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Excitation of 3D TS-Waves in a Swept-Wing Boundary Layer by Surface Vibrations and Freestream Vortices

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Abstract. There are several kinds of velocity disturbances, which may affect the transition to turbulence in a swept wing boundary layer. Tollmien-Schlichting (TS) waves are among most important of them. The properties of TS waves and their potential competition with cross-flow waves on a swept wing are poorly studied in theoretical works and were not studied experimentally at all. This paper presents the method of excitation of fully controlled 3D TS waves via interaction of free-stream vortices and surface vibrations. The experimental approach developed here will be used for investigation of the corresponding receptivity problem.

MOTIVATION

Most of theoretical and experimental works on stability and receptivity problems in a swept wing boundary layers deal with cross-flow waves and vortices, see e.g. reviews in [1-3]. Meanwhile in some cases, say on a suction side of a long laminar run wing installed at moderate positive angle of attack, TS waves may win the competition with cross-flow waves and predominate in transition to turbulence. Nevertheless their stability characteristics and their emergence caused by external perturbations (the so-called receptivity process) turned out to have not been studied experimentally at all. One of the potential receptivity mechanisms to be studied is the generation of TS waves due to scattering of free-stream vortices on surface non-uniformities and vibrations. The goal of the present study is to develop an experimental approach to such studies and to fill the gap mentioned above.

EXPERIMENTAL APPROACH

Experimental Setup

In general, the experimental setup was similar to that described in [4]. The experiments were carried out in the Minimum Turbulence Level (MTL) wind tunnel of Royal Institute of Technology (KTH) at a freestream speed of about 10 m/s. A wing model with a chord length of 800 mm was mounted in the wind-tunnel test section at a +1.5° angle of attack (the angle is measured normal to the leading edge) and 35° sweep angle. For comparison, results for a crossflow dominated case with −5° angle of attack are also presented. The influence of the test section sidewalls was minimized by installation of two contoured wall bumps, which provided the spanwise uniformity of the base flow.

Surface vibrations were created by an array of small latex membranes driven by pressure fluctuations excited by a set of loudspeakers installed outside of the test section. All the pipelines connecting loudspeakers and membranes

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were mounted inside the body of the model. Membranes were distributed along the span with a step of 8 mm. An electronic equipment provided an individual excitation of membranes and a trigger signal for data acquisition system. It was possible to excite either all membranes or a single membrane. The source was mounted flush with the model surface at 15% of the chord length, counting from the leading edge. Another source of external disturbances was installed upstream of the model. It was a thin tungsten wire mounted parallel to the leading edge. Being at rest, the wire did not produce any noticeable disturbances. Being actuated at certain frequency, the wire generated free-stream vortices propagating downstream along the external part of the boundary layer. All the measurements were carried out by means of a hot-wire anemometer.

Preparatory calculations

Both design of the experimental setup and planning of the measurement campaign were based on prior CFD calculations. The details concerning a shape of the mentioned above contoured wall bumps may be found in [5, 6]. The preliminary analysis of stability curves provided us with the suitable location of the built-in disturbance source and the ranges of frequencies and wavenumbers to be studied. The concordance between the calculated and measured stability characteristics was demonstrated in precursory experiments, see [7].

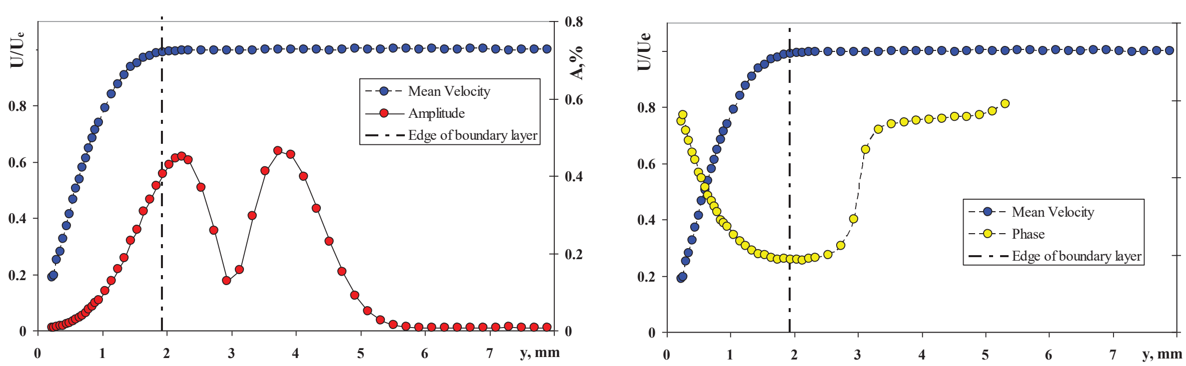
RESULTS OF MEASUREMENTS

The following notation is used here for data presentation. Spanwise axis parallel to the leading edge is z' and the corresponding wavenumber β'. The coordinate parallel to the model surface measured from the leading edge and in the direction normal to that is x'_s .The surface vibrator is located at x'_{s0}. The wall-normal coordinate is y. Frequencies are designated as f, subscript s refers to surface vibrations (of latex membranes), and subscript v denotes freestream vortices (created by vibrating wire).

