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Structural differences between small and large momentum-defect turbulent boundary layers

Yvan Maciel[a,*], Ayse G. Gungor[b], Mark Simens[c]

[a] Department of Mechanical Engineering, Laval University, Quebec City, Quebec, G1V 0A6 Canada
[b] Faculty of Aeronautics and Astronautics, Istanbul Technical University,Maslak, Istanbul, 34469 Turkey
[c] School of Aeronautics, Universidad Politécnica de Madrid, Madrid, 28040 Spain

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ABSTRACT

We analyse how coherent structures in turbulent boundary layers (TBL) change in response to a strong adverse pressure gradient by using two direct numerical simulation databases. One zone of a zero-pressure-gradient TBL and three zones of a strongly decelerated TBL, corresponding to three ranges of mean velocity defect, with the shape factor varying from 1.54 to 3.75, are considered. We investigate the properties of three-dimensional sweeps, ejections and streamwise-velocity structures. The identified sweeps and ejections contribute everywhere more than 30% to the Reynolds shear stress in both flows. The effect of increasing mean velocity defect in the adverse-pressure-gradient TBL is significant. Streamwise-velocity structures and all wall-attached sweeps and ejections, that is near-wall ones and taller ones that reach the wall region (important in the logarithmic layer of the zero-pressure-gradient TBL), lose their streamwise elongation and become less organised. Wall-attached sweeps and ejections become progressively less numerous and spanwise elongated structures become more frequent. Their strength diminishes in comparison to wall-detached ones and they lose their role as the main contributors to the Reynolds shear stress. In terms of spatial organisation, a pair of side-by-side sweep and ejection is still the dominant configuration, but the probability of such an event has decreased. This fact, together with other results of spatial organisation of structures, does not point toward the presence of a Kelvin-Helmholtz-type instability or a varicose instability of low-speed structures in the outer region, two instabilities that have been suggested in the literature to explain the turbulence regeneration process in large velocity defect turbulent boundary layers.

1. Introduction

A turbulent boundary layer (TBL) subjected to a strong or prolonged adverse pressure gradient (APG) develops a large mean velocity defect in the outer region. As a result, the mean shear rates in the outer region are no longer small in comparison to their near-wall counterparts, in contrast to canonical wall-bounded turbulent flows such as zero-pressure-gradient (ZPG) boundary layers and fully-developed pipe and channel flows. Consequently, turbulence activity and production is small near the wall and important in the outer region of the flow (Skåre and Krogstad, 1994; Na and Moin, 1998; Elsberry et al., 2000). Furthermore, an inflectional instability of the mean flow might be present in the outer region since the mean velocity profile now possesses an unstable-type inflection point there. As it is further discussed below, a few studies suggest that the physical mechanisms and coherent structures responsible for the production and transport of turbulence might be different in boundary layers with a moderate to large mean velocity defect, but our knowledge on these important topics is very limited.

In the case of canonical wall-bounded turbulent flows, coherent structures and turbulence regeneration processes have been analysed extensively. Jiménez (2013), Jiménez and Kawahara (2013) and Marusic and Adrian (2013) provide recent reviews from different viewpoints on the current state of knowledge. In the buffer layer, it is generally accepted that the turbulence regeneration process involves the generation and amplification of long streamwise jets (streaks of the streamwise velocity) by a lift-up effect caused by quasi-streamwise vortices. The amplified streaks become unstable and nonlinear mechanisms generate new vortices. Since (Kline et al., 1967) it is recognised that ejections of near-wall fluid, due to the lift-up and bursting processes of low-momentum streaks,

* Corresponding author.
E-mail addresses: yvan.maciel@gmc.ulaval.ca, ymaciel@gmc.ulaval.ca (Y. Maciel), ayse.gungor@itu.edu.tr (A.G. Gungor), markphilsimens@gmail.com (M. Simens).

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account for a large portion of the generation of Reynolds shear stress and turbulent kinetic energy. The logarithmic layer is another important flow region of canonical wall flows since at high Reynolds number a large part of the turbulent kinetic energy is produced there (Marusic et al., 2010). Low-momentum streaks, sweeps and ejections of the logarithmic layer are bigger, span various scales and are themselves turbulent. Moreover, the dynamical processes involved are multiscale and more complex (Jiménez, 2012). Townsend (1961) hypothesised that the energy-containing motions consist of a hierarchy of self-similar wall-attached (extending to the wall) structures, hence whose size is proportional to the distance of their centres from the wall. This hypothesis is at the base of at least three distinct conceptual models of the coherent structures found in the logarithmic layer. In one of these models (Marusic and Adrian, 2013), the self-similar wall-attached structures are organised groups of streamwise aligned hairpin vortices, termed hairpin packets (Adrian et al., 2000). These hairpin packets are assumed to originate close to the wall and to grow self-similarly. They induce large regions of streamwise-elongated streamwise momentum deficit, as well as ejections and sweeps. In another conceptual model (Jiménez, 2013), the self-similar wall-attached structures of the logarithmic layer are large-scale streaks, ejections, sweeps and vortex clusters (of a more disorganised character than the hairpin packets in the previous model) which are not born close to the wall. A shear-related temporally intermittent bursting of the streaks, leading to the sweeps and ejections, would be involved in the production of turbulence. Individual vortices are seen as too disorganised and small to play a significant role in the generation of Reynolds shear stresses, but vorticity in the vortex clusters retains enough organisation to induce large-scale circulation. In a third conceptual model (Hwang, 2015), the main mechanism of turbulence production in the outer region is considered very similar to the near-wall one. It consists in the amplification of long streaky motions by a lift-up effect caused by several shorter quasi-streamwise vortices that tend to be streamwise aligned. The amplified streaks become unstable, breakdown and nonlinear mechanisms generate new vortices.

