A FIRST EXPERIMENTAL APPROACH TO THE DISTRIBUTED 3D-VORTEX RECEPTIVITY OF A BOUNDARY LAYER ON AN AIRFOIL

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Introduction

This paper is devoted to an investigation of the distributed linear receptivity of a two-dimensional laminar boundary layer on the curved surface of an airfoil with respect to non-stationary free-stream vortices. The vortices represent a periodic, anti-symmetric vortex street localized along the spanwise coordinate with the vorticity vector directed initially (i.e. upstream the airfoil) perpendicular to the flow velocity vector and the leading edge of the airfoil. The vortex-street frequency was chosen to be close to that of the most amplified 2D TS-wave. Hot-wire measurements were performed as a set of spanwise scans, which cover a part of the streamwise region of the continuously excited 3D TS-wave train. Due to different phase speeds of the outer disturbance and the TS-waves this wave train is found to be modulated in spanwise and streamwise directions. Using a phase-locked measurement system the complex TS-wave amplitude is determined at the maximum of the TS-eigenfunction inside the boundary layer and Fourier decomposed into spanwise wavenumber spectra. In a similar way the complex amplitude of the free-stream vortices is determined as a reference.

After performing an analysis of the distributed vortex receptivity problem a notion of a receptivity density function (coefficient) $\overline{G_v'}(x, f, \beta)$ has been introduced and analytical expressions for its determining from experimental data have been derived. The values of the distributed vortex receptivity coefficients were determined experimentally. It is found that, in contrast to the 3D vibrational receptivity [1] and the 3D roughness-acoustic receptivity [2], the amplitudes of the distributed vortex receptivity coefficient are the largest for 2D modes and attenuate rapidly with increasing TS-wave propagation angle.

The boundary-layer receptivity to external perturbations represents a very important aspect of the laminar-turbulent transition problem. This paper focuses on the experimental investigation of a linear mechanism of transformation of non-stationary 3D free-stream vortices into 3D Tollmien – Schlichting waves due to scattering of the former on the “natural” surface and flow non-uniformities in a plane boundary layer on an airfoil.

The problem of vortex receptivity is poorly studied, so far. Most of the previous experiments in this field are theoretical ones and were devoted to two-dimensional receptivity problems. For *steady* streamwise vortices the quantitative experimental data by Kendall were compared with calculations by Bertolotti in a joint work [3]. A very good agreement has been found for the mechanism of excitation of streamwise streaks under the influence of free-stream streamwise vortices. A very similar problem has been studied in detail in recent experiments [4] by Boiko for the cases of both 2D (Blasius) and 3D (swept-wing) boundary layer.

The mechanism of transformation of wall-normal *steady* free-stream vortices to steady boundary-layer perturbations (again streaks) was investigated experimentally and theoretically by Ustinov [5]. It was shown that an interaction of these vortices with a blunt leading edge of the experimental model leads to formation of very strong streaks (streamwise vortices) inside the boundary layer. The theory predicted very well the experimental observations.

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Abstract

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At the moment the only available quantitative experimental study of the receptivity problem for *unsteady* free-stream vortices has been performed by Dietz [6] for scattering of a weak vortex street (with 2D spanwise vorticity) on a *localized* two-dimensional surface roughness in a Blasius flow. The excitation of 2D Tollmien – Schlichting waves has been observed and documented under controlled experimental conditions. This receptivity mechanism was studied theoretically by Wu [7] and a good agreement with the experimental data was found.

Since the scattering of unsteady free stream vortices can play an important role in the laminar-turbulent transition process on an airfoil the goal of the present investigation is to determine quantitatively the 3D *distributed* receptivity characteristics of a laminar boundary layer on the curved surface of an airfoil. The vortex axis initially is perpendicular to the flow direction and the airfoil chord and the vortex frequency was chosen to be in the region of the most amplified TS-frequencies. The pressure distribution of the airfoil, as well as the surface curvature, are functions of the streamwise coordinate.

At first, an analytic simulation of the problem was performed in order to find a proper definition for the distributed receptivity function, which could be linked to the well established formulations for the localized receptivity mechanisms due to 3D surface vibrations [1] and scattering of acoustic waves on 3D surface roughness [2]. Then, an experimental investigation was carried out. The results of it were processed using the analytic formulas obtained at the first stage.

