VERIFICATION AND CHARACTERIZATION OF PREDOMINANT INSTABILITIES OF SWEPT-WING BOUNDARY LAYERS

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Summary The problem of identification and verification of the most important linear stability mechanisms of initial stages of laminar-turbulent transition in three-dimensional (3D) swept-wing boundary layers is discussed based on experimental and theoretical investigations performed, in particular, for real swept airfoil sections. Detailed analysis of all main boundary-layer stability characteristics with respect to the cross-flow (CF) instability modes and 3D Tollmien-Schlichting (TS) instability modes is carried out based on experimental data, as well as on computations within the framework of linear stability theories and the Parabolized Stability Equation (PSE) approach. The possibility of a very good agreement between all main measured and calculated stability characteristics is shown. Role of surface curvature and base-flow non-parallelism is discussed.

INTRODUCTION

Laminar-turbulent transition in 3D boundary-layer flows is of great scientific interest and significant importance for a wide range of technical applications. Its importance for aeronautical application has increased with the need for low-emission aircraft.

In general, there are several flow instability mechanisms which trigger transition in the swept-wing boundary layers, each having their own characteristics as well as sources of the disturbance excitation. The most significant of these instability mechanisms are: (*a*) the attachment-line instability, (*b*) the stationary and non-stationary cross-flow (CF) instability, (*c*) the Tollmien-Schlichting (TS) instability, and (*d*) the instability of separated shear layers that is important in presence of laminar separation zones.

The relative contribution of these modes to the transition process depends on the pressure gradient and the sweep angle. For instance, in case of a favorable, i.e., negative, streamwise pressure gradient (such as on the upper side of a long-laminar-run swept wing installed at a small positive or negative angle of attack) and a sufficiently large sweep angle, one may expect predominance of the stationary and/or traveling CF-instability modes inducing very specific transition scenarios. Meanwhile, in the case of nearly zero chordwise pressure gradients or weak adverse ones, the 3D TS-instability waves may prevail. Although the CF-mode instability of swept-wing boundary layers has been studied intensively for many years, the detailed qualitative agreement between all measured and calculated linear stability characteristics has not been obtained previously for real nonparallel boundary layers developing on curved surfaces of real swept airfoils. This is especially true for non-stationary CF-instability modes. For the 3D TS-instability characteristics of swept-wing boundary layers, the investigations are even rarer. This can be explained by the extreme complexity of accurate quantitative experimental investigations of these problems.

The present paper is devoted to description of the significant advancements in the described field achieved recently. These advancements are related to the CF- and TS-instability mechanisms.

EXPERIMENTAL AND THEORETICAL APPROACHES

The presentation starts with analysis of the problem and with description of recent steps directed towards its solution. In particular the present experimental approach is described. This approach is based on performing measurements in 3D boundary layers developing over a swept airfoil section equipped with specially designed contoured sidewalls helping to provide satisfaction of the sweep condition inherent for an infinite-span wing. In one of studies (called study '*A*'), an adverse chordwise pressure gradient was achieved at a negative angle of attack of the airfoil section. This gradient provided conditions favorable for predominance of the CF-instability mechanism. In another experiment (called study '*B*'), achieved at a positive angle of attack, the chordwise pressure gradient was very weak (close to zero one). The TS-instability mechanism was expected to be predominant in this case. The airfoil section was the same in the two studied cases, while the shapes of the sidewalls were different. The experiments were performed in Stockholm in the low-turbulence wind tunnel MTL of the Royal Institute of Technology (KTH).

All measurements were carried out at fully controlled disturbance conditions with excitation of either several oblique CF- or TS-modes of the frequency-spanwise-wavenumber spectrum or, alternatively, with excitation of spanwise-localized time-periodic wave trains of CF- or TS-instability modes. The excitation was carried out by specially designed disturbance sources representing either spanwise periodic or spanwise localized surface vibrators. The calculations consisted of two important steps: (*i*) the base-flow computations simulating the experimental conditions and (*ii*) the flow instability computations based on either locally-parallel linear stability theory or on the Parabolized Stability Equation (PSE) approach which took into account both the base-flow non-parallelism and the surface curvature. All main measurements were carried out by means of hot-wire anemometry, including two-component ones.

