The three-dimensional structure of large scale motions in turbulent boundary layer

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Résumé :

La charactérisation et la modélisation des couches limites turbulentes restent des problèmes importants dans de nombreux domaines tels que les transports, l'energie ou l'environnement. Ces dernières années, il a été montré que des structures cohérentes à grandes échelles, qui apparaissent principalement à grand nombre de Reynolds, jouent un rôle important et modifient entre autre les caractéristiques du frottement. Ces très grandes structures sont difficilement mesurables sur des expériences à grand nombre de Reynolds. La simulation numérique directe (DNS) permet une analyse plus détaillée de ces structures mais pour des nombres de Reynolds modérés. Une DNS de couche limite turbulent de plaque plane a été intégrée et différentes procédures d'extraction de ces structures cohérentes en 2D et en 3D ont été comparées afin d'étudier plus précisément l'influence de ces procédures d'extraction sur les statistiques des structures. L'objectif est de pourvoir relier plus facilement les résultats issus de DNS aux résultats obtenus en 2D par PIV.

Abstract :

The characterization and modelling of turbulent boundary layers are still challenging problems in variety of research domains such as transportation, energy production or geophysics. Recently, large scale coherent structures that appear at large Reynolds numbers have been shown to have a significant impact on the drag behaviour. These very large scale structures are not easily accessible via the measurements in large Reynolds number experiments. The direct numerical simulation (DNS) enables a more detail analysis of these structures. In the current study, a DNS of turbulent boundary layer has been performed. Two-dimensional and three-dimensional extracting procedures have been compared in order to investigate the influence of these procedures on the statistics of the detected structures. The aim of present study is to propose a framework to compare the DNS results with ones obtained from 2D PIV.

Mots clefs : Turbulent Boundary Layer, Direct Numerical Simulation, Coherent Structures

1 Introduction

Numerous experimental studies, mostly based on one point measurement, serve to envision the details of wall turbulence. Meanwhile, the advances in computational resources allow to simulate the turbulent boundary layer (TBL) flow at significant Reynolds numbers. Numerical simulations and the progress of optical metrology techniques open some new possibilities to study the coherent motions of turbulence. However, the direct investigation of 3D structures in physical space is still mainly accessible from large Direct Numerical Simulation. Few DNS at significant Reynolds numbers have already been performed to allow such a study. Schlatter and Orlu [4] have shown that rigorous approach to set up numerical simulation is substantial since different simulations for same canonical flow case give inconsistent measures even for basic quantities. Sillero *et al* [7] investigated channel flows large scale structures in detail. However, the statistics of very large scales can be affected by the simulation parameters such as the choice of the forcing or the computational domain.

2 Direct numerical simulation

A DNS of zero pressure gradient turbulent boundary layer up to $Re_\theta = 2550$ is performed with the numerical code Incompact3d [1] [2] using a simulation domain of size $600\delta_i \times 20\delta_i \times 20\delta_i$ where δ_i is the boundary layer thickness of the inlet Blasius profile. Transition to turbulence is forced at $Re_\theta \simeq 300$ with a random tripping of several spanwise modes as suggested by Schlatter and Orlu [5]. The advantage of this method over recycling methods is to avoid some unwanted streamwise correlations between inlet and outlet that could act upon large scale turbulence statistics for not sufficiently long simulation domains. More than half a thousand three-dimensional velocity and pressure fields have been collected within approximately 21 characteristic time based on u_τ and δ at the middle of simulation domain ($Re_\theta = 1522$). This fairly long integration time allow us to extract well converged statistics even at large scales. In addition, time resolved data at four different planes perpendicular to the flow at $Re_\theta = 922,\ 1522,\ 2063$ and 2365 were also recorded and are used to compare space and time statistics of large scale coherent structures. Current DNS shows good agreement with other state of the art TBL simulations [1, 6], as shown in figure 1.

