

Study of the Log. Layer Structure in Wall Turbulence Over a Very Large Range of Reynolds Number

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Abstract — An investigation was conducted of the logarithmic layer structure in turbulent boundary layers spanning three orders of magnitude change in Reynolds number. This was achieved by using two laboratory scale facilities and the atmospheric surface layer at the SLTEST facility in Utah. Several experimental techniques were used in order to probe the three-dimensional nature of the flow structures. Two-point correlation statistics are found to agree well over all Reynolds numbers with outer flow scaling, and large-scale coherence recently noted in the logarithmic region of laboratory-scale boundary layers are also present in the atmospheric surface layer flow.

1. Introduction

Recent studies ([1, 2, 3, 4]) have presented clear evidence that the logarithmic region in wall turbulence (defined here tentatively as $z^+ > 100$; $z/\delta < 0.15$) is populated by very long streamwise organized motions. Here z is the wall-normal distance, δ is boundary layer thickness and the + superscript means normalization with wall variables (U_τ and ν/U_τ). In this paper we use two-point correlations and other diagnostics to investigate how the log region structures change and scale with increasing Reynolds number. To do this we use three separate experimental facilities and three different measurement techniques to obtain a Reynolds number range of nominally $10^3 \leq Re_\tau \leq 10^6$, where $Re_\tau = \delta U_\tau / \nu$.

2. Experimental Facilities

The experiments were conducted in three different facilities: a low-speed wind tunnel at the University of Minnesota ($Re_\tau \leq 4,000$), the high Reynolds number boundary layer wind tunnel in the University of Melbourne ($Re_\tau \leq 20,000$), and at the SLTEST site on the salt flats of Western Utah ($Re_\tau \approx 10^6$). For details of each facility, see [5], [6] and [7] respectively. Figure 1 shows the measurement techniques used. They include an array of 18 sonic anemometers, a spanwise array of 10 hot-wires ([2]) and a dual-plane simultaneous PIV system ([8]). Taylor's hypothesis is used to convert the time-series data from the arrays to streamwise distance.

3. Results and Discussion

The Utah experiments were conducted under nominally neutrally buoyant conditions and the velocity profiles obtained were as expected from a shear-driven wall bounded flow. Figure 2 shows excellent agreement of the mean velocity profile, with a small indication that flow is marginally transitionally rough. Turbulence statistics (not shown here) also agree well with the expected trends.

Comparisons of the two-point correlations of the fluctuating streamwise velocity (R_{uu}) in the log layer are shown in figure 3, for the three sets of experiments. Scaled with δ (outer variable) the plots are seen to agree remarkably well over the three orders of magnitude change in Re_τ . It is noted that δ changed significantly between the three experiments; being nominally 0.07

