LARGE SCALE ORGANIZATION OF A NEAR WALL TURBULENT BOUNDARY LAYER

15TH EUROPEAN TURBULENCE CONFERENCE, 25-28 AUGUST, 2015, DELFT, THE NETHERLANDS

R. Dekou, J.M. Foucaut & M. Stanislas
Université Lille Nord de France, Ecole Centrale de Lille, LML UMR CNRS 8107, Lille, France

Abstract An experimental database at a Reynolds number based on momentum thickness Re_θ close to 9800, was obtained in the Laboratoire de Mécanique de Lille wind tunnel with stereo-PIV (SPIV) and hot wire anemometry (HWA) [1]. With a Linear Stochastic Estimation procedure based on correlations computation, a 3 component field is reconstructed at high frequency from stereo-PIV at 4Hz and hot wire data at 30kHz. This paper describes methods for extracting large scale coherent structures (streaks and vortices) from the reconstructed PIV field. The outcoming features are characterized (size, intensity and life time), and the results are discussed with emphasis on the origin of the structures, their spatio-temporal organization and energetic contribution to the flow.

MOTIVATION

Large scales streaky structures and vortices play an important role in the turbulence production process of a boundary layer. Adrian has proposed a model at very large scale which suggests that hairpin type vortices are bounding regions of low speed fluids with ejections between their legs and sweeps outside. But at high Reynolds number, the main characteristics of these structures (size, intensity and life time) and the way they interact with the near wall structures is not fully understood and of strong interest. At these Reynolds numbers, large scale structures are three dimensional complex features which wander in and out of the measurement domain and their main characteristics are known to vary with the wall normal position, being wider and less intense as they move away from the wall. Extracting them, therefore, is not an easy task both for experiments and DNS. It is for this purpose that an experimental database at high Reynolds number ($Re_\tau = 3610$) was built in the frame of the WALLTURB project. This experiment was carried out with a free stream velocity $U_\infty = 5$ m/s and a friction velocity $u_\tau = 0.188$ m/s estimated using a Clauser chart fit. The set-up is depicted in Figure 1, measurements were made in a zero pressure gradient turbulent boundary layer over a flat plate using Stereo PIV at 4Hz and a rake of HotWires sampled at 30kHz. The acquistion time of the hot wire signal was $6s$ and measurements were repeated over 534 blocks to ensure convergence. At high Reynolds numbers the PIV sampling rate of 4Hz is not enough to follow superstructures evolution in time and the field of view is strongly limited by the available laser power. In contrast, HWA allows time-resolved measurements but limited to one velocity component and with a spatial resolution much lower than the PIV. An option is to combine these experimental tools and to use recent mathematical methods such as LSE in order to reconstruct a fully time-resolved field with 3 velocity components and a good spatial resolution. In this paper post-processing results from the reconstructed PIV field are discussed, log region dominant structures, such as low and high momentum regions as well as vortices are extracted and carefully examined in order to complete the understanding of the turbulent boundary at high Reynold numbers.

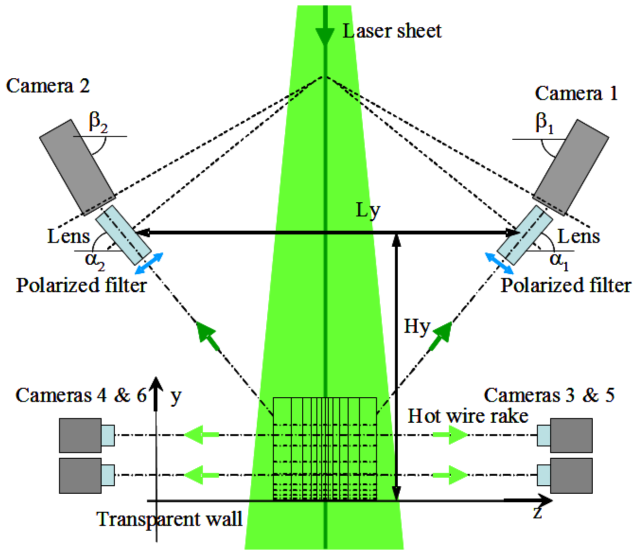

Figure 1. 3D view of the SPIV and HWA setup.

