Investigation of a spatially evolving three-dimensional boundary layer subjected to spanwise pressure gradient

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A spatially-evolving three-dimensional boundary layer (3DBL), subjected to a spanwise pressure gradient (SPG), is investigated by means of highly-resolved large-eddy simulation. The study has been undertaken in the context of efforts to develop and test novel hybrid LES-RANS schemes for non-equilibrium near-wall flows with an emphasis on three-dimensional near-wall straining. As is well recognised, turbulence closures, originally developed for 2DBLs, tend to return poor results for 3DBLs. Understanding the need for more advanced closures, especially in the context of particular near-wall models coupled to LES, requires insight into the mean-flow and turbulence properties of 3DBLs. Such flows have attracted considerable interest, and have been the subjects of a number of past experimental and computational studies for a variety of 3D conditions and configurations. An initially fully established 2DBL at $Re_{\theta} \approx 1200$ and $Re_{\tau} \approx 500$, generated with a precursor simulation, evolves over a flat plate in zero pressure gradient and is deflected from the initial streamwise direction by means of a SPG of magnitude $\delta_{99,in} \partial C_p / \partial z \approx 0.07$, imposed at some streamwise location and applied over $30\delta_{99,in}$. A higher spanwise deflection, and thus skewness, occurs in the slow-moving fluid near the surface than in the outer layer (defined as the region above the point of maximum cross flow). Fig. 1 shows a schematic of the 3DBL, where the mean velocity profiles, relevant directions and deviation angles are identified.

Simulations were performed over several meshes, the finest being used on a restricted domain ($x/\delta_{99,in}$=10) including 384×160×192 grid points, using up to 180 processors and requiring around 6100 CPU hours. A wide range of flow-physical properties have been studied, including mean-flow properties, second moments, strain angles relative to stress angles, and wall-normal two-point correlations of velocity fluctuations and their angles, relative to wall-shear fluctuations. Fig. 2 illustrates the degree of skewness in the boundary layer, while Fig. 4 demonstrates skewnwess-provoked wall-normal turbulence damping and shear-stress lag relative to strain. In addition, results of test simulations demonstrate the degree to which the fidelity of the simulation in the near-wall layer suffers from the deliberate imposition of approximate wall shear stress that does not feature the correct spectral properties. These latter results are specifically pertinent to zonal hybrid schemes in which approximate information is available, at best, about the frictional wall properties. A broader exposition of results is reported in Bentaleb and Leschziner (2012).

