THE MODULATION AND CORRELATION OF NEAR-WALL AND LOG LAYER STRUCTURES IN TURBULENT BOUNDARY LAYERS.

Callum Atkinson[1], Nicolas A. Buchmann[1] & Julio Soria [1,2]
[1]*Laboratory for Turbulence Research in Aerospace and Combustion, Department of Mechanical and Aerospace Engineering, Monash University, Australia*
[2]*Department of Aeronautical Engineering, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia*

Abstract Amplitude modulation and the correlation between large-scale structures in the logarithmic region and small-scale fluctuations in the near-wall region (y^+ 5 to 15) of zero-pressure gradient turbulent boundary layers are investigated using data from direct numerical simulations ($\mathrm{Re}_\tau = 2000$) and highly magnified particle image velocimetry measurements ($\mathrm{Re}_\tau = 8100$) of zero pressure gradient turbulent boundary layers. Fluctuations in both streamwise, wall-normal and spanwise directions are considered at multiple scales using Hilbert and Empirical Mode Decomposition.

INTRODUCTION

Turbulent flow in the near-wall region contains the highest turbulence intensity and production and as the source of vorticity generation, has subsequently been the focus of substantial research. The ability to directly simulate the physic of such flows, albeit at moderate Reynolds numbers, has lead to the idea of an autonomous cycle of turbulent flow in the buffer layer region of $y^+ \approx 20$ to 60 that appears to operate independently of the outer flow [6]. It remains to be seen whether this cycle dominates or persists at higher Reynolds numbers.

Recent experiments undertaken at Reynolds numbers in the range of $\mathrm{Re}_\tau \approx 3,000$ to $20,000$ have shown increasing evidence for the 'foot-print' or superposition of large-scale structures ($> \delta$) in logarthmic layer on near-wall fluctuations [5]. This suggests a greater coupling of between the outer and near-wall flow regions, at least at higher Reynolds numbers, which is more in keeping with Townsend's attached eddy hypothesis [10]. Recently large-scale fluctuations have also been observed to modulate the amplitude of small-scale turbulence, where large-scale low-speed regions correspond to regions of less intense small-scale near-wall fluctuations [8]. The large-scale fluctuations in the near-wall region were shown to be strongly correlated with large-scale fluctuation in the logarithmic layer such that the near-wall fluctuations appear to be amplitude modulated by the large-scale structures in the logarithmic region. This effect was explored using hot-wire anemometry measurement of only the streamwise velocity component, down to a minimum wall height of $y^+ = 15$.

The potential modulation and coupling between the near-wall and outer flow structures has important implications and applications not only to the understanding of the physics of wall bounded turbulent flow, but also to their modeling and measurement. As Reynolds numbers increase the corresponding decrease in the relative size of the near-wall region makes it increasingly difficult to measure. Without measurements of this region it is often necessary to perform separate measurements of the wall shear stress [1] or infer the shear stress from the logarithmic law with the assumption of universal constants, limitations of which are discussed in [11]. Marusic [7] uses the concept of amplitude modulation and the superposition of large-scale fluctuation in the logarithmic layer to express a model for the prediction of near-wall streamwise velocity fluctuations based on measured fluctuations in the outer region of the flow. If such a prediction could be extended to the wall-normal and spanwise fluctuations this could enable estimation of the near wall flow structures and hence enable simultaneous measurement of outer and inner flow, which is sorely lacking in most High Reynolds number experiments.

In this paper velocity field data from a moderate Reynolds number direct numerical simulation (DNS) of a zero-pressure gradient turbulent boundary layer (ZPG-TBL) at $Re_\tau = 2000$ [2, 9] and experimental planar particle image velocimetry (PIV) measurements of a high Reynolds number ZPG-TBL at $Re_\tau = 8100$ are used to examine the correlation and amplitude modulation between fluctuations in the lower buffer and viscous layers and those in the log layer. The use of a highly magnified PIV system enables measurements of both streamwise and wall-normal velocity fluctuations down to y^+ 3, lower than that typically provided by hot-wire anemometry (HWA). The correlation and modulation of streamwise, wall-normal and spanwise velocity fluctuations are investigated at multiple scales via Hilbert and Empirical Mode Decomposition [4].

EXPERIMENTAL AND NUMERICAL DATABASES

Planar PIV measurements were performed in a streamwise, wall-normal plane at a station approximately 22 m downstream of the contraction in the high Reynolds number turbulent boundary layer wind tunnel (HRNBLWT) at Melbourne

University providing a boundary layer thickness of $\delta \approx 0.35$ m. Measurements were performed in conjunction with researchers at Melbourne University spanning Reynolds numbers of $\mathrm{Re}_\tau \approx 8,000$ to $21,000$. A series of nine 12 megapixel cameras were used in order to simultaneously measure a domain of $2\delta \times 1.5\delta$ with spatial resolutions and PIV interrogation window dimensions ranging from $60^+ \times 60^+$ down to $9^+ \times 3^+$ wall-units. Further details of these experiments can be found in de Silva et al. [3]. Data from the DNS were provided by researchers at Universidad Politecnica de Madrid, details of which can be found in [2, 9].

