Evolution of vortices in wall vicinity of turbulent channel flow at low Reynolds number

Oaki IIDA*
*Department of Mechanical Engineering,
Nagoya Institute of Technology,
Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan
E-mail: iida.oaki@nitech.ac.jp

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Abstract
Direct numerical simulations of unsteady turbulent channel flow are performed to study the evolution of streamwise vortices in the wall vicinity. In the first stage of those numerical simulations, turbulence decays temporarily after one of the walls bounding the flow becomes free-slip, and streamwise vortices in the vicinity of that wall almost disappear. In the second stage, the boundary condition is restored to a non-slip wall, and vortices in the near-wall region are excited again by the imposed mean shear there. In this second stage, the increase in skin friction coefficient is found to be triggered by the enhanced sweep motion (inrush motion of high-speed fluids), and the increase in the number of the vortices related to the sweep in the wall vicinity. By studying evolution of streamwise vortices in the wall vicinity, it is found that the persistent streamwise vortices in the wall vicinity are connected to the vortices away from the wall, and they shift downward when accompanied by intense inrush motion toward the wall. In contrast, newly generated vortices in the wall vicinity, disconnected to the vortices away from the wall, tend to soon be attenuated.

Key words: Turbulent channel flow, Streamwise vortices, Sweep, Ejection, Numerical simulation

1. Introduction

One of the important problems in wall turbulence is how streamwise vortices are generated and maintained, and this has been the focus of many experimental and numerical studies. Several papers have reviewed the history of the study of wall turbulence (Robinson, 1991; Panton, 2001; Klewicki, 2010) with most of their attention on vortices.

In near-wall turbulence, streamwise vortices not only generate Reynolds shear stress, but also induce regions of intense dissipation and skin friction (Robinson, 1991). They also account for the general shape of the mean velocity profiles and basic statistics of wall turbulence (Hamilton, et al, 1995; Jimenez and Moin, 1991). Hence, correct understanding of their generation is important not only for a fundamental understanding of turbulence, but also from a practical point of view, since it may result in development of efficient strategies for reducing drag (Choi, et al, 1994) and controlling mixing (Tardu, 2008).

Several mechanisms have been proposed for the generation of streamwise vortices in fully developed turbulent channel flow. The major mechanisms of their generation are related to the quasi-periodic and spatially organized process of regeneration of the streaky structure of low-speed fluids, i.e., low-speed streaks (Hamilton, et al, 1995; Waleffe, 1997; Waleffe, 1998). In this process, breakdown of low-speed streaks due to sinuous instability is followed by the generation of new streamwise vortices, which later alternatively regenerate low-speed streaks by a linear mechanism. This quasi-cyclic mechanism is verified in an idealized flow configuration at a low Reynolds number, where a minimal unit of the turbulence structure is maintained by intentionally reducing the computational region (Jimenez and Moin, 1991). In more detailed studies, the linear term as well as the advection and non-linear vortex stretching terms were found to be important for generating and maintaining new streamwise vortices (Waleffe, 1997; Kim and Lim, 2000; Schoppa and Hussain, 2002). However, there is a concern that in a minimal flow condition, other important mechanisms for generating streamwise vortices may disappear (Panton, 2001; Philip and Manneville, 2011).
Other mechanisms act on the streamwise vortices in the very vicinity of the wall, where the new vortices are generated in the region of inrush motion of high-speed fluids related to the existing vortices. This mechanism of parent-offspring vortices was actually verified in the several direct simulations of turbulent channel flow (Brooke and Hanratty, 1993; Bernard, et al., 1993), though some authors (Jimenez and Pinelli, 1999) conjecture that this mechanism has only limited effects on generation of streamwise vortices. Schoppa and Hussain, 2002 showed that both mechanisms could be compatible by supposing that the STG (streak transient growth) instability triggers the sinuous instability of low-speed streaks, which is followed by the non-linear evolution of streamwise vortices, because STG is related to the correlation between streamwise and spanwise velocity fluctuations of remnant streamwise vortices.

Our recent DNS studies (Iida and Nagano, 1998; Iida, et al., 2010) showed a strong correlation between small-scale vortices and sweep. Coincidently, the experimental study of a high Reynolds number (Hutchins, et al., 2011) also verifies the correlation between the inrush motion of the high-speed fluids and streamwise vortices in the wall vicinity of the turbulent boundary layer. However, the detailed mechanism is still not well known regarding how the tiny vortices in the wall vicinity are generated and evolve, how they are related to sweep, and how the sweep is enhanced.

