Generation of Unsteady CF-Instability Modes by Vibrational and Vibration-Vortex Localized Receptivity Mechanisms

Y. S. Kachanov[1, a)], V. I. Borodulin[1, b)], A. V. Ivanov[1, c)], D. A. Mischenko[1, d)], R. Örlü[2, e)], A. Hanifi[2, f)], and S. Hein[3, g)]

[1]*Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Institutskaya str., 4/1, Novosibirsk, 630090, Russia*
[2]*Linné FLOW Centre, Dept. of Mechanics, KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden*
[3]*Institute of Aerodynamics and Flow Technology, DLR, 37073, Göttingen, Germany*

[a)] Corresponding author: kachanov@itam.nsc.ru
[b)]bo@itam.nsc.ru
[c)]aniva101010@gmail.com
[d)] D.A.Mischenko@itam.nsc.ru
[e)]ramis@mech.kth.se
[f)]hanifi@kth.se
[g)]stefan.hein@dlr.de

Abstract. The paper is based on results obtained within an international project 'RECEPT' of the European Framework Program FP7. The experiments were carried out in a three-dimensional boundary layer developing on an experimental model of a long-laminar-run swept airfoil (sweep angle of 35°). The model was mounted in a test section of the low-turbulence wind-tunnel MTL (KTH, Stockholm) at an angle of attack of −5° and equipped with sidewalls provided satisfaction of infinite-span conditions. The cross-flow (CF) instability modes were predominant in this case, while the Tollmien–Schlichting (TS) waves were suppressed by a favorable pressure gradient. The main measurements were carried out by means of hot-wire anemometry at conditions of excitation of fully controlled, unsteady surface and flow perturbations. These perturbations were excited by special sources: (1) a row of oscillating membranes and (2) a vibrating wire, at frequencies of f_s and f_v, respectively. A very good, quantitative agreement between the measured and calculated (by linear stability theory based on PSE approach) amplification curves was found at surface frequency f_s. However, the evolution of the CF-modes excited at difference combination frequency $f_{sv-} = f_s - f_v$ turned out to be very much different from the theoretical one. Thorough analysis of the obtained results has shown that the only explanation of these discrepancies can be associated with presence of a distributed receptivity mechanism due to scattering of freestream vortices on the CF-instability waves excited by surface vibrations. Another unusual and unexpected phenomenon found in the present experiments is associated with anomalous amplification of difference combination modes with the zero spanwise wavenumbers β'. This phenomenon was observed in the flow, which is stable with respect to both CF- and TS-waves having $\beta' = 0$ for all frequencies. There is no explanation of this finding at present.

INTRODUCTION

A detailed review of the state of the art in the field of investigations of localized receptivity mechanisms responsible for excitation of steady and unsteady CF-instability modes in swept-wing boundary layers can be found in refs. [1–3]. In this section, we mention only the most significant aspects of the present study and its motivation.

All previous quantitative measurements of swept-wing boundary-layer receptivity characteristics at excitation of nonstationary CF-instability modes by surface- and freestream perturbations were carried out on experimental models

International Conference on the Methods of Aerophysical Research (ICMAR 2018)
AIP Conf. Proc. 2027, 020010-1–020010-8; https://doi.org/10.1063/1.5065088
Published by AIP Publishing. 978-0-7354-1747-2/$30.00

of swept *plates*, i.e. in absence of surface curvature at conditions when the chordwise pressure gradient was induced by contoured wall bumps rather than by curved shape of the airfoil surface. Meanwhile, it is well known that the surface curvature is able to affect very significantly the 3D boundary-layer instability and transition [4, 5]. Moreover, the experimental results on the excitation of unsteady CF-instability modes by vibration-vortex and roughness-vortex localized receptivity mechanisms has never been compared with theoretical ones and, thus, the validity of the corresponding receptivity theories has never been checked for these important problems. In the present experiments, the 3D boundary-layer receptivity was systematically studied on a real swept airfoil section equipped with sidewalls, which provided base-flow conditions simulating an infinite-span swept wing. The results of these measurements are compared with calculations based on PSE linear stability theory. It is expected that at the next step of this research, the localized receptivity characteristics will be calculated as well and compared with the measured ones.

