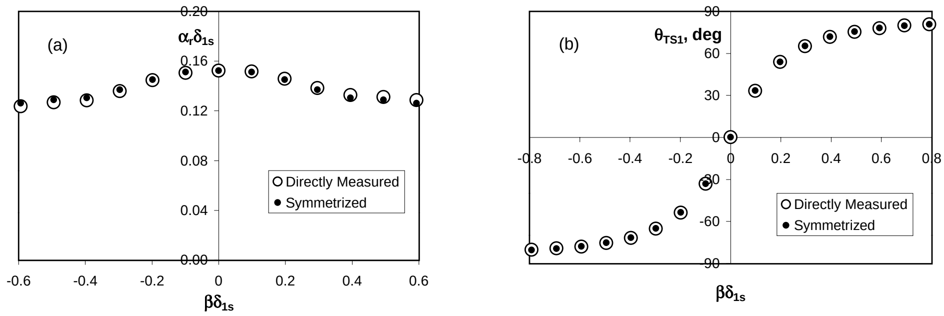

Fig. 11. Normal TS-mode streamwise wavenumber (*a*) and propagation angle (*b*) versus the spanwise wavenumber.

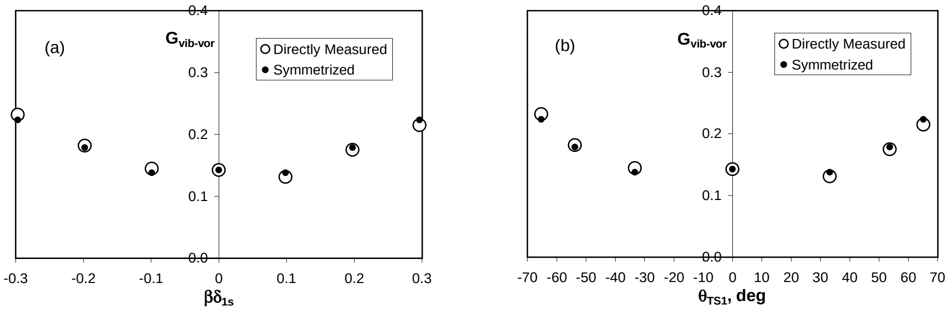

Fig. 12. Vibration-vortex receptivity coefficients versus spanwise wavenumber (*a*)
and TS-wave propagation angle (*b*).

4. Conclusions

The quantitative experimental study of the linear 3D receptivity of Blasius boundary layer to the 2D unsteady free-stream vortices due to their scattering on surface vibrations is performed for the case of vorticity vector parallel to the wall and perpendicular to the free-stream velocity vector. It is found that the harmonic in time free-stream vortices excite a TS-wave train. The receptivity coefficients are shown to increase with the TS-wave propagation angle and the spanwise wavenumber. The values of the receptivity coefficients are found to be rather close to those obtained in previous experiments on roughness-acoustic and vibration-acoustic receptivity. The receptivity coefficients are independent of the specific shape of surface vibrations and can be used for verification of the corresponding receptivity theories.

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