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On the identification of intense Reynolds stress structures in wall-bounded flows using information-limited two-dimensional planar data

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ABSTRACT

Historically the majority of investigations into the transfer of momentum have been focused on the classification and statistical analysis of single points of above average Reynolds stress. These regions of intense Reynolds stress are responsible for the majority of the wall-normal transfer of momentum and most of the production of turbulent kinetic energy. Single point hot-wire measurements were critical in understanding the roll of the regions of intense Reynolds stress, but provide no information about their formation, spatial extent, orientation, nor their position relative to other types of coherent structures. DNS of turbulent wall-bounded shear flows overcomes this information-limit by providing the full three-dimensional (3D) volumetric flow field information, albeit limited to low Reynolds numbers. Advancements in particle image velocimetry (PIV) have enabled the measurement of High Reynolds number turbulent wall-bounded shear flows, with measurements of two instantaneous velocity components in a single two-dimensional (2D) plane (e.g. streamwise wall-normal plane). However, the deductions and conclusions based on these information limited 2D measurements may be detrimentally affected by the lack of information from the third dimension. This study aims to address this issue by using DNS from a turbulent channel flow at $Re_\tau = 945$ and comparing the geometric characterisation of intense Reynolds stress objects computed from the full 3D flow fields with those computed from the information-limited 2D flow fields that span streamwise wall-normal planes.

1. Introduction

Understanding the mechanisms and dynamics associated with momentum, heat and scalar transport is of fundamental importance to our ability to model, predict and control drag, heat transfer and mixing rates encountered in wall-bounded turbulent flows. Historically the majority of investigations into the transfer of momentum were focused on the classification and statistical analysis of single points of above average Reynolds stress dating back to the study by [1] of the statistical properties of the Reynolds stresses, who observed that near-wall low-velocity streaks undergo a process of lift-up, oscillation, breakup and ejection, which they called bursting. Subsequently [2] showed that most of the turbulence production of turbulent kinetic energy in the near-wall region occurs during those bursts in regions of intense Reynolds stress which are also responsible for the majority of the wall-normal transfer of momentum. In order to investigate these phenomena in more detail a range of conditional-sampling techniques using single point velocity measurement were developed to identify the structures involved in the process including the u-level detection technique [3], VITA (Variable-interval time-averaged) [4] and VISA (Variable-interval space-averaged) [5] techniques. [6] considering the available techniques and concluded the quadrant analysis [7,8,3] yielded the best compromise between detection probability and false positives. More in-depth considerations and overviews of the quadrant analysis as it pertains to wall-bounded turbulence can be found in [9–11].

Quadrant analysis based on single point velocity measurements were critical in understanding the roll of the regions of intense

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Reynolds stress, but provide no information about their formation, spatial extent, orientation, nor their position relative to other types of coherent structures. However, recent advancements in particle image velocity (PIV) have enabled the instantaneous experimental measurement of two and three velocity components and their fluctuations in a single two-dimensional (2D) plane (e.g. streamwise wall-normal plane) [12,13] and been applied to the investigation of organisation and extent of momentum structures in wall-bounded turbulence [14]. The statistical extent, spacing and direction of these structures have been investigated by 2D spatial cross-correlations of PIV velocity fields [15,16] and additionally via the thresholding, clustering and classification of the extent and orientation of individual structures [16]. The three-dimensional (3D) coverage of these structures was explored by [17] via the use of Taylor's hypothesis to extend time-resolved PIV measurements to 3D, however as discussed in [18] the extent to which Taylor's hypothesis can accurately reconstruct these structures is limited and varies with wall-normal height.

Recently, [11] performed an extensive statistical analysis of the extent, orientation, number per unit volume, aspect ratio and spacing of Reynolds stress structures using 3D velocity fields data from the direct numerical simulation of turbulent channel flows at $\mathrm{Re}_\tau = 934$ and 2003. These structures were detected by thresholding the magnitude of the instantaneous product of the fluctuating velocity components relative to the product of the streamwise and wall-normal turbulence intensities at each wall height. Following a percolation analysis, [11] found the optimal value for the Hyperbolic-hole size, H, associated with the root mean squared of the velocity fluctuations in the streamwise and wall-normal directions, to be 1.75, which resulted in the identification of the maximum number of structures or clusters. [11] describe the structures identified by this approach as 'sponges of flakes' or complex 3D interconnected branches of Reynolds stress.

Unfortunately DNS cannot be used to examine the geometry and properties of these Reynolds stress structures at the significantly higher Reynolds numbers encountered in laboratory, industrial and atmospheric flows. Analysis of high Reynolds number wall-bounded turbulence requires the use of experimental data such as that provided by PIV. While there has been significant advancement in the instantaneous experimental measurement of 3D velocity fields [19,20], these multi-camera tomographic techniques suffer from inherently low accuracy and spatial dynamic range [21,22], lower than that of 2D PIV. This lack of spatial dynamic range becomes increasingly important at higher Reynolds numbers as the range of scales increases. If instead of 3D measurements, the available multiple cameras are orientated in the same plane with a small overlap in their field of view, 2D PIV measurements can be performed over a significantly larger spatial dynamic range as used by [13] to simultaneously resolve down to the viscous sub layer and over two boundary layer thickness 2δ in a zero pressure gradient turbulent boundary layer with a friction velocity Reynolds number up to $\mathrm{Re}_\tau = 20{,}000$ [13]. Extremely high spatial resolution measurements such as these have the potential to deliver significant insight into the 2D structure of high Reynolds number turbulent flows, however the degree to which such information-limited 2D measurements can deliver relevant information about what are highly 3D structures is unknown.