While performing the present study, several unexpected results related to excitation of travelling CF-instability modes by the vibration-vortex receptivity mechanism were found. These results and their possible interpretations are discussed in the present paper.

USED APPROACHES

Experimental Setup

The measurements were performed in the Minimum Turbulence Level (MTL) wind tunnel of KTH Royal Institute of Technology (Stockholm) at a freestream speed of about 10 m/s. The main measurements were carried out by means of a hot-wire anemometer. A section of a 35° swept-wing airfoil with normal to the leading edge chord length of c = 800 mm was mounted in the wind-tunnel test section at a −5° angle of attack (measured in the plane perpendicular to the leading edge). In order to provide the spanwise base-flow uniformity (to meet the sweep condition inherent for infinite-span swept wings) the model was equipped with contoured sidewalls (see refs. [6–8] for more detail). Their shapes were calculated numerically and corresponded to satisfaction of the sweep condition for potential flow at the boundary-layer edge [6]. General view on the model in the wind-tunnel test section is given in Fig. 1.

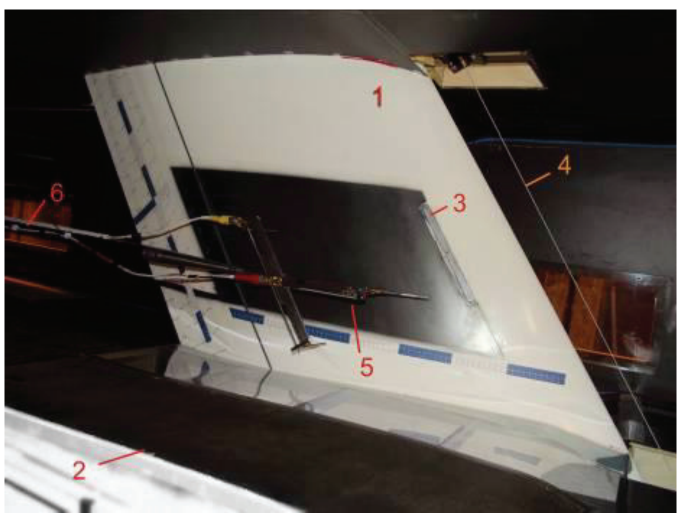


FIGURE 1. Experimental model of a 35° swept wing installed in wind-tunnel test section. Flow direction is from right to left. 1 – airfoil section, 2 – sidewalls, 3 – surface disturbance source, 4 – vibrating wire, 5 – traverse 'Komarik', 6 – sting of standard wind-tunnel traverse

The experiments were performed at fully controlled disturbance conditions. A source of controlled nonuniformities (vibrations) of the airfoil surface was able to work in broad ranges of frequencies, spanwise wavenumbers, and amplitudes. The source was located at chordwise position x'/c = 0.15. The main part of the source represented a spanwise row of circular latex membranes, mounted flush with the model surface oscillating under the influence of pressure fluctuations excited by a set of speakers, acting as pumps (Fig. 2). The speakers were located outside the wind-tunnel test section and were connected to the source by an array of plastic pipes. The spanwise spacing of the membranes was selected to be equal to 8 mm in the main measurements. In various regimes of measurements either all membranes or part of them (including important case of one membrane) were activated. At the spanwise-periodic excitation, the spanwise wavelength λ'_z of the surface vibrations was equal to either 8 mm (when all membranes oscillated in phase) or 16 mm (when neighboring membranes oscillated with opposite phases). Depending on the level of excitation, the membranes oscillated with amplitudes from several microns to many dozens of microns.