In contrast, in many previous studies (Tardu, et al., 2008, Kim and Lim, 2000; Brooke and Hanratty, 1993), a linear vortex stretching term was found to be generally indispensable for evolution of streamwise vortices. Hence, removing and imposing the mean shear in the wall vicinity must annihilate and generate streamwise vortices, respectively. In this study, the direct numerical simulations of unsteady turbulent channel flow are performed. The changes of boundary condition make the flow unsteady; after the boundary condition of one wall is changed from non-slip to free-slip condition, it is changed back to a non-slip condition. During these procedures, the streamwise vortices in the wall vicinity first disappear after the free-slip boundary condition is imposed. Then, by returning it to the non-slip wall, streamwise vortices emerge again in the wall vicinity.

To investigate the most probable mechanisms of the evolution of tiny vortices, two mechanisms are considered. First, the tiny vortices newly generated are detected and traced over time; we define the tiny or small-scale vortices as those which cores are at about distance $y = 10$ from the wall by the viscous length as discussed later. Second, the mechanism where the vortices away from the wall are shifted downward to wall vicinity is investigated. All the vortices we discuss are represented by the isosurface of typical scalar known to be well related to actual vortical motion.

2. Numerical Procedures

Figure 1 shows the configuration and coordinate system of the unsteady channel flow, where the streamwise, wall-normal and spanwise directions are $x$, $y$ and $z$, respectively. First, one of the walls bounding the fully developed channel flow is changed into the free-slip wall, and turbulence in this wall vicinity decays (Fig. 1a). Then, the boundary condition is again returned to a non-slip wall, and turbulence in this wall vicinity is excited again (Fig. 1b). Over all the period of numerical simulations, the boundary condition of the other wall (upper wall) is set to be non-slip.

A mean pressure gradient is, however, determined so that the friction velocity in the upper side of the wall is constant. When a flow is assumed to be statistically steady, the relation between the mean pressure $P$ and velocity $U$ is given as

$$\frac{1}{\rho} \frac{\partial P}{\partial x} + v \frac{\partial^2 U}{\partial y^2} - \frac{\partial u v}{\partial y} = 0,$$

where $\nu$ is kinetic viscosity, while $u$ and $v$ are the streamwise and wall-normal velocity fluctuations, respectively.

![Fig. 1 Flow geometry and coordinate system. Boundary condition of lower side wall is changed from non-slip wall to free-slip wall. After decay in the lower side of a channel, the boundary condition is returned to non-slip wall.](image-url)

Hence, in a Poiseuille flow bounded by non-slip walls, $\frac{\partial P}{\partial x}$ and $\frac{\partial U}{\partial y}$ at wall are related as follows:

$$\frac{1}{\rho} \frac{\partial P}{\partial x} = v \left( \frac{\partial U}{\partial y} \right)_{wall}.$$ 

In contrast, in a free-slip flow, their relation becomes

$$-2 \frac{1}{\rho} \frac{\partial P}{\partial x} = v \left( \frac{\partial U}{\partial y} \right)_{wall}.$$ 

Assuming the invariance of wall friction $\nu \frac{\partial U}{\partial y}$ in a fully developed state, a mean pressure gradient of a Poiseuille flow is two times as large as that of a free-slip flow. Hereafter, all the velocities, time and distance are non-dimensionalized by $Q$ and reference velocity $\frac{U}{\delta}$, where $P$ is that of a Poiseuille flow, unless another non-dimensionalization is indicated. The Reynolds number $Re$ defined by the reference velocity $\frac{U}{\delta}$, $V$, and $\delta$ is set to be 100 in the entire simulation of decaying and transition period other than the simulation to check the code validity, which $Re$ is set to be 150; this Reynolds number is the parameter representing a flow configuration, which determines the final state of turbulence instead of representing the condition of turbulence at every moment.

