COMPUTATIONAL MECHANICS
WCCM VI in conjunction with APCOM'04, *Sept. 5-10, 2004, Beijing, China*

MS022-174

Dynamical Roles of Large-Scale Structures in Turbulent Channel Flow

Kaoru Iwamoto*, Nobuhide Kasagi, Yuji Suzuki

Department of Mechanical Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan
e-mail: {iwamoto, kasagi, ysuzuki}@thtlab.t.u-tokyo.ac.jp

Abstract Direct numerical simulation of a turbulent channel flow at $Re_\tau = 1160$ was made in order to examine the relationship between the near-wall quasi-streamwise vortices and the large-scale outer-layer structures. The number of the total grid points is about 2 billions, and the effective computational speed is about 1.4 TFLOPS by using 512 CPUs and 600 GB main memory on the Earth Simulator. The visualized flow field and the turbulent statistics suggest that the near-wall quasi-streamwise vortices are located between low- and high-speed streaky structures as those in low Reynolds number flows. On the other hand, the large-scale low/high-speed regions are formed away from the wall, and the small-scale vortices are clustered preferably in the low-speed regions. The streaky structures, of which spanwise spacing is about 100 wall units, exist only near the wall ($y^+ < 30$), while the large-scale structures exist from the center of the channel to the near-wall region ($y^+ \sim 30$). The large-scale structures have larger contribution to the Reynolds stress than that of clusters of small-scale vortices in the outer layer, so that they sustain the production of turbulent kinetic energy by themselves. It is also found that the small-scale vortices do not agglomerate autonomously, but become clustered with the advective effect of the low-speed large-scale structures.

Key words: turbulent channel flow, large-scale structures, DNS, high Reynolds number

INTRODUCTION

Up to now, various Reynolds number effects in wall turbulence have been reported. Zagarola & Smits [1] suggest that the overlap region between inner and outer scalings in wall-bounded turbulence may yield a log law rather than a power law at very high Reynolds numbers. Moser *et al.*[2] have made direct numerical simulation (DNS) of fully-developed turbulent channel flows at $Re_\tau = 180-590$ (hereafter, Re_τ denotes the friction Reynolds number defined by the wall friction velocity u_τ, the channel half-width δ, and the kinematic viscosity ν). They conclude that the wall-limiting behavior of root-mean-square (rms) velocity fluctuations strongly depends on the Reynolds number, but obvious low-Reynolds-number effects are absent at $Re_\tau > 395$. It is well known that near-wall streamwise vortices play an important role in the transport mechanism in wall turbulence, at least, at low Reynolds number flows [3, 4, 5]. Those streamwise vortices and streaky structures, which are scaled with the viscous wall units [6], are closely associated with the regenerative mechanism [7].

On the other hand, the relationship between the near-wall coherent structures and the large-scale outer-layer structures at higher Reynolds numbers still remains unresolved. Adrian *et al.*[8] show that packets of large-scale hairpin vortices around the low-speed large-scale structures are often observed in high-Reynolds-number wall turbulence. Zhou *et al.*[9] have studied the evolution of a single hairpin vortex-like structure in a low-Reynolds-number channel flow by DNS, and found a packet of hairpins that propagate coherently as reported in Adrian *et al.*[8]. Figure 1 shows a conceptual diagram of the turbulent kinetic

