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Analysis of the Contribution of Large Scale Motions to the Skin Friction of a Zero-Pressure-Gradient Turbulent Boundary Layer Using the Renard-Deck Decomposition

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Abstract

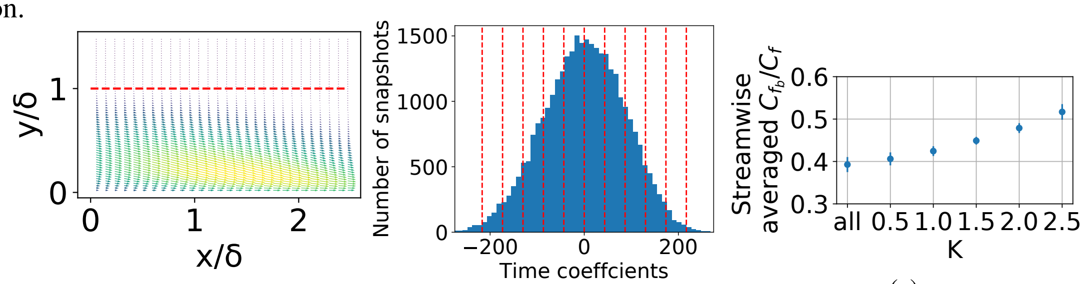
Coherent flow structures in turbulent boundary layers have been an active field of research for many decades, as they might be the key to reveal the mechanics of turbulence production and transport in turbulent shear flows. Renard and Deck (2016) proposed a theoretical decomposition for the mean skin-friction coefficient based on the mean kinetic energy budget in the streamwise direction. This decomposition, referred to as the Renard-Deck (RD) decomposition, decomposes the mean skin friction generation into three physical mechanisms in an absolute reference frame, namely, direct viscous dissipation, turbulent kinetic energy production, and spatial growth. In this study, the large scale motions (LSMs) are extracted using a proper orthogonal decomposition (POD) of the velocity field based on high-spatial-resolution two-dimensional – two-component particle image velocimetry (HSR 2C-2D PIV) of a zero-pressure-gradient turbulent boundary layer (ZPG-TBL), and their effect on the skin friction via RD decomposition.

The high Reynolds number turbulent boundary layer experiment was performed at the Laboratoire de Mécanique des Fluides de Lille (LMFL) in the LMFL High Reynolds Number Boundary Layer Wind Tunnel. The measurement took place in the streamwise – wall-normal plane along the centreline of the wind tunnel, where the ZPG-TBL at the measurement location has a free-stream velocity of $9m/s$, a Reynolds number based on the momentum thickness of $Re_\theta = 8,120$, a boundary layer thickness of $\delta \approx 103mm$ and a viscous length of $l^+ \approx 40\mu m$. The PIV images were captured with a $47MP$ Imperx Tiger T8810 camera which has a $57mm$-diagonal array of size $8,864 \times 5,288$ pixels. This results in a field of view of $255mm \times 152mm$, or $2.46\delta \times 1.45\delta$ in terms of the boundary layer thickness, with a spatial resolution of 21.7 wall units in the streamwise direction and 5.42 wall units in the wall-normal direction. A more detailed description of the experiment, as well as an analysis on the method to correct for the lens distortion introduced by the large sensor size, can be found in Sun et al. (2021).

The LSMs present in the ZPG-TBL are extracted from the velocity field using POD by the snapshot method (Sirovich, 1987). Due to the limited field of view of the acquired data, the LSMs in the present study are defined as the flow structures that have a wall-normal extent of approximately the full boundary layer, which are identified by the most energetic POD mode as shown in figure 1a. This mode accounts for 16% of the turbulent kinetic energy in the flow. Velocity field snapshots containing stronger LSMs than others are identified using the time coefficient of the most energetic POD mode, ϕ_1, whose distribution is presented in figure 1b. The distribution of ϕ_1 is Gaussian-like, with its absolute value representing the strength of the LSM present in each snapshot. Therefore, the following criterion is used to determine the snapshots containing strong LSMs,

$$|\phi_{1,n}| \geq K\sigma_{\phi_1}, \quad (1)$$

where $\phi_{1,n}$ represents the time coefficient of the most energetic POD mode for snapshot n, and σ_{ϕ_1} represents the standard deviation of the time coefficient for all snapshots. A higher K value represents a tighter selection criterion.



(a) (b) (c)

Figure 1: (a) A vector plot of the fluctuating velocity of the most energetic POD mode. The colours of the vectors represent the velocity fluctuation magnitude. The red dashed line represents the boundary layer thickness. (b) Distribution of the time coefficient of the most energetic POD mode, ϕ_1. The red dashed line represents $\pm 2.5\sigma$, $\pm 2\sigma$, $\pm 1.5\sigma$, $\pm\sigma$, $\pm 0.5\sigma$ and the mean value of ϕ_1. (c) Streamwise averaged C_{f_b}/C_f for different K values. The error bars in C_{f_b}/C_f represents its standard deviation along the streamwise direction.

Renard and Deck (2016) decomposition (RD decomposition) of the skin friction coefficient based on the mean kinetic energy budget of the fluid motion in an absolute frame of reference, which is given by

$$C_f = \underbrace{\frac{2}{U_e^3}\int_0^\infty \mu\left(\frac{\partial U}{\partial y}\right)^2 dy}_{C_{fa}} + \underbrace{\frac{2}{U_e^3}\int_0^\infty -\langle u'v'\rangle\frac{\partial U}{\partial y}dy}_{C_{f_b}} + \underbrace{\frac{2}{U_e^3}\int_0^\infty (U-U_e)\frac{\partial}{\partial y}\left(\frac{\tau}{\rho}\right)dy}_{C_{fc}}, \tag{2}$$

where $\tau = \mu(\partial U/\partial y) - \langle u'v'\rangle$, U denotes the mean streamwise velocity, U_e denotes the free stream velocity, $\langle u'v'\rangle$ denotes the Reynolds shear stress, μ denotes the dynamic viscosity and ρ denotes the density. The RD decomposition decomposes the skin friction into physically interpretable terms that are local at each streamwise position. The first term, C_{f_a} represents the viscous dissipation of the mean streamwise kinetic energy, and it depends only on the mean values of the fluid field therefore has no direct contribution from the LSMs. The second term, C_{f_b}, represents the production of the turbulent kinetic energy extracted from the mean streamwise kinetic energy and is the term of relevance in the analysis of the contribution of LSMs. The last term, C_{f_c}, accounts for the growth of the boundary layer effect, as the growth of the boundary layer is slow for a ZPG-TBL, this term is negligible. A conditional statistics analysis is performed by calculating the C_{f_b} term using the snapshots containing strong LSMs as identified by equation 1. The resulting streamwise averaged value of C_{f_b}/C_f for different threshold value K is presented in figure 1c. This results show that LSM dominated snapshots results in an increase of C_{f_b}, indicating that the LSMs are a significant contributor to the turbulent production term in the RD decomposition of the skin friction.

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