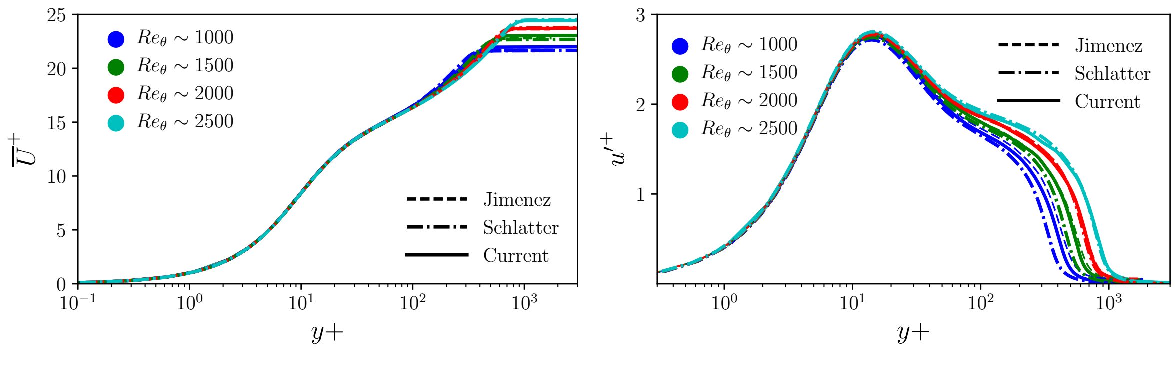

FIGURE 1 – Comparison of the mean velocity profile and streamwise Reynolds stress with the results of Jimenez *et al* [1] and Schlatter *et al* [4]

1. http://www.incompact3d.com/

3 Structure detection

Large scale structures are detected with a threshold applied on streamwise velocity fluctuations, similar to the methodology exercised on the data acquired from particle image velocimetry (PIV) on a large field of view at higher Reynolds numbers [8]. A binary image indicating the low momentum regions is obtained by thesholding ;

$$F_i = \begin{cases} 1 \text{ when } u' < C_{thr}\,\sigma_u \\ 0 \text{ otherwise} \end{cases} \tag{1}$$

where σ_u is mean streamwise fluctuating velocity $\sqrt{\overline{u'^2}}/u_\tau$ at 100 wall units from the wall, and C_{thr} is the coefficient for a threshold. Both two-dimensional and three-dimensional detection procedures have been used to extract streamwise low momentum large scale structures. The effect of the threshold for each type of structure have been investigated by analysing the statistics of the detected structures. An example of detected structures in a physical domain of length 10δ is shown in figure 2. The statistics of streamwise structures extracted in 2D and 3D are compared to investigate the effects of a detection in 2D as well as the comparison of large scales extracted from space and time (with time-resolved PIV for instance).