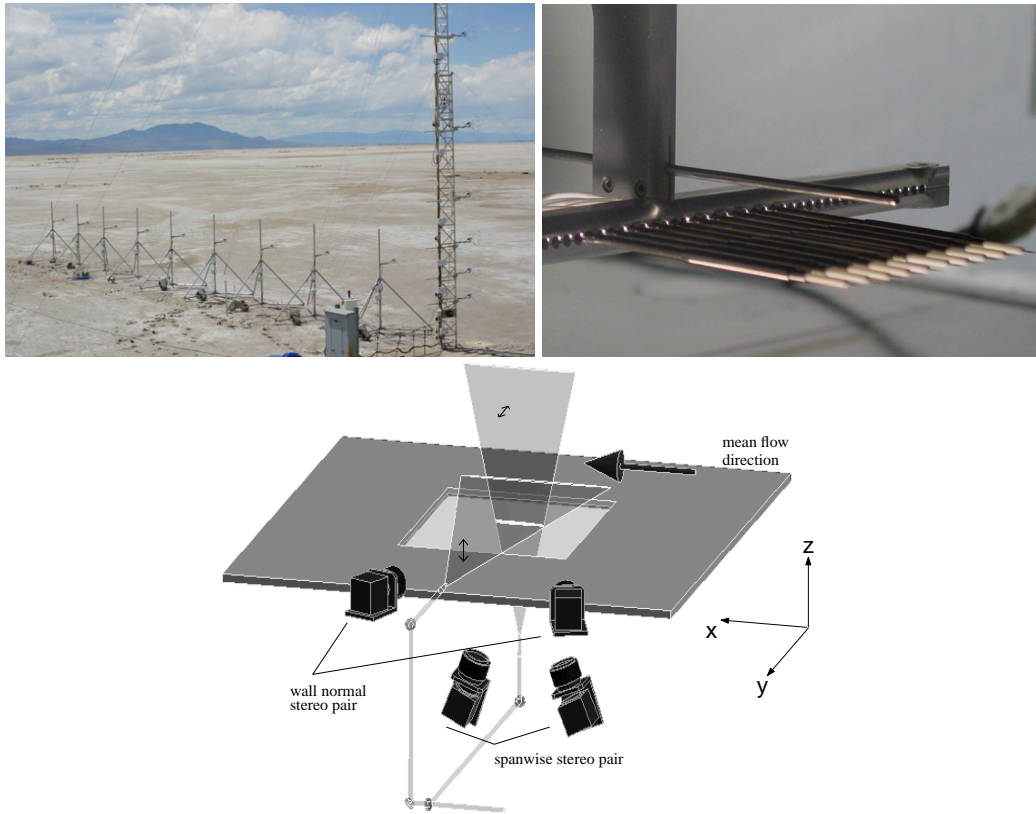


Figure 1: Details of three measurement facilities: sonic anemometer array at SLTEST Utah, 10 hot-wire array used in Melbourne, and dual-plane stereo PIV used in Minnesota.

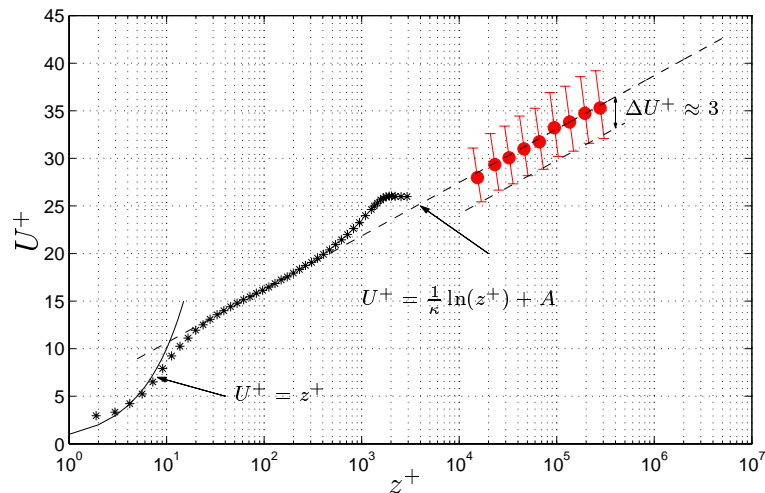


Figure 2: Mean velocity profiles: (\bullet) SLTEST data $Re_\tau \approx O(10^6)$; ($*$) low Reynolds number laboratory data $Re_\tau = 1800$.

m, 0.33 m, and 60 m for the Minnesota, Melbourne and Utah experiments respectively. The $Re_\tau = 1100$ data show some small Reynolds number dependence but this becomes negligible for $Re_\tau \geq 2500$ with the establishment of a well defined log region. The average inclination