INVESTIGATION METHODS

Given a set of observables which correspond to the streamwise velocity $u_1'(t, \mathbf{x}')$ measured at the N_h hot-wires probes of the two dimensional rake with coordinates given by $\mathbf{x}' = (x_1', ..., x_{N_h}')$, and conditional variables corresponding to the three components of the velocity field $\mathbf{u}'(t, \mathbf{x}) = (u_1', u_2', u_3')\ (t, \mathbf{x})$ in the PIV y-z plane, $\mathbf{x} = (x_1, ..., x_{N_p})$ and N_p is the number of PIV points. A single-time formulation for the linear approximation of the velocity component $\hat{u}_i(t, \mathbf{x})$ is implemented as:

$$\hat{u}_i(t', \mathbf{x}) = \sum_{k=1}^{N_h} u_1'(t' + \tau(x_k'), x_k').a_{k,i}(\mathbf{x}) \qquad i = 1, 2, 3 \tag{1}$$

The $a_{k,i}(\mathbf{x})$ coefficients are obtained from the space-time correlations between the observables and the variables, following LSE method of [2], and $\tau(x_k')$ is the time delay evaluated between a point $x_{i,i=1-N_p}$ in the PIV plane and the observer $x'_{k,k=1-N_h}$. As an example of post-processing of this reconstructed velocity field, Figure 2 displays low (green) and high (yellow) momentum regions. To obtain this result; first a threshold is applied on normalized streamwise velocity fluctuations and then 3D morphological operations (erosion and dilatation) with a carefully selected 3D structuring element are combined with a volume-size-based cleaning procedure to remove the noise and smooth the object boundaries. For a quantitative characterisation, histograms of the life time and of the mean hydraulic diameter of uniform momentum regions are computed and a analysis is performed to see their contribution to Reynolds stresses $u'u'$ and $u'v'$.

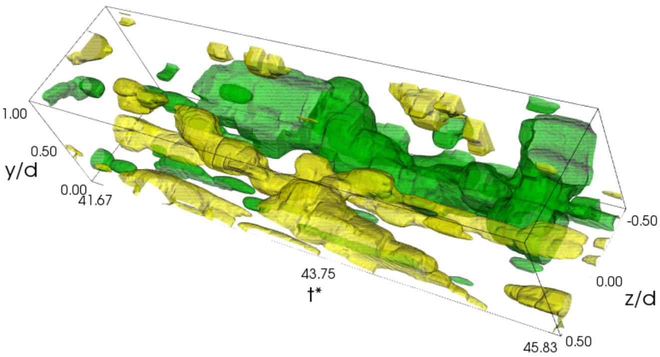

Figure 2. Streamwise low (green) and high (yellow) momentum regions.

Large scale vortices are also displayed in Figure 3. The extraction algorithm is complex and will be described in the full paper. Like for the uniform momentum regions, histograms of vortex mean circulation and mean radius are computed and the effect of wall distance is investigated.

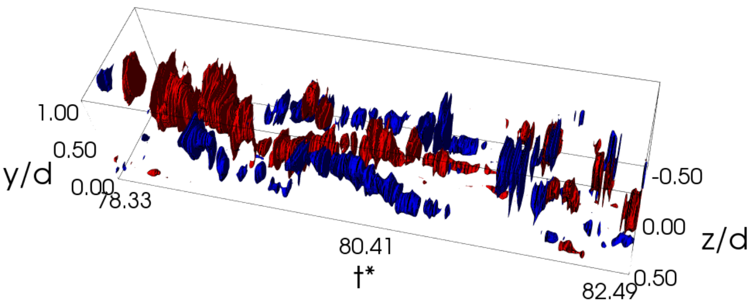

Figure 3. Positive (red) and negative (blue) large scale vortices

References

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[2] V Durgesh and JW Naughton. Multi-time-delay lse-pod complementary approach applied to unsteady high Reynolds number near wake flow. *Experiments in fluids*, **49**(3):571–583, 2010.