In this study, the spectral method, i.e., the Fourier spectral method in the $x$ and $z$ directions and the Chebychev tau methods in the $y$ direction, are used for the spatial discretization (Kim, et al., 1987); the second-order Crank-Nicolson and the second-order Adams-Bashforth methods are used for the time integral. The computational region of $4 \pi \delta \times 2 \delta \times 2 \pi \delta$ is resolved by the grid resolution of $64 \times 65 \times 64$; results are also verified by the same numerical simulation of $128 \times 129 \times 128$ grid points. As discussed later, the numerical results agree well with each other. In the case of $64 \times 65 \times 64$, grid resolutions of $x$ and $z$ are 19.6 and 9.6/\delta, respectively, while that of $y$ is 0.12 to 5/\delta.

Figure 2 shows a comparison in the mean velocity profiles between our data and the data of Kuroda, 1990 used as the standard database of a turbulent channel flow; his DNS has $128 \times 97 \times 128$ grid points for $5 \pi \delta \times 2 \delta \times 2 \pi \delta$ computational region. Our data of channel flow included in Fig. 2 are also at a fully developed state; $Re = 150$ and 100 are calculated by $64 \times 65 \times 64$ grid points, though they develop from different decaying turbulence, which initial condition is obtained from the fully developed channel flow at a different time. In both Reynolds numbers, Kuroda and our data agree quite well, indicating the reliability of our numerical simulations. In the following sections, the mean value is defined at each transitional time, and the fluctuation is defined as the deviation from thus defined mean value.

3. Results and Discussions

3.1 Statistics and turbulence structure of transient period

Hereafter we discuss the statistics and turbulence structure in transition period. A non-slip boundary condition is imposed at time $t_f=100$ after a free-slip condition is imposed on the bottom wall; $t_f$ is normalized by mean pressure gradient of Poiseuille flow and channel half width. The time when the non-slip boundary condition is imposed is redefined as $t=0$ when the vortices in the wall vicinity disappear and those away from the wall still remain.

Figure 3a shows the time evolution of skin friction coefficient $c_f$, which is defined by the skin friction at the lower wall and bulk mean velocity over an entire channel, and bulk Reynolds number $Re_b$, defined as a bulk mean velocity over an entire channel, $V$, and $2\delta$ just after $t=0$. Both $c_f$ and $Re_b$ are normalized by those of the fully developed channel flow, which are 0.00968 and 2890, respectively. All lines represent numerical simulations of $Re=100$ calculated by $64 \times 65 \times 64$ grid points, though they develop from different decaying turbulence, which initial condition is obtained from the fully developed channel flow at a different time. In the time evolution of $Re_b$, data of different initial
Fig. 3 (a) Time evolution of skin friction coefficient $c_f$ in the lower side of the channel, and bulk Reynolds number $Re_m$.

All lines represent numerical simulations of $Re=100$ calculated by $64 \times 65 \times 64$ grid points, though their initial conditions are obtained from the fully developed channel flow at the different time. Case of thick lines is discussed in later figures; (b) Time evolution of the Reynolds shear stress $-\overline{u'v'}$; (c) Time evolution of the ratio of sweep $(u')$, to ejection $(v')$; sweep and ejection are calculated as Reynolds shear stress of $u>0$, $v<0$ and $u<0$, $v>0$, respectively.

conditions are collapsed into an identical profile. In contrast, in the time evolution of $c_f$, effects of the initial condition are visible. In most cases, including the case of thick line and symbols, however, there are three kinds of regimes observed in the time evolution of $c_f$. In the first period after the non-slip boundary condition is imposed, $c_f$ sharply decreases ($0<t<400$). Then, in the second period ($400<t<800$), $c_f$ bounces back and continues to increase. Finally, in the third period ($t>800$), it reaches the equilibrium state after the small decay. In contrast to $c_f$, the bulk Reynolds number is constant over the entire calculation, and hence, the increase and decrease in $c_f$ are attributed to the friction velocity on the lower wall.

It is also noted from the comparison between the results of the different grid resolution that the effect of resolution is small, and the behavior of $c_f$ in the period of the transition is qualitatively identical; initial data of the case with finer grid points are similar to those of thick lines. Although some differences are observed at the end of the transition, this may be attributable to the unsteady flow simulation. Hereafter, data of thick lines are discussed in detail to show how sweep is related to increase in $c_f$, though other data are also used for detecting the vortices.

