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# Large scale organization of a near wall turbulent boundary layer

R. Dekou[a], J.-M. Foucaut[a,*], S. Roux[b], M. Stanislas[a], J. Delville[c]

[a] Boulevard Paul Langevin, Villeneuve d'Acsq Cedex 59655, France
[b] Avenue du Professeur Jean Rouxel BP 539, Carquefou Cedex 44475, France
[c] Pprime in Poitiers, France

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ABSTRACT

An experimental database at a Reynolds number $Re_\theta$ based on momentum thickness close to 9800, was obtained in the Laboratoire de Mécanique de Lille wind tunnel with stereo-PIV (SPIV) and Hot Wires Anemometry (HWA) (Delville et al., wallturb joined experiment to assess the large scale structures in a high reynolds number turbulent boundary layer. In: Progress in Wall Turbulence: Understanding and Modeling. Springer; 2011. p. 65–73.); using a Linear Stochastic Estimation procedure based on correlations computation, a 3 component field is reconstructed here at high frequency from stereo-PIV at 4 Hz and hot wire data at 30 kHz. The present paper describes the results obtained on large scale coherent structures (uniform momentum regions and vortices) by post-processing this reconstruction. Structures are characterized (size, intensity and life time), and results are discussed with emphasis on the spatio-temporal organization of the coherent structures and their energetic contribution to the flow.



## 1. Introduction

Recent numerical studies and experiments have revealed the existence of very long meandering structures consisting of alternance of low and high speed fluid within the logarithmic and wake regions (Abe et al., 2004; Ganapathisubramani et al., 2006a; Hutchins and Marusic, 2007a; Lee and Sung, 2011). The terms Large Scale Motion (LSM) and Very Large Scale Motion (VLSM) refer respectively to structures with a streamwise extent of 1–3$\delta$ and greater than 3$\delta$. Because they play an important role in the turbulence production across the boundary layer (Ganapathisubramani et al., 2005a; 2003; 2006b) and are thought to be responsible for small scales amplitude modulation near the wall, Hutchins and Marusic (2007b) many authors have investigated them in turbulent wall layers for various flow configurations (zero pressure gradient turbulent boundary layer, Hutchins et al., 2011 and Hambleton et al., 2006, pipe flows, Guala et al., 2006, channel flows, Monty et al., 2009). Some general conclusions can be drawn from these studies. First, both low and high speed regions share similarities in averaged size, Sillero et al. (2014) have suggested that this is true only for pipe and turbulent boundary layer flows whereas there is a discrepancy between the two structures in channel flows. Conversely, Dennis and Nickels (2011b) found that low speed regions within a zero pressure turbulent boundary layer are slightly longer than high speed ones and their energetic contribution to the Reynolds shear stress $\overline{u'v'}$ is more significant. Secondly, the structures streamwise length scales on $\delta$, increases with the wall normal distance in the log region and decreases beyond Ganapathisubramani et al. (2003) and (Ganapathisubramani et al., 2006a). Their spanwise width increases monotonically with the wall normal distance (Lee and Sung, 2011). Together with a detailed analysis of large scale vortices, a large scale motion model was provided in Adrian et al. (2000). This model suggests that hairpin-type vortices are bounding the regions of low speed fluid, with ejections between their legs and sweeps outside (Ganapathisubramani et al., 2003; 2006b; 2005b). Following Dennis and Nickels (2011a), the hairpins are mostly inclined at 35–40° with the streamwise direction. Ganapathisubramani et al. (2005b) and Ganapathisubramani et al. (2006b) suggest 45°. On average, they are aligned along the streamwise direction to form hairpin packets which move downstream with the same convection velocity. The packets increase in spanwise scale as they evolve downstream. Ganapathisubramani et al. (2003) have investigated the energetic contribution of low momentum regions enveloped by cores of vorticity of opposite sign to the total shear stress at $Re_\tau = 1060$. These regions labeled as 'hairpin packets' were found to contribute to more than 25% of the total stress $-\overline{u'v'}$ even though they occupy less than 4% of the total streamwise-spanwise area examined in the logarithmic region. In addition, Lee and Sung (2011) found that the VLSMs separately contribute approximately to more than 45% of the total Reynolds shear stress included in all patches. It is now obvious that very large scale motions play a crucial role in the turbulence production, however, their characterization is not complete. The spatial resolution of the data

* Corresponding author. Tel.: +33 320337160.
*E-mail addresses:* raoulflorent.dekoutiomajou@ec-lille.fr (R. Dekou), jean-marc.foucaut@ec-lille.fr (J.-M. Foucaut), michel.stanislas@ec-lille.fr (M. Stanislas).

