EXPERIMENTAL INVESTIGATION OF CHARACTERISTICS OF STEADY AND UNSTEADY CROSSFLOW-INSTABILITY MODES DEVELOPING IN A 35-DEGREE SWEPT-AIRFOIL BOUNDARY LAYER

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The present study is a part of 'RECEPT' project devoted to investigation of the receptivity and amplitude-based transition prediction in a boundary layer on a swept wing. The experimental part of the project assumes obtaining the cross-flow instability characteristics, which are necessary for determining the receptivity coefficients (along with some other quantities). Stability characteristics are required in form $\alpha(f, \beta)$. Here f and β are frequency and spanwise wavenumber of the cross-flow (CF) instability modes, respectively. The streamwise wavenumber α is complex: $\alpha = (\alpha_r + i\alpha_i)$. Vector (α_r, β) describes the speed and the propagation angle of a particular cross-flow mode, while the imaginary part $(-\alpha_i)$ represents the disturbance increment.

The measurements were performed in the low-turbulence MTL wind tunnel of KTH. A section of a 35° swept-wing airfoil was installed in the wind tunnel at a −5° angle of attack. In order to provide the spanwise base-flow uniformity (to meet the sweep condition) the model was equipped with contoured sidewalls. Their shapes were calculated numerically. Initial disturbances were introduced into the boundary layer by means of a special source. Their downstream evolution was studied by a hot-wire anemometer and used for obtaining the stability and receptivity characteristics. The list of methodological problems to be solved in this experiment was the following: (*i*) how to configure the disturbance source; (*ii*) how to provide accurate traversing of the hot-wire probe; (*iii*) how to reduce collected data to sought quantities.

The disturbance source was a set of flexible membranes installed flush with the model surface and arranged in line along the span. A set of pipes and loudspeakers were used to drive membranes' oscillations. Such a source is able to produce either a pair of CF-modes with certain frequency and absolute value of the spanwise wavenumber or a disturbance with broad frequency-wavenumber spectrum. In case of excitation of a pair of CF-modes, the values of $\alpha(f, \beta)$ can be measured directly at the cost of increased time required for source re-adjustment and data acquisition. Instead of investigating CF-modes one by one, we can activate only one membrane, to document the evolution of the produced spanwise-localized wave-train/wavepacket, and to subject it to Fourier decomposition. This approach minimizes duration of the data acquisition at the price of a reduced accuracy (as every particular frequency-wavenumber mode is very weak). A reasonable compromise was found: to excite only one membrane by harmonic in time signal, to record the resulting disturbance field and then repeat the procedure for several other frequencies within the range of interest. Prior to these, we have found the dimensionless wall-distances corresponding to maxima of the CF-modes' amplitudes and kept them during all subsequent measurements. Finally, for every frequency we performed a set of spanwise scans downstream the source. The resulting data arrays $u(x', z')$ and $\varphi(x', z')$ contained all data required for obtaining $(\alpha_r + i\alpha_i)$. Here u and φ are amplitude and phase of velocity disturbance at given frequency, (x', z') are chordwise and spanwise coordinates. Additional measurements were performed to demonstrate the linearity of the problem. We have changed the driving signal by a factor of two and found that phases of velocity disturbances have not changed, as well as the scaled spatial amplitude distributions.

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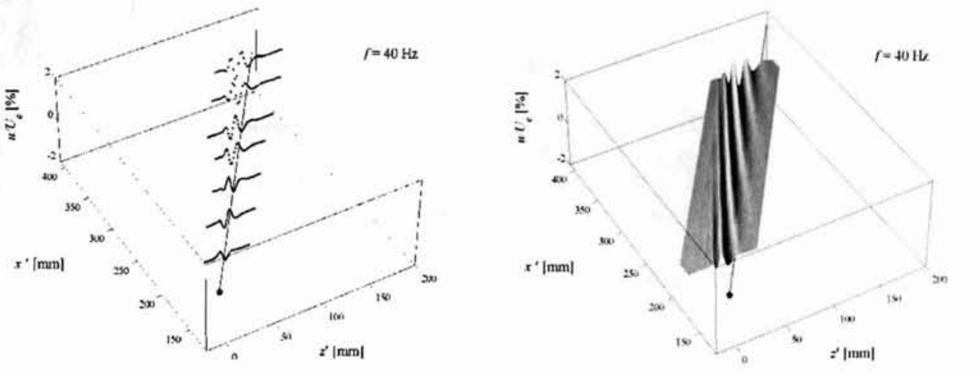
The traversing of the hot-wire probe must provide an acceptable spatial accuracy and minimum blockage of the flow. The standard traverse of the MTL wind tunnel was upgraded by installation of an additional slim and precision (y_n, z')-mechanism on it (y_n is normal to the wall coordinate). During the measurements inside boundary layer, the mechanism was supported by the model's surface. Thus, any displacements along (y_n, z') were measured with accuracy of several microns. As an actual starting position of the mechanism with respect to the model was not exactly known (except for the streamwise coordinate), it was necessary to find references for y_n and z'. For the y_n there is a natural reference, the model surface. The z' referencing was arranged with the help of a laser sheet and a tiny light sensor installed on the (y_n, z')-mechanism. The maximum response of the light sensor corresponded to the known z'-position. In this way, all spanwise scans were matched precisely with each other.

Obtaining stability characteristics is a straightforward procedure. Having $u(x', z')$ and $\varphi(x', z')$, we perform Fourier transform of $u(z')\exp(i\varphi(z'))$ distributions for every x' position and get amplitudes $B(\beta', x')$ and phases $\phi(\beta', x')$ of normal instability modes. Then, the spatial increments can be found as $-\alpha_i' = \partial(\ln B)/\partial x'$, while streamwise wavenumbers as $\alpha_r' = \partial\phi/\partial x'$. The latter formula needs 'unwrapped' phase distributions, whereas after Fourier transform we have all values reduced to the interval $(-\pi, \pi)$. At any reasonable streamwise spacing of z' scans, the '2π' uncertainty may be a problem for the majority of harmonics of the frequency- wavenumber spectrum. The simplest solution of this problem is to perform phase unwrapping in (x, z') space, where x is directed parallel to the incident flow. As the wave train under investigation does not deviate much away from x-axis, phase incursions between neighboring chordwise positions became moderate. The values $\hat{\alpha}_r = \partial\phi/\partial x$ can be converted then as follows: $\alpha_r' = \hat{\alpha}_r/\cos(\chi) - \beta'\tan(\chi)$, here χ is the sweep angle of 35°. Correctness of the phase unwrapping was checked by comparison of measured disturbance fields with their reconstructions $u = \Sigma\, u_0 \exp(i(-\alpha' x' - \beta' z' + \phi_0))$, see the figure below.



One instance ($t = 0$) of measured (left) and reconstructed (right) disturbance fields.
Each point on the left diagram is a result of hot-wire measurements. For the right diagram, harmonics with $|\beta'| < 1$ rad/mm were summed. Circle at $z' = 0$ is source position. The line starting at source is directed along x-axis

The dependencies $\alpha'(f, \beta')$ and all the derived quantities (like propagation angles, phase velocities etc.) are successfully obtained, compared with calculations, and used for analysis of the receptivity problem.

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