INTERACTION OF ACOUSTIC WAVES AND ROUGHNESS ELEMENTS IN A THREE-DIMENSIONAL BOUNDARY LAYER

Nima Shahriari[1], Ardeshir Hanifi [1,2] & Dan S. Henningson [1]
[1]*KTH Royal Institute of Technology, Department of Mechanics, Linné Flow Centre, SeRC, SE-100 44 Stockholm, Sweden*
[2]*Swedish Defence Research Agency, FOI, SE-164 90 Stockholm, Sweden*

Abstract Acoustic receptivity of distributed micron-sized roughness elements is investigated for a swept-wing boundary layer by means of direct numerical simulations (DNS) and parabolised stability equations (PSE) computations. The geometry and flow configuration follow the experiments by [4] and DNS calculations by [7]. Acoustic wave has been modeled by superposing a periodic fluctuation $\varepsilon cos(\omega t)$ to the inflow streamwise velocity component. A range of amplitudes and frequencies are considered to perform simulations and to study acoustic wave-roughness elements interaction.

BACKGROUND

The laminar-turbulent transition process causes a drastic increase of friction drag on modern aircraft and has been extensively studied due to its practical and fundamental importance over the past decades. Transition control in three-dimensional boundary layers on swept-wing geometries by means of distributed micron-sized roughness elements (DMSR) has been investigated experimentally by Saric and coworkers [5]. They report that application of DMSR on the leading edge of a swept wing can significantly delay laminar-turbulent transition. However, similar investigations by other groups have not been successful to the same extent though they have been performed in wind tunnels with low free-stream turbulence (FST). Additionally, transition control by means of DMSR found to be intractable at low level of FST [2]. These observations raise the question about the importance of other type of external disturbances such as acoustic noise in those cases. On the other hand, mainly based on the experiments by Bippes [1], it has been generally accepted that the acoustic perturbations do not have any effects on the laminar-turbulent transition on swept wings. Therefore, there are still unsolved issues regarding the robustness and efficiency of DMSR as a mean for transition control.

The aim of this work is to gain a better understanding of the receptivity mechanisms of micron-sized roughness elements in presence of acoustic noise. This will enable us to characterise the effects of acoustic (nonstationary) and vortical (stationary) perturbations, separately or simultaneously, on the flow behaviour.

NUMERICAL SIMULATIONS

The wing geometry used in the present investigation is a swept natural laminar-flow wing, NLF(2)-0415 aerofoil [6]. The flow configuration follows the experiments by [4] where a sweep angle $\phi = 45°$, an angle of attack $\alpha = -4°$ and chord Reynolds number of $Re_c = 2.4 \times 10^6$ has been used. This setup has been recently studied through direct numerical simulations (DNS) by Tempelmann et al. [7], where boundary-layer response to spanwise distributed micron-sized roughness elements is investigated. In the current work DNS has been performed using the incompressible spectral element code NEK5000 [3]. The spanwise-periodic roughness elements are meshed in the leading-edge region of the swept wing in a manner similar to that in[7]. Furthermore, acoustic wave disturbance within an incompressible framework is modeled by superposing a small periodic fluctuation $\varepsilon cos(\omega t)$, with frequency $\omega/2\pi$ and amplitude ε, on the streamwise velocity component of inflow, similar to the work by [8] and [9].

A range of different amplitudes and frequencies of acoustic waves will be considered in simulations. Figure 1 shows freestream modes caused by the periodic forcing at boundaries for the selected amplitude of $\varepsilon = \mathcal{O}(10^{-3})$ and frequency $f = 100$Hz. Stationary crossflow vortices are excited by roughness elements and as a result of acoustic wave-roughness element interaction, nonstationary vortices are also generated. We accompany DNS results with linear and nonlinear PSE calculations to check the DNS results. This enables us to distinguish between contribution of receptivity and nonlinear interaction to the final amplitude of disturbances. Amplitudes of the fundamental stationary mode and its two harmonics predicted by DNS and PSE calculations are shown in figure 2, where a good agreement between the results can be seen. The nonstationary crossflow perturbations with the same spanwise periodicity as the DMSR elements are generated in the boundary layer as well. The initial amplitude of these modes are smaller than the stationary modes but their amplification is larger. For $\varepsilon = 10^{-3}$, at most downstream position the amplitude of nonstationary modes is around one order of magnitude smaller than those of stationary ones. Further simulations with variation of amplitude and frequency of the acoustic wave will be performed to get a broader picture of the interaction of acoustic filed and DMSR.

