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# Quantitative study of localized mechanisms of excitation of cross-flow instability modes in a swept-wing boundary layer

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**Abstract**. An experimental study of two efficient receptivity mechanisms of excitation of cross-flow (CF) instability modes is carried out in a boundary layer of a real airfoil section of a swept wing due to: (*i*) action of localized surface vibrations, and (*ii*) scattering of 2D freestream vortices on them. It is found that the two mechanisms lead to rather efficient excitation of CF-modes both at surface vibration frequency and at combination 'vortex-vibration' frequencies. First estimations of the corresponding localized receptivity coefficients are obtained. Direct comparison of the experimental amplification curves of the excited CF-modes with those calculated based on the linear stability theory (LST) has shown that the experimental data obtained at vibration frequency are in excellent agreement with the LST. At the same time, growth rates of the CF-modes excited at combination frequencies are found to be completely inconsistent with the LST. A possible explanation of this phenomenon via action of a new efficient distributed receptivity mechanism is suggested. This mechanism is associated with scattering of freestream vortices on rather high-amplitude CF-modes excited by surface vibrations.

## 1. Introduction

The receptivity stage of excitation of boundary-layer instability modes by various external perturbations is the first stage of the laminar-turbulent transition process. A number of experiments devoted to the investigation of various receptivity mechanisms has shown that excitation of cross-flow (CF) instability modes (stationary and nonstationary ones) due to: (*i*) action of localized surface nonuniformities (roughnesses and vibrations) [1] and (*ii*) scattering of freestream vortices on them [2, 3] are the most efficient ones. Investigation of them is very important for a correct understanding of the physics of the transition process and for designing modern advanced methods of transition prediction. In spite of great practical importance of these receptivity problems, the mechanism (*i*) is still insufficiently studied, while detailed experimental investigations of mechanism (*ii*) are in their very beginning at present. Moreover, almost all previous receptivity experiments were carried out not on real swept wing sections but on swept plates with pressure gradients induced by wall bumps in absence of surface curvature and at conditions when the flow characteristics in the vicinity of the experimental model nose are very much different from those observed on real swept airfoils.

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The present experiments have been performed for the first time on a real airfoil section of a swept wing in presence of all real effects such as the surface curvature, the boundary-layer non-parallelism, the shape of the airfoil nose part, etc. This paper is devoted to a brief description of some preliminary results of these experiments.

## 2. Experimental setup

The experiments were carried out in a 3D boundary layer of a high-accuracy airfoil section of a swept wing mounted at an angle of attack $\alpha = -5°$ in a test section (1.2×0.8×7 m) of the low-turbulence wind tunnel MTL of KTH (Stockholm) at a freestream velocity $C_o$ = 10 m/s (measured in a reference point). The boundary layer was stable at these experimental conditions to the Tollmien-Schlichting (TS) waves, but unstable to the steady and unsteady CF-instability modes in a broad range of problem parameters due to the presence of a so-called ‘favorable’ (for the TS instability) chordwise pressure gradient.

The experimental model was manufactured at the University of Stuttgart based on advanced modern technology [4, 5]. It consists of an airfoil section with chord length normal to the leading edge of 800 mm and sweep angle of 35 degrees. In order to achieve infinite swept wing conditions in the wind tunnel experiment, sidewalls of special shape were mounted at both sides of the model at the ceiling and at the floor of the test section (see figure 1). The subsequent measurements and their comparison with calculations have shown that this base flow is almost spanwise uniform.