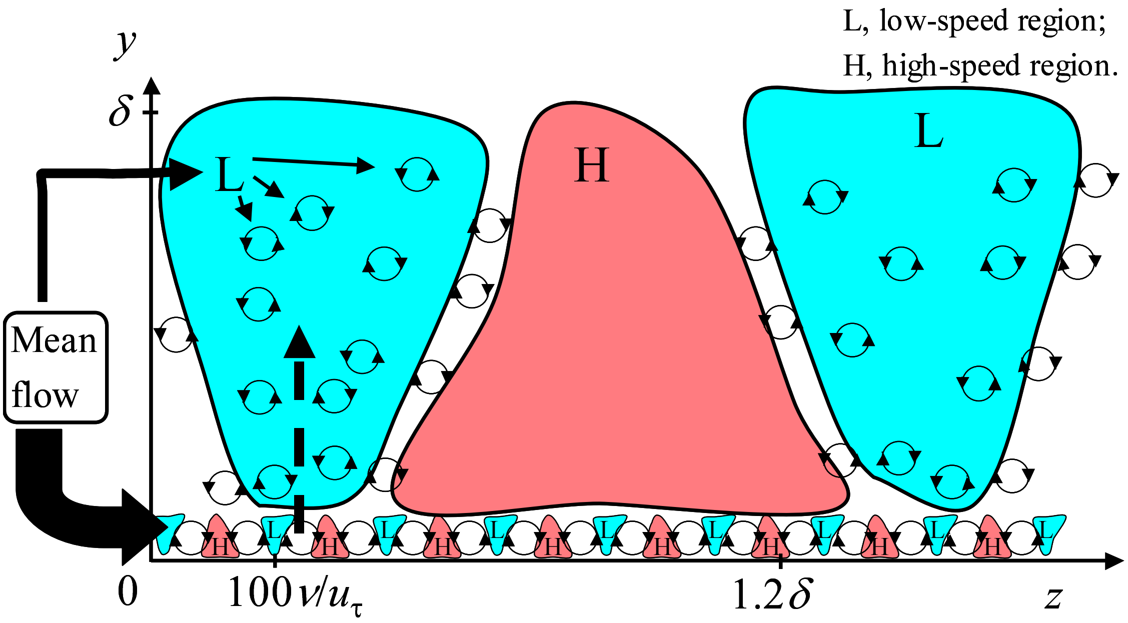

Fig. 1 Conceptual diagram of energy flow between the near-wall vortices and the large-scale outer-layer structures.

paths between the near-wall vortices and the large-scale outer-layer structures. The near-wall vortices gain the large turbulent kinetic energy from the mean flow. Most energy is dissipated by themselves, while the rest is transferred to the large-scale structures through the nonlinear interaction [10]. On the other hand, the large-scale structures also gain substantial energy from the mean flow. The energy is not dissipated by themselves, but transferred to the smaller vortices through the energy cascade. The following contradictory hypotheses about the origin of the large-scale structures can be considered:

1. The near-wall streamwise vortices agglomerate autonomously, and form the clustered structures, which result in the low-speed large-scale structures. Therefore, the energy transfer from the near-wall coherent structures to the large-scale structures is essential to the formation of the large-scale structures.

2. The large-scale structures exist independently on the near-wall coherent structures. The small-scale vortices do not agglomerate autonomously and are clustered by the action of the low-speed large-scale structures. Therefore, the energy transfer from the mean flow to the large-scale structures is indispensable for the generation of the large-scale structures.

In the present study, DNSs of turbulent channel flow at moderate Reynolds number of $Re_\tau = 650$ and 1160 are carried out to examine the above-mentioned hypotheses.

FUNDAMENTAL CHARACTERISTICS OF LARGE-SCALE STRUCTURES

In this section, the fundamental characteristics of the near-wall coherent structures and large-scale structures are evaluated through the DNS. The numerical method used in the present study is almost the same as that of Kim *et al.*[11]; a pseudo-spectral method with Fourier series is employed in the streamwise (x) and spanwise (z) directions, while a Chebyshev polynomial expansion is used in the wall-normal (y) direction. A fourth-order Runge-Kutta scheme and a second-order Crank-Nicolson scheme are used for time discretization of the nonlinear terms and the viscous terms, respectively. The average of pressure gradient is kept constant. For $Re_\tau = 1160$, the size of the computational domain is $6\pi\delta \times 2\delta \times 2\pi\delta$, and the wave number is $1152 \times 513 \times 1024$ in x-, y-, and z-directions, respectively. The $3/2$ rule is applied to avoid the aliasing errors involved in computing the nonlinear terms pseudo-spectrally. The number of the total grid points is about 2 billions, and the effective computational speed is about 1.4 TFLOPS by using

