TRANSITION TO TURBULENCE IN A OBLIQUE SHOCK-WAVE/BOUNDARY-LAYER INTERACTION AT M=1.5

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Abstract Direct numerical simulations are carried out for different forcing techniques to trigger transition during the interaction between an oblique shock-wave and a laminar boundary-layer at $M = 1.5$. Three forcing methods are used: a) forcing of oblique unstable modes, whose shape and behaviour are determined by the local linear stability theory, b) broadband free-stream acoustic disturbances, and c) a cold plasma flow control device. While the oblique-mode breakdown is dominant for low-amplitude forcing, long streaky structures drive the transition process in a high-amplitude disturbance environment. LES are also performed on the experimental setup by the Institute of Theoretical and Applied Mechanics (ITAM) from Novosibirsk State University with cold plasma actuation. As well as the disturbance type, the effect of Reynolds number and forcing amplitude will be investigated.

INTRODUCTION

For high speed flight and in gas turbines, shock-wave/boundary-layer interaction may occur, with detrimental effects on performance. Flow separation, transition to turbulence, unsteadiness and three-dimensional (3D) effects can take place simultaneously, actively changing the pressure and skin friction distributions of the flow field. The interest is here focused on the use of effective forcing techniques to trigger and control the transition location and investigate its effect on the structure of the interaction between an oblique shock-wave and a laminar boundary-layer (LBL).

NUMERICAL METHOD AND SETUP

Three different methods are used to force the LBL and trigger transition. Firstly, specific unstable modes, whose shape is defined by the eigenfunctions and eigenvalues predicted by the local linear stability theory (LST), are added to the base flow variables at the inlet. The second type of forcing is based on broadband acoustic free-stream disturbances located outside the boundary-layer, which have been demonstrated to be critical in the receptivity process of high-supersonic boundary-layers at high Mach numbers [1]. The third method uses a modelled cold plasma flow control device [2] to force the unstable modes of the boundary-layer. A DNS study is carried out at $M = 1.5$, with a shock generator plate angle $\theta = 2.5°$ and Reynolds number based on the shock impingement location $Re_{ximp^*} = 3 \times 10^5$, where the three different forcing methods are compared. As part of the EU-FP7 TFAST project, for a higher Reynolds number range between $Re_{ximp^*} = 1 \times 10^6 - 3 \times 10^6$ based on the experiments conducted by ITAM with cold plasma actuation, LES is performed at different forcing amplitudes for laminar, transitional and turbulent interactions at $M = 1.5$ and $\theta = 3 - 4°$.

RESULTS

Local LST within the separation bubble shows that the most unstable mode is a 3D oblique mode. A pair of oblique modes with streamwise wavenumber $\alpha = 0.21$, spanwise wavenumbers $\beta = \pm 0.23$ and frequency $\omega = 0.101$ are therefore selected to force the LBL at the inflow. Iso-surfaces of the instantaneous vertical vorticity (ω_y) are plotted in Fig. 1-a for $\omega_y = \pm 0.050$ (red and black) and coloured with the streamwise velocity. As previously found in the literature [3, 4], the mechanism that dominates is an oblique-mode breakdown and the appearance of strong streamwise vortices is confirmed by Fig. 1-b, where the contours of the streamwise vorticity (ω_x) in z-y planes are plotted at different streamwise locations. When low-amplitude free-stream acoustic disturbances are applied the transition scenario is again dominated by an oblique-mode breakdown. For high-amplitude disturbances, bypass transition occurs in the interaction region and the length of the separation bubble is strongly reduced. Fig. 2 shows iso-surfaces of the vertical vorticity for $\omega_y = \pm 0.075$ (red/black) and coloured with the streamwise velocity. Transition happens via long streaky structures and the inset plot shows the formation of a hairpin structure near the wall that precedes the long streaks. The variation in transition location due to disturbance environment will be quantified in the final paper along with differences in the transition mechanism.