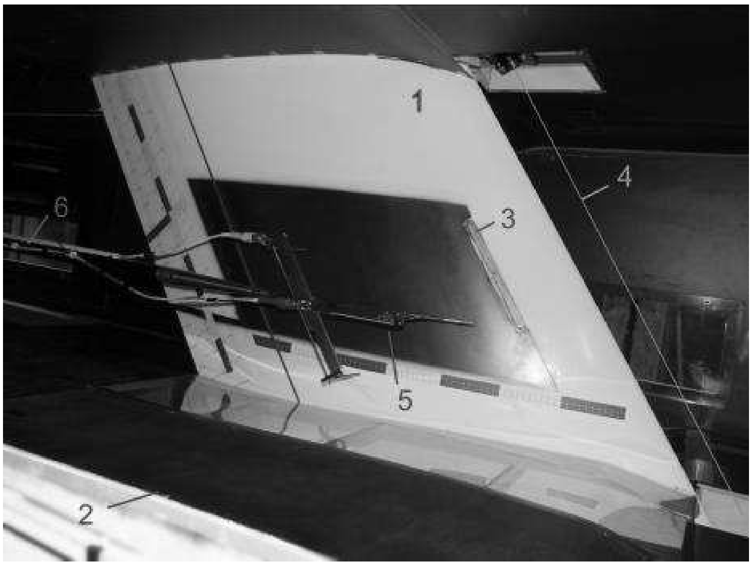


**Figure 1.** Experimental model in wind-tunnel test section. 1 – airfoil, 2 – sidewalls, 3 – surface disturbance source, 4 – vibrating wire, 5 – high-precision traverse mechanism ’Komarik‘, 6 – sting of main traverse of MTL.

The experiments were carried out at fully controlled disturbance conditions. Controlled unsteady surface- and freestream perturbations were excited by special disturbance sources. The source of localized surface vibrations consisted of a spanwise block of equal elastic circular membranes (having a spanwise spacing $\lambda'_z$ of 8 mm). These membranes were mounted flush with the surface of the airfoil at a chord position of 120 mm and could oscillate with appropriate frequency $f_s$ under the influence of weak pressure fluctuations excited by a set of loudspeakers located outside of the wind-tunnel and connected with the source by long plastic tubes. (An analogue of this source was successfully tested for the first time for the excitation of unsteady Görtler instability modes [6]). The shape of the surface vibrations was carefully measured by high-precision laser displacement meter (optoNCDT-1605) in every studied regime (see figure 2). In various series of experiments the surface disturbances represented either *1* – an isolated single vibrating membrane (figure 2*a*) or *2* – a spanwise row of membranes where adjacent membranes oscillated in antiphase (figure 2*b*). The amplitudes of the surface vibrations were about 100 μm (varied in different frequency regimes). Controlled 2D freestream vortices were excited by a wire vibrating with frequency $f_v$ (having diameter of 50 μm). The wire was tensioned parallel to the leading edge of the model not far upstream to it and vibrated perpendicular to the freestream direction. As a result, the wire excited an antisymmetric vortex street with a streamwise velocity fluctuation amplitude of several tenths of a percent of $C_o$, which evolved downstream along the outer edge of the boundary layer.

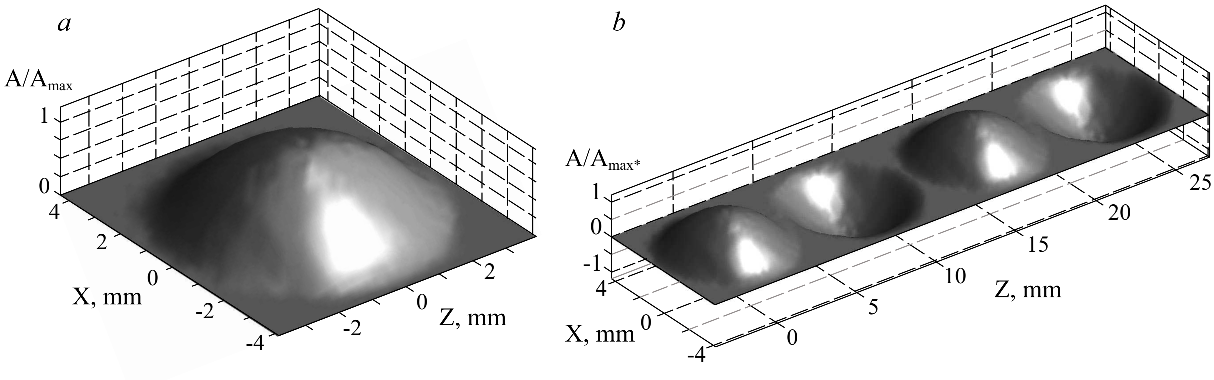


**Figure 2.** Instantaneous shape of isolated single vibrating membrane (*a*) and of four neighbouring membranes (*b*) at a fixed time.