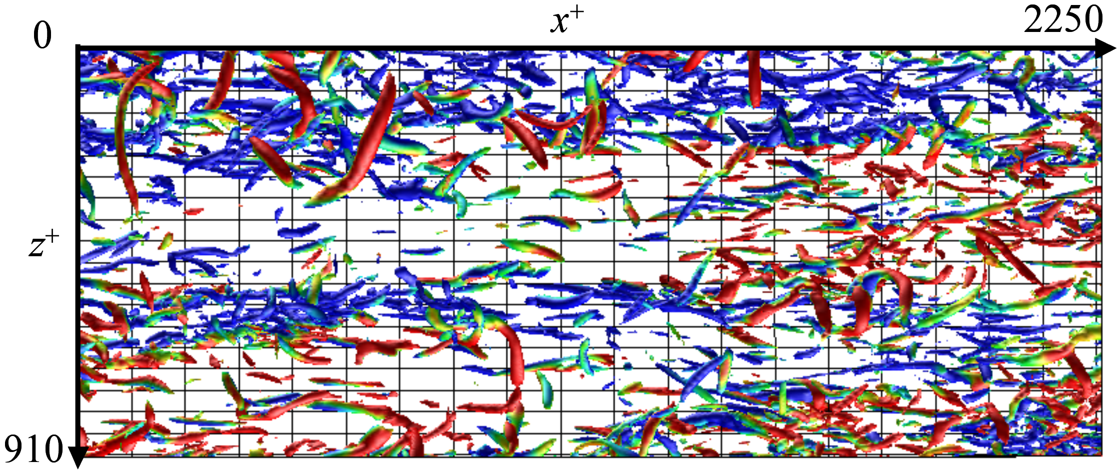

Fig. 2 Plane view of vortices at $Re_\tau = 1160$. Iso-surface, $Q^+ = -0.02$; blue to red, $u'^+ = -1$ to $u'^+ = 1$. Total computational volume is 21865 and 7288 wall units in the x- and z-directions, respectively.

512 CPUs and 600 GB main memory on the Earth Simulator [12], which is the fastest supercomputer in the world. The two-point correlations in the x- and z-directions at any y-location fall off to zero values for large separations, indicating that the computational domain is sufficiently large (not shown here). The energy density associated with the high wavenumbers is several decades lower than the energy density corresponding to low wavenumbers, pointing that the grid resolution is adequate (not shown here). Hereafter, u, v, and w denote the velocity components in the x-, y-, and z-directions, respectively. Superscript $(+)$ represents quantities non-dimensionalized with u_τ and ν.

Figure 2 shows a $(x-z)$ plane view of an instantaneous flow field at $Re_\tau = 1160$, in which the vortices identified with isosurfaces of the second invariant of the deformation tensor ($Q^+ \equiv u'^+_{i,j} u'^+_{j,i} = -0.02$) are visualized. It is found that the vortices form clusters in low-speed regions, and that some hairpin vortices are observed in high-speed regions.

Figure 3 shows a $(y-z)$ cross-stream plane of an instantaneous flow field, in which contours of the streamwise velocity fluctuation u' and vortices ($Q^+ < -0.005$) are visualized, in order to examine the relationship between the near-wall vortices and the large-scale outer-layer structures. The near-wall vortices are located between low- and high-speed streaky structures as same as those in low Reynolds number flows [4]. Away from the wall, large-scale low/high-speed structures prevail, and the vortices are clustered preferably in the low-speed regions. The streaky structures, of which spanwise spacing is about $100\nu/u_\tau$, exist only near the wall ($y^+ < 30$), while the large-scale structures exist from the center of the channel to the near-wall region ($y^+ \sim 30$).

