Mitteilung

Projektgruppe/Fachkreis: Turbulence and Transition

Secondary instabilities of stationary crossflow vortices:
Comparison of LST-2D and PSE-3D with DNS.

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Introduction

A significant reduction of aircraft drag could be attained by achieving laminar flow on wings. The need to control the laminar-turbulent transition process in swept-wing flows motivates the research on three-dimensional boundary layers. Laminar-turbulent transition in swept wing boundary layers is often initiated by stationary or travelling crossflow instabilities. At low levels of free stream turbulence such as those in free-flight conditions, the transition process of three-dimensional flows is known to be dominated by stationary crossflow vortices. Those vortices redistribute momentum across the boundary layer and result in a distortion of the otherwise spanwise invariant boundary layer. The distorted boundary layer is characterized by strong shear layers and is prone to the growth of secondary instabilies that finally trigger the laminar breakdown.

The secondary instability problem of crossflow vortices can be studied with different approaches. Koch et al. [1] used secondary instability theory and modelled the saturated crossflow vortices by nonlinear equilibrium solutions. Groot et al. [2] employed two-dimensional linear stability theory (LST-2D) to study an experimentally measured baseflow. Then, Casacuberta et al. [3] compared the secondary instability modes computed with LST-2D with the ones extracted from an unsteady direct numerical simulation (DNS). The LST-2D equations were derived in a non-orthogonal coordinate system following the approach of Li and Choudari [4]. In this work, we go beyond established approaches by employing both LST-2D and plane-marching parabolized stability equations (PSE-3D) in a non-orthogonal coordinate system, validating these methodologies through a comparative study with DNS results.

Numerical approach

A DNS computation of a swept-wing configuration was carried out with Nek5000 in a separate study, providing both the distorted base flow and the data for the secondary instability analyses. The NOLOT/LST-2D and NOLOT/PSE-3D codes have been employed to analyse the distorted baseflow. The former is a *local* approach, which solves a generalized eigenvalue problem, the latter is a *nonlocal* approach which is solved by a marching procedure in streamwise direction taking into account the upstream flow information to march downstream.

To overcome the well known dilemma of the extraction procedure for the baseflow to use for the stability analysis [5] the LST-2D/PSE-3D approach has been formulated in a non-orthogonal coordinate system. This formulation simultaneously allows for the fulfillment of the periodicity in the spanwise direction and accommodates the slow variation of the baseflow in the out-of-plane direction required by the PSE-3D. In this study the aforementioned direction is taken to be the one along which the derivative in the streamwise direction is the lowest, which closely resembles the crossflow vortex axis direction.

Results

The instability results (LST-2D and PSE-3D) are compared against the DNS data in Figures 1 and 2 for a type III secondary instability for a frequency of 900 Hz. This type of secondary instability is dominant in the near-wall region and can be interpreted as low-frequency travelling crossflow instabilities which are modulated by the presence of the stationary crossflow vortices. The integrated amplification rate versus the dimensionless surface arc length is shown in Figure 1. It can be noted that the LST-2D computation underpredicts the values attained in the DNS, while switching to a marching procedure (PSE-3D) allows for a more accurate match until station x/δ_0

≈ 650, where transition to turbulence starts to take place. In Figure 2 the normalized magnitude of the streamwise velocity amplitude function ($|\hat{u}|/|\hat{u}_{max}|$) is shown for LST-2D (left) and PSE-3D (right) at a station $x/\delta_0 \approx 450$. Also, the PSE-3D approach yields improvements in the resulting amplitude function compared to the LST-2D solution, demonstrating a generally good match with the DNS data. Further analysis will be presented during the workshop.

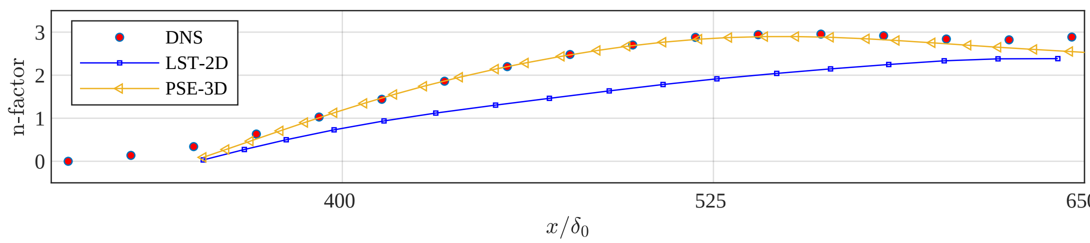

Figure 1: n-factor curves versus x/δ_0 for a type III secondary instability for a frequency of 900 Hz for: DNS (red dots), LST-2D (blue squares) and PSE-3D (yellow triangles). δ_0 is the displacement thickness at the first station of the instability computation.

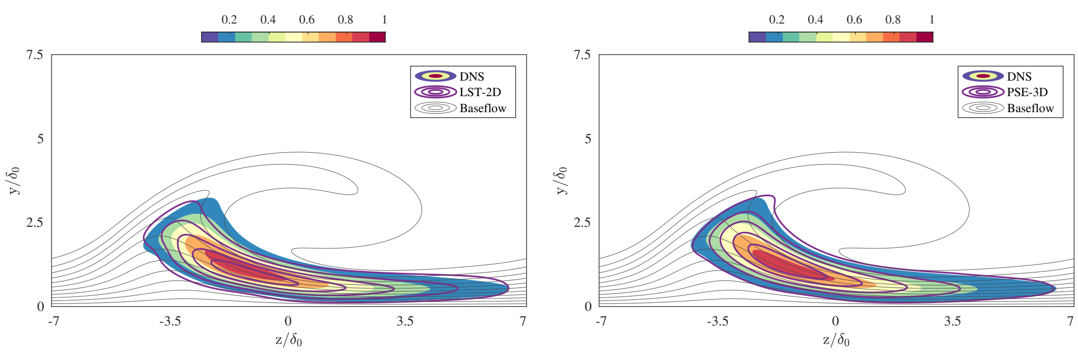

Figure 2: Normalized magnitude of the streamwise velocity component amplitude function ($|\hat{u}|/|\hat{u}_{max}|$) for a type III secondary instability for a frequency of 900 Hz at $x/\delta_0 \approx 700$. DNS (filled contour) compared with LST-2D (left) and PSE 3D (right) both represented in solid purple lines. Isolines of streamwise velocity component of the distorted baseflow (solid black).

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