In the main experiments the disturbance sources oscillated at the following frequencies: $f_s = 2 \div 140$ Hz, $f_v = 40$ or 65 Hz. A rather efficient excitation of controlled CF-modes in the boundary layer was found at the surface vibration frequencies $f_s$ (associated with the receptivity mechanism (*i*)), as well as at the two combinational frequencies $f_{CF+} = f_s + f_v$ and $f_{CF-} = f_s - f_v$ (associated with the receptivity mechanism (*ii*)). As expected, the freestream disturbances did not lead to excitation of boundary-layer perturbations at the freestream vortex frequency $f_v$. In set (*1*) of measurements, spanwise-localized wave trains of time-periodic CF-modes having a broad range of spanwise wavenumbers $\beta'$ were excited at frequency $f_s$ in the boundary layer, while in set (*2*), the surface vibrator excited spanwise-periodic and time-periodic CF-modes with $\beta' = \pm 2\pi/\lambda'_z$ only.

In the present experiments, it was convenient to use following spatial coordinates: $x'_s$ denotes the arclength in chordwise direction along the curved surface (i.e. in a plane perpendicular to the leading edge) with its origin located at the airfoil leading edge; $z'$ is parallel to the airfoil leading edge spanwise axis. The region of the main measurements was located at $x'_s = 171 \div 429$ mm, while the surface disturbance source position was $x'_{so} = 132$ mm.

## 3. Properties of excited CF-modes. New distributed receptivity mechanism

Examples of amplitudes and phases of excited wave-trains of CF-modes (measured in experimental series (*1*) in a regime of excitation with $f_s = 80$ Hz and $f_{CF-} = 15$ Hz) are shown in figure 3*a* and figure 3*b,* respectively. It is seen that the phase distributions display basically an almost monotonous growth in the $z'$-direction (figure 3). This fact is observed practically in all cases and indicates that the CF-modes propagated in the $z'$-direction (i.e. against the cross flow) dominate in the boundary layer. The spanwise-wavenumber spectra obtained from the distributions shown in figure 3 are presented in figure 4 and corroborate this statement. Indeed, almost all excited modes of the frequency-wavenumber spectra have positive spanwise wavenumbers between $\beta' = 0$ and 1 rad/mm, approximately.

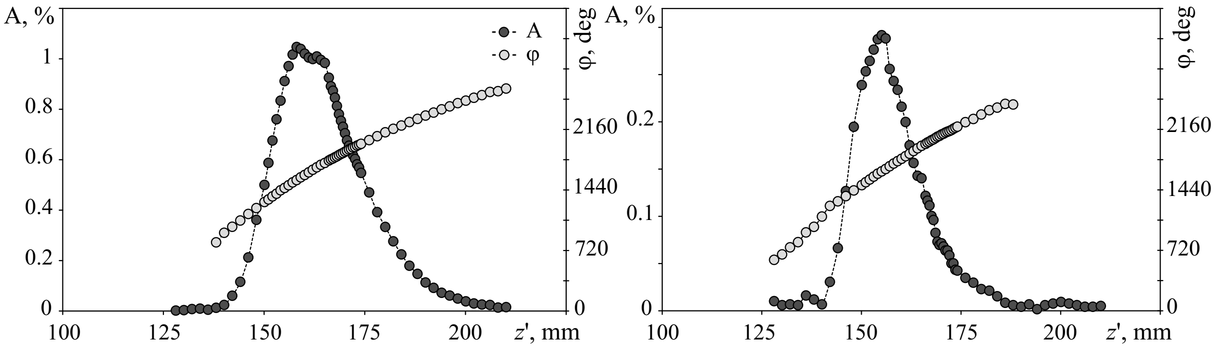

**Figure 3.** Amplitudes and phases of the wave-trains of CF-instability modes excited at $f_s$ = 80 Hz (*a*) and $f_{CF-}$ = 15 Hz (*b*). $x'_s$ = 362 mm.