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**Table 1**
Main flow properties with $\delta$ the boundary layer thickness, $u_\tau$ the friction velocity and $\theta$ the momentum thickness. The Reynolds numbers are $Re_\tau = \frac{U_\tau.\delta}{\nu}$ and $Re_\theta = \frac{U_\infty.\theta}{\nu}$.

| Facility | $U_\infty$(m/s) | $\delta$(m) | $u_\tau$(m/s) | $Re_\theta$ | $Re_\tau$ |
|---|---|---|---|---|---|
| LML | 5. | 0.28 | 0.188 | 9830 | 3610 |

and the interrogation window size in PIV set the range of scale that can be resolved. The first parameter defines the size of the smallest eddies detected and the last one the maximum size of the eddies. Optimizing both of them is difficult and many studies focus on a particular range of scale (Herpin et al., 2013 and Gao et al., 2011 have looked particularly at the small scales). Switching from low and moderate Reynolds numbers to higher ones, the structures size increases. Studies at Reynolds $Re_\tau \approx 1100$ revealed that their streamwise extent is $2\delta$ (Ganapathisubramani et al., 2003) and Hambleton et al. (2006), further studies at Mach 2 (Ganapathisubramani et al., 2006a) and $Re_\tau = 6.6 \times 10^5$ (Hutchins and Marusic, 2007a) revealed structures whose length can go up to $8\delta$ and $20\delta$ respectively. These long streamwise extents, combined with the three dimensional aspect of the structures and their meandering behavior complexify their extraction and analysis. Thus, new simulations and PIV experiments with enough spatial and temporal resolution and with a large field of view need to be performed at high Reynolds number to complete the existing model. 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. Measurements were made in a zero pressure gradient turbulent boundary layer over a flat plate using Stereo PIV at 4 Hz for the spatial resolution and Hot Wires Anemometry (HWA) at 30 kHz for the temporal one. Based on such data, an interesting approach is to use Linear Stochastic Estimation (LSE) in order to reconstruct a fully time-resolved field with 3 velocity components and a good spatial resolution. The first part of the present paper briefly describes the experimental set-up, then the LSE procedure used for reconstruction is discussed and a statistical validation is performed on the reconstructed field. The last part is dedicated to the characterization of large scale structures extracted from the reconstructed field: a statistical analysis of relevant quantities (size, life time, intensity, and Reynolds stress) is carried out on coherent structures and conclusions are provided.

## 2. Experimental set-up

The experiment was carried out in the LML wind tunnel during a WALLTURB test campaign. A full description of this wind tunnel can be found in Carlier and Stanislas (2005) and the WALLTURB program is described in Stanislas et al. (2012).

The present experiment was carried out with a free stream velocity $U_\infty = 5$ m/s and a Reynolds number based on momentum thickness $Re_\theta = 9830$. A Clauser chart fit was used to estimate the friction velocity $u_\tau = 0.188$ m/s corresponding to a Reynolds number based on friction velocity $Re_\tau = 3610$. Table 1 summarizes the main characteristics of the boundary layer. The Hot Wire Rake (HWR) was positioned streamwise at $x = 18$ m from the boundary layer starting point. This hot wire rake is made of 143 single hot wire probes grouped in 13 vertical combs along the spanwise direction z with 11 probes on each of them. The probes are logarithmically distributed as shown in Fig. 1. The first two rows are below the PIV measurement plane and were not used in the present study. The sensing wires are 0.5 mm long and 2.5 $\mu$m in diameter ($l^+ = 11.8$ and $d^+ = 0.006$ respectively). The acquisition time of the hot wire signal is 6 s, the sampling frequency is 30 KHz and measurements are repeated over 534 blocks to ensure convergence.