Response of the boundary layer to the excitation was measured in three different regimes: with only wire actuated, with membrane actuated, or both sources worked together.

The oscillating wire generated freestream vortices very much similar to a von Kármán vortex street. The disposition of the vortex street with respect to the boundary layer is illustrated in Fig. 1. Both amplitudes and phases of the vortical perturbations were independent of spanwise coordinate z'. The amplitudes shown in Fig. 1, a are measured in percentage of edge velocity U_e . The studied frequency range of f_v was 53 to 96 Hz.

Performance of the localized surface vibrator was investigated within frequency range 98 to 255 Hz (the most unstable TS waves). It was found that single membrane generates a train of TS waves, which occupy a relatively broad range of spanwise wavenumbers $\beta' \approx \pm 1$ rad/mm, see Fig. 2. Further downstream disturbances with $\beta' < -0.1$ rad/mm and $\beta' > 0.4$ rad/mm decay significantly. The evolution of TS wave train is much different from that observed for cross-flow waves excited by the same oscillating membrane on the same model (installed at −5° angle of attack), see Fig. 3 and compare it with Fig. 2.



(a) (b)

FIGURE 1. Amplitude (a) and phase (b) wall-normal profiles of perturbations generated by oscillating wire, measured at the streamwise location of the surface vibrator, f_v = 65 Hz. The mean velocity profile is shown for reference. Model installed at +1.5° angle of attack

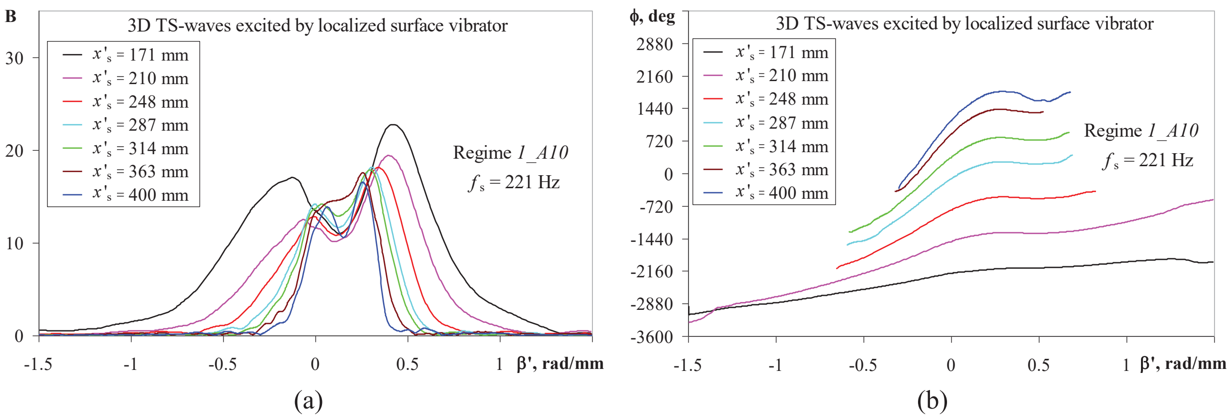


FIGURE 2. Downstream evolution of spanwise-wavenumber spectra of TS modes excited by the z'-localized surface vibrator (model installed at +1.5° angle of attack). Amplitude spectra (a) and phase spectra (b)