In this paper we present a systematic comparison of the statistical geometric description of Reynolds stress structures as obtained from both the full 3D velocity fields and from 2D streamwise wall-normal planes of the same turbulent channel DNS of [23] at $\mathrm{Re}_\tau = 945$. Structures were independently identified using a 2D and 3D cluster identification algorithm in order to determine the extent to which information-limiting data restricted in this case to a 2D domain influences the PDFs of the geometric characterisation of intense momentum flux structures.

2. Direct numerical simulation of turbulent channel flow

The fields studied within are generated via the DNS of the incompressible isothermal Navier–Stokes equations. In physical space the momentum and continuity equations are given by

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \nu \nabla^2 U_i, \quad \text{and} \tag{1}$$

$$\frac{\partial U_i}{\partial x_i} = 0, \tag{2}$$

respectively, with the indices $i = 1, 2, 3$ and $j = 1, 2, 3$. The Laplacian operator $\nabla^2 \equiv \boldsymbol{\nabla} \cdot \boldsymbol{\nabla}$, where $\boldsymbol{\nabla} \equiv (\partial/\partial x, \partial/\partial y, \partial/\partial z)$. The coordinates $\mathbf{x} \equiv (x_1, x_2, x_3) \equiv (x, y, z)$, where x is the streamwise direction, y the wall-normal, and z the spanwise, with associated instantaneous velocity components $\mathbf{U} \equiv (U_1, U_2, U_3) \equiv (U, V, W)$. The bold type face denotes a vector quantity. The constant kinematic viscosity is ν, and ρ is the constant fluid density. The system is non-dimensionalised by the centreline velocity (u_0) and channel half height (h) unless otherwise specified.

For algorithmic efficiency the code solves the Navier–Stokes equations in terms of the wall-normal vorticity and Laplacian of the wall-normal velocity, with the system of equations detailed in [24]. The flow variables are discretised using a collocated Chebyshev discretisation in y, and Fourier discretisation in x and z de-aliased using the two thirds rule. The linear terms are evaluated in Fourier/Chebyshev space, and the nonlinear terms are evaluated via grid to spectral transforms as opposed to evaluating the interaction coefficients explicitly [24].

The smooth wall turbulent channel flow simulated here has a friction velocity based Reynolds number $Re_\tau \equiv u_\tau h/\nu = 945$, where the friction velocity $u_\tau = \sqrt{\tau_{wall}/\rho}$, with τ_{wall} the magnitude of the wall shear stress. The centreline Reynolds number $Re_0 = u_0 h/\nu = 20\,580$, where u_0 is the centreline velocity. The size of the domain in the streamwise, wall-normal and spanwise directions respectively is $(L_x, L_y, L_z) = (\pi, 2, \pi/2)$. The number of collocated grid points in the streamwise (N_x) and spanwise (N_z) directions is related to the dealised truncation wavenumber $T = 127$ by $N_x = N_z = 3(T+1) = 384$. The grid spacing in the streamwise (Δx) and spanwise (Δz) directions is constant, and in viscous units the spacings are $\Delta x^+ = \Delta x u_\tau/\nu = 7.8$ and $\Delta z^+ = \Delta z u_\tau/\nu = 3.9$. The number of Chebyshev collocated grid points in the wall-normal direction is $N_y = 385$. In viscous units the wall-normal cell spacing at the wall is $\Delta y^+_{wall} = \Delta y_{wall} u_\tau/\nu = 0.03$, which increases as it approaches the maximum cell spacing at the centreline of $\Delta y^+_{cl} = \Delta y_{cl} u_\tau/\nu = 7.6$. The statistics are accumulated over 45 flow-through times, where one flow through time is defined as u_0/L_x.

The flow field is now characterised on the basis of statistical quantities and instantaneous intense Reynolds stress objects or clusters. The instantaneous velocity field, $\mathbf{U}$, is decomposed into its fluctuating component, $\mathbf{u}$, and its time averaged mean, $\bar{\mathbf{u}}$, where the overbar denotes time averaging. The mean streamwise profile, $\bar{u}$, is illustrated in viscous units ($\bar{u}^+ = \bar{u}/u_\tau$) in Fig. 1(a) against $y^+ = y u_\tau/\nu$. Also in viscous units, the Reynolds stress ($-\overline{uv}^+ \equiv -\overline{uv}/u_\tau^2$) is illustrated in Fig. 1(b), along with the root-mean-square (rms) profiles of the streamwise velocity ($u'^+ \equiv u'/u_\tau$) and wall-normal velocity ($v'^+ \equiv v'/u_\tau$). Note the $'$ superscript denotes the rms of the associated variable.

The pertinent statistical profiles shown in Fig. 1(a) and (b) of the present DNS [25,26] are consistent and compare favourably with the previous DNS of [27]. An instantaneous flow field is illustrated in Fig. 1(c), via iso-surfaces of $|uv|/[u'v'] = 1.7$, with the flow from left to right. This is an illustration of the clustering method described in the following section. The clusters are coloured by uv, where red is positive and blue is negative. The spanwise normal