Determination of Distributed Receptivity Coefficients

The distributed generation of 3D TS-waves on a 2D airfoil by 3D free-stream vortices, which are periodic in time, can be described in the following way. Both the TS-wave and the vortex street have a certain *fixed real frequency* $\omega = 2\pi f$ and a certain *fixed real spanwise wavenumber* β. It is convenient to present the perturbation of the streamwise velocity component, associated with the generated TS-wave, as:

$$\overline{u}'(x,y,z,t) = \overline{B}'(x,y)\exp[i(\beta z - \omega t)], \tag{1}$$

where $\overline{B}'(x,y)$ is the *complex* TS-wave amplitude. (All complex functions are marked with bars on the top as vectors.) Similarly, the perturbation of the streamwise velocity component, associated with the free-stream vortex street, can be presented as:

$$\overline{u}_v(x,y,z,t) = \overline{B}_v(x,y)\exp[i(\beta z - \omega t)], \tag{2}$$

where $\overline{B}_v(x,y)$ is the *complex* free-stream vortex amplitude.

The total change of the TS-velocity perturbation $d\overline{u}'(x,y,z,t)$ on an infinitely small interval dx of the streamwise coordinate (around the position x) is:

$$d\overline{u}'(x,y_m,z,t) = d\overline{u}_s(x,y_m,z,t) + d\overline{u}_r(x,y_m,z,t), \tag{3}$$

where $d\overline{u}_s(x,y_m,z,t)$ is a portion of change *due to the boundary layer instability* (i.e. due to the evolution of the previously generated TS-wave), $d\overline{u}_r(x,y_m,z,t)$ is a portion of change *due to the distributed receptivity* (i.e. an additionally generated portion of the TS-wave), and y_m is the wall-normal position of the amplitude maximum of the TS-wave with the frequency f and spanwise wavenumber β. For the right side of equation (3) we get:

$$d\overline{u}_s(x,y_m,z,t) = i\overline{\alpha}(x)\overline{u}'(x,y_m,z,t)dx = i\overline{\alpha}(x)\overline{B}'(x,y_m)\exp[i(\beta z - \omega t)]dx, \tag{4}$$

where

$$\overline{\alpha}(x) = \alpha_r(x) + i\alpha_i(x) \tag{4a}$$

is the complex wavenumber (an eigenvalue) of the TS-wave, and

$$d\overline{u}_r(x,y_m,z,t)=\overline{u}_v(x,y,z,t)\big|_{y=\delta}\overline{G}_v^{'}(x)dx=\overline{B}_v(x,y)\big|_{y=\delta}\exp[i(\beta z-\omega t)]\overline{G}_v^{'}(x)dx \qquad (5)$$

where δ is the boundary layer thickness and $\overline{G}_v^{'}(x)$ is *the* complex *distributed receptivity function* (or *the receptivity density function*). Substitution of (4) and (5) into (3) gives us the main equation, which connects all three complex functions (the TS-wave amplitude, the free-stream vortex amplitude, and the receptivity function):

$$\frac{d\overline{B}'(x,y_m)}{dx}=i\overline{\alpha}(x)\overline{B}'(x,y_m)+\overline{B}_v(x,y)\big|_{y=\delta}\overline{G}_v^{'}(x). \qquad (6)$$

The complex TS-wave amplitude generated in a distributed way in standard form is:

$$\overline{B}'(x,y)=B_o^{'}(y)\exp[i\phi_o^{'}(y)]\exp[i\int_{x_o}^{x}\overline{\alpha}'(x)dx], \qquad (7)$$

where $B'_o(y)$ and $\phi'_o(y)$ are real initial amplitude and phase of the excited TS-wave and

$$\overline{\alpha}'(x)=\alpha'_r(x)+i\alpha'_i(x). \qquad (8)$$

where $\alpha'_r(x)$ and $-\alpha'_i(x)$ are the real streamwise wavenumber and amplification rate of the TS-wave excited in the flow by the distributed receptivity mechanism.

After substitution of (7), (8) into (6) and designation

$$\Delta\overline{\alpha}(x)\overset{df}{=}\overline{\alpha}'(x)-\overline{\alpha}(x),\ \text{i.e.}\ \Delta\alpha_r(x)\overset{df}{=}\alpha'_r(x)-\alpha_r(x)\ \text{and}\ \Delta\alpha_i(x)\overset{df}{=}\alpha'_i(x)-\alpha_i(x), \qquad (9)$$

we finally get as a possible definition of the complex distributed-receptivity function for a given frequency f and spanwise wave number β**:**

$$\boxed{\overline{G}_v^{'}(x)=\frac{\overline{B}'(x,y_m)}{\overline{B}_v(x,y)\big|_{y=\delta}}i\Delta\overline{\alpha}(x)}. \qquad (10)$$

The main difference to a definition for localized receptivity is the presence of the term $i\Delta\overline{\alpha}(x)$. It can be seen from equation (10) that, despite the *distributed* receptivity is studied, the corresponding receptivity coefficient is a function of x and can be obtained locally.

