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ON THE OUTER LARGE-SCALE MOTIONS OF WALL TURBULENCE AND THEIR INTERACTION WITH NEAR-WALL STRUCTURES

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ABSTRACT

Large Eddy Simulation of turbulent channel and pipe flows with moderate streamwise length of $8\pi\delta$*, and very long pipe flows of* $32\pi\delta$ *(almost 100 times longer than the boundary layer thickness!) were conducted to investigate the outer large-scale motions and their interaction with near-wall turbulence. It was recongnized that both channel and pipe contained large streamwise elongated structures in the log or outer layer, and in the region above* $y/\delta > 0.5$ *their streamwise size was slightly smaller in the pipe flow (*$\lambda_x/\delta = 2 \sim 4$*) than in the channel flow (*$\lambda_x/\delta = 3 \sim 5$*). It was also found that the maximum streamwise size of the structure in the pipe flow reached almost 14 times the radius of the pipe in the log layer.*

INTRODUCTION

It has been widely acknowledged that wall turbulence contains outer large-scale motions of a size at least comparable to the boundary layer thickness (*e.g.* Kim & Adrian[1]). In contrast to the small-scale structures near the wall, less attention has been paid to the large structures until recently. However, according to the recent studies on the structures of high Reynolds-number (*Re*) turbulence and their *Re* scaling, the outer large structures and especially their interaction with the small scales near the wall appear to be an important issue in the understanding of wall turbulence. In fact, the *Re* dependence of the streamwise velocity fluctuations near the wall could be explained as a contribution of the outer motions to the inner structures, and evidence of this idea has been shown, for example, by DeGraaff & Eaton[2], in which they successfully discovered that the streamwise velocity rms collapses well in inner-outer mixed scaling.

The objective of this study is to investigate the large scale structures of wall-turbulence typically appear in the outer layer in the context of their *Re* scaling and interaction with the buffer layer turbulence. In the present work, we especially focus on two topics: difference of the outer large motions between the plane channel and pipe flows, and their streamwise largest size in the pipe flow.

NUMERICAL METHODS

The practical difficulty of studying the large-scale structures lies in the fact that they require a large experimental setup or a computational domain at sufficiently high *Re* conditions in order to properly capture their entire motions, and this requirement has been the stumbling block to both experiments and DNS (*e.g.* Del Álamo & Jiménez[3]) for large-scale studies. Alternatively we have adopted large eddy simulation (LES) as an analysis tool, which will be a promising method because we can save much computational resources to be consumed for the dissipative small eddies.

The analysis models adopted in this study are the plane channel (the half-height, δ) and pipe (the radius, δ), both of which consist of moderately long analysis region of $8\pi\delta$ for streamwise direction. In addition, we also conduct the very long pipe LES of the size $32\pi\delta$ to capture the largest scales typically appear in the log layer (*see* Table 1 for detail). Hereafter, x, y, and z indicate the streamwise, normal-wall, and spanwise/azimuthal directions, respectively. The streamwise direction is supposed to be periodic, and constant pressure gradient is imposed to obtain statistically steady state. It should be noted that sufficiently fine grid resolutions of $h_x^+ \sim 30$ and $h_z^+ \sim 20$ are adopted for streamwise and spanwise/azimuthal directions near the wall to properly capture the sublayer streaks considering the interaction between the near-wall turbulence and outer large motions. The governing equations are the filtered incompressible Navier-Stokes and continuity equations. We have adopted the fully conservative high-order FD scheme for uniform Cartesian staggered grids by Morinishi *et al.*[4] and the extension of the method to the non-uniform grids in cylindrical coordinates. All spatial derivatives are discretized by the fourth-order FD, except for the SGS term which is discretized by the second-order. An isotropic eddy viscosity model developed previously by Tsubokura[5] for the dynamic procedure using FD method is adopted.

Table 1
Numerical conditions for plane channel and pipe flows:.

geom.	Re_τ	*Dom. sz.*	*Grid num.*
		$L_x \times L_z$	$N_x \times N_y \times N_z$
plane	395	$8\pi\delta \times 4\pi\delta$	$360 \times 45 \times 256$
	590	$8\pi\delta \times 4\pi\delta$	$512 \times 65 \times 384$
	1180	$8\pi\delta \times 2.25\pi\delta$	$1024 \times 129 \times 432$
pipe	395	$8\pi\delta \times 2\pi$	$360 \times 23 \times 128$
	590	$8\pi\delta \times 2\pi$	$512 \times 33 \times 192$
	1180	$8\pi\delta \times 2\pi$	$1024 \times 65 \times 384$
	1180	$32\pi\delta \times 2\pi$	$4096 \times 65 \times 384$
	2360^*	$32\pi\delta \times 2\pi$	$8192 \times 129 \times 768$