Figure 3b shows the time evolution of the Reynolds shear stress $-\overline{u'v'}$. Initially, a significant amount of the Reynolds shear stress remains. After the mean shear is imposed, however, the Reynolds shear stress continues to decrease over the half channel region due to the enhanced dissipation rate, reaches the lowest value in the period of $100<t<400$, and significantly increases over the period of $t=400$ to 600. Figure 3c shows the time evolution of the ratio of sweep to ejection event. It is interesting to see that in the period of the increasing Reynolds shear stress ($400<t<600$), the sweep is more enhanced than the ejection in the wall vicinity, indicating that it triggers the increase in skin friction in the wall vicinity as previously indicated (Choi, et al., 1994). When $c_f$ is leveled around $t=600$, however, the ratio of sweep to ejection peaks. The close relation between the small scale vortices in the wall vicinity and sweep is also verified in the experiment of the higher Reynolds number (Hutchins, et al., 2011).

Figure 4 shows the time evolution of r.m.s. of velocity fluctuations. It is noted that there is a definite increase in all components of r.m.s. velocity fluctuations between $t=200$ and $t=600$ in the lower-wall side in both numerical simulations of different grid resolution, which are qualitatively in good agreement with each other.

Fig. 4 Time evolution of r.m.s. of velocity fluctuations. (a)$u_{rms}$, (b)$v_{rms}$, (c)$w_{rms}$.
3.2 Detection of streamwise vortices and conditional average

Fig. 5 Time evolution of vortical structures in x-z plane of y=10. Sides of each figure are $4\pi\delta$ and $2\pi\delta$ in the x and z directions, respectively. Black isosurfaces represent $I^2=I_{rms}^2$ in the region of $y<10$. Red and blue contours represent the sweep and ejection (first contour line is 0.25, and contour interval is 0.5 in both cases): (a) $t=420$, (b) $t=580$.

Figures 5a and b show the time evolution of intense ejection, sweep and vortical structures represented by the second invariant of the deformation tensor $I^2 = \frac{1}{2} \epsilon_{ij} \epsilon_{ij} = \frac{1}{2} \omega_i s_i$; $\omega_i$ and $s_i$ are the components of vorticity vector and strain tensor, respectively.

Fig. 6 Schematics of longitudinal vortices detected and averaged in cases 1, 2 and 3: (a) cases 1A and 1B vortices which cross the lines of $y=10$ and 30, respectively, (b) case 2 vortices with their upper edges at $y=10$, and (c) cases 3A-C vortices with their lower edges at $y=14$. Case 3A vortices are shifted downward to reach $y=10$. Case 3B vortices disappear before they are shifted to reach $y=10$. Case 3C vortices are not observed to shift downward before they disappear. The length of case 1 is more than 140 $v/\nu$ in the streamwise direction, while that of case 2 is less than 60 $v/\nu$.

The comparison between $t=420$ and 580 reveals that there is a definite qualitative difference in turbulence structure; at $t=420$, the intense ejection and sweep in the wall vicinity are very rare, while they significantly increase at $t=580$. This is also true in the longitudinal vortices represented by black isosurfaces. During the transition, longitudinal vortices are almost always accompanied by intense sweep on their sides, while the ejection related to vortices is relatively weak; however, at the end of the transition, a strong ejection is also accompanied by vortices. The streamwise vortices are detected by isosurfaces of $I^2$, the threshold value of which is set to be $I_{rms}^2$, i.e., its root-mean-square value over all the grid points in a flow domain. The detected vortices are closely related to the intense sweep as shown in Fig. 5, and their emergence in the wall vicinity is also in good agreement with the increase in $c_f$ as shown in Fig. 3. Hence, some physical significance should be attached to detecting the isosurface of $I^2$.

Hereafter, the streamwise vortices are detected by $I^2$ and averaged in three different ways, as shown in Fig. 6, where detected vortices are represented by solid lines, while those not detected are represented by broken lines. First, all the vortices detected at $y=10$ and 30, which have a greater streamwise length than 140 (approximately 7 grid spacing), are averaged; vortices of streamwise length 140 almost correspond to those detected in Jeong et al., 1997. The vortices are sampled at a fixed time. In all cases, the core of the vortex is detected as the maximum location of $I^2$, and all the vortices are averaged with their cores overlapped; vortices with the core of $y=10$ and 30 are defined as...
Fig. 7 Time evolution of \( \bar{u}v \), where \( \bar{A} \) represents the conditional average of \( A \), and velocity vectors in the cross-streamwise plane of cases 1A (left-hand side figure) and 1B (right-hand side figure): (a) \( t=400 \), (b) \( t=600 \).