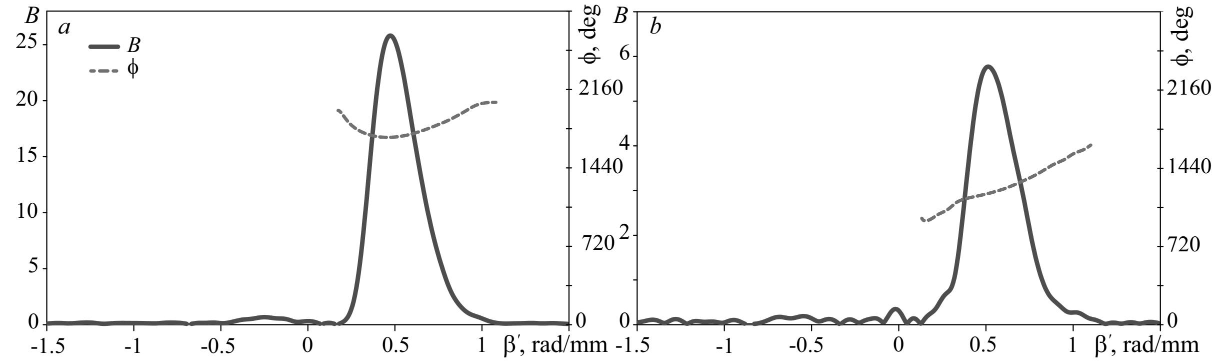

**Figure 4.** Spanwise-wavenumber spectra of amplitudes and phases of wave-trains of CF-instability modes excited at surface frequency $f_s$ = 80 Hz (*a*) and $f_{CF-}$ = 15 Hz (*b*). $x'_s$ = 362 mm.

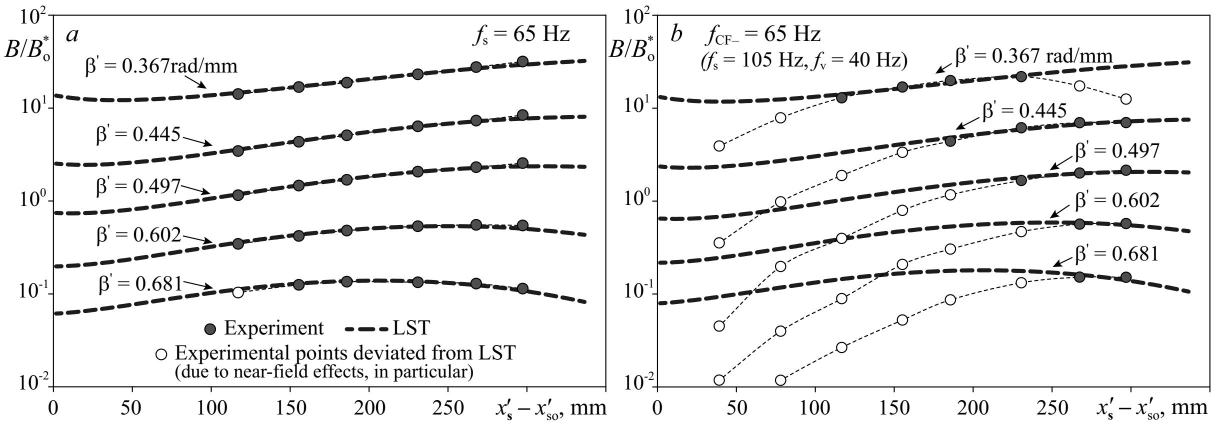

**Figure 5.** Measured (circles) and calculated (bold dashed lines) amplification curves of spectral amplitudes of CF-modes of fixed frequency $f$ = 65 Hz excited in experiments by surface vibrations directly at frequency $f_s$ (*a*) and by local 'vortex-vibrational' receptivity mechanism at difference combination frequency $f_{CF-}$ and evolving downstream under influence of a suggested distributed receptivity mechanism (*b*).

A very good, quantitative agreement between the measured and calculated by linear stability theory (LST) amplification curves was found at surface frequency $f_s$ (see figure 5*a*). At the same time, the amplification curves of the CF-modes excited at difference combination frequency $f_{CF-}$ turned out to be very much different from those predicted by the LST (figure 5*b*), as well as from those measured experimentally for the disturbances excited directly by the surface vibrations (note that surface frequency $f_s$ in figure 5*a* is equal to difference combination frequency $f_{CF-}$ in figure 5*b*). We suppose that this phenomenon could be explained by action of a new, unstudied distributed receptivity mechanism associated with scattering of freestream vortices on high-amplitude CF-modes excited by surface vibrations.