Figure 4 shows the contour of one-dimensional spanwise pre-multiplied power spectra of u'. The obvious peak can be found at $y^+ \approx 15$ and spanwise wavelength $\lambda_z^+ \approx 120$ ($\lambda_z/\delta \approx 0.1$), indicating that the near-wall streaky structures have large contribution to the near-wall streamwise velocity fluctuations as those in low-Reynolds-number flows [3]. On the other hand, the second peak can be also identified at $y^+ \approx 300$ and $\lambda_z/\delta \approx 1.2$, which is only observed in higher Reynolds number.

ORIGIN OF LARGE-SCALE STRUCTURES

In this section, origin of the large-scale structures are studied through DNS at $Re_\tau = 650$. The computational method is the same as that of $Re_\tau = 1160$ [10]. In order to examine the effect of the energy production in the large-scale structures, the energy transfer from the mean flow to the large-scale structures is intercepted by using the Navier-Stokes equation with an additional blocking term as shown below:

$$\frac{\partial \widehat{u_i^+}}{\partial t^+}(k_1,k_3) + \widehat{u_j^+ \frac{\partial u_i^+}{\partial x_j^+}}(k_1,k_3) - \alpha(k_3)\cdot \widehat{u_j^+}(k_1,k_3)\cdot \frac{\partial \widehat{u_i^+}}{\partial x_j^+}(0,0) = -\frac{\partial \widehat{p^+}}{\partial x_i^+}(k_1,k_3) + \frac{\partial^2 \widehat{u_i^+}}{\partial x_j^+ \partial x_j^+}(k_1,k_3)\ , \qquad (1)$$

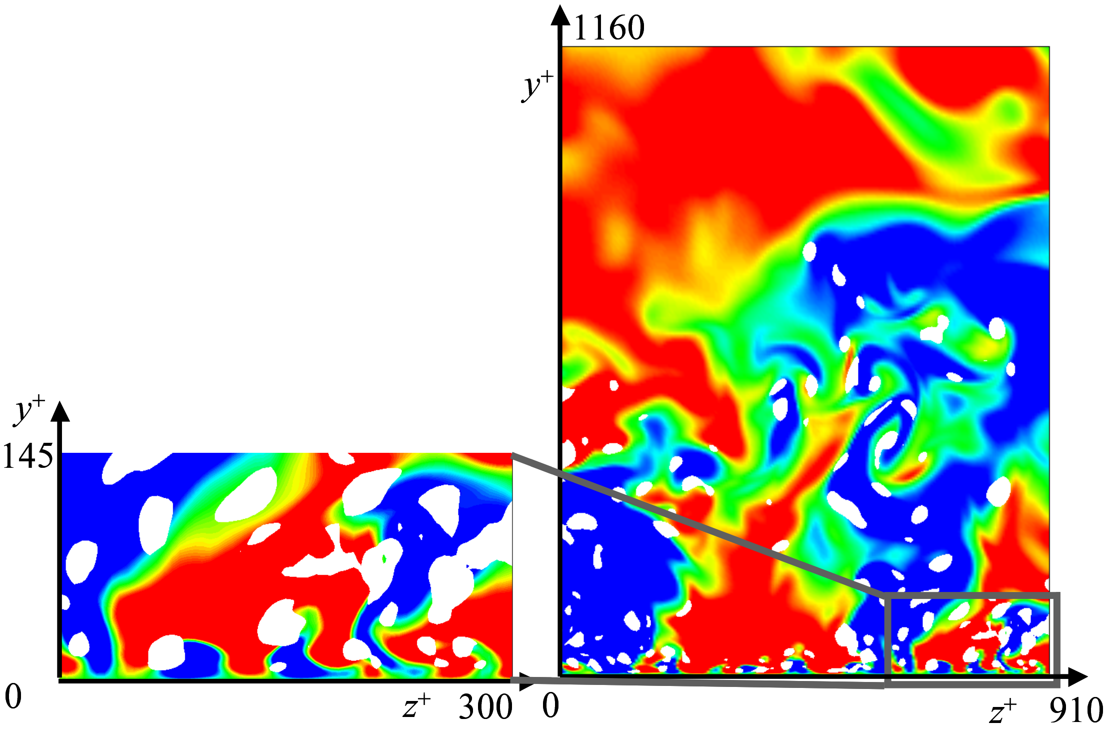

Fig. 3 Cross view of instantaneous velocity field at Re_τ = 1160. Contours of the streamwise velocity fluctuation, blue to red, $u'^+ = -1$ to $u'^+ = 1$; white, $Q^+ < -0.005$. Total computational volume is 2320 and 7288 wall units in the y- and z-directions, respectively.