The red and blue contours represent \( -\bar{u}v >0 \) and \( -\bar{u}v <0 \), respectively. The contour interval is 0.2 in all figures. Sides of each figure are \( 100v/u_Q \) and \( 118v/u_Q \) in \( y \) and \( z \) directions, respectively.

case 1A and 1B, respectively.

Second, to clarify the evolution mechanism of tiny vortices, the newly generated streamwise vortices are selectively detected and averaged, which is defined as case 2. When the upper edges of the isosurfaces of \( II \) are at \( y=10 \), and their streamwise length is less than three grid spaces \( (60v/u_Q) \), these isosurfaces are detected as the newly generated vortices and averaged at \( y=10 \). Time evolution of these vortices is traced by considering their advection velocity.

Finally, the vortices which have their lower edges at \( y=14 \) are averaged for the three different conditions; some vortices are shifted down to reach \( y=10 \), while others, though shifted downward, cannot reach \( y=10 \). The former and latter are defined as case 3A and 3B, respectively. In contrast, those whose edge is not shifted downward at all are defined as cases 3C. In this study, these three different groups of vortices are compared at the edge of \( y=14 \), to clarify the condition for the vortex to be shifted downward. In all cases, 10 independent numerical simulations with the different initial conditions are performed to increase the number of the detected vortices. Moreover, the counter-clockwise vortices are averaged as clockwise vortices by reflecting \( z \) and \( w \) into \( -z \) and \( -w \).

The time evolution of streamwise vortices detected as cases 1A and 1B is presented in Fig. 7. In case 1A, the number of vortices detected is 159 and 204 at \( t=400 \) and \( t=600 \), respectively, while in case 1B, the number of the vortices detected is 307 and 368 at \( t=400 \) and \( t=600 \), respectively. The distribution of the product of averaged velocities \( -\bar{u}v \), which has two local maximums around the vortex, is presented as well as the velocity vectors; superscript \( \bar{\cdot} \) represents the average of detected vortices. A local maximum with the upward motion of the vortex represents the peak of ejection, while that with downward motion is the peak of sweep. By comparing peak values at \( t=400 \), it is noted that the vortex at \( y=10 \) has stronger sweep, while that at \( y=30 \) has stronger ejection. This is in good agreement with the dominance of the sweep in the wall vicinity, and dominance of the ejection away from the wall. With time, the intensity of \( -\bar{u}v \) increases especially in the wall vicinity, and both the ejection and sweep are enhanced, although the sweep is still dominant in the wall vicinity. This result is in good agreement with previous studies that found the sweep to be related to small-scale vortices in the wall vicinity (Brooke and Hanratty, 1993; Bernard, et al., 1993).

Next, to study the time evolution of small vortices in the wall vicinity, their advection velocity is estimated. Figure 8a shows the time evolution of the spatial correlation of \( II \), which is defined as \( R_{ii}(dx, dt, t = 500) \); \( t=500 \) is chosen because it is at the middle of the transition period. It is first calculated as
though the value of circulation motion cannot be observed at all. In contrast, in Fig. 8b, the streamwise vortex is definitely observed, $T=2)$. Close correlation among (b), (c) and (d) indicates the validity of the estimated velocity. First, in Fig. 9a, the streamwise vortex in the wall vicinity. It is noted from Figs. 9a to 9c that the maximum location of the sweep is shifted toward the wall when the streamwise vortex is generated, which is in good agreement with our previous study (Iida and Nagano, 1998; Iida, et al., 2010). After $T=2$, however, $\| \mathbf{H} \|_{\infty}$ of detected streamwise vortex becomes less than unity, and cannot be detected as a vortex. Next, we examine the downward shifting of vortical structures away from the wall.

