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On near-wall turbulence in minimal flow units

Guang Yin, Wei-Xi Huang, Chun-Xiao Xu*

AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

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ABSTRACT

In the present work, direct numerical simulations are carried out for turbulent flows in a channel with minimal sizes in spanwise and streamwise directions required to get the so-called 'healthy' turbulence below a prescribed wall-normal height y_h (i.e., $y_h^+ = 100$) at $Re_\tau = 1000$, 2000 and 4000. It is found that, in the near-wall region ($y < y_h$), the mean velocity profiles from the small flow domain agree well with those in the full-sized channel; the velocity fluctuations show good agreement with those of the full-sized simulation at scales smaller than the corresponding minimal channel size; turbulence statistics at different Reynolds numbers scale well in wall units, showing Reynolds number independence. All the results imply that the near-wall turbulence produced by minimal flow units reflect some universal properties of wall turbulence. Further comparison shows that the near-wall velocity fluctuations in the minimal channel are in good consensus with the universal signals in the predictive model for near-wall turbulence (Marusic et al., 2010a).

1. Introduction

It is widely accepted that the main coherent structures in near-wall turbulence are streamwise elongated low-speed streaks and quasi-streamwise vortices. The regenerations of the two structures form a quasi-cyclic process, which is self-sustaining and independent of the outer motions, plays an important role in maintaining the turbulence within the near-wall region. Numerical experiments show that the characteristics of the quasi-cyclic process can be studied in a small computational domain, where a single or a few streaks can be isolated. The minimal spanwise size of the domain is $L_z^+ \approx 100$ (Jiménez & Moin, 1991), which approximately equals the average spacing between two adjacent low-speed streaks in the buffer layer (Kline et al., 1967). The cycle is found to be autonomous in the sense that it persists after artificially damping the outer flow above the viscous wall region (i.e. $y^+ > 60$) (Jiménez & Pinelli, 1999).

The spanwise scale of the near-wall coherent structures grows with the distance from the wall. When the structure reaches the logarithmic layer, its spanwise width is approximately proportional to its wall-normal height, i.e. $\lambda_z^+ \propto y^+$. Structures with different spanwise widths and central heights form a hierarchy of attached eddies (Townsend, 1976). When smaller-scale motions are removed, the coherent structures at a prescribed spanwise scale are shown to be self-sustaining, undergoing a similar regeneration process (Hwang & Cossu, 2010). Based on these observations, Flores and Jiménez (2010) extended the concept of the minimal channel in the buffer layer (Jiménez & Moin, 1991) to the logarithmic layer or outer regions. As the wall-attached structures become larger with their increasing height, a hierarchy of small boxes can be used to isolated motions at prescribed as well as at smaller scales. A so-called 'healthy' turbulence can be sustained as the mean velocity profile from the minimal channel agrees well with that in the full-sized domain within a higher region above the buffer layer. The streamwise and wall-normal fluctuations are lower from the smaller boxes than in the full-sized domain due to the lack of effects exerted by larger-scale outer motions especially at higher Reynolds numbers. Statistical properties were evaluated in Flores and Jiménez (2010) at only one Reynolds number while the Reynolds number effects need further investigation.

Furthermore, a series of numerical simulations at Re_τ (Reynolds number based on wall friction velocity u_τ and channel half height h) up to 660 were carried out by Hwang (2013). In this study, the spanwise width of $L_z^+ \approx 100$ was used to sustain 'healthy' turbulence below $y^+ \approx 40$. To remove motions wider than $\lambda_z^+ \approx 100$, Hwang found that a simple restriction of spanwise width was not enough and an additional numerical filter of spanwise wavenumber $k_z = 0$ was used to eliminate the spanwise uniform eddies. Preliminary tests showed that this filter could also damp the outer motions especially in terms of the wall-normal velocity. When comparing the second-order statistics and the one-dimensional spectra at different Reynolds numbers, Hwang observed that the streamwise fluctuation and its one-dimensional spectra can be scaled well by wall friction velocity below $y^+ \approx 40$, exhibiting

* Corresponding author.
E-mail address: xucx@tsinghua.edu.cn (C.-X. Xu).

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the Re_τ independence in the near-wall layer. Extended researches, where the motions at a given spanwise scale in the range $100\delta_\nu \le \lambda_z \le 1.5h$ (δ_ν denotes the viscous length scale) can be isolated, were performed by further damping the smaller-scale motions using over damped large eddy simulation (Hwang, 2015). The results revealed the existence of both self-sustaining and self-similar properties at different spanwise length scales, which support the attach eddy hypothesis (Townsend, 1976; Perry & Chong, 1982).

The influence of the large-scale outer motions on the near-wall turbulence has received great attention over the last decade. Despite the Reynolds number independence, and the similarities of the near-wall fluctuations with increasing Reynolds numbers, large-scale structures can penetrate deeply into the near-wall region and change the statistical behavior of the near-wall turbulence. Streamwise velocity intensities show that the small-scale motions are almost invariant with the Reynolds numbers over the turbulent boundary layer but the large-scale outer motions contain higher energy with the increasing Reynolds numbers (Marusic et al., 2010b). Based on the experimental measurements of turbulent boundary layer, Hutchins and Marusic (2007) summarized the influence of the outer large-scale motions on the near-wall motions as the superposition and modulation effects, and proposed a simple mathematical model with the large-scale signals in the center of the log-layer as the only input to predict the near-wall signals (Marusic et al., 2010a; Mathis et al., 2011). The parameters, including the superposition and modulation coefficients and the near-wall universal signals have to be predetermined by calibrating the experimental data.