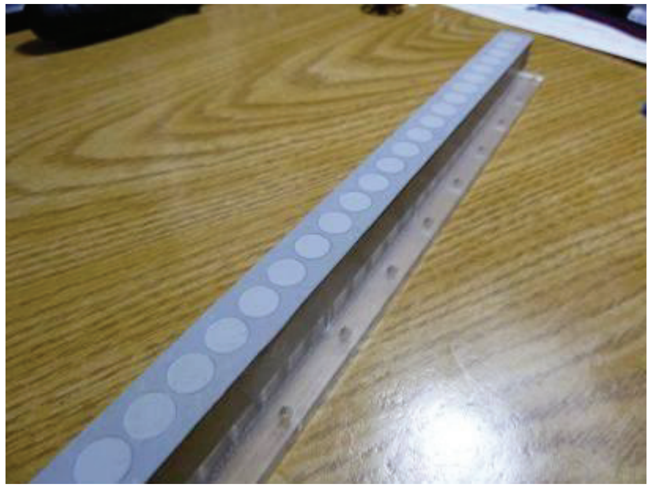
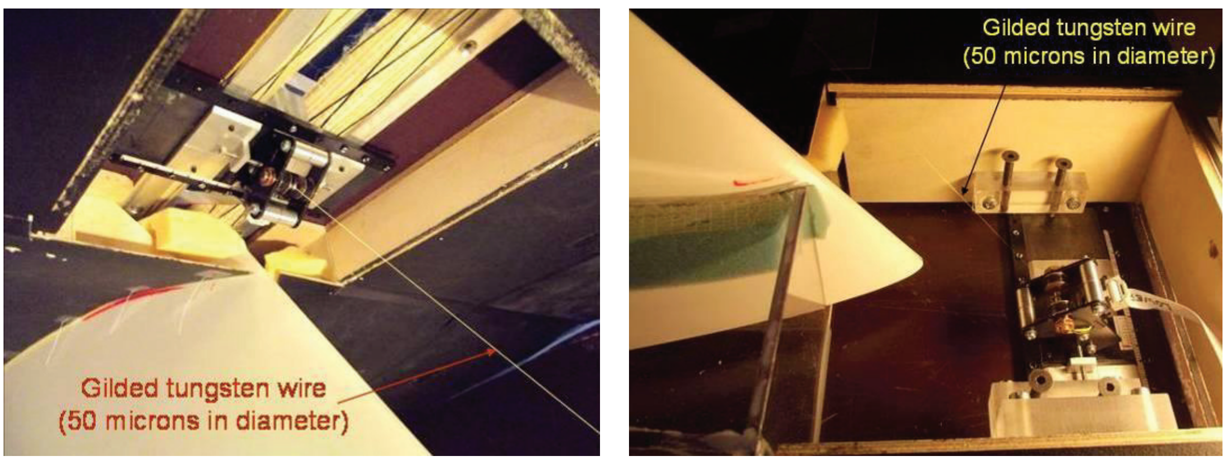


FIGURE 2. Main body of the source of surface nonuniformities with latex membranes



(a) (b)

FIGURE 3. Source of freestream vortices consisted of vibrating wire in front of the airfoil leading edge driven by upper (a) and lower (b) shakers

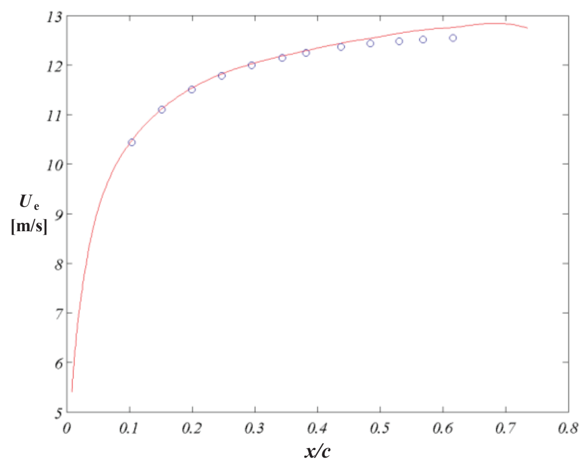
The freestream vortices were generated by a thin gilded tungsten wire oscillating in the free stream at desired amplitude and frequency. The wire had a diameter of 50 microns that ensured absence of an uncontrolled von Kármán-vortex street downstream of it. The controlled freestream vortices were produced by the wire wake oscillating together with the wire in the direction perpendicular to the freestream and to the airfoil leading edge. The amplitude of the velocity fluctuations within the produced vortex street was of order of several tenth of a percent of the mean flow velocity. The wire oscillations were driven by two specially designed electromagnetic shakers (Fig. 3) fed from the same generator and amplifier as those used for excitation of the surface nonuniformities. These shakers, together with the system of adjustment of the wire positioning and tension, provided extremely stable characteristics of the generated freestream vortices, including their frequencies, amplitude and phase, spanwise uniformity, and the vortex street offset with respect to the airfoil leading edge. The amplitude and phase of the wire oscillations was permanently monitored by a Hall detector installed into one of shakers.

