Large-scale structures in wall-bounded turbulence: (implications to control strategies)

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A review is provided of large and very large scale structures in wall-bounded turbulent flows. Collating from a variety of sources, a detailed three-dimensional instantaneous and conditionally averaged view of these large-scale events is presented. The relationship between these events and both the interfacial bulging and the near-wall coherent cycle is investigated, and links are drawn with the now well-studied processes of amplitude modulation and superposition between the large-scales and the small-scale turbulence. It is now relatively well accepted that the importance of these large-scale events increases with Reynolds number. The Reynolds number (and in particular the friction Reynolds number Re_τ), is a measure of the ratio between the large scales and the viscous length-scale and hence can be considered to be a measure of the scale separation existing in turbulent boundary layers ($Re_\tau = U_\tau \delta / \nu$, where δ is the boundary layer thickness and ν / U_τ, the ratio between the kinematic viscosity and the friction velocity, is the viscous length-scale). The energy due to the near-wall streaks in the streamwise velocity component appears in the energy spectra at streamwise and spanwise wavelengths of $\lambda_x^+ \approx 1000$ and $\lambda_y^+ \approx 100$ respectively (where the plus superscript denotes normalisation with the viscous length-scale). The large scale logarithmic energy, appears in the spectra centered approximated in the log region at $\lambda_x / \delta \approx 6$ and $\lambda_y / \delta \approx 0.7$ (Hutchins & Marusic, 2007). Hence, we can see that the large-scale structures are approximately $6Re_\tau/1000$ times larger in size than the near-wall cycle. At Reynolds numbers close to transition, there is little or no separation in scale, but by $Re_\tau \approx 16000$, we expect a scale separation of $O(100)$. In addition to increasing scale separation, we note that as Reynolds number increases, under viscous scaling, the amount of turbulent energy contained in these large-scales also increases in comparison to the small-scale energy from the near-wall cycle (which remains constant). This has two effects. (i) the superimposed large-scale footprint at the wall increases in strength relative to the near-wall cycle, causing an increasingly prominent large-scale quasi-steady variation of the wall shear stress. As these large-scale regions of modified wall-shear stress become very large in terms of viscous length-scales, we would expect the size, amplitude and convection velocity of the near-wall viscous scaled events to locally conform to this modified large-scale value of the shear stress. Indeed, this response provides the origin of the observed amplitude and frequency modulation observed in the near-wall region (Mathis *et al.*, 2009, 2013)(ii) a diminishing proportion of the total turbulent production is due to the near-wall region, with the logarithmic region becoming dominant at $Re_\tau \sim$O(10000) (Marusic *et al.*, 2010). Both of these effects might suggest a decreasing effectiveness at high Reynolds numbers for control strategies that only directly modify the near-wall region. Based on this observation, several control strategies and experiments that have sought to directly modify the large-scale structures in the logarithmic and wake regions of higher Reynolds number turbulent boundary layers are investigated. These include: highly directional riblet surfaces with a capacity to impose a large-scale spanwise periodicity into the logarithmic region (Nugroho *et al.*, 2013); perturbations to the inlet tripping conditions, which have the ability to modify the boundary layer evolution via modifications to the large-scale wake region structure; active control of the large-scale log region events using wall-normal jets. Effective control or interruption of these large-scale structures will require increased understanding of their origins as the flow evolves from low to high Reynolds number, to this end large-scale novel PIV experiments, both in the conventional wind-tunnel frame of reference (de Silva *et al.*, 2014), and with a stationary time-resolved PIV system imaging a towed flat plate (Lee *et al.*, 2014) will also be presented.

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