One motivation of the present study is to investigate the possibility of using minimal flow units (MFU) to construct a reduced-order model for near-wall turbulence at high Reynolds numbers. Therefore, further questions are raised for this purpose. Does the Reynolds-number-independence of MFU, studied only up to $Re_\tau = 660$ and within buffer layer ($y_h^+ \approx 40$) (Hwang, 2013), still holds at high Reynolds numbers in a region further away from the wall? It was shown that the outer large-scale motions have significant influence on the near-wall region in the full-sized domain (Mathis et al., 2009, 2011; Agostini & Leschziner, 2014) and can't be resolved in smaller boxes. However, to what extent can the near-wall turbulence in the minimal channel reproduce the statistical properties in the full-sized channel, especially at high Reynolds numbers? To answer these questions, direct numerical simulations were performed to turbulent flows in the minimal channel up to $Re_\tau = 4000$ with $y_h^+ = 100$ at the lower bound of the logarithmic region, the location usually used for applying the off-wall boundary condition (Tuerke & Jiménez, 2013; Mizuno & Jiménez, 2013). The additional numerical filtering of spanwise uniform eddies was also used in the same way as Hwang (2013). Since the comparisons between simulations with and without the spanwise filtering in the spanwise minimal boxes are only provided at $Re_\tau = 180$ in the literature, the results of which suggested the filtering mainly damps the outer motions and does not influence the near-wall region below $y^+ \approx 40$, this study makes further comparisons at higher Reynolds numbers. Significant changes are observed especially in wall-normal and spanwise velocity fluctuations with the spanwise filtering. Free from the influence of the outer region due to the filtering and the limited domain size, the MFU should bear some similarities with the near-wall universal signals in the predictive model of Marusic et al. (2010a). This has also been verified in the present study by directly comparing the MFU data with the universal signals.

The paper is organized as followed: Section 2 describes the numerical method and the computation parameters. Section 3 provides the statistical results and discussion, as well as a description of similarities between the near-wall velocity fluctuations in the minimal channel and the universal signals in the predictive model (Marusic et al., 2010a). Finally, the conclusion is drawn in Section 4.

2. Numerical method

Flow between two infinite flat plates which locate at $y = 0$ and $y = 2h$ is considered in the present study. The streamwise, wall-normal and spanwise directions are denoted by x, y, z and the corresponding velocity components are u, v, w. The governing equations are the Navier-Stokes equations written in rotational form and the continuity equation

$$\frac{\partial \boldsymbol{u}}{\partial t} = \boldsymbol{u} \times \boldsymbol{\omega} - \nabla \Pi + \nu \nabla^2 \boldsymbol{u} \tag{1a}$$

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1b}$$

Here $\boldsymbol{u}$ denotes velocity vector, $\boldsymbol{\omega}$ vorticity vector, and Π the total pressure. The equations are non-dimensionalized by the half channel height h and the bulk mean velocity U_m. The Reynolds number is defined as $Re_m = U_m h/\nu$, where ν denotes the kinematic viscosity. In the streamwise and spanwise directions the periodic conditions are used, and the no-slip condition is imposed at the walls. Fourier–Galerkin method is adopted for the discretization in the streamwise and spanwise directions, and the aliasing errors are removed by using the 3/2-rule. In the wall-normal direction, the equations are discretized by using the seven-point compact finite difference scheme. Time integration is accomplished by using a third-order time-splitting method (Karniadakis et al., 1991). The bulk flow rate is kept constant for all the simulations by adjusting the driving mean pressure gradient.

As mentioned in the Introduction, a filter should be applied in order to further remove the spanwise uniform motions. The filtering method is the same as used in Hwang (2013) and is described briefly hereafter. In the present study, the time advancement of the governing equations is accomplished through three sub-steps incorporating the nonlinear, pressure and viscous terms, respectively, as shown in the following:

$$u_i^{k+1/3} = \sum_{q=0}^{2} \alpha_q u_i^{k-q} + \Delta t \sum_{q=0}^{2} \beta_q N_i^{k-q} \tag{2a}$$

$$u_i^{k+2/3} = u_i^{k+1/3} - \Delta t \frac{\partial \Pi^{k+1}}{\partial x_i} \tag{2b}$$

$$\left(\gamma_0 - \frac{\Delta t}{Re_m} \nabla^2 \right) u_i^{k+1} = u_i^{k+2/3} \tag{2c}$$

where k is the index of time step, and $N_i = (\boldsymbol{u} \times \boldsymbol{\omega})_i$ denotes the nonlinear term. The coefficients in (2a) and (2c) are given by $\alpha_0 = 3, \alpha_1 = -3/2, \alpha_2 = 1/3$, $\beta_0 = 3, \beta_1 = -3, \beta_2 = 1$ and $\gamma_0 = 11/6$ to achieve third-order time accuracy (Karniadakis et al., 1991). To remove the spanwise uniform fluctuations, the right-hand-side terms of the streamwise and wall-normal momentum equations are forced to be zero at the spanwise wavenumber of $k_z = 0$ in each sub-step,

$$\widehat{RHS_x}(k_x \neq 0, y, k_z = 0) = 0 \tag{3a}$$

$$\widehat{RHS_y}(k_x \neq 0, y, k_z = 0) = 0 \tag{3b}$$

where the over hat $\hat{.}$ denotes the Fourier transformed quantity in the streamwise and spanwise directions.

Table 1 displays the parameters of the present simulations. Again, it is desired to obtain healthy turbulence in the minimal channel up to $y_h^+ \approx 100$ in the present study. Therefore, the spanwise width of the channel should satisfy $L_z^+ \approx 3y_h^+$ according to