Experimental Investigation

The experiments were carried out in the Laminar Wind Tunnel (LWT) of the IAG. The LWT is an open return tunnel with a turbulence level less than $Tu = 2\cdot10^{-4}$. The boundary layer measurements were performed on a symmetrical airfoil section (XIS40MOD, $c = 0.6$ m) at zero angle of attack and at a flow speed of 29.8 m/s. The streamwise coordinate x is measured along the arclength, starting from the leading edge.

A sketch of the experiment is shown in Fig. 1 and the main parameters are shown in Fig. 2. The periodic vortex street was generated by a 25 μm tungsten wire placed 44 mm upstream of the airfoil leading edge. Two micro piezo-actuators, located in two streamlined stems, are used to drive the wire at a frequency of 1088 Hz. To minimize the influence of the stems on the pressure distribution of the airfoil, they are placed 750 mm apart from one another and inclined to the local free stream direction. The piezo-actuators were

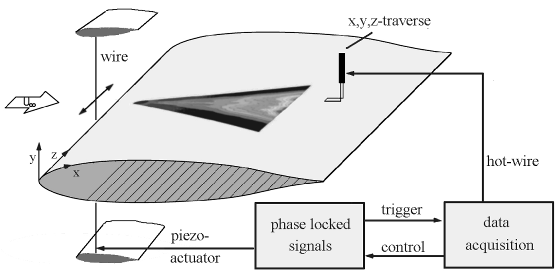

Fig. 1. Experimental set-up.

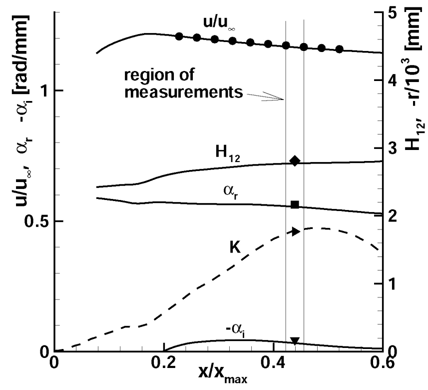

Fig. 2. Velocity distribution, boundary layer parameters and surface curvature K, symbolsdenote measured values.

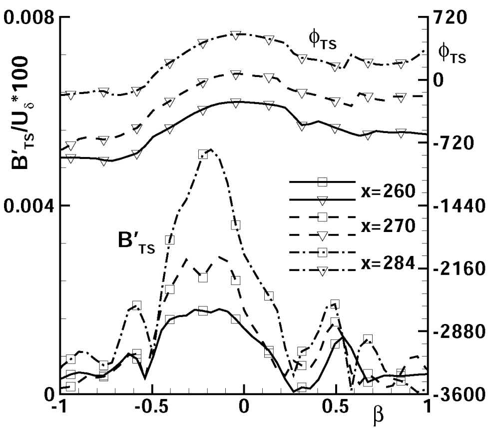

Fig. 3: Wavenumber spectrum of the excited TS-wave train

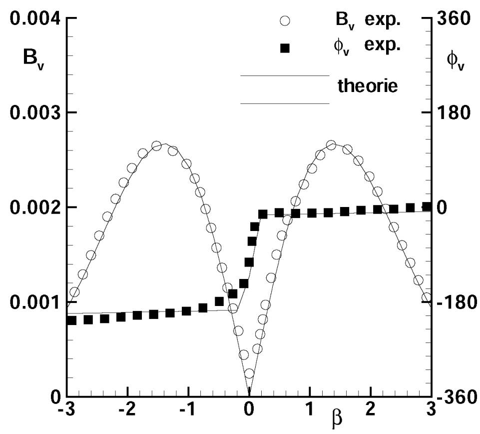

Fig. 4: Wavenumber spectrum of the vortex street, y = 20 mm

adjusted to produce a standing wave on the wire (the fifth eigen mode with wavelength of 150 mm) with a maximum amplitude of approximately 3 mm peak to peak.

The AC-signal for the vibrating wire, the point source, and the trigger for the data acquisition were generated strictly phase locked from the same clock. The time signals at every measurement point were analyzed with an FFT and the amplitude and phase obtained at the reference frequency were used for further data processing.