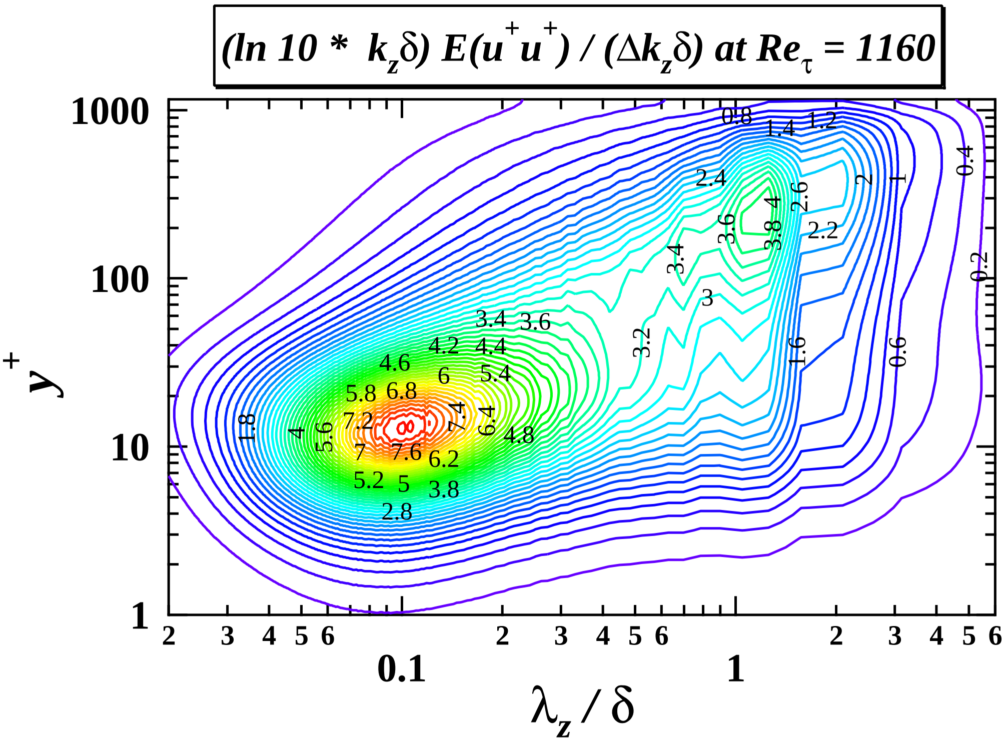

Fig. 4 Contour of one-dimensional spanwise pre-multiplied power spectra of u' at $Re_\tau = 1160$.

