EXPLORING THE CONNECTION BETWEEN INTERFACIAL BULGING AT THE EDGE OF THE TURBULENT BOUNDARY LAYER AND LARGE-SCALE MOTIONS NEAR THE WALL

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Abstract We here explore the apparent connection between the large-scale interfacial bulging that is known to occur at the intermittent turbulent / non-turbulent interface of the turbulent boundary layer, and the very large-scale motions (or superstructures) that have been recently shown to predominate the logarithmic region of the layer. Building upon recent observations of amplitude modulation between large and small-scale structures in the turbulent boundary layer, we probe further the apparent link between superstructure events in the logarithmic region and zones of increased small scale turbulent activity at the edge of the boundary layer. Through analysis of the hotwire signals close to the outer limit of the boundary layer, we demonstrate that increased small-scale activity at the edge of the layer is strongly associated with bulging. By conditioning these hotwire signals with simultaneously acquired fluctuating wall shear stress signals, we demonstrate that the interfacial bulging is associated with a very large-scale footprint at the wall (consistent with the scale and arrangements that have previously been reported for very large scale motions). For the final conference presentation, this analysis will be extended to include recent large field-of-view high resolution PIV data obtained at $Re_\tau \approx 14000$ in the high Reynolds number boundary layer wind tunnel at the University of Melbourne.

EXPERIMENTS

The data from Hutchins *et al.* [2] are re-analysed here. These measurements were conducted in a zero pressure gradient turbulent boundary layer at friction Reynolds number $Re_\tau \approx 14000$. The experimental set-up (sketched in figure 1) consists of a spanwise array of 10 flush-mounted hot film skin friction sensors (Dantec 55P47, glue-on type). These sensors are separated by 0.08δ (where δ is the boundary layer thickness) such that they cover a spanwise domain of $\approx 0.7\delta$. There is also a standard hot-wire sensor mounted at $z/\delta \approx 0.8\delta$, sensing the velocity fluctuations close to the interface (or outer edge) of the turbulent boundary layer. For the original experiments, there were two hot-wires mounted on this sting, but we here only make use of data from the left-hand sensor as shown in figure 1. This sensor can be traversed in the wall-normal direction, but for this analysis we consider only data where the sensor is fixed in the highly intermittent interfacial zone of the boundary layer ($z \approx 0.77\delta$). Further details are provided in [2]. Throughout this analysis, x, y and z will be used to denote the streamwise, spanwise and wall-normal axes, with u, v and w denoting the respective fluctuating velocity components.

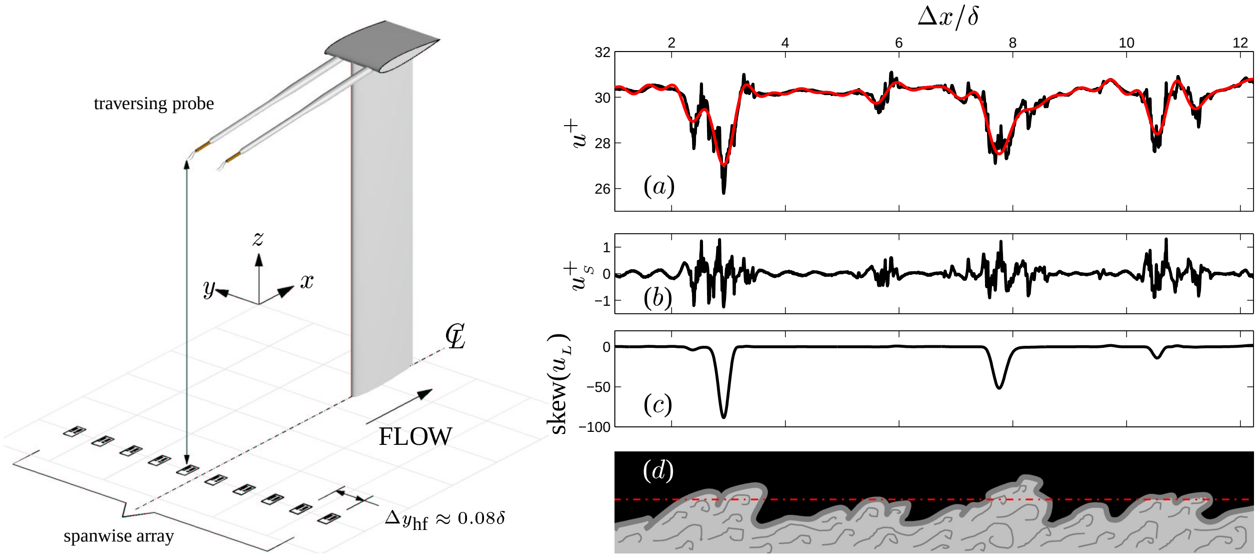

Figure 1. (Left) Diagram of the measurement array. (Right) (a) fluctuating velocity signal at $z/\delta \approx 0.77$ (large-scale component u_L is shown in red); (b) decomposed small-scale component u_S; (c) skewness of the large-scale component; (d) schematic of the edge of the boundary layer, showing the turbulent / non-turbulent interface. Red dot-dashed line represents a hot-wire measurement at $z/\delta = 0.77$.