Figure 9 shows the averaged streamwise vortex of case 2, and its time evolution. The number of vortices detected is 301, including both clockwise ($\alpha_\theta>0$) and counterclockwise ($\alpha_\theta<0$) vortices. Fig. 9c represents the time when the case 2 vortex is detected at $y=10$. The vortex, defined as the isosurface of $\mathbf{H}(x_i,y=10,z_j)$, is indicated by the arrow A in Fig. 9c, where the small circulating motion around the isosurface is clearly observed. It is noted that the tiny vortex is related to the sweep, which has a much larger scale than the vortex. In case 2, the intense ejection is not visible at all; the contours at the left side of the vortex are not ejection, but interaction that negatively contributes to the Reynolds shear stress.

Also noted is the larger scale circulating motion right above the tiny vortex. This circulating motion is more clearly observed in the upwind side of the detected vortex as indicated by the arrow B. The sweep related to the tiny vortex seems to be driven by this circulating motion with its core more away from the wall, which is in very good agreement with parent-offspring regeneration mechanism proposed by Brooke and Hanratty, 1993, though the origin of this circulating motion cannot be identified in this study.

Time development of the vortex can be also discussed in Fig. 9, where the location of the vortex in the streamwise direction is shifted by a distance proportional to the advection velocity. The streamwise vortex, which emerged in Fig. 9c (defined as the time $T=0$), is traced back to Fig. 9a ($T=6$) and b ($T=2$), while its evolution is shown in Fig. 9d ($T=2$). Close correlation among (b), (c) and (d) indicates the validity of the estimated velocity. First, in Fig. 9a, the circulation motion cannot be observed at all. In contrast, in Fig. 8b, the streamwise vortex is definitely observed, though the value of $\| \mathbf{H} \|_{\infty}$ is still below 1, and hence cannot be detected as a vortex in the detection procedure. The comparison of these figures indicates that the large-scale sweep is critically important for the generation of a new streamwise vortex in the wall vicinity. It is noted from Figs. 9a to 9c that the maximum location of the sweep is shifted toward the wall when the streamwise vortex is generated, which is in good agreement with our previous study (Iida and Nagano, 1998; Iida, et al., 2010). After $T=2$, however, $\| \mathbf{H} \|_{\infty}$ of detected streamwise vortex becomes less than unity, and cannot be detected as a vortex. Next, we examine the downward shifting of vortical structures away from the wall.

Figure 10 shows the case 3 vortices defined in Fig. 6 at the time when the vortices are detected at $y=14$; this time is defined as $T=0$. The number of detected vortices is 149, 297 and 860 in cases 3A, 3B and 3C, respectively; case 3B vortex is not shown here because cases 3A and 3B vortices have similar characteristics. Hence, most vortices are in case 3C, and not shifted downward, though the effects of case 3A vortices are not negligible on $\epsilon$.
The difference in flow structures between the cases with and without downward stretching is obvious. When the vortical structure is shifted to reach \( y = 10 \), which is defined as case 3A, it is accompanied by a more intense sweep. Although not shown here, comparison between cases 3B and 3C also reveals that cases 3B is accompanied by more intense sweep than case 3C which is not shifted at all (peak values of the sweep are 0.92 and 0.73 in cases 3B and 3C, respectively, while that of case 3A is 0.96). All vortices are, however, accompanied by ejection, though it is weaker than sweep. It is also noted that in case 3A, there is a definite inrush motion toward the wall, while in case 3C, downward motion is related to the spanwise flow, and hence does not directly rush into the wall; in case 3C, flow in the sweep side goes diagonally toward the wall rather than rushing directly into the wall.

Despite the definite difference in sweep among the different cases, it is difficult to see any difference in the streamwise velocity fluctuation (Fig. 10b). The difference in the sweep is attributed to the vertical velocity difference, as shown in Fig. 10c, where the downward velocity \((v=0)\) has the largest value in case 3A. In contrast, the difference in...
Fig. 10 The upper and lower figures represent cases 3A and 3C, respectively: (a) the Reynolds shear stress $-\overline{uv}$ (contour interval $\Delta C = 0.1$), (b) streamwise velocity fluctuation $\overline{u}$ ( $\Delta C = 0.2$), (c) vertical velocity $\overline{v}$ ( $\Delta C = 0.02$). In (a), isosurface of $\overline{k}/\overline{k}_{rms}$ as well as velocity vectors are also included. Blue and red represent negative and positive values, respectively. Sides of each figure are $40\nu/\nu_Q$ and $60\nu/\nu_Q$ in $y$ and $z$ directions, respectively.