The system of generation of input signals for feeding the two disturbance sources had 8-channels. All signals at every channel were produced by a computer controlled 8-channel arbitrary waveform generator, passed through a D/A converter, and an 8-channel power amplifier. They excited two shakers of the vibrating wire producing freestream vortices (2 channels) and loudspeakers driving membranes of the source of surface nonuniformities (6 channels).

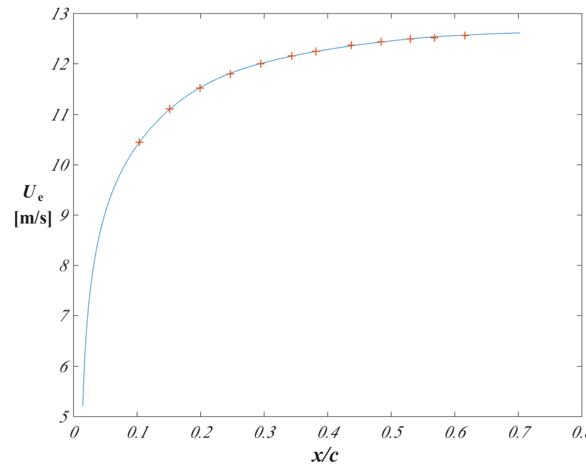
More detailed description of: (1) the experimental model, (2) the traversing systems, (3) the technique of peculiar spanwise positioning of the traverse 'Komarik' by means of a laser sheet, (4) the methods of measurements of shape oscillations of the surface source membranes, and other peculiarities of the receptivity experiments can be found in refs. [6–8].

Theoretical Approaches

CFD computations were performed in design-stage of the experiment. In these computations the wind-tunnel walls were included and their shape corresponded to the one used in the experiment. The pressure distribution from the CFD computations of experimental setup was used to perform the boundary-layer computations. In order to get a perfect fit between the boundary-layer edge velocity from computations and experimental data, some small modifications were made. The differences are thought to be an effect of traverse system. In Fig. 4, these values are shown.



(a)



(b)

FIGURE 4. Comparison of measured (symbols) and computed (lines) values of the streamwise velocity component (along wind-tunnel axis) at the edge of the boundary layer. Original pressure distribution (a) and modified pressure distribution (b)

The boundary-layer computations have been performed under assumption of infinite swept wing. Then, stability characteristics of perturbations have been computed using a nonlocal-nonparallel approach based on the parabolized stability equations (PSE). To mimic the experiment as closely as possible, amplitude of perturbations was measured at the same wall-normal position as in the experiments.

Regimes of Receptivity Measurements and Goals of Present Paper

The base-flow structure used in the present experiments and calculations is described in detail in ref. [9]. It was the same in all studied cases. In this accelerating flow, the TS-instability was suppressed by a favorable (for the TS-modes) chordwise pressure gradient, while the CF-instability was predominant.

The methodology of the receptivity measurements and ways of estimation of the localized receptivity coefficients are briefly described in ref. [9]. The receptivity problem associated with excitation of unsteady CF-instability modes by either surface nonuniformities or by freestream vortices in presence of surface nonuniformities has been studied with the following parameters varied: (1) freestream vortex frequency f_v, (2) frequency of surface nonuniformity f_s, (3) difference-mode frequency $f_{sv-} = f_s - f_v$, (4) sum-mode frequency $f_{sv+} = f_s + f_v$, (5) spanwise wavenumber β' (spatial scale λ'_z) of surface nonuniformities and excited CF-waves (as well as the propagation angle of the latter). The complete list of regimes studied in the receptivity experiments is presented in Tables 1 and 2. Note that the cases with quasi-stationary frequency of surface nonuniformity f_{sur} = 2.0 Hz corresponds physically to scattering of freestream vortices on surface roughness (as far as the model wash time was significantly less than the period of the 2 Hz signal).