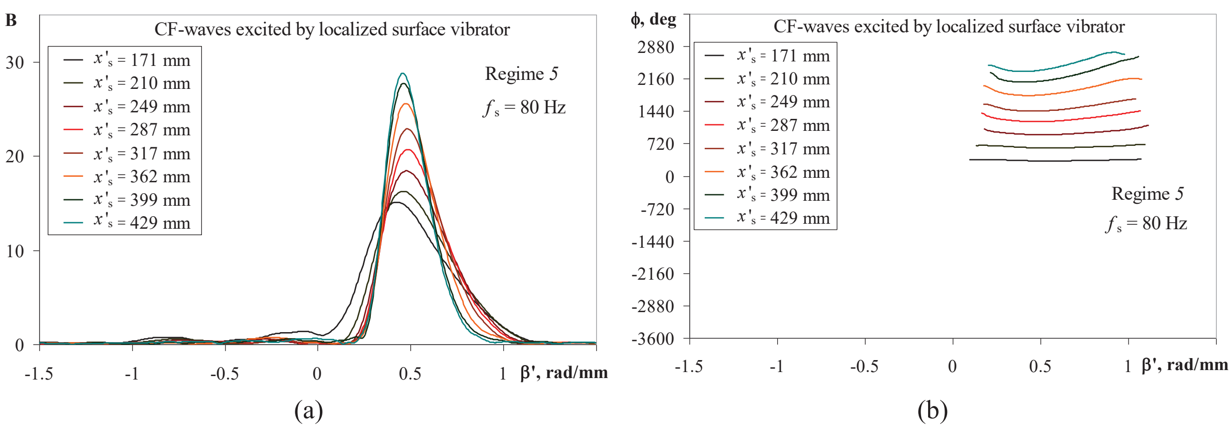


FIGURE 3. Downstream evolution of spanwise-wavenumber spectra of CF modes excited by the z'-localized surface vibrator (model installed at +1.5° angle of attack). Amplitude spectra (a) and phase spectra (b)

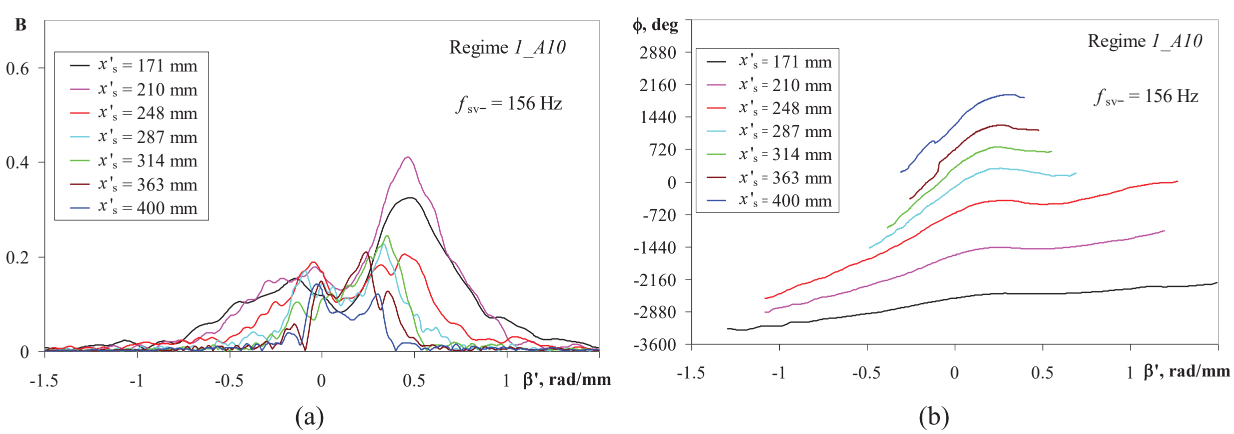


FIGURE 4. Spanwise-wavenumber spectra of TS-modes excited by scatter of freestream vortices on the same z'-localized surface vibrator (model installed at +1.5° angle of attack). Amplitude spectra (a) and phase spectra (b)

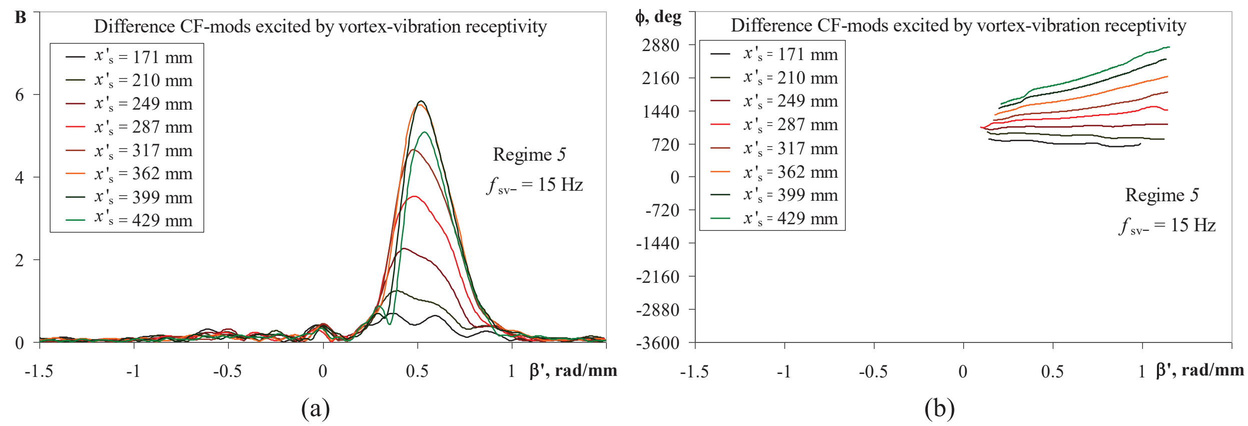


FIGURE 5. Spanwise-wavenumber spectra of CF modes excited by scatter of freestream vortices on the same z'-localized surface vibrator (model installed at +1.5° angle of attack). Amplitude spectra (a) and phase spectra (b)