RESULTS

Figure 1 shows an example of the small $(\lambda_x < 500^+)$ and large scale $(\lambda_x > 500^+)$ fluctuations in the streamwise velocity component at a height of $y^+ = 5$ wall units in the experimental boundary layer at $\mathrm{Re}_\tau \approx 8000$. Results show similar correlation between the envelope of the small-scale fluctuations and the larger-scale, similar to that reported by [8] at $y^+ = 15$. This paper will explore similar correlation between wall-normal fluctuations in the experimental database with the addition of spanwise velocity component in the DNS.

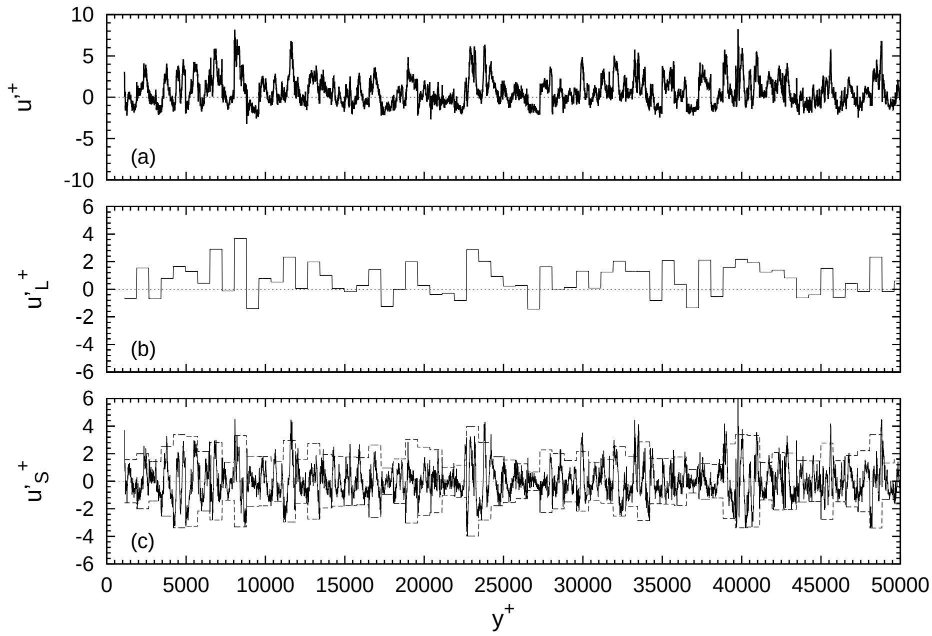

Figure 1. Example of large and small scale fluctuating streamwise velocity from PIV measurements at $y^+ = 5$ and $\mathrm{Re}_\tau \approx 8000$: (a) total velocity fluctuations; (b) large-scale fluctuations $\lambda > 500^+$; (c) small-scale fluctuations and envelope. Note data is not continuous in x direction but is rather a series of statistically independent measurements, each of length $x = 500^+$.

References

[1] Omid Amili and Julio Soria. A film-based wall shear stress sensor for wall-bounded turbulent flows. *Experiments in Fluids*, **51**(1):137–147, 2011.

[2] G. Borrel, J. A. Sillero, and J. Jiménez. A code for direct numerical simulation of turbulent boundary layers at high reynolds numbers in BG/P supercomputers. *Computers & Fluids*, 2012.

[3] C. M. de Silva, K. A. Chauchan, C. H. Atkinson, N. A. Buchmann, N. Hutchins, J. Soria, and I. Marusic. Implementation of large scale piv measurements for wall bounded turbulence at high reynolds numbers. Launcheston, Australia, 3-7 December, 2012.

[4] N. E. Huang, Z. Shen, and S. R. Long. A new view of nonlinear water waves: The hilbert spectrum. *Annu. Rev. Fluid Mech.*, **31**:417–457, 1999.

[5] N. Hutchins and I. Marusic. Evidence of very long meandering features in the logarithmic region of turbulent bound layers. *J. Fluid Mech.*, **579**:1–28, 2007.

[6] J. JimÃľnez and A. Pinelli. The autonomous cycle of near-wall turbulence. *J. Fluid Mech.*, **389**:335–359, 1999.

[7] I. Marusic. Predictive model for wall-bounded turbulent flow. *Science*, **329**(193):193–196, 2010.

[8] R Mathis, N. Hutchins, and I. Marusic. Large-scale amplitude modulation of the small-scale structures in turbulent boundary layers. *J. Fluid Mech.*, **628**:311–337.

[9] J. Sillero, J. Jiménez, R. D. Moser, and N. P. Malaya. Direct simulation of a zero-pressure-gradient turbulent boundary layer up to Re_θ = 6650. *J. Phys: Conf. Ser.*, **318**:022023, 2011.

[10] A. A. Townsend. *The Structure of Turbulent Shear Flows.* Cambridge University Press, UK, 1956.

[11] T. Wei, R. Schmidt, and P. McMurtry. Comment on the clauser chart method for determining the friction velocity. *Experiments in Fluids*, **38**:695–699, 2005.