In all the above conceptual models, for both near-wall and logarithmic layers, ejections and sweeps are the specific coherent motions that carry most of the Reynolds shear stress. As such, they play a crucial and direct role in terms of momentum flux and production of turbulent energy (even if they are not considered by all to be part of the key coherent structures in the turbulence regeneration cycle). For that reason they have been studied extensively with the help of one-point quadrant analysis in the plane of streamwise and wall-normal velocity fluctuations (Robinson, 1991; Wallace, 2016). Lozano-Durán et al. (2012) have recently extended the quadrant analysis to three-dimensional structures in a direct numerical simulation (DNS) study of turbulent channel flows focusing on the logarithmic and wake layers. They called Qs the three-dimensional uv structures that are split according to their quadrant position in the (u, v) plane. They found that wall-detached Qs (in the sense of not reaching the wall at their base) are generally background fluctuations while wall-attached Q2s (ejections) and Q4s (sweeps) are bigger and carry most of the Reynolds shear stress in channel flows. The wall-attached Q2s and Q4s tend to be side-by-side, lodged within low- and high-speed streaks respectively. More recently, Lozano-Durán and Jiménez (2014) studied the time evolution of these three-dimensional ejections and sweeps. They found that wall-attached Q2s and Q4s are essentially mirror images of each other and they suggested that they are both manifestations of a single quasi-streamwise roller lying between them. They also showed that their dynamics is controlled by the local mean shear and that most of them are not born close to the wall.

In comparison to canonical wall flows, the information on coherent structures found in APG TBLs is much more limited. The seminal paper of Kline et al. (1967) on near-wall structures of turbulent boundary layers considered cases with negative and positive pressure gradients, but these were fairly mild. They found that a positive pressure gradient tends to make near-wall ejections of low-speed fluid more violent and more frequent. Almost 30 years passed before the next detailed study of coherent motions in an APG TBL by Krogstad and Skåre (1995). They compared an equilibrium large-defect APG TBL with a ZPG TBL and found that the streamwise correlation length of u was considerably shorter in the APG case throughout the boundary layer, suggesting less streaky u structures, a result also obtained later in equilibrium APG TBLs with moderate velocity defect (Lee and Sung, 2009) and in non-equilibrium large-velocity-defect TBLs (Rahgozar and Maciel, 2011; 2012; Gungor et al., 2014). Krogstad and Skåre (1995) also determined that the strongest motions in the lower part of their APG TBL are first and fourth quadrant motions, while in a ZPG TBL the strongest motions are second and fourth quadrant ones. In a non-equilibrium APG TBL, Nagano et al. (1998) also found that the contribution of sweeps to the Reynolds shear stress increases in the lower half of the boundary layer as the mean velocity defect increases in comparison to that of ejections. In the case of a turbulent separation bubble simulated by Na and Moin (1998), Chong et al. (1998) suggested that in the APG zone prior to detachment more of the coherent structures which contribute to the Reynolds shear stress are structures which are not connected to the wall. Lee and Sung (2009) investigated two equilibrium mild-APG turbulent boundary layers together with a ZPG TBL and found that the near-wall streaks became weaker and more irregular as the velocity defect increased. In the case of a non-equilibrium TBL with a moderate adverse pressure gradient, Harun et al. (2013) showed that the large-scale u-structures are more energised by the pressure gradient in the outer region than the small-scale ones. In an experimental study of a TBL subjected to a strong adverse pressure gradient, Shafiei Mayam (2009) found streamwise-aligned groups of spanwise vortices that were more compact in the streamwise direction and more inclined with respect to the wall than in ZPG TBLs. Rahgozar and Maciel (2011) studied the same flow and observed that u-structures become less streaky as the mean velocity defect increases and that energetic high-speed structures start to dominate the lower half of the boundary layer.

Very few researchers have attempted so far to identify the turbulence regeneration processes present in large-defect boundary layers. Although the focus of their study was not on this issue, Elsberry et al. (2000) suggested that the outer peaks of Reynolds stresses and turbulent kinetic energy production are due to the inflectional instability of the mean velocity profile as in mixing layers. On top of the possible presence of the latter instability, Marquillie et al. (2011) found varicose instability modes of low-speed streaks through linear modal stability analysis in the case of a channel flow with a curved wall. These modes were due to the wall-normal inflection points of the base flow consisting of the mean flow with a superimposed conditional streak. However, the type and strength of the instability was found to be strongly dependent on the base flow considered (mean velocity profile and specific conditional streak added). By analysing three different large-velocity-defect TBLs, Gungor et al. (2014; 2016) found that the outer-region turbulent statistics of TBLs close to separation resemble those of single-stream mixing layers, as already partly observed by Simpson et al. (1977), Driver (1991) and Na and Moin (1998). They also concluded that these boundary layers are globally less efficient in extracting turbulent energy from the mean flow than the zero-pressure-gradient boundary layer, even throughout