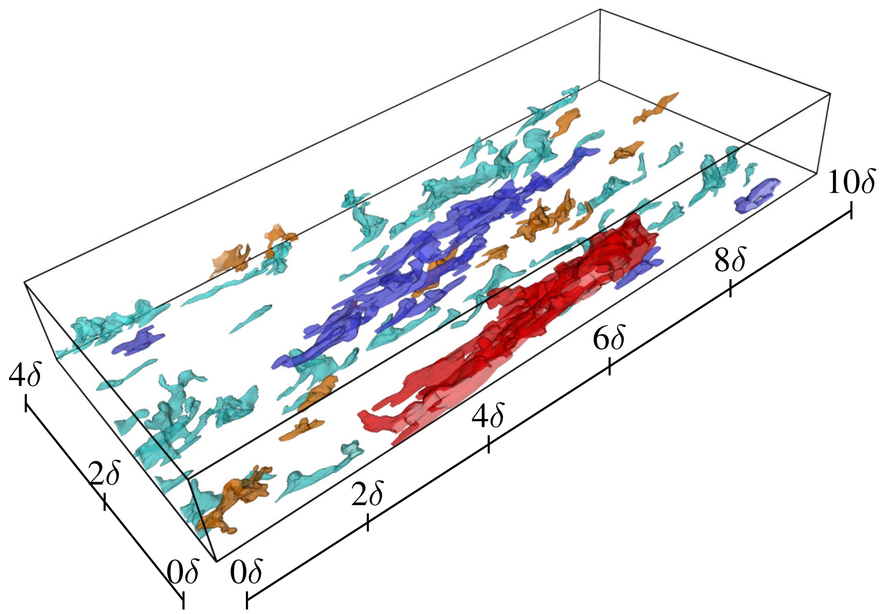

FIGURE 2 – Large scale motion in a TBL ($Re_\theta \approx 2060$ and $\delta \approx 8$), low [●] and high [●] momentum regions from the streamwise velocity fluctuations ; ejection/Q2 [●] and sweep/Q4 [●] components of Reynolds stress

Particular attention is paid to the structures attached to the wall as they are known to play a significant role in the Townsend-Perry model [9, 3] of wall turbulence. In our detection procedure, the structures with a minimum distance from the wall of 50 wall units were retained to be analysed. The histogram of length L_x of low momentum streamwise structures is given in figure 3. The analyses are performed in spatial domains of 20δ long centred on the Reynolds $Re_\theta = 2063$.

As noticed by Srinath *et al* [8] in a similar 2D study from PIV results, the repartition of the length follow a -2 power law corresponding to the population density assumption. The same detection procedure in

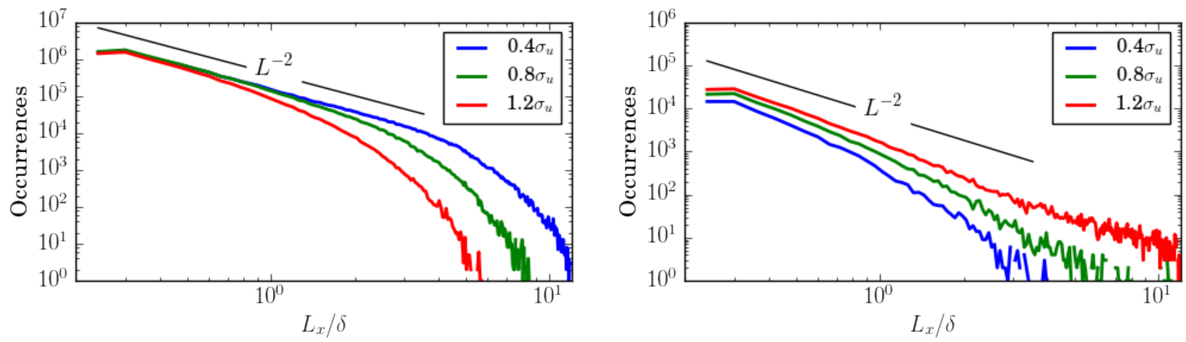

FIGURE 3 – The histogram of lengths in x-direction for 2D *(left)* and 3D structures *(right)* for low momentum regions with σ_u at $y^+ = 100$

3D exhibits a different behaviour. When using the same threshold the number of detected structures are much smaller and the average length of the structures is significantly increased. By analysing the population of detected structures, the reason of this difference is that most of the large scale structures are connected by the side leading to a complex multiple branch structures in 3D.