## 4. Localized receptivity coefficients

The excitation of CF-instability modes by the two localized receptivity mechanisms studied in the present paper can be characterized quantitatively by the so-called receptivity coefficients ([1 – 3]):

$$\bar{G}_s(f_s, \beta') = \frac{\bar{B}_o(f_s, \beta')}{\bar{C}(f_s, \beta')} \tag{1}$$

$$\bar{G}_{sv}(f_{CF\pm}, \beta') = \frac{\bar{B}_o(f_{CF\pm}, \beta')}{\bar{C}(f_s, \beta')\bar{B}(f_v)} \tag{2}$$

Here $\bar{G}_s$ and $\bar{G}_{sv}$ are the complex receptivity coefficients for the excitation of CF-modes associated with mechanisms (*i*) and (*ii*), respectively; $\bar{B}_o$ denotes the "initial" complex amplitude of excited CF-modes (defined at the position of the surface vibrator); $\bar{B}_v$ is the complex amplitude of the controlled freestream vortices measured at the boundary layer edge at $x'_s = x'_{so}$; and $\bar{C}$ is the complex "resonant" Fourier-spectrum of the surface vibrations (i.e. those spectral modes which have the same spanwise ($\beta'$) and streamwise ($\alpha_r$) wavenumbers as the corresponding CF-instability modes).

The values of $\alpha_r$ and the shape of the surface vibrations were measured experimentally. Therefore, it was not difficult to find $\bar{C}$. The values of $\bar{B}_v$ were measured as well, while it was impossible to measure $\bar{B}_o$ directly due to presence of the so-called disturbance source "near field". These data were obtained by upstream extrapolation of the experimental streamwise distributions of disturbance phases and logarithms of amplitudes by means of either the LST or a well-tested PAL-procedure (special combined polynomial functions [1]) to the surface source position. Examples of such extrapolations are shown at figure 6. Note that the difference between these two methods of estimation of the initial spectra $\bar{B}_o$ might be rather significant. Since the CF-modes excited at combination frequencies $f_{CF\pm}$ do not evolve downstream in agreement with the LST, only PAL-procedure was used for the estimation of their initial spectra $\bar{B}_o$.

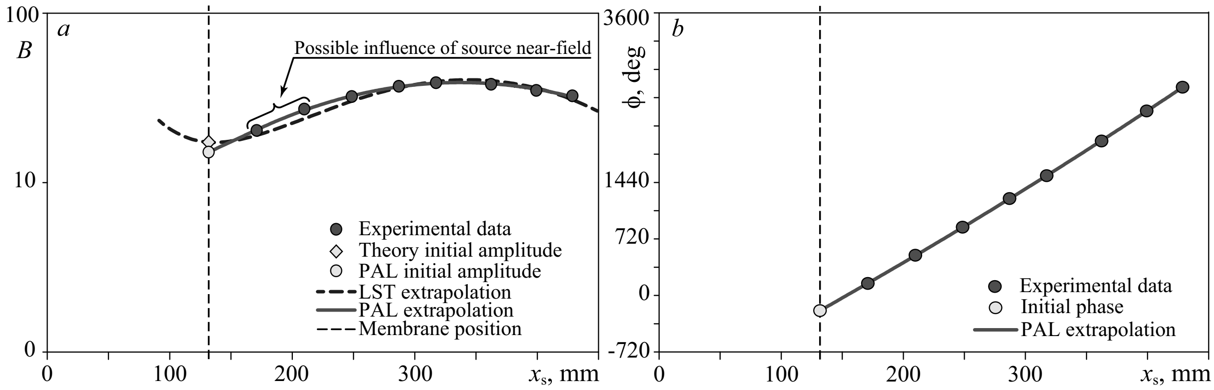


**Figure 6.** Example of extrapolation of experimental amplitudes (*a*) and phases (*b*) to the surface vibrator location. $f_s$ = 105 Hz, $\beta'$ = 0.576 rad/mm.

