Predicting the Response of Small-Scale Near-Wall Turbulence to Large-Scale Outer Motions

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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_o^+ are denoted $u_{o,LS}^+$, the empirical relationship for the actual near-wall fluctuations u^+ takes the form,

$$u^+(y^+) = u*(y^+)[1+\beta(y^+)\theta u_{o,LS}^+] + \alpha(y^+)\theta u_{o,LS}^+ \quad (1)$$

in which α, β are empirical functions, derived from experimental data, and θ in an angle that accounts for the correlation between the large-scale motions at y_o^+ 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_τ=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 α, β given by the originators of eq. (1) for $u*$. An example of the analysis, for $y^+ = 13.5$, is given in Fig. 1 (a).

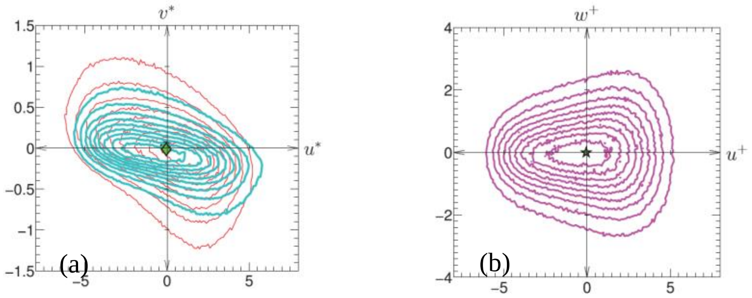

Figure 1. Joint PDFs of velocity fluctuations at $y^+ = 13.5$ from DNS; (a) for "universal" $u*, v*$ fluctuations ($u*$ extracted from eq. (1) and $v*$ from the EMD small scale) for highly positive large-scale fluctuations (red contours) and highly negative large-scale fluctuations (green contours);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

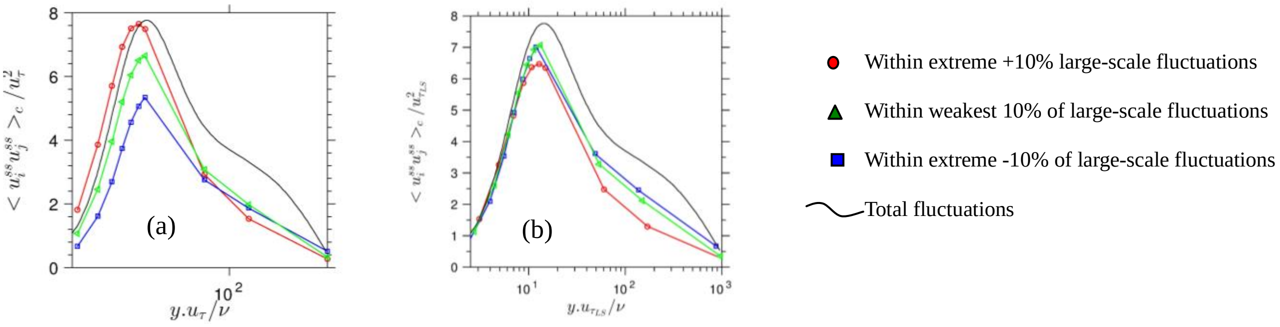

Figure 2. Profiles of streamwise small-scale-fluctuations energy, conditioned on large-scale motions; (a) scaling with mean friction velocity; (b) scaling with local large-scale friction velocity. Black line: total, time-averaged energy.

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" universality assumption that underpins some current descriptions.

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

$$U_i^+ = u_i^* \times \underbrace{\left(1 + \frac{u_{1,LS}}{\langle U_{1,LS} \rangle}\right)}_{\text{modulation}} \times \underbrace{\left(1 + \chi_i(y^+) \frac{u_{1,LS}}{\langle U_{1,LS} \rangle}\right)^{-1}}_{\text{splatting}} + \underbrace{\frac{u_{i,LS} + \langle U_{i,LS} \rangle}{u_\tau}}_{\text{superposition}} \quad (2)$$

in which <…> denotes time-mean value and $\chi_i(y^+)$, 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_i^*, 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_i^*.

A full account of the research summarized herein is given in references below.

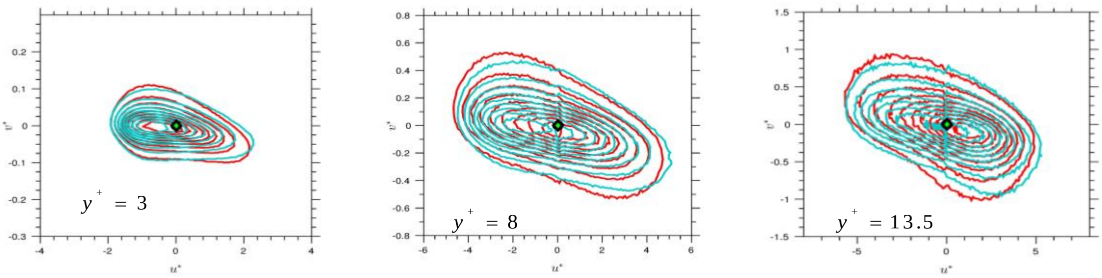

Figure 3. Joint (*u*-*v*) PDFs of the universal signal u_i^* extracted from eq. (2) at three levels of y^+. Each plot has two sets of contours, one (red) pertaining to regions of extreme 10% positive and the other (green) for regions of extreme 10% negative large-scale fluctuations.

References

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Further relevant references

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