TABLE 1. Studied receptivity regimes with *spanwise-localized* surface non-uniformities.

Names of Regimes	f_s [Hz]	f_v [Hz]	F_{sv-} [Hz]	F_{sv+} [Hz]
Regime 1	65	40	25	105
Regime 2	85	40	45	125
Regime 3	105	40	65	145
Regime 4	67	65	2	132
Regime 5	80	65	15	145
Regime 6	110	65	45	175
Regime 7	140	65	75	205

TABLE 2. Studied receptivity regimes with *spanwise-periodic* surface non-uniformities.

Names of Regimes	f_s [Hz]	f_v [Hz]	F_{sv-} [Hz]	F_{sv+} [Hz]	λ_z' [mm]
Regime M1-16	67	65	2	132	16
Regime M1-8	67	65	2	132	8
Regime M2-16	20	65	45	85	16
Regime M3-16	8	65	57	73	16
Regime M3RS-16	8 (Reduced Surface amplitude)	65	57	73	16
Regime M4-16	2	65	63	67	16
Regime M4-8	2	65	63	67	8

The receptivity data have been subjected to a deep mathematical processing with the final goal of obtaining the corresponding localized receptivity coefficients determined in Fourier space for every particular Fourier mode of the frequency-wavenumber spectrum. This complicated procedure of obtaining the localized receptivity coefficients include approximations of the experimentally obtained streamwise distributions of spectral mode amplitudes and phases by the corresponding theoretical distributions and an upstream extrapolation of the them to the location of the surface disturbance source.

Meanwhile during performing such deep data processing several serious difficulties were encountered. Two of them are associated with obtaining evidence of existence of some unknown previously receptivity and/or instability mechanisms. The present paper is devoted to description of these new mechanisms.

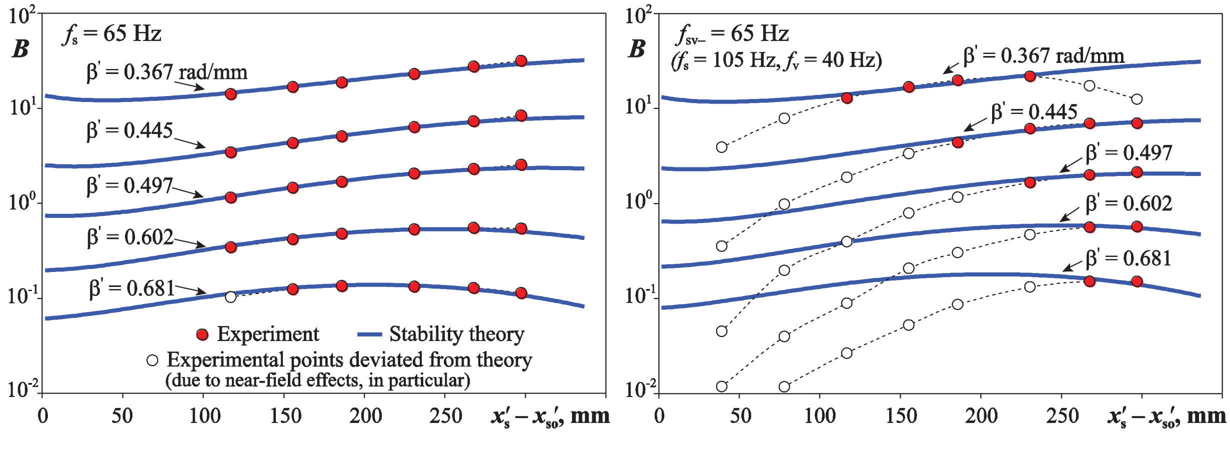
PHYSICALLY REASONABLE AND INTRIGUING BEHAVIORS OF DISTURBANCES

CF-Modes Excited at Surface and Difference Frequencies

A very good, quantitative agreement between the measured and calculated amplification curves was found at surface frequency f_s. For the case of spanwise-localized surface vibrations this agreement is illustrated in Fig. 5, a obtained for *Regime 1*. Such theoretical amplification curves matched with the experimental points were used for upstream extrapolation of the experimental data and for finding the initial amplitudes at the vibrator center required for estimation of the localized receptivity coefficients.