RESULTS

Conditional averages presented in Hutchins *et al.* [2] have demonstrated that a large-scale negative skin friction fluctuation measured at the wall is associated with increased activity in small-scale turbulent u fluctuations towards the edge

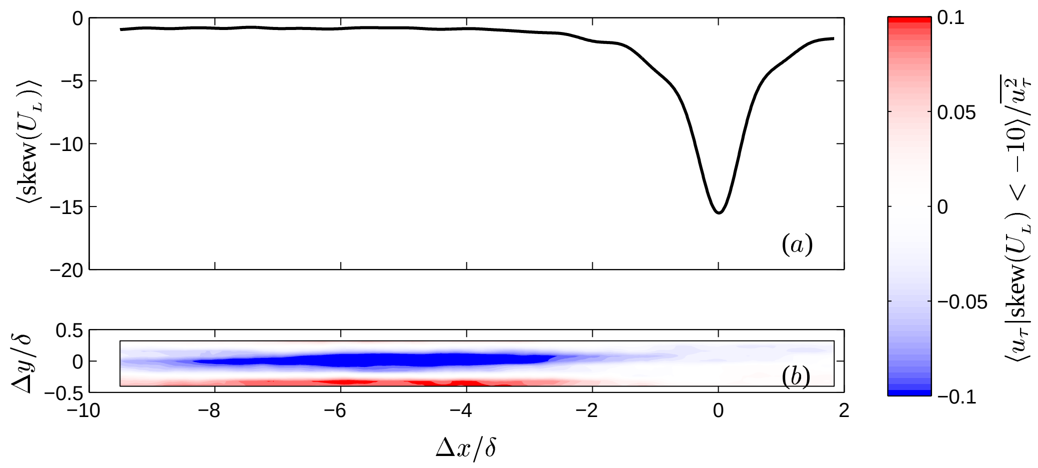

Figure 2. (a) shows condition event $\langle\text{skew}(u_L) < -10\rangle$ at $z/\delta = 0.77$, used to identify the interfacial bulge; (b) shows a two dimensional streamwise-spanwise map of the shear stress at the wall conditioned on the bulge event.

of the layer (see figure 9 in [2]). In the original work, the authors lacked a thorough explanation for this phenomenon. To explore this further, figure 1(a) shows the fluctuating velocity signal close to the edge of the layer at $z/\delta = 0.77$. The signal is highly intermittent, with quiescent regions occasionally punctuated by periods of intense turbulence. This distinctive signal is a result of the hot-wire measuring a path through the turbulent / non-turbulent interface as illustrated by the red dot-dashed line in the schematic of figure 1(d). The small-scale component of the velocity signal is shown in Figure 1(b). This decomposition is achieved using a spectral filter with a cut-off wavelength $\lambda_x^+ = 7000$. The small-scale signal in figure 1(b) demonstrates that at these locations, almost all small-scale activity is associated with the interfacial bulging. Thus the result from [2] (figure 9) can be reinterpreted as indicating a strong correlation between the very large-scale coherent structures in the buffer (and log) region with the interfacial bulging at the edge of the layer. To explore this further, we produce a conditionally averaged view of the footprint sensed by the spanwise array of skin friction sensors, conditioned on the occurrence of the interfacial bulging at the edge of the layer. To achieve this, it is first necessary to decide on a suitable signal that can indicate the presence of bulging. Figure 1(c) shows the skewness of the large-scale component (the large scale component is shown by the red line in figure 1a). It is observed that high negative values of this quantity are an excellent marker of the turbulent bulges. We use this signal to conditionally average the skin friction fluctuations at the wall (on situations where skew(u_L) exceeds some negative threshold). The resulting conditionally averaged skin friction signal at the wall is shown in figure 2(b). It is clear that the interfacial bulge (shown in plot a and occurring at $\Delta x = 0$), is accompanied by a noticeable large-scale skin friction footprint at the wall, with a form that is very similar to the previously observed superstructure event. This conditional average leads us to believe that the very large-scale features that are known to populate the logarithmic region (with a footprint down to the wall) are associated with the bulging that characterises the turbulent / non-turbulent interface at the edge of the boundary layer.

From the present data, it is impossible to establish any causal relationship between the bulging and the superstructure events. A ‘wall-up’ type description might imply that the bulging is merely the downstream end of a superstructure event, that has grown to the edge of the turbulent boundary layer. This would fit with Adrian’s suggestion [1] that the VLSM (or superstructures) might be concatenations of packet or ramp-like events. The conditional average shown in figure 2 would suggest that the largest (or oldest) packets are at the downstream end of the superstructure. On the other hand, a ‘top-down’ interpretation could suggest that entraining wake processes (associated with interfacial bulging) might interact with the wall and log region to create the very large scale motions. Present efforts are directed towards obtaining time resolved PIV [3] of a developing turbulent boundary layer in an attempt to answer these questions.

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