The experiments showed that 3D TS-waves are excited rather efficiently by the two studied receptivity mechanisms: (1) the localized surface vibrations (with frequency f_s) and (2) the scattering of freestream vortices (with frequency f_v) on localized surface vibrators occurred at two combinational frequencies $f_{sv-} = f_s - f_v$ and $f_{sv+} = f_s + f_v$. It turned out that in contrast to the case of excitation of CF-modes studied in complementary experiments, the spectra of the excited perturbations are very different at the two frequencies: the surface one f_s (Fig. 2 and Fig. 3) and the combination one f_{sv-} (Fig. 4 and Fig. 5). In particular, the TS-wave spectra are much broader, include both positive and negative wavenumbers, and become narrower downstream. It was found that, in contrast to the case of excitation of CF-waves, the effect of anomalous amplification of combination modes at scattering of freestream vortices on surface vibrations was not observed for the 3D TS-waves (see Fig. 6), i.e. the distributed receptivity was not observed.

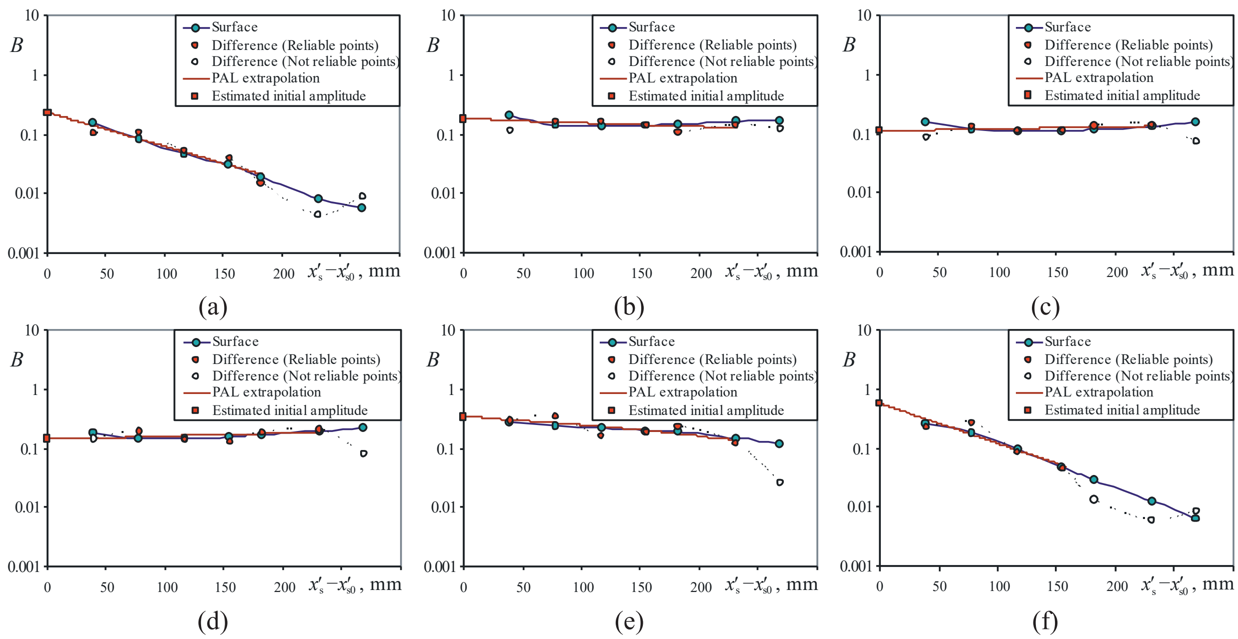


FIGURE 6. Comparison of amplification curves of TS-modes excited by surface vibrator directly (*Surface*) and by scattering of freestream vortices on surface vibrations, at difference frequency (*Difference*). $f_s = f_{sv-}$ = 156 Hz. Six spanwise wavenumbers: $\beta' = -0.367$ (a), 0 (b), 0.131 (c), 0.236 (d), 0.367 (e), and 0.628 (f), rad/mm

CONCLUSION

An effective method for investigation of stability and receptivity of the swept wing boundary layer with respect to TS waves has been developed. A localized excitation of 3D TS waves due to interaction of surface vibrations and freestream vortices was found and documented. The distributed generation of TS waves was not registered.

The whole dataset obtained in this work may be a reference for subsequent theoretical studies.

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