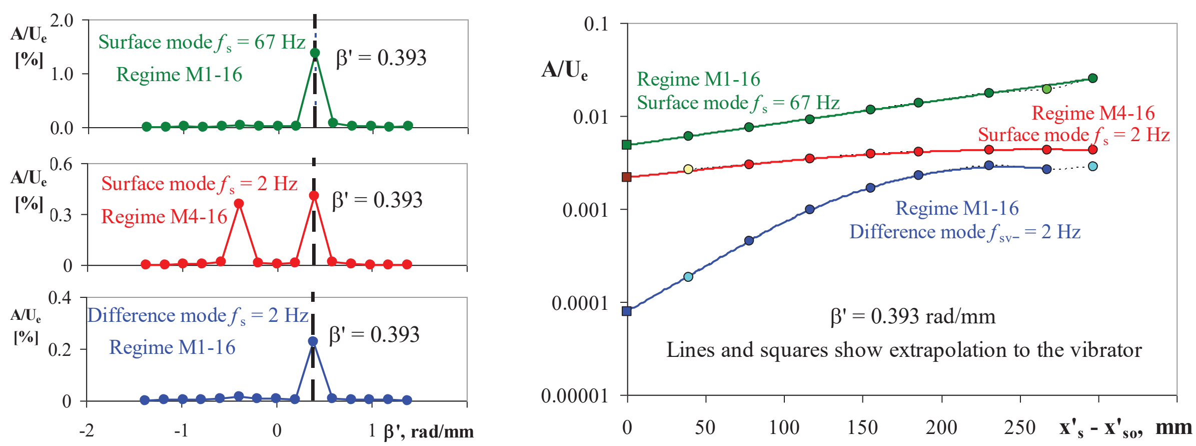
However, the amplification curves of the CF-modes excited at difference combination frequency f_{sv-} turned out to be very much different from those predicted by the stability theory, as well as from those measured experimentally for the disturbances excited by the surface nonuniformities directly. This difference is illustrated in Fig. 5, b obtained in *Regime 3*, in which the difference mode had the same frequency as the surface mode excited in *Regime 1* (Fig. 5, a).

Similar results were also obtained in the cases of spanwise-periodic surface vibrations for discrete spanwise-wavenumber spectra of perturbations. This fact is illustrated in Fig. 6 for the case of comparison *Regimes M1-16* and *M4-16*. The comparison is performed for the modes with spanwise wavenumbers β' = +0.392 rad/mm. In *Regime M1-16*, the surface mode (excited by vibrations) has frequency of 67 Hz (upper spectrum in Fig. 6, a and upper amplification curve in Fig. 6, b), while in *Regime M4-16*, the frequency of the surface mode is 2.0 Hz (middle spectrum in Fig. 6, a and middle amplification curve in Fig. 6, b). The difference mode excited in *Regime M1-16* (lower spectrum in Fig. 6, a and lower amplification curve in Fig. 6, b) has the same frequency of 2.0 Hz as the surface mode in *Regime M4-16*. However, its amplification curve is completely unlike from that of the 2-Hz mode observed in *Regime M1-16* (cf. middle and lower curves in Fig. 6, b). It is important to note that these two curves correspond to exactly the same modes of the frequency-wavenumber spectrum. *The only* distinction between them is that the 2-Hz mode observed in *Regime M4-16* is excited by surface vibrations directly, while the one observed in *Regime M1-16*, is produced due to scattering of freestream vortices on surface perturbations with frequency f_s. Similar mismatch of amplification curves observed for surface and difference modes of the same frequency and spanwise wavenumber was found for other frequencies.