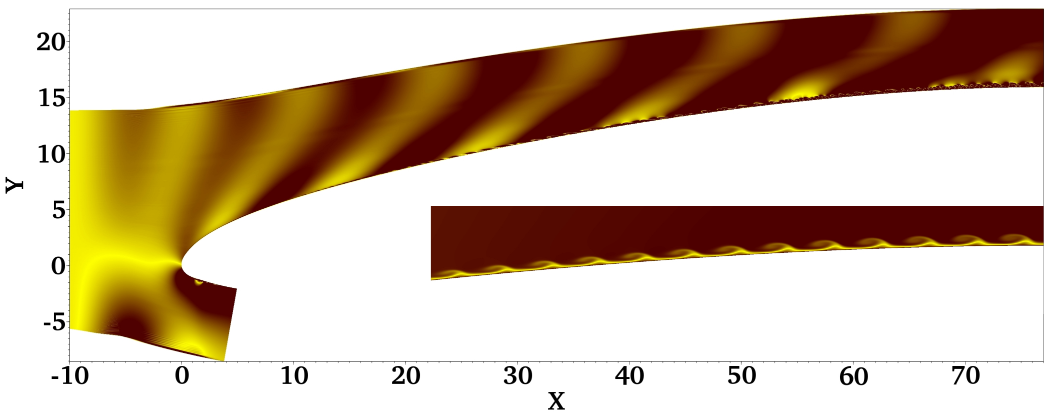

Figure 1. Pseudocolor of freestream modes caused by the periodic forcing at boundaries for the selected amplitude of $\varepsilon = \mathcal{O}(10^{-3})$ and frequency $f = 100$Hz. The close up sections shows the structure of crossflow vortices inside the boundary layer.

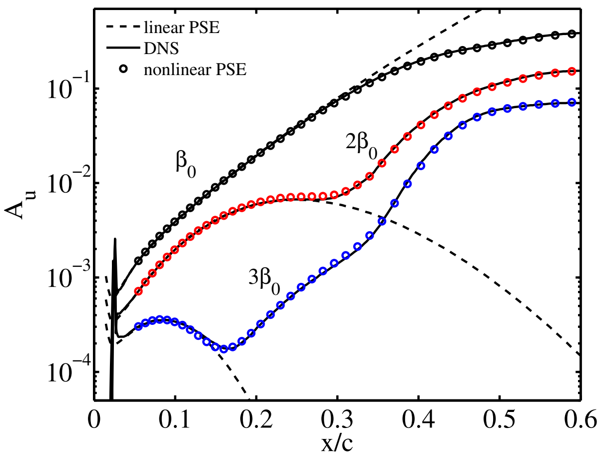

Figure 2. Disturbance amplitudes of first three stationary crossflow modes predicted by DNS (−), nonlinear PSE (∘) and linear PSE (−−).

References

[1] H. Deyhle and H. Bippes. Disturbance growth in an unstable three-dimensional boundary layer and its dependence on environmental conditions. *Journal of fluid mechanics*, **316**:73–114, 1996.

[2] R. S. Downs. *Environmental influences on crossflow instability*. PhD thesis, Texas A&M University, 2012.

[3] P. F Fischer, J. W. Lottes, and S. G. Kerkemeier. nek5000 Web page, 2008. http://nek5000.mcs.anl.gov.

[4] M.S. Reibert. *Nonlinear stability, saturation, and transition in crossflow-dominated boundary layers*. PhD thesis, Arizona State University, 1996.

[5] W.S. Saric, R. Carrillo, and MS Reibert. Leading-edge roughness as a transition control mechanism. Technical report, AIAA-98-0781, 1998.

[6] D.M. Somers and K.H. Horstmann. Design of a medium-speed natural-laminar-flow airfoil for commuter aircraft applications. *DFVLR-IB*, **29**(85):26, 1985.

[7] D. Tempelmann, L.U. Schrader, A. Hanifi, L. Brandt, and D.S. Henningson. Swept wing boundary-layer receptivity to localized surface roughness. *Journal of Fluid Mechanics*, **1**(1):1–29, 2011.

[8] J.B.V. Wanderley and T.C. Corke. Boundary layer receptivity to free-stream sound on elliptic leading edges of flat plates. *Journal of Fluid Mechanics*, **429**:1–21, 2001.

[9] W. Würz, S. Herr, A. Wörner, U. Rist, S. Wagner, and YS Kachanov. Three-dimensional acoustic-roughness receptivity of a boundary layer on an airfoil: experiment and direct numerical simulations. *Journal of Fluid Mechanics*, **478**(1):135–163, 2003.