HISTORY EFFECTS IN ADVERSE PRESSURE GRADIENT TURBULENT BOUNDARY LAYERS – SIMULATIONS & EXPERIMENTS

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Summary The present investigation focusses on the concerted investigation of pressure gradient and streamwise curvature effects on turbulent boundary layers. In particular, a number of direct and large-eddy simulations covering a wide range of pressure gradient parameters and streamwise histories on flat and curved surfaces is performed and will be compared with wind tunnel experiments that overlap and extend the Reynolds number range. Results are aimed at isolating the effects of pressure gradients, streamwise curvature and streamwise (pressure gradient) histories, which have traditionally inhibited to draw firm conclusions from the available data.

MOTIVATION

The quest for more efficient airplanes, trains and other ground vehicles is directly coupled to reducing the form and/or friction drag without compromising the other. A prototype of a canonical flow on which our understanding of friction drag has been developed is the zero-pressure gradient (ZPG) turbulent boundary layer (TBL). Despite its importance for fundamental research, most flows of relevance in technical applications are exposed to various pressure gradients and surface curvature which instead may lead to changes (increase) of the form drag. The applicability of knowledge from canonical wall-bounded flows is hence limited when it comes to these complex flows and geometries (see e.g. Ref. [4]). While the effect of pressure gradient and surface curvature has been the focus of much attention, their combined effect is not a simple superposition and therefore deserves special attention [8]. Although a number of simulations and experiments on e.g. adverse pressure gradients (APG) were performed in the past (spanning a wide range of Reynolds numbers Re and the values of the Clauser pressure gradient parameter β), it is hard to draw firm conclusions from the available data due to the differently varying streamwise gradients of β, i.e. different upstream histories leading to a particular pressure gradient condition. The present contribution aims therefore at establishing different upstream histories on curved and flat surfaces, and in particular to maintain a region of constant β, in order to study the genuine effect of the imposed pressure gradient and its upstream history separately.

METHODS AND OUTLOOK

A number of direct numerical and large-eddy simulations (DNS and LES) have been performed in flat plate ZPG [5, 6] and APG [1] TBLs with different power-law free-stream parameters m. Additionally, the results of a DNS of the flow around a wing section represented by a NACA4412 profile are at hand (Fig. 1), which complement the numerical data base and already indicate clear dependencies on pressure gradient and upstream histories as evident from Fig. 2: By comparing the wing and the flat plate at a matched Re_τ and β, it is possible to assess the effect of history, i.e. of $\beta(x)$, on the state of the TBL. As apparent, the wake region in the mean velocity as well as the outer peak in the variance profile are significantly affected by the history of the pressure gradient; a manifestation of the interaction between the large-scale motions, which are more energetic due to the APG, and the outer flow. Further simulations are being performed in which a sufficiently long constant β range is established. To extend the Re-range and cross-validate numerical and physical experiments, wind tunnel experiments are currently ongoing in the Minimum Turbulence Level (MTL) wind tunnel at KTH Royal Institute of Technology in which the desired pressure gradient conditions and histories will be established by means of wall inserts. Besides oil-film interferometry, hot-wire anemometry and particle image velocimetry will be employed to measure the wall shear stress and study the flow kinematics and dynamics, respectively.

The results from these concerted efforts will be presented at the congress.