RESULTS

Channel and Pipe flows with $L_x = 8\pi\delta$

One-dimensional premultiplied power spectra of the streamwise velocity component obtained in plane channel and pipe flows are plotted in Fig. 1 (near wall) and 2 (away from the wall). Figure 1 shows that the spectral tendency is the same for each geometrical configuration near the wall, while notable difference appears in or above the logarithmic layer. As indicated in Fig. 2(a), both the plane channel and pipe show a peak at the second largest mode ($\lambda_x/\delta = 4\pi$) at $y^+ \sim 200$, which indicates the typical size of the large scale motions. In case of the pipe, this energetic mode is mitigated above the logarithmic layer ($y^+ > 400$), while the channel maintains this spectral peak even in the wake region. These figures clearly suggest that near-wall organized structures are essentially the same between the plane channel and pipe, while outer large scales are different between them. It also should be mentioned that the peak at the second largest mode suggests that the numerical box for streamwise direction at the log layer is not sufficiently large enough to capture the streamwise largest motions.

Figures 3 and 4 indicate the grey-scale coded contours of instantaneous streamwise velocity fluctuations obtained in plane channel and pipe flows at $Re_\tau = 1180$. We can observe on the plane at $y^+ \sim 200$ the coherent streaky structures similar to the low-speed streaks in the near-wall region. However, their spanwise spacing is equivalent to the order of the channel height or the pipe radius. Figure. 4 also shows that the large lower-velocity zones (appearing as the large dark spots) align in the spanwise and azimuthal directions, and compared with the low-speed streaks appearing as very small black dots in the vicinity of the wall, their size are remarkably large. It is evident that the large scales penetrate deep into the near-wall region, which affects the characteristics of the near-wall region. The possible explanation of this deep penetration of the large scale is its contribution of the *Re*-number dependence of the rms of the streamwise velocity near the wall. The most notable difference of these large lower-velocity zones between plane and pipe flows are that , owing to the confined geometry of the pipe toward the pole, each large structure in the pipe seems to be interact with each other near the pole. As a result of this interaction, the size of the large structures in the pipe is slightly smaller than the ones observed in the plane channel flow, as shown in Fig. 3 ($y^+ \sim 200$)

To investigate the difference of the structures between channel and pipe flows, the peak wavelength of their premultiplied power spectra at $Re_\tau = 1180$ is indicated in Fig. 5. Both channel and pipe flows have very large streamwise elongated structures ($\lambda_x/\delta \sim 12$) in the middle of log layer ($y^+ \sim 300, y/\delta \sim 0.25$), then they become smaller in the *outer* layer ($y/\delta \sim 0.4$)(*see* Fig. 5(a)). Compared with that of channel flow in the outer layer ($\lambda_x/\delta = 3 \sim 5$), the elongated structure is slightly smaller in pipe flow ($\lambda_x/\delta = 2 \sim 4$). The spanwise size of the corresponding large structures in channel flows maintains the same in or above the log layer, while the jagged profile of the pipe for the azimuthal peak wavelength is remarkable (*see* Fig. 5(b)).

Very Long Pipe flows with $L_x = 32\pi\delta$

To evaluate the maximum streamwise size appearing in the log layer, the streamwise peak wavelength of the very long pipe flow at $Re_\tau = 1180$ is plotted in Fig. 6. For comparison, experimental results of Kim & Adrian are also plotted. We can identify that the maximum size reaches almost 14 times larger than the pipe radius in the log layer, and their agreement with the experimental data is excellent.

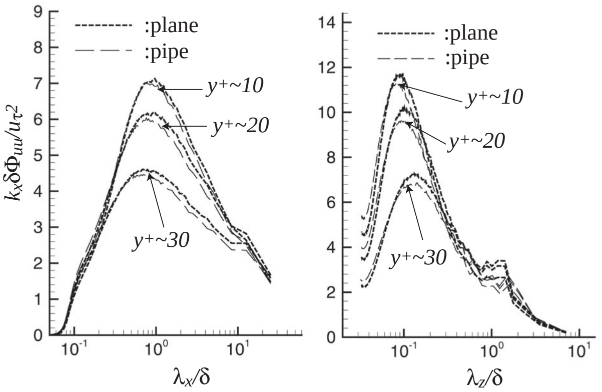

Fig. 1. 1-D premultiplied power spectra of the streamwise velocity ($y^+ \sim 20$) at $Re_\tau = 1180$: (a), streamwise; (b), spanwise or azimuthal.