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SOME IMPORTANT RESULTS

The experiments have shown that almost all stability characteristics of instability modes, dominated in the boundary layer in cases ‘*A*’ and ‘*B*’, are dramatically different from each other. In particular, this is observed for dependences of amplification rates of modes of the frequency-wavenumber spectrum on the wave propagation angle θ* (Figure 1). The same is true for the spanwise-wavenumber distributions of the instability-mode phase velocities C^*_x calculated in the direction of the potential flow velocity vector at the boundary-layer edge (Figure 2).

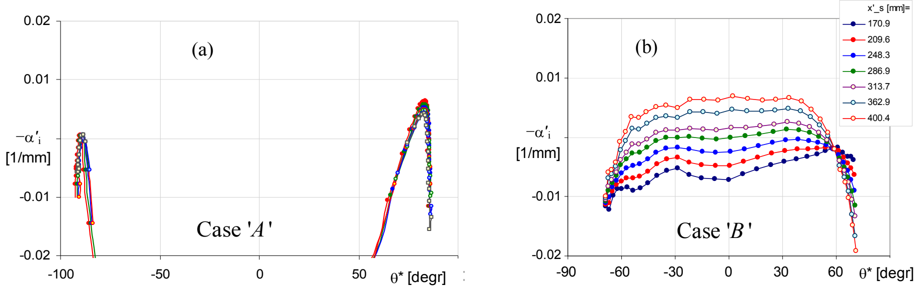

Figure 1. Radical difference of angular dependences of amplification rates of instability modes obtained in experiments ‘*A*’ (*f* = 40 Hz, plot *a*) and ‘*B*’ (*f* = 156 Hz, plot *b*).

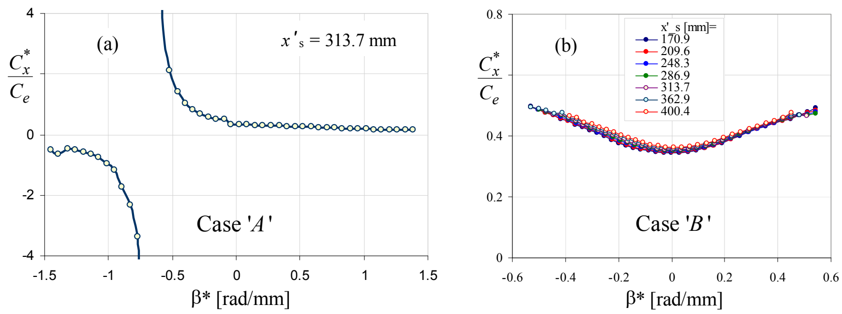

Figure 2. Radical difference of spanwise-wavenumber dependences of phase velocities of instability modes obtained in experiments ‘*A*’ (*f* = 40 Hz, plot *a*) and ‘*B*’ (*f* = 156 Hz, plot *b*).

Comparison of the measured and calculated stability characteristics has shown that in case ‘*A*’ the CF-instability modes are predominant in the flow (see e.g. Figure 3), while in case ‘*B*’ the TS-instability modes dominate.

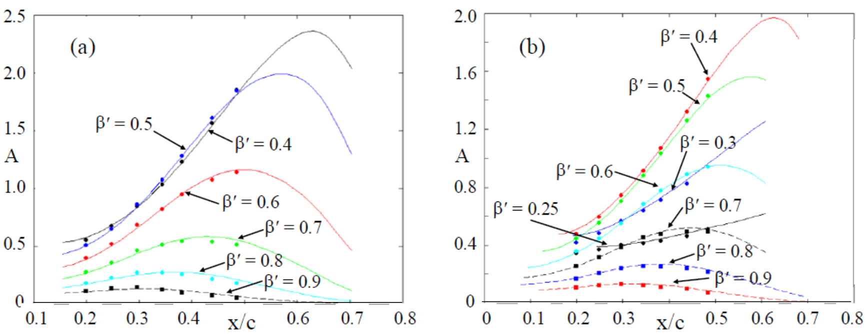

Figure 3. Comparison of measured amplification curves of boundary-layer disturbances, obtained in case ‘*A*’ for frequencies *f* = 60 Hz (*a*) and 40 Hz (*b*), with those calculated for the CF-instability waves.

CONCLUSIONS

The present study resulted in clear identification of two types of the 3D boundary layer instability observed on a swept-wing model at two different angles of attack: (*i*) the CF-modes in case ‘*A*’ and (*ii*) the TS-modes in case ‘*B*’. Their characteristics have been studied in detail and compared with each other. Very good agreement between all measured and calculated stability characteristics has been achieved, especially when the effects of the base-flow non-parallelism and the surface curvature were taken into account (in the framework of the PSE approach).

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