Fully mapped energy spectra in a high Reynolds number turbulent boundary layer

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Analysis of the surface formed from the pre-multiplied energy spectra of streamwise velocity fluctuations $k_x\phi_{uu}/U_\tau^2$ (as calculated at numerous wall-normal stations across the turbulent boundary layer) has provided much recent insight regarding the structure and energy content of the logarithmic region [1]. The manner in which this surface is formed is illustrated in figure 1. The axis system x, y and z refer to the streamwise, spanwise and wall-

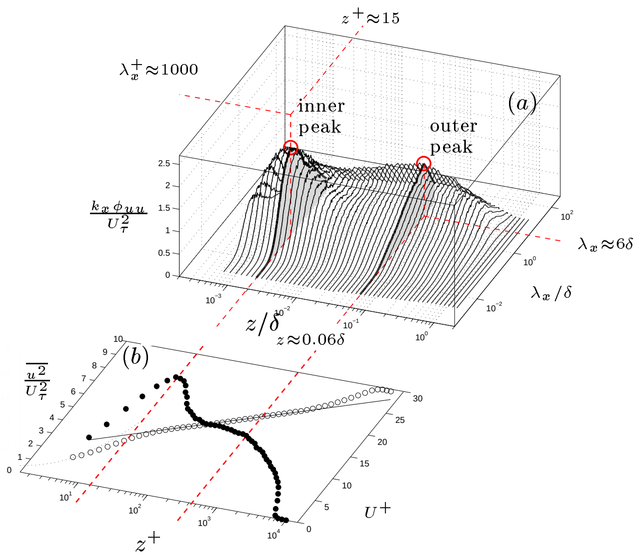

Fig. 1. (a) Premultiplied energy spectra of streamwise velocity fluctuation $k_x\phi_{uu}/U_\tau^2$ for a turbulent boundary layer at $Re_\tau \approx 7300$ as a three-dimensional surface plot for all wall-normal locations; (b) corresponding ($\circ$) mean velocity and ($\bullet$) broadband turbulence intensity profiles. Dashed lines denote inner and outer spectral peaks.

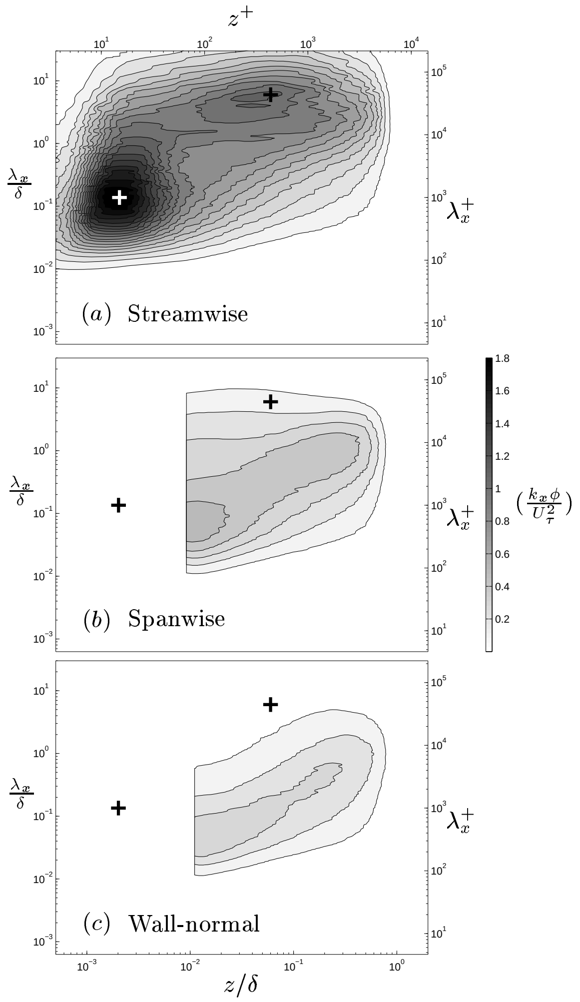

Fig. 2. Contours of pre-multiplied energy spectra for (a) streamwise $k_x\phi_{uu}/U_\tau^2$ (b) spanwise $k_x\phi_{vv}/U_\tau^2$ (c) wall-normal $k_x\phi_{ww}/U_\tau^2$ fluctuations. Contours are from 0.1 to 1.8 in steps of 0.1 (see gray scale). (+) symbols denote approximate locations of inner ($z^+ \approx 15, \lambda_x^+ \approx 1000$) and outer ($z/\delta \approx 0.06, \lambda_x/\delta \approx 6$) peaks in u spectra.

normal directions, with u, v and w denoting respective fluctuating velocity components. At adequate Reynolds number the surface in figure 1(a) assumes a bimodal appearance, comprised of an inner peak fixed in viscous wall-units and due to the near-wall cycle, along with an outer peak, scaling on boundary layer thickness and due to a much larger class of structure inhabiting the log region, termed the 'superstructure' [1]. As Reynolds number increases, the scale separation between these two peaks increases, in addition to which the outer peak becomes increasingly comparable in energy to the inner. Here we build on this picture, presenting similar energy surfaces for the wall-normal

(w) and spanwise (v) components. The novelty of these results lies not just in the manner of presentation and interpretation, but also in the excellent spatial and temporal resolution afforded by the high Reynolds number boundary layer facility at Melbourne. Details of this facility are given in [4]. Data are obtained using constant-temperature hot-wire anemometry (single-normal wires for u and $\times$-wires for v and w; nominal wirelength $l^+ = lU_\tau/\nu = 22$). The size of the $\times$-wire precludes the possibility of measuring v and w for $z^+ \lesssim 70$.

Figure 2 shows contour maps of pre-multiplied energy spectra for all three velocity components at $Re_\tau = 7300$. These maps are iso-contours of surfaces constructed from individual spectra (such as those shown in figure 1). A full description of the bimodal appearance in the u spectra of plot (a), along with structural origins, is given in [1, 2]. For now, we just highlight the locations of the inner and outer peaks in all plots (using + symbols). Immediately noteworthy in the v and w spectra of plots (b) and (c) is the inclined ridge of energy where length-scale (λ) is proportional to distance from the wall (z). This is indicative of attached eddies [6, 5] (this inclined behaviour is also evident in the u spectra of a). However, an important distinction between the v and w components occurs in the near-wall region where the wall-normal fluctuations lack a large-scale energetic contribution, in contrast to the spanwise fluctuations which exhibit near-wall energy at large 'superstructure' type length-scales ($\lambda_x \sim 6\delta$). Such behaviour is consistent with the notion of attached eddies (where the wall-normal fluctuations will lack a large-scale component at the wall due to blocking or image vortices[5]). It is also consistent with the notion that the superstructure is associated with very large counter-rotating roll-modes [2]. These results are suspected to hold for very high Reynolds numbers. Measurements made in the log region of the atmospheric surface layer have also reported ϕ_{ww} as scaling only with inner variables (z, U_τ) [3].

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