Characteristics of overlap region in high-Reynolds number turbulent channel flow

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Abstract Direct numerical simulation of the fully developed turbulent channel flows have been carried out at the Reynolds number based on the friction velocity and the channel half width, 2000, 4000 and 8000. A hybrid 10th order accurate finite difference scheme in the stream and spanwise directions, and a second-order scheme in the wall-normal direction is adapted as the spatial discretization method. We observed the plateau profiles in the indicator function corresponded to the von Karman constant. Furthermore, second peak of streamwise pre-multiplied spectra were appeared in the same wall normal height, $300 < y^+ < 600$, in case of $Re_\tau = 4000$. Nevertheless, the effects of the lager than the channel half-height scale on the streamwise turbulent intensity are fixed contributions without dependence on Reynolds number. These results suggested that the new streamwise vortexes are formed between buffer layer and outer layer with increasing of Reynolds number.

Numerical procedures & DNS database

The target flow is an incompressible turbulent flow. The flow is assumed to be a fully developed turbulent channel flow driven by the constant mean pressure gradient in the streamwise direction.
To solve the above turbulent fields numerically, we used two-types DNS codes of a turbulent channel flow. One is a hybrid Fourier spectral and the second-order central differencing method (PSM) [1]. The other is a hybrid 10th order accurate finite differencing and the second-order method (FDM). In both cords, second-order central differencing method was adapted for the wall-normal discretization method. Numerical conditions were tabled in Table 1. Present DNS were carried out by using the SX-9 at the Cyber Science Center, Tohoku University and the K computer at RIKEN.

Table 1. Numerical conditions

Method	Re_τ	N_x, N_y, N_z	L_x, L_y, L_z	$\Delta x^+, \Delta y^+, \Delta z^+$	Tu_τ/h
PSM	2000	2000, 2032, 1920	$16h$,	16.0, 0.5-2.0, 6.7	9.3
FDM	4000	5760, 2048, 3072	$2h$,	13.3, 0.5-8.0, 8.3	5.0
FDM	8000	7200, 4096, 5760	$6.4h$	17.8, 0.5-8.0, 8.9	3.0

$Re_\tau = u_\tau h/\nu$: friction Reynolds number, u_τ : friction velocity, h: channel half depth, ν: kinematic viscosity, L_x (N_x, Δx), L_y (N_y ,Δy), L_z (N_z, Δz,): computational domain (grid number, resolution) for stream (x), vertical (y), and spanwise (z) directions, respectively.

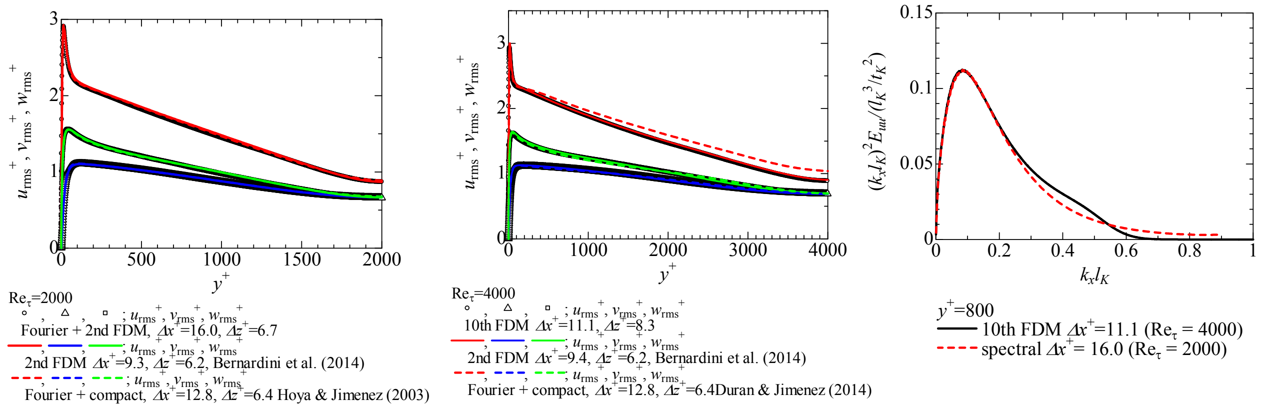
Results & disscussion

Figures 1-(1) and (2) shows the turbulent intensity profiles in cases of $Re_\tau = 2000$ and 4000, respectively. To validate the present DNS database, DNS database of the previous studies [2, 3, 4] were also plotted in Figs.2-(1) and (2). In case of Re_τ=2000 as shown in Fig.1-(1), present results by PSM were good agreements with others. In contrast, streamwise turbulent intensities in result of Lozano-Duran and Jimenez [4] was different with others in the wall-normal height $y^+ > 500$ in case of Re_τ =4000 as shown in Fig.1-(2). To check the spatial-discretization scheme effect on this difference, the dissipation spectra at y^+ =800 were shown in Fig. 1-(3). Because the profile of FDM in case of Re_τ =4000 doesn't show the tendency of lack of grid resolution, this difference was caused by computational domain size. Consequently, present DNS database has the satisfactory accuracy to investigate the high-Re effects.