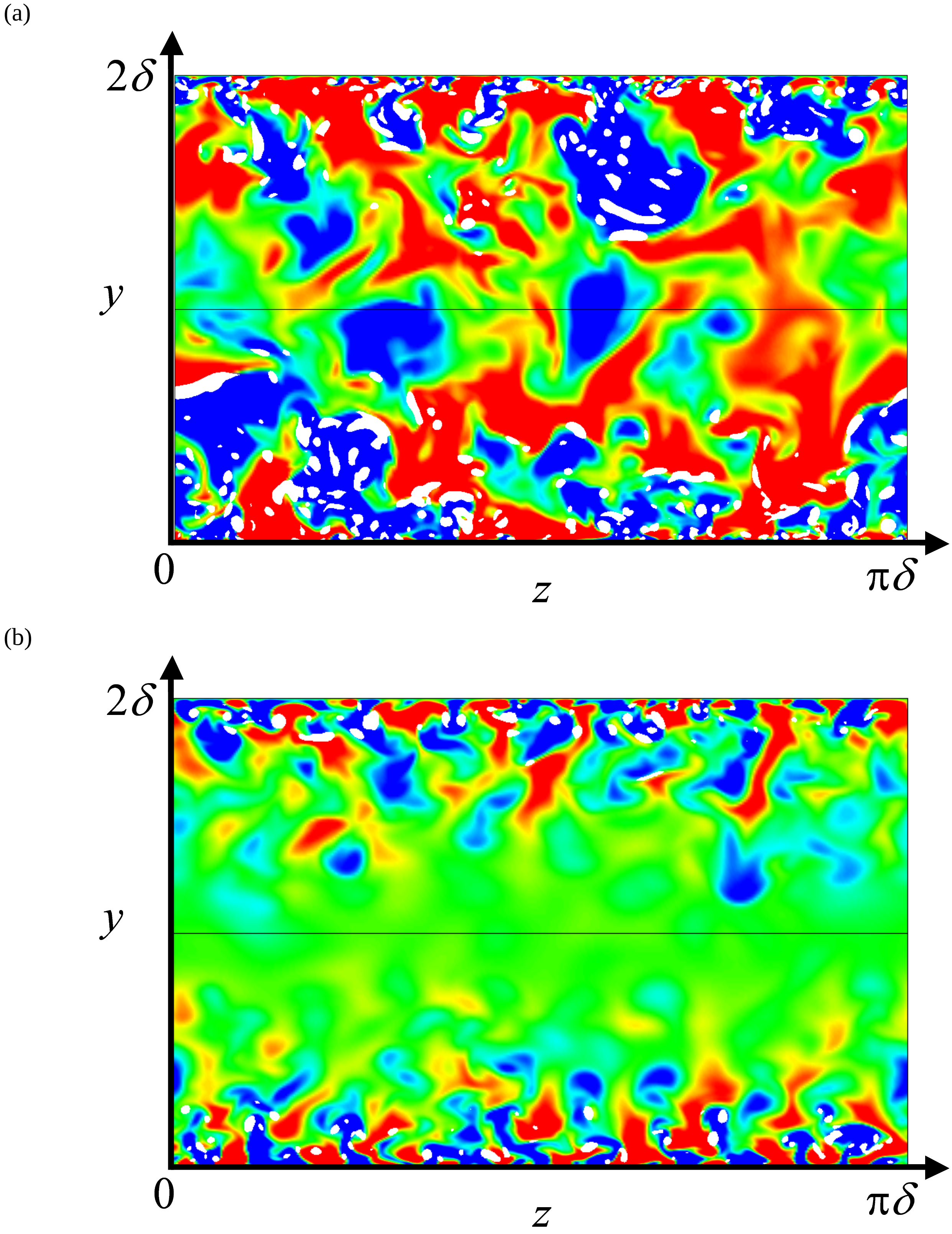

Fig. 5 Cross-sectional view of instantaneous velocity field at $Re_\tau = 650$. (a) Original flow; (b) with the intercept of the energy transfer from the mean flow to the large-scale structures. Contours of the streamwise velocity fluctuation, blue to red, $u'^+ = -1$ to $u'^+ = 1$; white, $Q^+ < -0.005$.

where $\widehat{\cdot}$ denotes the Fourier coefficient. In Eq. (1), k_1 and k_3 denote wavenumbers in the x- and z-directions, respectively. The third term on the left-hand side is the additional term for offsetting the energy transfer from the mean flow to the velocity fluctuations of the wavenumber (k_1, k_3). Since the large-scale structures have the streamwise normal Reynolds stress mainly at $\lambda_z/\delta > 0.6$ as shown in Fig. 4, we employ the coefficient $\alpha = 1$ for the spanwise wavelength $\lambda_z/\delta > 0.6$ (i.e., $\alpha(2\pi k_3/L_z \leq 5) = 1$), otherwise $\alpha = 0$. A fully-developed flow field is used as the initial condition, and the mean velocity profile is fixed in order to hold the Reynolds number.

