1. Background

In a series of experimental studies, extending over a period of some 10 years, Marusic, Mathis, Hutchins and their collaborators (e.g. [1]) have investigated the response of the near-wall streaks in the viscosity-affected sublayer to large-scale outer structures, the latter typically present at a distance of 0.1-0.2 of the boundary-layer thickness from the wall. They show, in particular, that the outer structures affect the near-wall turbulent fluctuations in two ways: by “footprinting” and “modulation”, the former being a superposition process and the latter being a more subtle interaction leading to amplification/attenuation of small-scale fluctuations. One particularly notable outcome of this work has been the proposal of an empirical relationship that permits the statistics of the near-wall turbulence to be “predicted”, at any Reynolds number, from a “universal” small-scale signal, unaffected by large-scale motions (and thus Reynolds number), and a record of the Reynolds-number-dependent large-scale outer fluctuations in the log-law region. Thus, if the universal signal is denoted $u^*$, the outer large-scale motions at location $y_+$ are denoted $u_{LS}^*$, the empirical relationship for the actual near-wall fluctuations $u'$ takes the form,

$$u'(y_+) = u^*(y_+)[1 + \beta(y_+)\theta u_{LS}^*] + \alpha(y_+)\theta u_{LS}^*$$

in which $\alpha, \beta$ are empirical functions, derived from experimental data, and $\theta$ in an angle that accounts for the correlation between the large-scale motions at $y_+$ and those at $y'$. In the above equation, the latter term represents the superposition (footprinting) process and the former the modulating influence of the large-scale motions.

In a recent PoF paper [2], the present authors have investigated eq. (1) by reference to DNS data for channel flow at $Re_\tau=1020$, and have shown that the symmetric response to high-speed and low-speed large-scale fluctuations, implied by the eq. (1), is not supported by the data. The authors separated large-scale from small-scale motions using a two-dimensional version of the Empirical Mode Decomposition of Huang et al. [3], and then extracted the joint PDFs of $u^*, v^*$ (the latter assumed to be the EMD-derived small-scale motion) from eq.(1), subject to $\alpha, \beta$ given by the originators of eq. (1) for $u^*$. An example of the analysis, for $y' = 13.5$, is given in Fig. 1 (a).

Figure 1. Joint PDFs of velocity fluctuations at $y' = 13.5$ from DNS; (a) for “universal” $u^*, v^*$ fluctuations ($u^*$ extracted from eq. (1) and $v^*$ from the EMD small scale) for highly positive large-scale fluctuations (red contours) and highly negative large-scale fluctuations (green contours); (b) for small-scale $(u, w)$ fluctuations, illustrating “splatting”.

The present authors are of the view that the non-universality displayed in Fig. 1(a) is a likely consequence of “splatting” (sweeps/ejections), implied by Fig. 1(b), and a failure of eq. (1) to take the effects of this process into account. In [3] the authors presented a preliminary alternative to eq. (1), which reduced the differences between the PDFs in Fig. 1(a), thus improving the universality of the $(u^*, v^*)$ field. The authors have
pursued this work further, deriving additional statistical data, extracted from the DNS, and extending the model presented in [3]. They also examine, albeit as a minor aspect, the validity of the “Quasi-Steady” model of Chernyshenko et al [4], which is based on the proposition that scaling in eq. (1) should be effected with the local large-scale friction velocity.

2. Research Contribution

We consider ensemble-averaged statistics, conditioned on large-scale motions. Spatial $(x-z)$ snapshots are obtained at various $\gamma^+$ levels. In each snapshot, domains of positive and negative large-scale fluctuations are identified. Only patches of extreme +/- 10% events within the PDF of the all large-scale motions are considered. Statistics of small-scale motions are then extracted within these patches. This is also the approach underpinning Fig. 1(a).

![Figure 2](image.png)

**Figure 2.** Profiles of streamwise small-scale-fluctuations energy, conditioned on large-scale motions; (a) scaling with mean friction velocity; (b) scaling with local large-scale friction velocity. Black line: total, time-averaged energy.

Fig. 2 gives profiles of the streamwise small-scale intensity, scaled with the mean and local large-scale friction velocity, respectively. Differences among the conditional profiles indicate effects of modulation and splatting only (footprinting is automatically eliminated). Clearly, neither mean scaling nor local scaling renders the small-scale statistics universal, Fig. 2(b) thus contradicting the “Quasi-Steady” universal assumption that underpins some current descriptions.

The phenomenological model proposed herein, in contrast to eq. (1), “predicts” the (instantaneous) velocity field at any $\gamma^+$ level from the following equation:

$$U^+ = U^+ \times \left( 1 + \frac{u_{1,LS}}{U_{1,LS}} \right) \times \left( 1 + X_i(y^+) \right) \left( \frac{u_{1,LS} + \langle U_{1,LS} \rangle}{u_{z}} \right)$$

in which $<...>$ denotes time-mean value and $X_i(y^+)$, to be given in detail in a paper to follow (because of its complexity), is also made to depend on the sign of $(u^+, v^+)$, i.e. on whether fluctuations are associated with ejections or sweeps. This model, when inverted to yield $u^+$, with all other quantities taken from the DNS data, gives the PDFs in Fig. 3, thus returning a good level of universality for the statistics of $u^+$. A full account of the research summarized herein is given in references below.
Figure 3. Joint (u-v) PDFs of the universal signal $\omega_i$ extracted from eq. (2) at three levels of $y'$. Each plot has two sets of contours, one (red) pertaining to regions of extreme 10% positive and the other (green) for regions of extreme 10% negative large-scale fluctuations.

References


Further relevant references

7. Agostini, L, and Leschziner, M A (2015), Predicting the response of small-scale near-wall turbulence to large-scale outer motions outer large-scale structures on near-wall turbulence in channel flow, in press, Physics of Fluids.