Figure 2-(1) shows the indicator function ($\beta = 1/\kappa$, κ is the von Karman constant). The plateau profiles ($1/\kappa = 2.56$) were observed at $300 < y^+ < 600$ in case of Re_τ =4000. Figure 2-(2) and (3) show contour maps of streamwise pre-multiplied spectra in cases of $Re_\tau = 2000$ and 4000. The second peak of pre-multiplied spectra can be found at $300 < y^+ < 600$, and wavelength (λ_x^+) is almost 30,000 in case of Re_τ =4000. This wall-normal height, $300 < y^+ < 600$ is corresponded to the upper limit of inner layer, $y/h < 0.2$. Thus, it is pointed out that high-Re effects are typically appeared in overlap region [5].

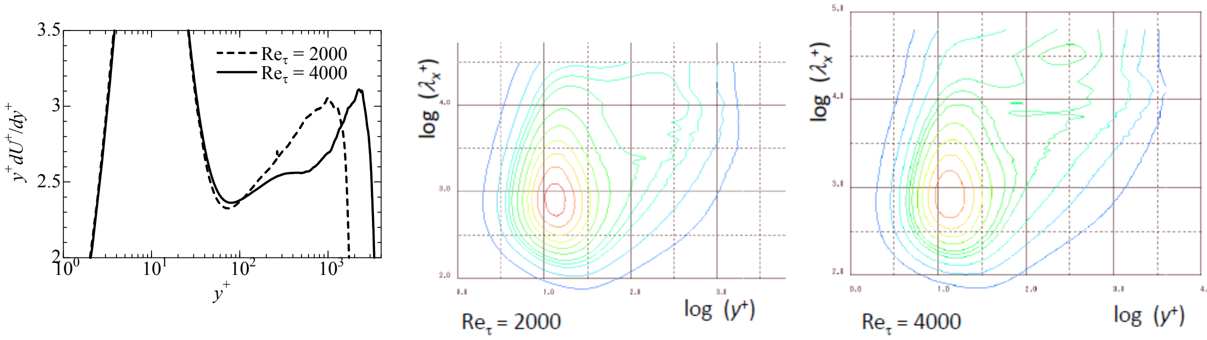
Figure 3-(2) shows the contribution of the spanwise wave-lengths (λ_z) larger than the channel half height (h) on the streamwise turbulent intensity. In the overlap region, these contributions were not increased but constant with increasing of Re. In contrast, the spanwise wave-lengths less than the channel half-height were increased with increasing of Re under the inner layer, $y/h < 0.2$. These are indicated that turbulent energy transfer from the large-scale structures to the buffer layer (y^+=15) structures are not conducted directly but indirectly. Figure 3-(3) show the contour plots of instantaneous streamwise turbulent velocity in cases of $Re_\tau = 2000$ and 8000. In case of $Re_\tau = 8000$, streamwise

vortexes scaled by the inner layer height (y/h = 0.2) were observed. These results suggested that the new streamwise vortexes are formed between buffer layer and outer layer in high-Re (0.2 Re_τ >> 100), and these vortexes were played the roles to energy transfer from outer layer to the vicinity wall as shown in Fig.3-(2).



(1) turbulent intensities, (2) turbulent intensities, (3) dissipation spectra

Figure 1. Validation of present DNS database.



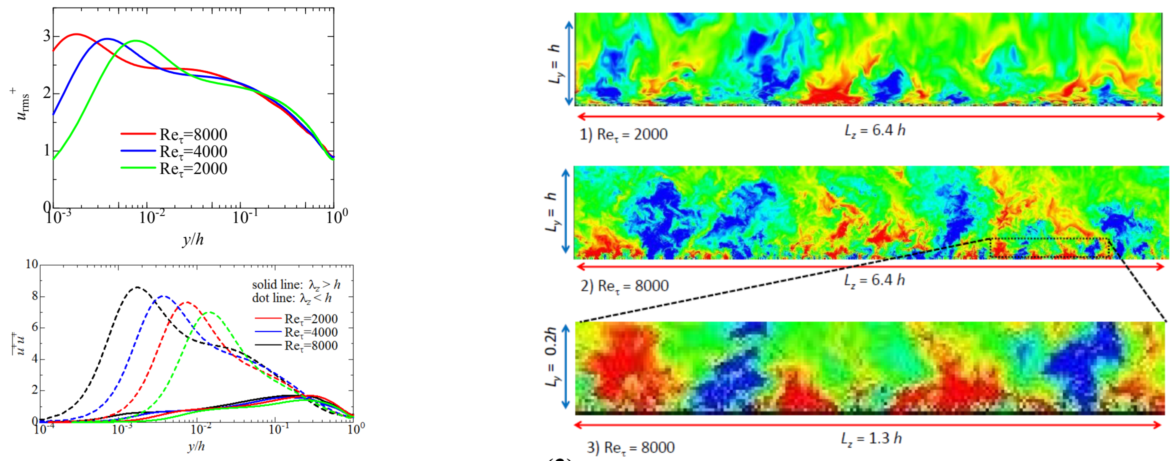
(1) **(2)** **(3)**

Figure 2. Characteristics of log-layer.

(1) Karman constant, (2,3) contour maps of streamwise pre-multiplied spectra, contour lines: $k_x E_{uu}/u_\tau^2$ = 0.2(blue), 0.4, 0.6, 0.7, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0(red)

(1)

(2)



(3)

Figure 3. Formation of new streamwise vortexes between buffer layer and outer layer in high-Re cases. (1) streamwise turbulent intensity, (2) contribution of boundary layer scales on turbulent intensities, (3) color contour plots of instantaneous streamwise turbulent velocities, -1.2 (blue) < u^+ < 1.2 (red).

References

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