EXPERIMENTAL INVESTIGATION OF THE NEAR AND FAR FIELD STRUCTURE OF HIGH REYNOLDS NUMBER TURBULENT BOUNDARY LAYERS

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Abstract A multiple camera, multiple resolution PIV system is used to capture a large streamwise, wall-normal field of view ($2\delta \times 1.5\delta$), while simultaneously resolving the near-wall flow down to a height of $y^+ \approx 3$ at Reynolds numbers of $\mathrm{Re}_\tau \approx 8,000$ to $20,000$. The high spatial resolution in the near-wall vicinity is used to provide a direct estimate of the wall shear stress and subsequent analysis of both the small near-wall and larger outer flow structure conditional on the local friction velocity and conversely on larger scale fluctuations. Conditional two-point correlations, and conditional mean structures will be presented.

INTRODUCTION

One of the primary challenges of studying wall-bounded turbulent flows is the simultaneously observation and measurement of the large range of scales that are present. This separation of scales increases with Reynolds number, limiting not only the Reynolds numbers that can currently be resolved by direct numerical simulations (DNS), but also the smallest scales that can be measured by the finite size of hot-wire probes and the limited range of scales that can be measured by the image sensors used in particle image velocimetry (PIV). In practice experimental measurements are often further complication by the presence of the wall which can lead to interference effects and failure of hot-wires probes and strong laser sheet reflections and optical distortions in the case of PIV. As a result of this high Reynolds number experimental measurement of wall-bounded turbulence are rarely presented or reliable at $y^+ < 15$. Recently Kähler [5] demonstrated that high magnification PIV could be used to resolve the viscous sub layer in large wind tunnels, however this magnification requires a substantial sacrifice in terms of field of view.

Turbulent flow in the near-wall region is of significant importance due to the its role in the generation of turbulent kinetic energy and enstrophy and in the accurate determination of the friction velocity. While this region has received extensive study at lower Reynolds numbers ($\mathrm{Re}_\tau < 1000$) [4], recent experiments undertaken at higher Reynolds numbers, where the energy content of logarithmic layer becomes more substantial ($\mathrm{Re}_\tau > 7,000$), have shown increasing evidence of an interaction between the near-wall and the larger structures of the logarithmic layer [3, 6]. Much of this evidence has been obtained by hot-wire measurements, which while instructive are limited to the region of the flow above $y^+ > 15$ at $\mathrm{Re}_\tau > 7000$ and are unable to provide an instantaneous image of the spatial form and extent of such interaction.

This paper will present the results of a multiple camera, multiple resolution planar PIV experiment that enables the instantaneous measurement of both the large-scale velocity fluctuations of the logarithmic and wake regions along with simultaneous higher resolution measurement of the viscous and buffer layers. Velocity profiles, probability density profiles and velocity power spectra with be presented and two-point correlations and the mean flow structure, conditioned on the friction velocity and large scale fluctuations, will be examined in the full paper.

EXPERIMENTAL SETUP

Planar PIV measurements were performed in a streamwise, wall-normal plane at a station approximately 21 m downstream of the contraction in the high Reynolds number turbulent boundary layer wind tunnel (HRNBLWT) at Melbourne University. The long development length provides a boundary layer thickness of $\delta \approx 0.35$ m at Reynolds numbers upto $\mathrm{Re}_\tau \approx 30,000$ with a viscous layer height on the order of 0.2 mm at $\mathrm{Re}_\tau \approx 8,000$. Measurements were performed as a collaboration between the Laboratory for Turbulent Research in Aerospace and Combustion at Monash University and the Department of Mechanical Engineering at Melbourne University and involved the use of nine (4008×2672) pixel PCO. 4000 cameras, arranged in two streamwise rows of 4 cameras with one further highly magnified camera mounted near the wall. This system allowed for a total field of view of approximately $2\delta \times 1.5\delta$ with spatial resolutions and PIV interrogation window dimensions ranging from $60^+ \times 60^+$ and $40^+ \times 40^+$ down to $9^+ \times 3^+$ wall-units at the wall. Further details of these experiments can be found in de Silva et al. [2].

RESULTS

An extensive comparison of the mean and fluctuating streamwise and wall-normal velocity profiles shows a good match between the present PIV results and those provided by hot-wire measurements undertaken in the same facility and flow conditions. The underestimation seen in the velocity fluctuations is the result of the spatial filtering associated mostly with the spanwise extent of the PIV light sheet and is presented after the application of Gaussian filtering with a standard deviation of $3^+ \times 1^+$, applied to remove measurement noise. Filtering was selected based on the velocity power spectrum as discussed in [1]. Importantly velocity profiles from the near-wall camera (see figure 1) also highlight the ability of the highly magnified PIV to provide reliable measurement of both the mean and fluctuating velocity down to a height of $y^+ \approx 3$, substantial lower than what was obtained by the hot-wire $(y^+ > 10)$. Assuming a linear profile below $y^+ < 3$ enables a direct computation of the wall shear stress and friction velocity, corresponding to a mean $u_\tau \approx 0.332$ m/s at $\mathrm{Re}_\tau \approx 8,000$, which is in excellent agreement with the value provided by [7] based on fitting to oil film interferometry measurements.

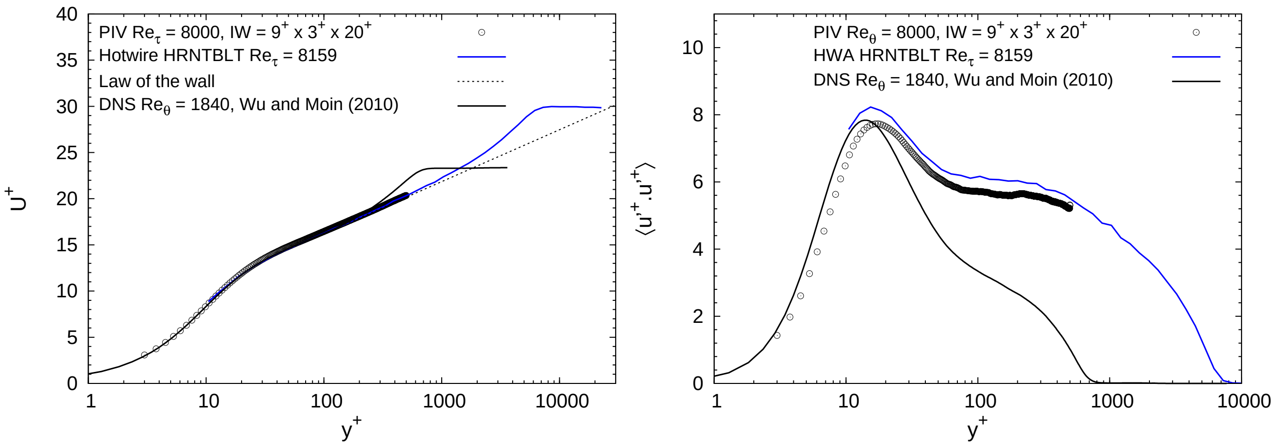

Figure 1. Mean streamwise velocity profile and streamwise Reynolds stress provided by the near-wall camera with a PIV interrogation region size corresponding to $9^+ \times 3^+ \times 20^+$ in the streamwise, wall-normal and spanwise directions, respectively. Hotwire results and lower Reynolds number DNS results of Wu and Moin [8] are shown for comparison.

The full paper will present further analysis and comparison of the velocity power spectra in addition to examination of the fluctuations in u_τ and the two-point correlation and mean flow structures in both the near wall and outer flow, conditioned on u_τ and conversely the influence of the large scale features on the near-wall flow field.

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