Figure 5 shows the contours of the instantaneous streamwise velocity fluctuation u' and the vortices in a cross-stream plane. The large-scale structures exist from the center of the channel to the near-wall region in the original turbulent channel flow, and the smaller vortices are clustered in the low-speed large-scale structures as shown in Fig. 5(a). On the other hand, when the energy transfer is intercepted, the large-scale structures and the clustered vortices disappear as shown in Fig. 5(b). Therefore, the direct energy transfer from the mean flow to the large-scale structures is indispensable for the generation of the large-scale structures. Moreover, the small-scale vortices do not agglomerate autonomously and are clustered by the action of the low-speed large-scale structures.

CONCLUSIONS

Direct numerical simulations of turbulent channel flows at $Re_\tau = 650$ and 1160 were made in order to examine the dynamical roles of the large-scale outer-layer structures, and the relationship between the near-wall vortices and the large-scale structures. The following conclusions are derived:

1. The streaky structures, of which spanwise spacing is about 100 wall units, exist only near the wall ($y^+ < 30$), while the large-scale structures, of which spanwise spacing is about 1.2δ, exist from the center of the channel to the near-wall region ($y^+ \sim 30$). The energy transfer from the mean flow to the large-scale structures is indispensable for the generation of the large-scale structures.

2. The quasi-streamwise vortices are located between low- and high-speed streaky structures in the near-wall region. Away from the wall, small-scale vortices are clustered preferably in the low-speed large-scale structures. Those vortices agglomerate by the action of the low-speed large-scale structures.

Acknowledgements The computer time for the present DNS at $Re_\tau = 1160$ was provided by the Earth Simulator Center, Japan [12].

REFERENCES

[1] M. V. Zagarola and A. J. Smits, *Mean-flow scaling of turbulent pipe flow*, J. Fluid Mech., 373, (1998), 33-79.

[2] R. D. Moser, J. Kim, and N. N. Mansour, *Direct numerical simulation of turbulent channel flow up to Re_τ = 590*, Phys. Fluids, 11, 4, (1999), 943-945.

[3] S. K. Robinson, *Coherent motions in the turbulent boundary layer*, Annu. Rev. Fluid Mech., 23, (1991), 601-639.

[4] N. Kasagi, Y. Sumitani, Y. Suzuki, and O. Iida, *Kinematics of the quasi-coherent vortical structure in near-wall turbulence*, Int. J. Heat Fluid Flow, 16, (1995), 2-10.

[5] A. G. Kravchenko, H. Choi, and P. Moin, *On the relation of near-wall streamwise vortices to wall skin friction in turbulent boundary layers*, Phys. Fluids, A 5, 12, (1993), 3307-3309.

[6] S. J. Kline, W. C. Reynolds, F. A. Schraub, and P. W. Runstadler, *The structure of turbulent boundary layers*, J. Fluid Mech., 30, (1967), 741-773.

[7] J. M. Hamilton, J. Kim, and F. Waleffe, *Regeneration mechanisms of near-wall turbulence structures*, J. Fluid Mech., 287, (1995), 317-348.

[8] R. J. Adrian, C. D. Meinhart, and C. D. Tomkins, *Vortex organization in the outer region of the turbulent boundary layer*, J. Fluid Mech., 422, (2000), 1-54.

[9] J. Zhou, R. J. Adrian, S. Balachandar, and T. M. Kendall, *Mechanisms for generating coherent packets of hairpin vortices in channel flow*, J. Fluid Mech., 387, (1999), 353-396.

[10] K. Iwamoto, Y. Suzuki, and N. Kasagi, *Reynolds number effect on wall turbulence: toward effective feedback control*, Int. J. Heat Fluid Flow, 23, (2002), 678-689.

[11] J. Kim, P. Moin, and R. Moser, *Turbulence statistics in fully developed channel flow at low Reynolds number*, J. Fluid Mech., 177, (1987), 133-166.

[12] http://www.es.jamstec.go.jp/esc/eng/index.html