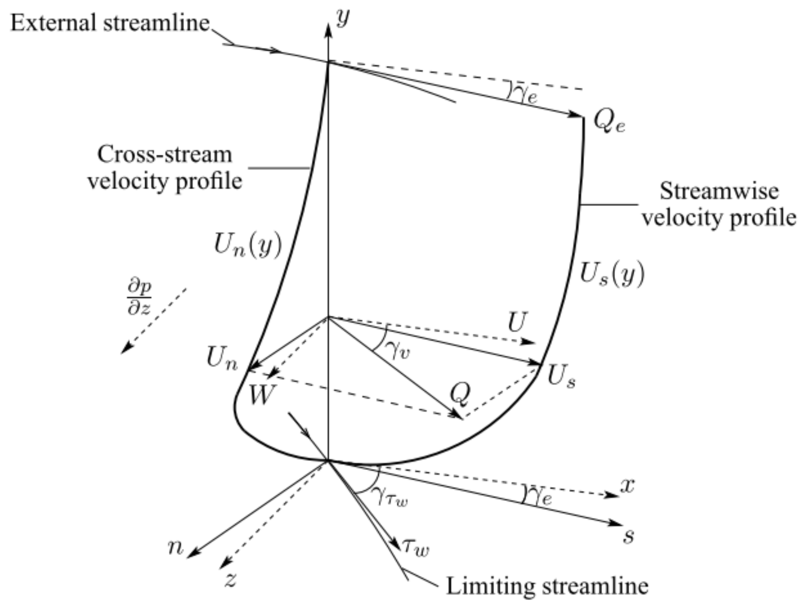

Fig. 1: Schematic diagram of 3D boundary layer

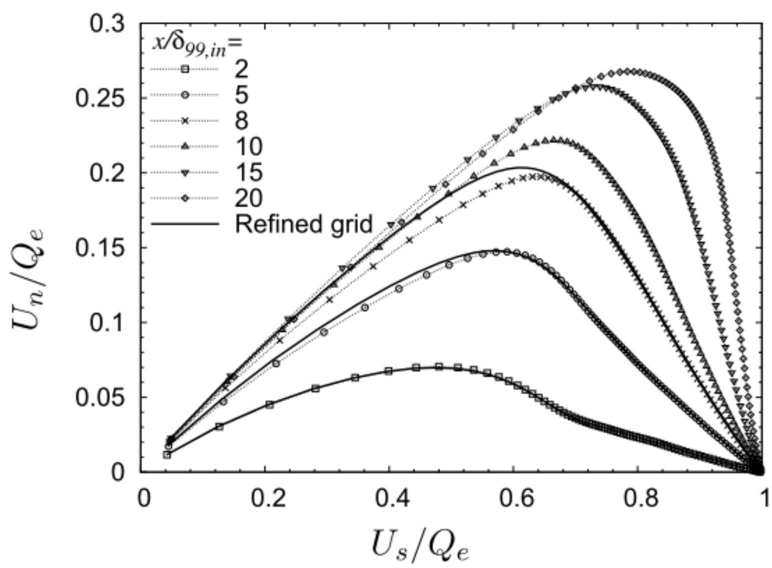

Fig. 2: Polar plots (hodograph) of velocity components

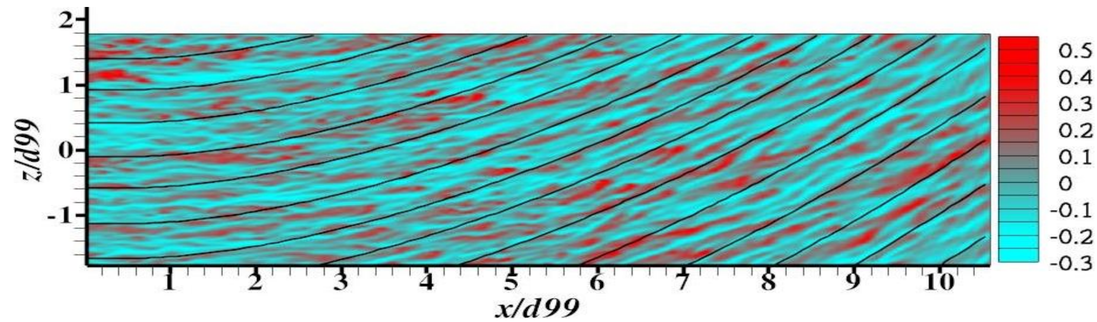

Fig. 3: Streamwise fluctuations u' at $y^+_{nominal} = 10.4$ (i.e. based on the inlet wall-shear-stress), identifying near-wall streaks, with superimposed streamlines of the time-averaged near-wall flow

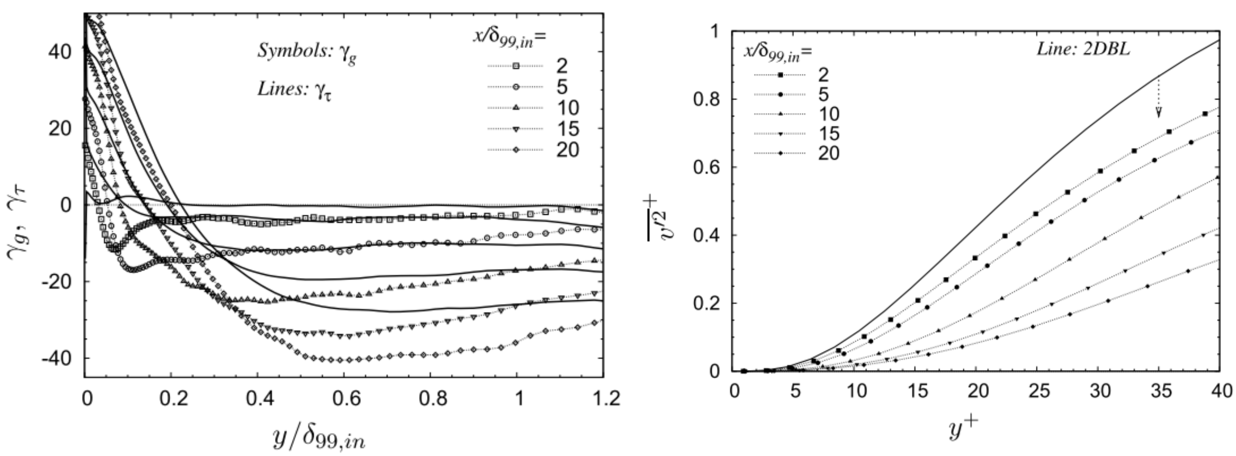

Fig. 4: Evolution of wall-normal stress (a), and lag between shear strain and shear-stress vectors (b).

References

Bentaleb, Y and Leschziner, M A (2013), The structure of a three-dimensional boundary layer subjected to streamwise-varying spanwise pressure gradient, Int. J. Heat and Fluid Flow, 43, pp. 109-119.