ON THE RELATION BETWEEN NEAR-WALL SKIN FRICTION AND LARGE-SCALE COHERENT MOTIONS IN TURBULENT BOUNDARY LAYERS

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INTRODUCTION

The present work aims for providing a correlation between the fluctuating near-wall shear stress and the coherent motions, namely the hairpin eddies, occurring in the outer region of turbulent boundary layers. In order to achieve this objective, an experimental investigation on turbulent channel flow, by means of Hot-Wire Anemometry, HWA, is being conducted, and supported by a numerical analysis of a Direct Numerical Simulation (DNS) calculation. A preliminary model, based upon the superposition and modulation effects exerted by the coherent structures into the near-wall region, through their footprints, was proven by Mathis et al. [1], [2],

$$\tau'_{wp}(t^+) = \tau'^{*}_{w}(t^+)\{1 + \beta u'^{+}_{OL}(t^+)\} + \alpha u'^{+}_{OL}(t^+), \qquad (1)$$

being $\tau'^{*}_{w}(t^+)$ the universal wall-shear stress, existing if there were no coherent motions affecting the near-wall region, and $u'^{+}_{OL}(t^+)$ the outer-large scale signal measured at the centre of the logarithmic layer.

However, this work is intended to develop a reversed comparable correlation to eq. (1), which could predict the hairpin package locations on time and space, by online reading the instant maps of the near-wall velocity fluctuations. The final aim is to control the hairpins packages, as they affect the stress-producing cycle in the viscous sub-layer, hence the turbulent flow sustainment. A bimodal behavior of the normalized power spectrum of the stream-wise velocity fluctuation - proven by Hutchins and Marusic [3] - definitely represents a proof of the strong correlation between the near-wall and outer region velocity fluctuation signal. As a result, the global friction drag can be reduced, as proven by Kang [4]. The approach of controlling the outer-region coherent structures is based upon the idea that their evolution time scales are comparable with the duty cycles of most flow actuator systems available.

The near-wall region is characterised by the presence of the stream-wise low-speed and high-speed streaks - directly responsible of the wall friction drag [5] – and some other low frequency signal components, shown on Figure 1, which, according to Agostini et al. [6], [7], directly represent the connection with the outer region, i.e. the hairpin footprints.

In order to achieve this objective, the Q-criterion defines a vortex tube as a low-pressure region confined by convex isobaric surfaces, such that the second invariant of the velocity gradient tensor $\boldsymbol{\nabla u}$, is positive [9], [10],

$$\boldsymbol{Q = \frac{1}{2}\left(\Omega^2 - S^2\right) > 0}, \qquad (2)$$

being $\boldsymbol{\Omega}$ and S are the anti-symmetric and symmetric parts of Q, and representing the rotation and strain rates of the fluid particle, respectively. The preliminary experimental setup and numerical analysis problem will be shown as following.

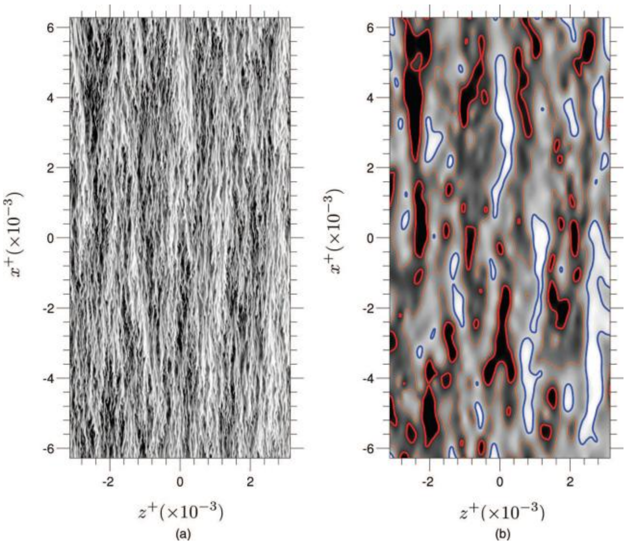
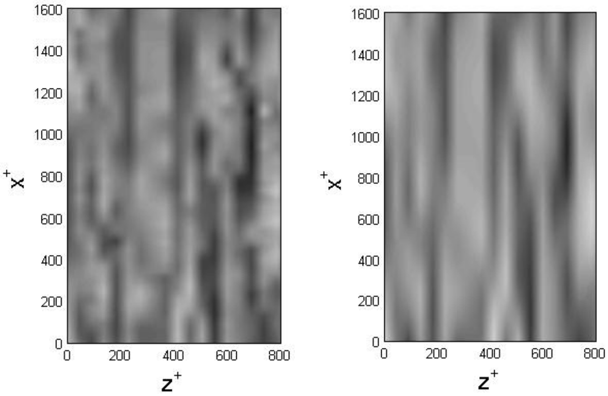


Figure 1: Snapshots of the streamwise velocity fluctuations at $\boldsymbol{y^+ = 13.5}$. (a) complete signal; (b) large-scale velocity fluctuations. Islands with red boundaries: positive fluctuations within the extreme 10% band; islands with blue boundaries: negative fluctuations within the extreme 10% band, [6].

