DIRECT NUMERICAL SIMULATION OF AN EQUILIBRIUM ADVERSE PRESSURE GRADIENT TURBULENT BOUNDARY LAYER AT THE VERGE OF SEPARATION

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Abstract The statistics and structure of a self-similar equilibrium adverse pressure gradient (APG) turbulent boundary layer (TBL) are investigated using a direct numerical simulation (DNS) of the flow at the verge of separation. Flow simulations are performed using the DNS TBL code of Simens et al. [8] and Borrell et al. [1] with the desired equilibrium APG achieved via the use of a tailored far-field boundary condition. The APG TBL develops over a momentum thickness based Reynolds number of $Re_\theta \approx 2000$ to 6000, achieving a region of constant friction coefficient (C_f), pressure velocity (u_p) and shape factor (H). One- and two-point statistics are presented under both inner wall (u_τ) and pressure velocity (u_p) based scaling.

INTRODUCTION

The separation of turbulent boundary layers has a significant impact of the performance and efficiency of a broad range of engineering systems including aircraft wings, wind turbine blades, and turbo-machinery and can have potentially catastrophic consequences. The accurate prediction of turbulent boundary layer (TBL) separation remains a significant change to engineering design and is typically complicated by the extensive range of streamwise pressure gradient distributions that occur in practical engineering flows over vehicles and through ducts and turbo-machinery. Direct numerical simulation of TBLs under adverse pressure gradients (APG) have been preformed by Lee and Sung [4] for weak pressure gradient and for a stronger separating non-equilibrium APG in the case of Gungor et al. [2]. In order to decouple the effect of upstream flow history and surface curvature from the influence of the local pressure gradient it is instructive to consider the case of a canonical self-similar adverse pressure gradient (APG) equilibrium turbulent boundary layer (TBL). Defined as a APG TBL with no spatial variation in skin friction coefficient (C_f) and shape factor (H), which exhibits statistical similarity over the equilibrium domain. In the present study simulations were performed using the TBL DNS code of Simens et al. [8] and Borrel et al. [1], with a far-field boundary condition applied in order to generate an equilibrium flow with a strong APG nearing the verge of separation.

DIRECT NUMERICAL SIMULATION AND BOUNDARY CONDITIONS

Simulation of the APG TBL was performed via direct numerical solution of the incompressible Navier-Stokes equations in a three-dimensional rectangular volume with a no-slip boundary condition applied along the flat floor of the domain. A Fourier decomposition was used to represent the flow in the periodic spanwise direction (z), with the compact finite difference method of [5] used in the aperiodic streamwise (x) and wall-normal (y) directions. The modified three sub-step Runge-Kutta scheme of [8] is used to step the equations forward in time. Following Sillero et al. [7] the flow at the inlet is a zero pressure gradient (ZPG) TBL specified by mapping and rescaling a streamwise wall-normal plane from a point in the simulation ≈ 60 inlet boundary layer thickness ($\delta_{99,I}$) downstream of the inlet. A ZPG was simulated for the initial $100\delta_{99,I}$ with the APG region initiated $\approx 40\delta_{99,I}$ downstream of the recycling plane by changing the boundary condition at the top of the domain to include both a zero spanwise vorticity and a wall normal suction velocity. This specified wall-normal velocity was estimated based on the analytical free-stream streamwise velocity distribution for a flow at the point of separation [6] $u_\infty(x) \propto x^m$ with $m = -0.23$ and the assumption that the streamlines of the outerflow follow the growth of the boundary layer thickness.

RESULTS

Initial results show the desired near constant non-dimensionalized pressure velocity $u_p/U_\infty = 1/U_\infty \sqrt{\delta^*/\rho \, \mathrm{d}P/\mathrm{d}x}$ over a domain from 200 to $600\delta_{99,I}$ (see figure 1). Examples of the velocity defect profiles at different stations through the equilibrium APG domain are shown in figure 2. The final manuscript will present one and two point statistics associated with the equilibrium APG. The collapse of each of these statistics will be examined under inner, outer and pressure based scalings.

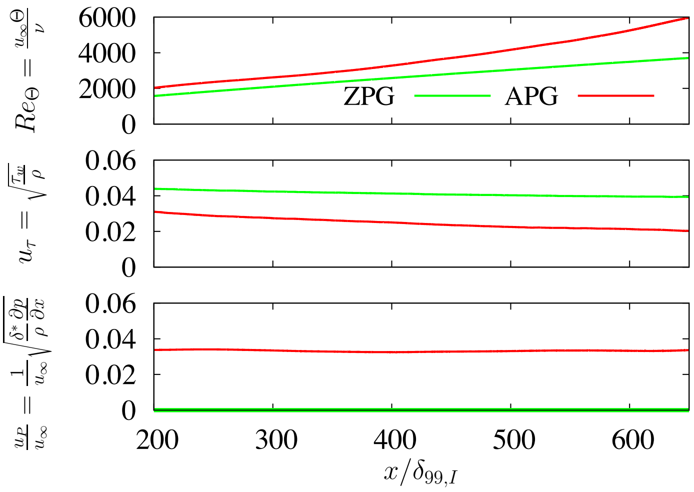

Figure 1. Properties of the adverse pressure gradient region of the present simulation.

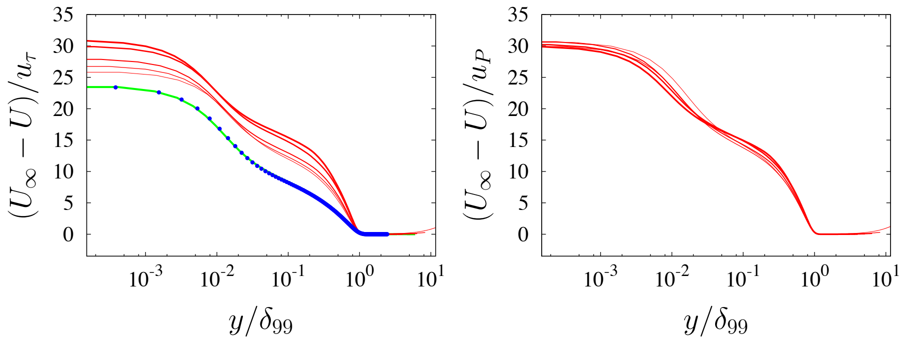

Figure 2. Mean velocity defect profiles in inner wall (u_τ) and pressure velocity (u_p) scaling. ZPG TBL DNS of Jiménez et al. [3] - blue dots; ZPG TBL DNS current simulation - green line; APG TBL DNS from current simulation at different stream wise locations - red lines.

ACKNOWLEDGEMENTS

The authors acknowledge the research funding from the Australian Research Council and European Research Council, and the computational resources provided by NCI and PRACE.

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