3D DISTRIBUTED BOUNDARY-LAYER RECEPTIVITY TO NON-STATIONARY FREE-STREAM VORTICES IN PRESENCE OF SURFACE ROUGHNESS

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Summary The paper is devoted to investigations of the three-dimensional (in general) problem of the Blasius boundary-layer receptivity to non-stationary free-stream vortices with spanwise and wall-normal orientations of the vorticity vector due to their scattering on distributed surface non-uniformities. The vortices under consideration are harmonic in time and the surface roughness (the waviness) is two-dimensional and periodic in the streamwise direction. The vortex and the roughness amplitudes are small enough to provide the linearity of the problem. The main goal of the study is to develop a method of experimental determination of the distributed receptivity coefficients for the problems specified and to obtain the experimental values of amplitudes and phases of the receptivity coefficients.

ANALYSIS AND EXPERIMENTAL METHOD

Prior to perform the experiments a theoretical analysis of the problem of the three-dimensional distributed vortex receptivity has been performed. The purpose of the analysis was *not* to obtain the distributed receptivity coefficients theoretically but rather to give their proper definitions for the problems under investigation and to develop a method of their experimental obtaining. The governing equation for complex amplitudes of the boundary-layer perturbations, excited by free-stream vortices in a distributed way in presence of surface roughness was obtained, and analytical solutions for resonant and non-resonant receptivity mechanisms were written out. The solutions contained functions and quantities which can be measured in experiment, as well as the unknown complex distributed receptivity coefficients. One of these coefficients is responsible for the distributed vortex receptivity on smooth surface, while another one - for the roughness-vortex distributed receptivity. A method of experimental determination of these coefficients was developed and applied in the experiments. This method is based on approximation of experimental streamwise distributions of spectral amplitudes and phases of the excited boundary-layer disturbances by means of the derived analytical solutions. The least square fit approximation at variation of the receptivity amplitudes and phases gave the possibility to find the unknown receptivity coefficients. An example of such approximation of experimental data by an analytical solution is presented in Fig. 1.

EXPERIMENTAL PROCEDURE

The measurements were performed at controlled disturbance conditions in a low-turbulence wind-tunnel of the Institute of Theoretical and Applied Mechanics in Novosibirsk at the free-stream velocity 9.18 m/s. The boundary layer under investigation was produced on a flat plate mounted in the wind-tunnel test section under the zero angle of attack. The periodical surface non-uniformities (with amplitudes of around 0.1 mm) were manufactured and pasted onto the plate. Their shapes were carefully measured and decomposed to the streamwise-wavenumber spectrum. The streamwise wavelengths of the roughness were varied and adjusted to provide the satisfaction of the resonant condition for the distributed vortex receptivity problem for excitation of either 2D or 3D Tollmien-Schlichting (TS) waves inclined at desirable angles to the flow direction. The non-stationary vortices were excited in the free stream in front of the leading edge by means of a thing oscillating wire. It was shown that the oscillating wire produces in the free-stream a vortex street similar to the von Karman street but with a very low amplitude of velocity fluctuations (below 0.4% of the free-stream velocity). In one set of experiments the wire was parallel to the plate surface and the vortex street was two-dimensional. In another experimental setup the wire produced a vortex street, which had a wall-normal orientation and was localized in the spanwise direction (i.e. it was three-dimensional relative to the boundary layer under investigation). In addition, some complementary linear-stability measurements were performed with the help of a “point source” when the free-stream vortices were switched off.

MAIN RESULTS

Primary results and data processing

The properties of all involved perturbations were investigated experimentally in detail (with the help of the hot-wire technique) both in the free-stream and inside the boundary layer. It was found that for the two studied orientations of the free-stream vorticity vector the vortices excite in the boundary layer TS-waves. In the case of wall-normal vorticity the perturbations represented wave-trains (harmonic in time but localized in the spanwise direction), while for the spanwise vorticity orientation a single 2D TS-wave was excited. The TS-wave amplitudes and phases depended significantly on the surface roughness parameters. In the 3D case the wave-trains were subjected to the spanwise Fourier transform and the streamwise distributions of the spectral amplitudes and phases were obtained in both experiments (for every fixed frequency and spanwise wavenumber). The application of the developed method gave the possibility to obtain the complex values of the distributed vortex receptivity coefficients for the two cases of vorticity-vector orientation. In case of wall-normal orientation the dependence of the distributed receptivity coefficients on the spanwise wavenumber (and the TS-wave propagation angle) is investigated.