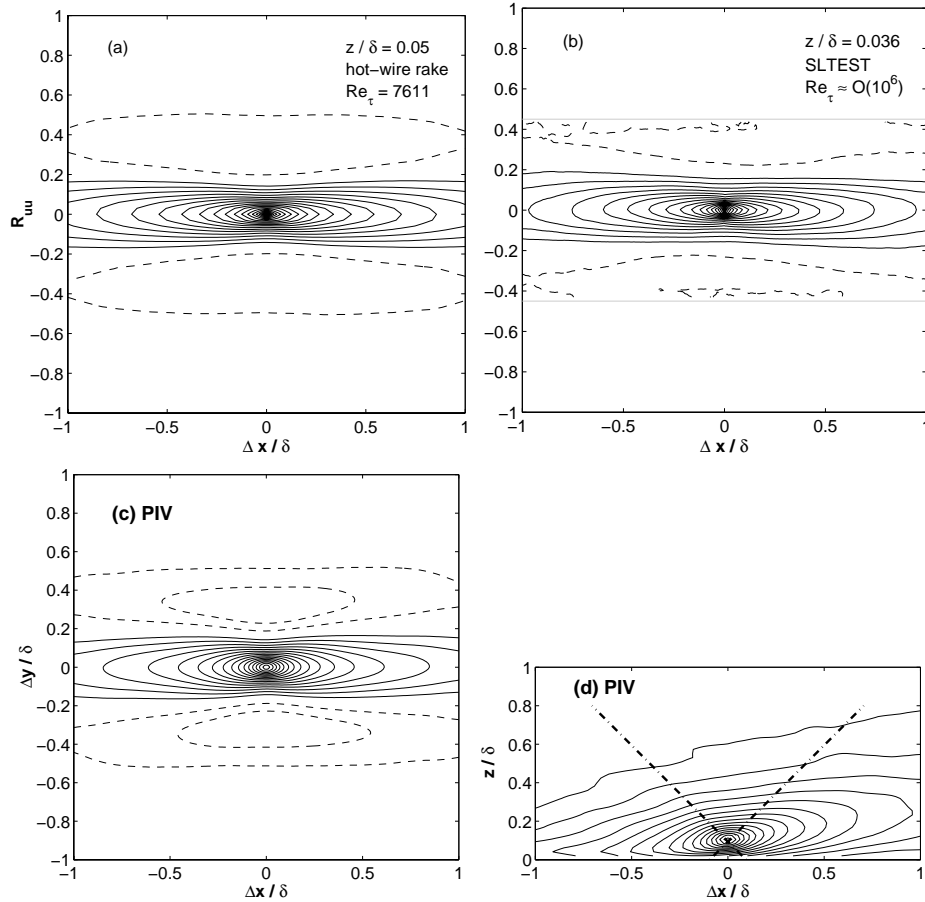


Figure 3: Two-point correlations of the streamwise velocity fluctuation R_{uu} . (a) Melbourne wind tunnel experiment using hot-wire spanwise array at $z_{ref}/\delta = 0.05$. (b) SLTEST spanwise rake at $Re_\tau \approx O(10^6)$. Contour levels are from $R_{uu} = -0.12$ to 0.96 in increments of 0.06 . Solid lines show positive contours and dashed show negative. The gray lines on (b) represent the maximum Δy (the spanwise limit of the correlation data). (c) and (d) PIV data in Minnesota wind tunnel at $Re_\tau = 1100$ in wall-parallel and wall-normal planes respectively. The condition point is in the logarithmic layer.

angle in (x, z) plane also agrees well with the vertical array data from SLTEST. This is shown in figure 4.

In the full paper, other comparisons are be presented including instantaneous fields that show evidence of streamwise structures extending over very long distances (up to 20δ) with significant amounts of spanwise meandering tending to mask these lengths from correlation statistics as shown in figures 3 and 4. We refer to these as “superstructures” and they are likely related to the VLSM structures discussed by Adrian and coworkers ([1]). Evidence for these large structures in found in all three facilities, including the atmospheric surface layer.

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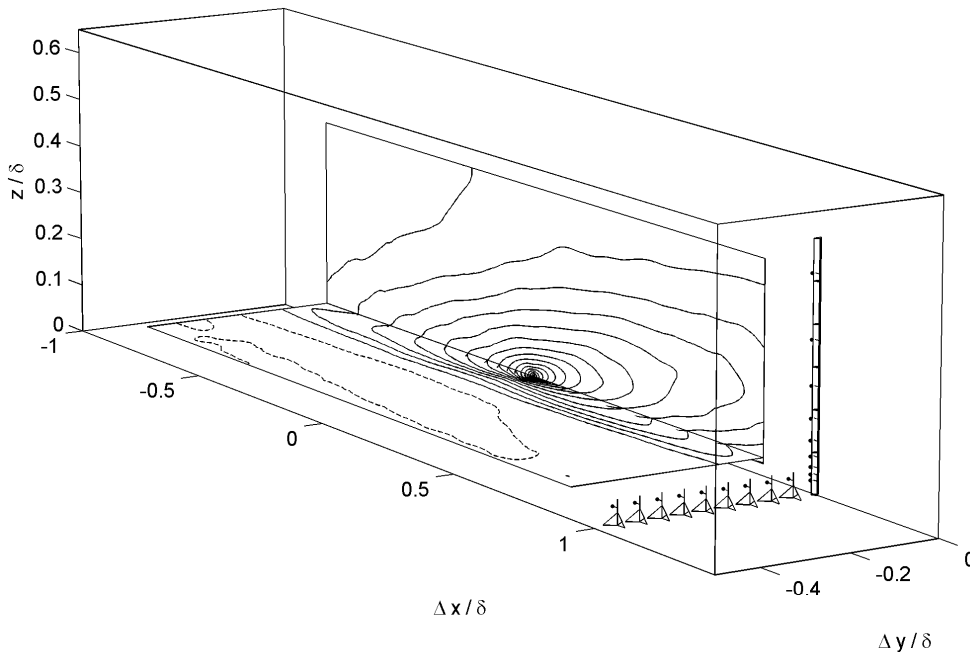


Figure 4: Iso-contours of R_{uu} for both the spanwise array and the tower in the Utah experiment. The condition point is at location of the common sonic anemometer between the horizontal and vertical arrays. Contour levels are from $R_{uu} = -0.06$ to 0.96 in increments of 0.06 . Solid lines show positive contours and dashed show negative. A schematic representation of the measurement array (spanning 30 m across and 25.7 m high) is included for clarity.

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