EXPERIMENTAL SETUP

In order to obtain a 2D contour map of the near-wall velocity fluctuation, a rake of 18 HWA sensors – Dantec 55P16, operated at an overheat ratio of 1.8 - was distributed in the span-wise direction of the channel. The probe is a cable-equipped miniature wire, with straight support and 1m BNC cable, connected to a home built anemometer unit. The sensing wire was a 5 µm diameter, platinum-plated tungsten wire, 1.25mm long. This corresponded to the ratio of sensing length to wire diameter l/d = 250, at a free-stream velocity set at 3 m/s. Measurements were made on a fully-turbulent boundary layer with a smooth wall. Data were sampled at 1 kHz for 180 seconds and digitized using a 16-bit National Instrument A/D board. Holes were drilled through the wall, to host the hotwire sensors with a span-wise spacing equal to 5mm, corresponding to $z^+ = 45.9$. A map of the normalised stream-wise voltage fluctuations was obtained at a wall distance of 0.45 mm, corresponding to $y^+ = 4.1$. In addition, a 75th order, low-pass FIR filter was applied to the signal with a cut-off frequency of 5 Hz, as shown on Figure 2, in order to distinguish the footprints of large-scale structures, in the near-wall region.

In order to achieve a reasonable comparison between Figures 1, 2 the same aspect ratio (2:1) was used. As shown on Figure 2, after filtering the data map, some large-scale footprints can be identified – darker islands on Figure 2-b.



(a) (b)

Figure 2: Map of the stream-wise normalized voltage fluctuations at $y^+=4.1$. (a) complete signal; (b) low pass filtered signal.

DATA ANALYSIS

In order to support the experimental work described above, DNS turbulent channel flow data at $Re_\tau = 1027$ were analysed. The grid domain was extending for 10302, 5151, and 1013 wall units in the stream-wise, span-wise, and normal-to-wall directions, respectively. 2D data were provided in slices, along the three directions - in particular, 7, 11, and 7 non-equi-spaced data planes along the stream-wise, normal-to-wall and span-wise directions, respectively. In order to obtain 3D volume data, interpolation along the wall normal direction - through which identifying the coherent motions - was necessary. Linear interpolation was preferred to cubic, after a comparison - in terms of normalized image cross-correlation - of the data coming from DNS with the closest interpolated planes. The identification of coherent motions was achieved by employing the Q-criterion.

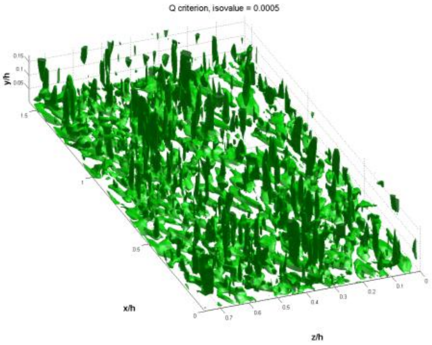


Figure 3: Identification of coherent structures by means of the Q-criterion. Results obtained from DNS data.

A temporal FIR low-pass filter was applied to the velocity fluctuation field in the near-wall region, $y^+ = 1.4$, in order to identify the hairpin footprints. A parametrical study leaded to choose a 75 order filter, with a cut-off frequency $f_c = 1.40$Hz. As can be seen from Figure 3, some large-scale motions develop from the inner to the outer regions - starting from $y^+ = 1.4$, up to $y^+ = 180$. A proper comparison of the 2D filtered data in the near-wall region, with the 3D Q-iso-surfaces – developed at later times, or further downstream in the channel – would enable to develop the inner-outer correlation model.

FUTURE DEVELOPMENTS

It is believed that, by applying the normalised cross-correlation, it will be possible to compare the contour maps of the velocity fluctuation, both at the near-wall and outer region, and determine the inner-outer correlation model, which would allow to predict where the hairpin packages are occurring. In order to support the DNS data results, a 3D PIV experimental setup will be accomplished, from which a complete volume dataset can be produced.

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