(a) (b)

FIGURE 5. Measured (circles) and calculated (bold lines) amplification curves of spectral densities of CF-modes of fixed frequency f = 65 Hz generated by vibrations in *Regime 1* (a) and at difference frequency in *Regime3* (b) in cases of *spanwise-localized* surface vibrations. Points marked with solid circles were used for matching with theoretical curves



(a) (b)

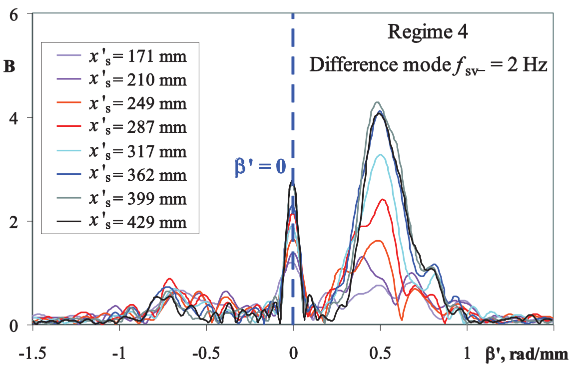
FIGURE 6. Comparison of measured amplification curves of CF-modes excited at β' = 0.393 rad/mm in regimes *M1-16* and *M4-16* for *spanwise-periodic* vibrations by either surface or vibration-vortex receptivity. Spanwise-wavenumber spectra (at $x'_s - x'_{so}$ = 186 mm) (a) and amplification curves for either surface or difference combination frequency (b)

Thorough analysis of the results obtained in all studied regimes has shown that the only cause of the detected phenomenon of anomalous amplification of difference modes is the presence of a distributed receptivity mechanism due to scattering of the freestream vortices on the CF-instability waves excited by surface vibrations. Although the distributed excitation of unsteady CF-modes by freestream vortices was observed previously (see e.g. experiments

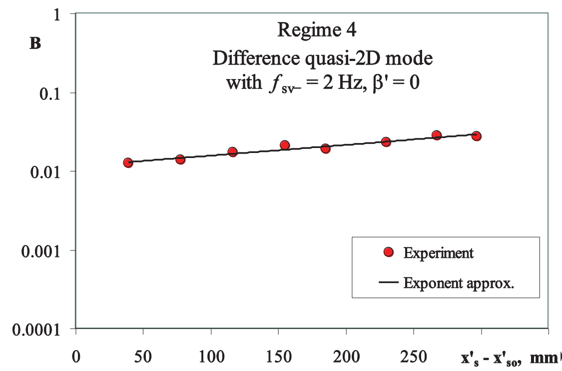
[10–12]), such receptivity mechanism associated with interaction of freestream vortices with previously excited unsteady CF-modes has never been documented.

Paradoxical Amplification of Quasi 2D Perturbations at Difference Frequencies

Another unusual and unexpected phenomenon found in the present experiments is an anomalous amplification of difference combination modes with zero spanwise wavenumbers β' (Fig. 7). This was observed in the flow, which is stable with respect to both CF- and TS-waves having $\beta' = 0$ for all frequencies. There is no explanation of this fact at present.



(a)



(b)

FIGURE 7. Anomalous amplification of zero-wavenumber difference combination mode with f_{sv-} = 2 Hz in case of *spanwise-localized* vibrations. Spanwise-wavenumber spectra (a) and amplification curve of difference mode with $\beta' = 0$ (b)

CONCLUSIONS

Two unexpected phenomena related to the freestream-vortex and surface-nonuniformity receptivity problems at excitation of unsteady CF-instability modes in a swept-wing boundary layer are found in the present study: (1) a mismatch of measured amplification curves for oblique difference combination modes with their linear-stability behavior and (2) appearance and anomalous amplification of quasi 2D boundary-layer disturbances at difference combination frequencies, which must quickly attenuate according to the linear stability theories for CF- and TS-modes.

The former of these findings seems to be associated with a new mechanism of distributed excitation of CF-modes due to scattering of freestream vortices on large-amplitude CF-waves excited previously by surface nonuniformities. Meanwhile, the second phenomenon does not have yet any reasonable explanation.

ACKNOWLEDGMENTS

The work reported here has been carried out within 'RECEPT' project of the EU Seventh Framework Programme, grant no ACPO-GA-2010-265094. The experimental study includes a significant contribution of P.H. Alfredsson, N. Tillmark, and A. Segalini.

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