The shape of the excited vortex street was carefully measured in the potential flow outside the boundary layer (at a distance of 20 mm from the

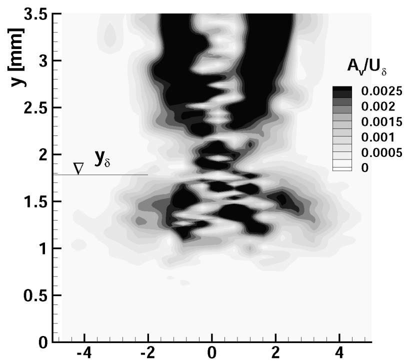

Fig. 5. Contours of the vortex-street amplitude in the (y,z) plane, x = 270 mm

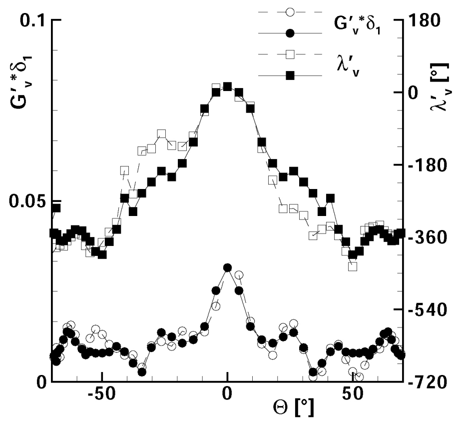

Fig. 6. Receptivity coefficients versus TS- propag ation angle. Solid symbols: symmetrized values

wall, note: $y_\delta = 1.79$ mm) by means of an X-wire probe of the hot-wire anemometer. It was found that this vortex street excites in the boundary layer a train of TS-waves propagating downstream.

To investigate the characteristics of the associated distributed receptivity mechanism two sets of main hot-wire measurements were performed. The first set was made inside the boundary layer; it consisted of 12 spanwise scans with 2 mm spacing in the streamwise direction. A constant, non-dimensional wall distance corresponding to $U/U_\delta = 0.42$ was used in order to be close to the maximum of the TS-eigenfunctions for different propagation angles. Typical spanwise wavenumber spectrum of the disturbance amplitude and phase excited in the boundary layer are shown in Fig. 3.

The reference measurements for the vortex amplitude and phase were made at the same position as the X-wire measurements. Figure 4 shows the spanwise wavenumber spectrum of the free-stream vortex in comparison with a calculation for a wake past a wire with a Gaussian spanwise distribution. The experimental vortex street is slightly not anti-symmetric and contains, in contrast to the theoretical one, a finite spectral amplitude at the zero spanwise wavenumber. It was also found that the initially vertical vortex lines were strongly inclined in the streamwise direction due to the presence of the stagnation point and the overall velocity distribution around the airfoil. Together with the interaction with the boundary layer a very complicated picture was observed in the vicinity of the boundary layer edge (Fig. 5).

To find the experimental values of the distributed receptivity function according to equation (10) it was necessary to conduct a third set of measurements (for exactly the same basic-flow conditions) to obtain the stability characteristics of the *pure* TS-waves, i.e. in absence of their distributed generation by the free-stream vortices. These characteristics were obtained with the help of an additional point source mounted at 0.31 $x/x_{\max}$, and displaced in spanwise direction by 0.13 $z/x_{\max}$ to avoid any interference when the generator of the free-stream vortices was turned off. The point source was driven by a loudspeaker at the same frequency (1088 Hz). Four spanwise scans were performed at the same non-dimensional wall distance as for the receptivity measurements. The results were compared to linear stability calculations.

All three kinds of spanwise distributions were interpolated to a constant grid and mapped for each spanwise cut to spanwise wavenumber spectra to allow the determination of streamwise distributions of the complex spectral amplitudes $\overline{B}'$ and $\overline{B}_v$. Finally the amplitudes (G'_v) and phases (λ'_v) of the distributed receptivity coefficients (Fig. 6) were evaluated by means of (10). Despite the free-stream vortex street is almost anti-symmetric and the spanwise wavenumber spectra of the excited TS-waves are significantly not symmetric, the distributed vortex receptivity mechanism is found to be almost symmetric. It is seen that the amplitudes of the receptivity coefficient are the largest for 2D modes and attenuate rapidly with the TS-wave propagation angle, in contrast to the 3D vibrational receptivity [1] and the 3D roughness-acoustic receptivity [2]. The receptivity phases decreases with this angle.

Conclusions

A method for the quantitative investigation of the distributed receptivity of boundary layers to 3D non-stationary free-stream perturbations has been developed and used successfully in an experiment with controlled disturbance conditions.

It is shown experimentally that the non-stationary 3D free-stream vortices with wall-normal orientation of vorticity excite quite effectively 3D TS-waves on "natural" 2D non-uniformities of an airfoil surface and the basic flow. The distributed vortex receptivity coefficients (amplitudes and phases) have been obtained in a range of spanwise wavenumbers (i.e. the TS-wave propagation angles). It is found that the flow is the most receptive to those free-stream vortices, which have the largest spanwise scales.

The results of the present experiments can be used for direct validation of linear distributed-receptivity theories.

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