References

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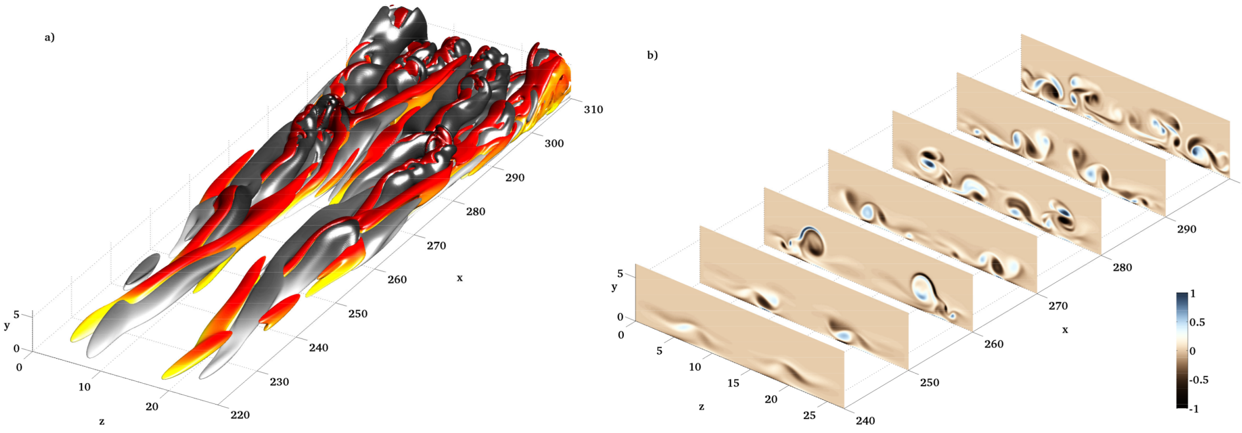

Figure 1. Flow structures forced by oblique modes. a) Iso-surfaces of the vertical vorticity for $\omega_y = +0.05$ (red) and $\omega_y = -0.05$ (black) and coloured with the streamwise velocity. b) Contours of the streamwise vorticity for different z-y planes at different x-locations showing the appearance of strong streamwise vortices associated to the oblique-mode breakdown.

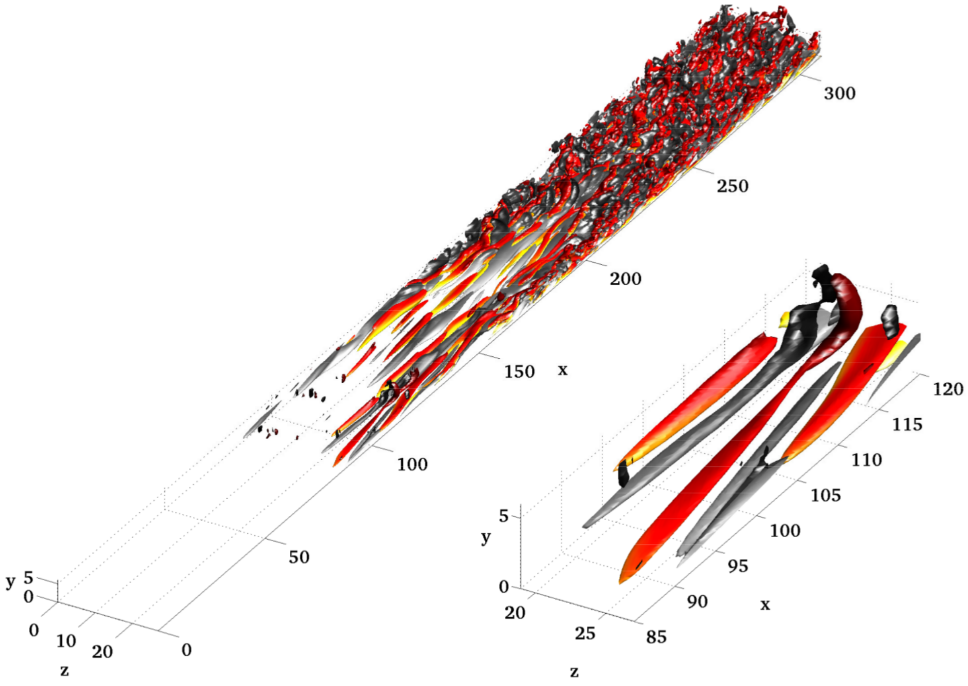

Figure 2. Flow structures forced by free-stream acoustic disturbance (high-amplitude). Iso-surfaces of the vertical vorticity are shown for $\omega_y = +0.075$ (red) and $\omega_y = -0.075$ (black) and coloured with the streamwise velocity. The inset shows the hairpin structure forming upstream the streaky structures of transition.