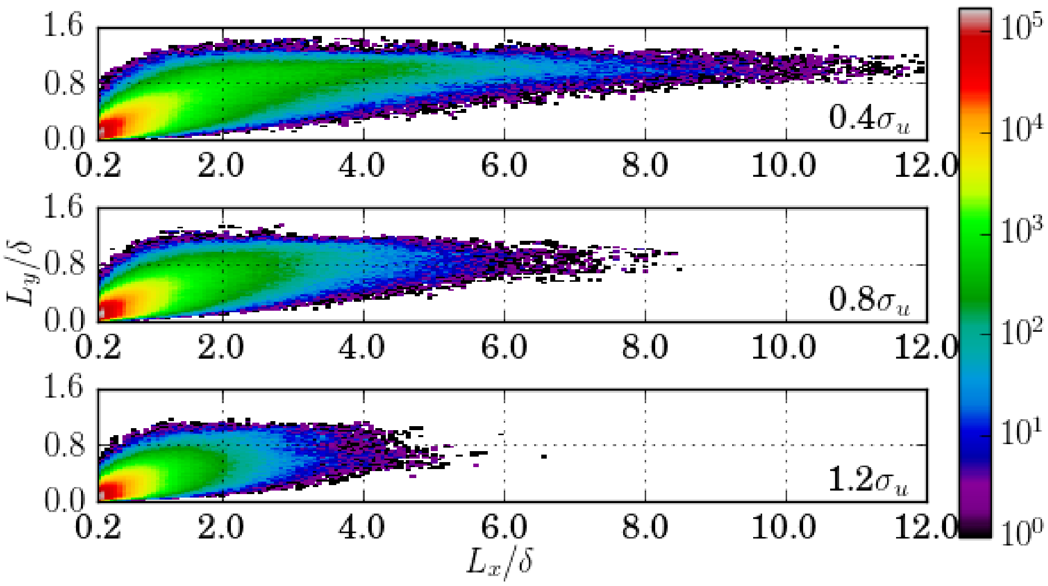

FIGURE 4 – The joint histogram of lengths for 2D structures in x-direction and y-direction for low momentum regions

The effect of the threshold has been investigated to ensure that the statistics of aspect ratio is not biased (see figure 4). Stronger threshold leads to shorter structures as expected, however distribution for length in y-direction is only weakly affected. These results enlighten the difficulties to compare statistics of the coherent structures from turbulence data of various origin and resolution.

4 Conclusion

The present study shows the difficulties to extract statistics of large scale motions and to propose detection procedures which allow a fair comparison for statistics of coherent structures from turbulence data of various origin and resolution. As numerical simulations are limited to moderate Reynolds numbers there are more attempts to study large scale structures from experiments. In this case a special care is needed to find detection criteria which can be generalized to different Reynolds numbers, spacial and time resolution.

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Références

[1] J. Jiménez, S. Hoyas, M. P. Simens, and Y. Mizuno. Turbulent boundary layers and channels at moderate Reynolds numbers. *J. Fluid Mech.*, 657 :335–360, 2010.

[2] S. Laizet and E. Lamballais. High-order compact schemes for incompressible flows : a simple and efficient method with the quasi-spectral accuracy. *J. Comp. Phys.*, 228(15) :5989–6015, 2009.

[3] A. E. Perry, S. Henbest, and M. S. Chong. A theoritical and experimental study of wall turbulence. *J. Fluid Mech.*, 165 :163–199, 1986.

[4] P. Schlatter, Q. Li, G. Brethouwer, A. V. Johansson, and D. S. Henningson. Simulations of spatially evolving turbulent boundary layers up to $Re_\theta = 4300$. *International Journal of Heat and Fluid Flow*, 31 :251–261, 2010.

[5] P. Schlatter and R. Örl ü. Turbulent boundary layers at moderate Reynolds numbers : inflow length and tripping effects. *J. Fluid. Mech.*, 710 :5–34, 2012.

[6] P. Schlatter and R Örlü. Assesment of direct numerical simulation data of turbulent boundary layers. *Journal of Fluid Mechanics*, 659 :116–126, 2010.

[7] J. Sillero, G. Borrell, J. Jimenez, and R. D. Moser. Hybrid OpenMP-MPI turbulent boundary layer code over 32k cores. In *Proceeding EuroMPI'11 Proceedings of the 18th European MPI Users' Group conference on Recent advances in the message passing interface*, pages 218–227, 2011.

[8] S. Srinath, J.C. Vassilicos, C. Cuvier, J.-P. Laval, J.-M. Foucaut, and M. Stanislas. A simple model for the streamwise energy spectra and its connection with large scale motions in a turbulent boundary layer. *to be submitted to J. Fluid. Mech.*, 2017.

[9] AA Townsend. Equilibrium layers and wall turbulence. *Journal of Fluid Mechanics*, 11(01) :97–120, 1961.