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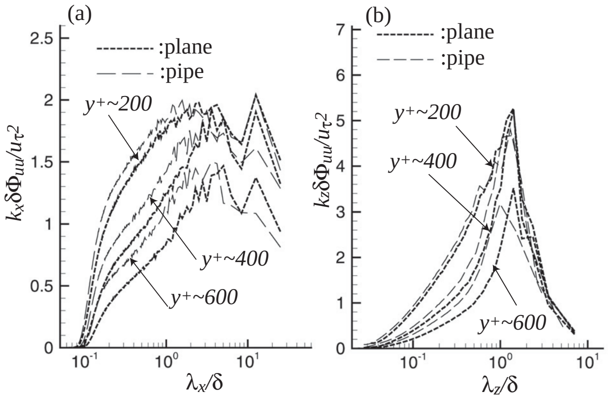

Fig. 2. 1-D premultiplied power spectra of the streamwise velocity ($y^+ \sim 200$) at $Re_\tau = 1180$: (a), streamwise; (b), spanwise or azimuthal.

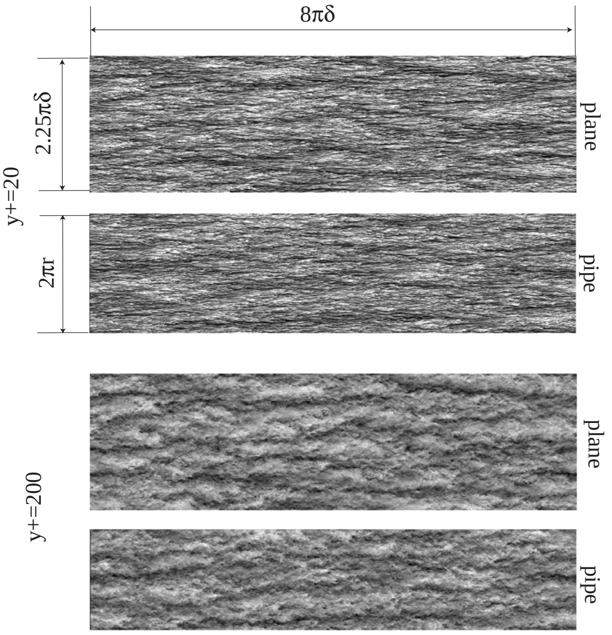

Fig. 3. Instantaneous streamwise velocity fluctuations on an $x-z$ plane at $y^+ \sim 20$ and 200 at $Re_\tau = 1180$.

[2] DeGraaff, D. B., and Eaton, J. K., J. Fluid Mech., Vol. 422, pp. 319, 2000.

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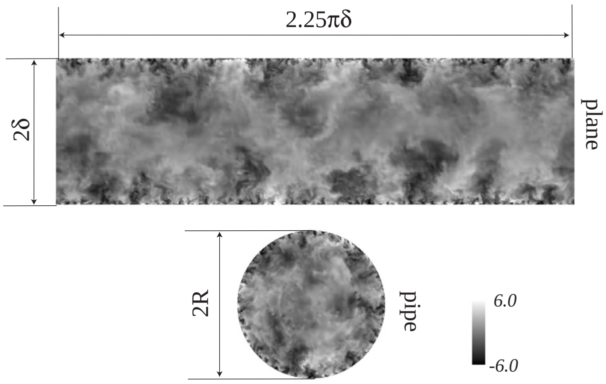

Fig. 4. Instantaneous streamwise velocity fluctuations on a $y-z$ plane at $Re_\tau = 1180$

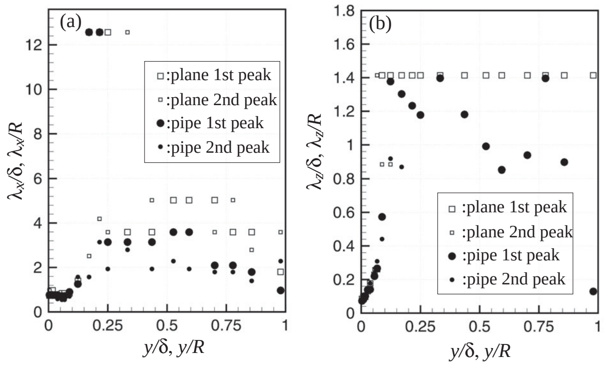

Fig. 5. Comparison of the peak wavelength of the premultiplied power spectra between *channel* and *pipe* flows at $Re_\tau = 1180$ in *outer* scaling: (a), streamwise; (b), spanwise or azimuthal.

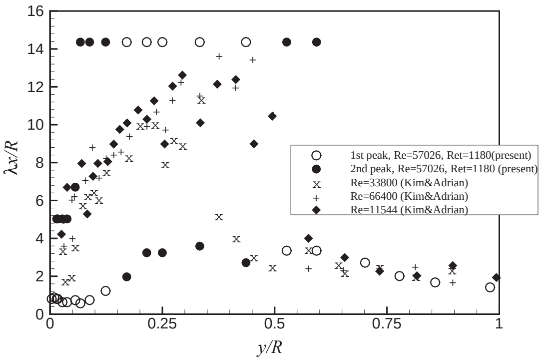

Fig. 6. The streamwise peak wavelength of the premultiplied power spectra of the very long pipe flow at $Re_\tau = 1180$ (Experimental data, Kim & Adrian)