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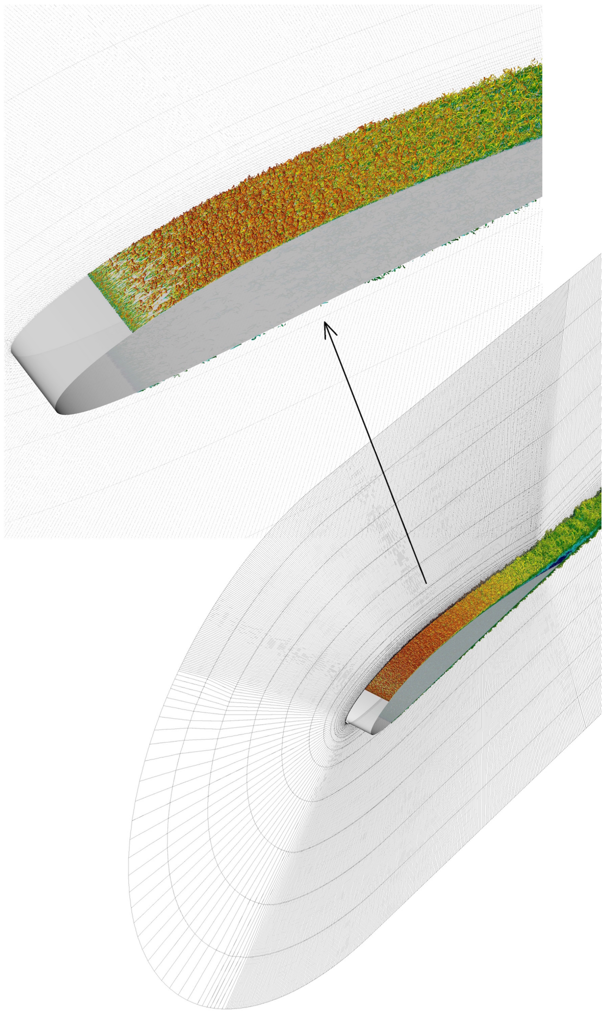

Figure 1: Instantaneous visualization of the flow around the NACA-4412 airfoil, with $Re_c = 400000$ and angle of attack of 5 degrees. The figure shows coherent vortices identified by means of the λ_2 criterion [2]. The spectral element mesh is also shown, but not the individual grid points within elements. Note that the flow is tripped at a distance 10% of the chord length downstream of the leading edge, both on the pressure and suction sides. For full details, see Ref. [7].

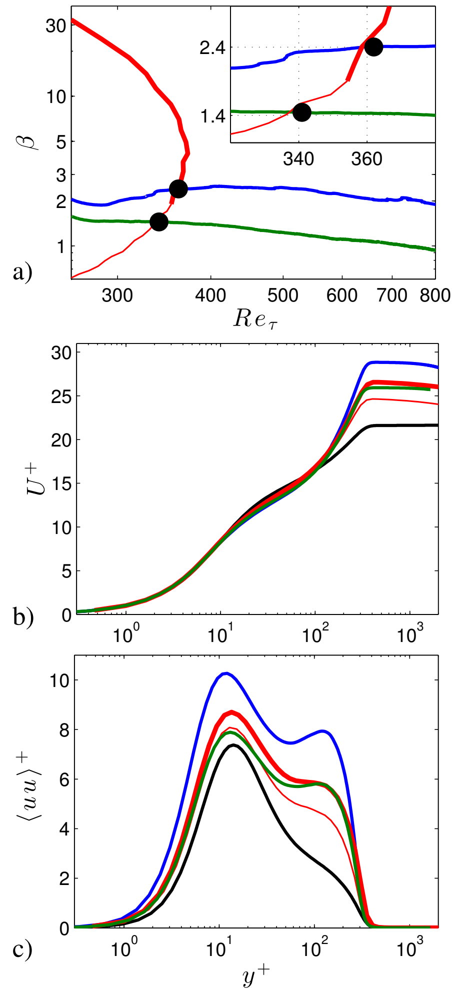

Figure 2: a) Clauser pressure gradient parameter β as function of friction Reynolds number Re_τ for the boundary layer on the wing (red), and the flat plate ($m = -0.13$: green, $m = -0.16$: blue). Inset indicates the matched $\beta - Re_\tau$ values. Inner-scaled b) mean and c) variance profiles for the matched conditions (filled circles) shown in a) compared with a ZPG TBL on a flat plate [5] at comparable Re_τ (black).

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