Figure 7 shows examples of estimated amplitudes and phases of the "vibrational" (figure 7*a*) and "vortex-vibrational" (figure 7*b*) receptivity coefficients versus spanwise wavenumber $\beta'$ obtained in one of the studied regimes of disturbance excitation. The character of the amplitude and phase distributions of $\bar{G}_s$ and $\bar{G}_{sv}$ are close to those found in previous experiments [1, 3] for the 25-degree model of a swept wing simulated on a swept plate. Although the exact values for the amplitudes of $\bar{G}_s$ obtained from upstream extrapolation by LST and PAL differ, both approaches nevertheless result in similar values and the dependence on spanwise wavenumber shows the same trend. The amplitudes $G_s$ of the vibrational receptivity coefficients decay with the spanwise wavenumber, while their phases $\lambda_s$ remain practically constant. Qualitatively the same dependence on $\beta'$ is found for the amplitudes of the vortex-vibrational receptivity coefficients $G_{sv}$, while their phases $\lambda_{sv}$ demonstrate a rather strong dependence on the spanwise wavenumber.

Since $\bar{G}_s$ and $\bar{G}_{sv}$ have different physical meaning and dimensions, it is impossible to compare them with each other directly. However the obtained data give us the possibility of comparison of effectiveness of the studied mechanisms at excitation of CF-modes if we assume that the amplitude of the freestream vortices is constant and is equal to 1% of the freestream speed (for instance). Such estimation shows that in this case the mechanism of excitation of CF-modes by the localized surface vibrations only is more efficient then the receptivity mechanism of "vortex-vibrational" type by a factor of 10 approximately. Of course, this relationship depends significantly on the freestream vortex amplitude.

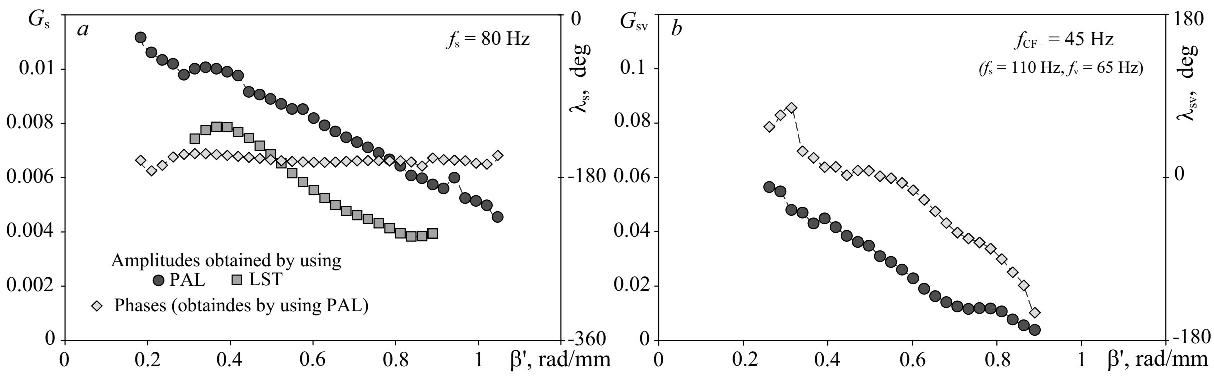


**Figure 7.** Estimated amplitudes and phases of localized receptivity coefficients for excitation of CF-modes by vibrational (*a*) and vortex-vibrational (*b*) receptivity mechanisms.

## 5. Conclusions

This paper is devoted to the first quantitative experimental results of investigations of localized mechanisms of excitation of CF-instability modes in a boundary layer of a real swept airfoil. They are obtained in the framework of the research project "RECEPT". A new unexpected physical phenomenon is found, which is associated with presumable action of a distributed receptivity mechanism of excitation of CF-modes at combination frequencies $f_{CF\pm}$ due to scattering of freestream vortices on other CF-modes excited by surface vibrations. For the first time values of two kinds of the local receptivity coefficients are estimated experimentally for a real swept airfoil. We are planning further to obtain and compare all experimental and theoretical results in much more detail including spectra of the excited boundary layer perturbations, amplification curves of the CF-modes, and the related receptivity coefficients.

**Acknowledgments**

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