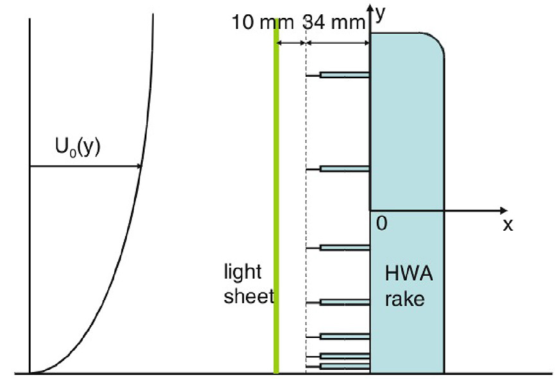


**Fig. 1.** Position of the rake relative to the SPIV measurement plane, probes on the rake are logarithmically distributed in wall-normal direction.

Because hot wire measurements are limited to one velocity component, a stereo-PIV system described in Delville et al. (2011) was used simultaneously, allowing measurements at 4 Hz. The resulting velocity field has 3 components with a spatial resolution of 2 mm in spanwise and wall normal directions. The laser sheet is parallel to the hot wire rake and positioned 1 cm upstream of it as shown in Fig. 1, it covers the entire boundary layer thickness over an area of $30 \times 30$ cm$^2$.

## 3. Linear Stochastic Estimation

From the hot wire and PIV measurements, the LSE (see e.g. Guezennec, 1989) is used to reconstruct a fully time-resolved 3 component velocity field with the same spatial resolution as the PIV. Given a set of observables located in space at $x'$ and in time at $t'$, the LSE allows the linear approximation of the conditional estimate of some quantity at a position $x$ and time $t$. In our case, the conditional variables to reconstruct at high frequency are the three components of the velocity fluctuations $\mathbf{u}'(t,\mathbf{x}) = (u', v', w')(t,\mathbf{x})$ in the PIV YZ plane, $\mathbf{x} = (x_1, ..., x_{N_p})$ with $N_p$ the number of points. The set of observables includes the streamwise velocity $u'(t', \mathbf{x}')$ measured by the $N_h$ hot-wires probes on the two dimensional rake, whose coordinates are given by $\mathbf{x}' = (x'_1, ..., x'_{N_h})$. A single-time formulation for the linear approximation of the velocity component $\hat{u}_i(t', \mathbf{x})$ is implemented as:

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

where $a_{k,i}(\mathbf{x})$ are coefficients relating the conditional field to the observers, and $\tau(x'_k)$ is the time delay evaluated between a point $x_{j, j=1-N_p}$ in the PIV plane and an observer $x'_{k, k=1-N_h}$.

In order to find the best coefficients $a_{k,i}(\mathbf{x})$ to estimate a space time resolved velocity field $\hat{u}_i(t, \mathbf{x})$ using time resolved hot wire measurements $u'(t', \mathbf{x}')$, we have to minimize an error function. In a least square sense, this function corresponds to the residual sum of squared errors (RSS) at instant $\tilde{t}$ where the PIV is known:

$$RSS = \sum_{j=1}^{N_p} \left( \hat{u}_i(\tilde{t}, x_j) - \sum_{k=1}^{N_h} u'(\tilde{t} + \tau(x'_k), x'_k) a_{k,i}(x_j) \right)^2 \quad i = 1, 2, 3 \tag{2}$$

In a matrix form, the error function can be rewritten as:

$$RSS = ||\mathbf{XB} - \mathbf{Y}||_2^2 \tag{3}$$

where $\mathbf{B}$ is a matrix of size $\mathbb{R}^{N_p \times N_h}$ which contains all the coefficients $a_{k,i}(\mathbf{x})$, $\mathbf{X}$ and $\mathbf{Y}$ correspond respectively to the measured hot wire $u'(\tilde{t} + \tau(x'_k), \mathbf{x}')$ and PIV $\hat{u}_i(\tilde{t}, \mathbf{x})$ velocity fields and $||.||_2^2$