Coefficients of distributed vortex receptivity

The receptivity coefficients are obtained both for the distributed vortex receptivity on smooth surface and for the roughness-vortex distributed receptivity (Fig. 2). A qualitative agreement for the receptivity-amplitude dependence on the TS-wave propagation angle with that obtained in previous experiments [1] have been observed in the former case. In contrast to almost all previously studied receptivity mechanisms, the two types of the distributed vortex-receptivity mechanisms, investigated in the wall-normal vorticity case, are the strongest for free-stream vortices having large spanwise scales, i.e. in a quasi-2D case (Fig. 2). The receptivity amplitudes drop very quickly with increasing the TS-wave propagation angle.

Important role of streamwise-wavenumber resonances

It is found that the most efficient excitation of the boundary-layer instability waves by a free-stream vortex takes place in the resonant receptivity case, which can be realised in the presence of surface roughness. In particular, in the case of wall-normal vorticity the strongest TS-wave excitation was observed at spanwise wavenumbers close to the resonant ones. The width of the resonance turned out to be rather large in the spanwise wavenumber spectrum. In the resonant ranges the efficiency of the excitation is enhanced very much due to the resonant phase synchronization of perturbations, even if the corresponding distributed receptivity coefficients have relatively small amplitudes. It is important to note, that the downstream TS-wave development observed in the resonant receptivity case can not be described by approaches based on the linear stability theory only, without consideration of the distributed receptivity mechanism. In particular, application of the well-known e^N-method of transition prediction is restricted for the resonantly excited modes.

CONCLUSION

The obtained quantitative results can be used for verification of theories of the distributed vortex receptivity, as well as for estimations of the influence of free-stream vortices on the boundary-layer laminar-turbulent transition.

ACKNOWLEDGEMENTS

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References

[1] Wuerz W., Herr S., Wagner S., Kachanov Y.S.: A first experimental approach to the distributed 3D-vortex receptivity of a boundary layer on an airfoil. *In: XI International Conference on Methods of Aerophysical Research. Proceedings. Part II.* - Novosibirsk: Inst. Theor. & Appl. Mech., 2002, pp. 173-178.

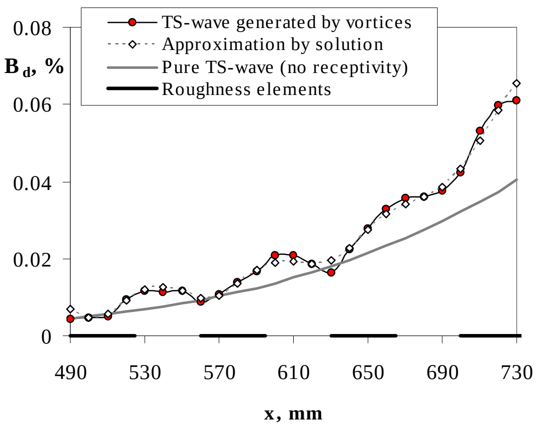

Fig.1. Downstream evolution of amplitudes of distributedly excited TS-wave and their approximation by an analytical solution in comparison with the case of absence of excitation (pure TS-wave) obtained for the spanwise orientation of vorticity vector.

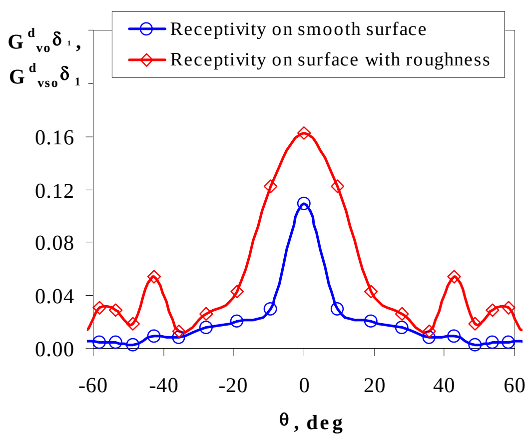

Fig. 2. Amplitudes of distributed receptivity coefficients vs. wave propagation angle for TS-wave excited by free-stream vortices (with wall-normal vorticity) for the smooth-surface vortex receptivity and the vortex roughness receptivity.