Fig. 11 Distribution of streamwise vorticity $\Omega_x$ (contour interval is 0.01) in all the cross-streamwise plane of case 3A. Blue and red represent negative and positive values, respectively. Sides of each figure are the same as Fig. 10. (c) represents the same cross-streamwise section of Fig. 10, while (a,b) and (d,e) are upwind and downwind cross-streamwise sections, respectively; each adjoining figure is one grid point away in the streamwise direction.
Fig. 12 Same as Fig. 11 for case 3C.

Fig. 13 Time evolution of vortical structures (isosurface of $k/\text{rms}^2$) and contour lines of streamwise vorticity at the $x$-$y$ plane of $z=15$ (contour interval is 0.01); (a) $T=0$, (b) $T=2$, (c) $T=4$, where $T=0$ represents the time when the vortices are detected at $y=14$. Upper and lower figures represent case 3A and case 3C, respectively. Blue and red contours represent negative and positive $\omega_x$, respectively. Sides of each figure are $80u_L$ and $40u_L$ in $x$ and $y$ directions, respectively.

the upward velocity ($v>0$) is negligibly small among the different cases. Hence, it is again confirmed that downward shifting of the vortex is accompanied by the stronger sweep triggered by a stronger downward motion. To clarify the difference between cases 3A and 3C, Figs. 11 and 12 are presented to show the distribution of the streamwise vorticity at all different cross-streamwise sections.

A marked difference is observed not in the vorticity of the detected vortices, but in the vorticity around them. The streamwise vorticity around the vortices has larger intensity in case 3A than in case 3C, though both have the same intensity of vorticity inside each vortex. Interestingly, as shown in Fig. 11, the strong downward motion of case 3A, which also generates the intense sweep, is related to distributions of adjoining streamwise vorticity; the case 3A vortex is accompanied by the intense streamwise vorticity of the opposite sign on its right-hand side, denoted by an arrow in
Fig. 11c, which indicates that the inrush motion toward the wall is enhanced by the vorticity of the opposite sign.

Figure 13 shows the averaged streamwise vortices of cases 3A and 3C, and their time evolution; x coordinate is shifted 1 grid point every 2T. It is noted that the vortex of case 3A is stretched in the streamwise (downwind) direction and its streamwise vorticity is intensified, whereas the vortex of case 3C disappears soon at T=2. Hence, case 3A is shifted downward mainly in the process of vortex stretching in the downwind direction.

Fig. 14 Distribution of (a) the Reynolds shear stress $-\overline{uv}$ (contour interval $\Delta C = 0.1$), (b) streamwise velocity fluctuation ($\Delta C = 0.2$). The time each vortex reaches $y=10$ is different from vortex to vortex. Blue and red represent negative and positive values, respectively. Sides of each figure are the same as those of Fig. 10.

The cross section of the case 3A vortex at the time when it reaches $y=10$ is discussed in Fig. 14. Case 3A vortices are averaged at $y=10$ when their lower edges reach $y=10$. It is clearly seen that the averaged vortex still has intense sweep in comparison to ejection; sweep dominates ejection. It is, however, interesting to see that the vortex is accompanied by the stronger low-speed fluids on its left-hand side as shown in Fig. 14b than that of Fig. 10b, where the core of the vortex is at a higher $y$ location. Hence, case 3A vortices are definitely different from case 2 vortices, which later disappear without pumping up low-speed fluids from the vicinity of the wall. Some case 2 might be in the final period of case 3A, while others might not be related to case 3A at all. In both cases, however, the probability of case 2 developing into case 1A in the future is smaller than that of case 3A.

4. Conclusions

Direct numerical simulations of unsteady turbulent channel flow are performed. In the first stage of the numerical simulations, turbulence decays on one side of a channel temporarily after the boundary condition is changed from no-slip wall to free-slip wall. In the second stage, the boundary condition is again changed back to a no-slip wall, and turbulence in near-wall region is excited again by the imposed mean shear there. The aim of our study is to investigate the evolution of small-scale vortices emerged in the wall vicinity in this second stage.

First, by detecting dozens of newly generated streamwise vortices in the vicinity of the wall and tracing them, these vortices are found to be closely attributable to the sweep related to the larger-scale circulation motion away from the wall. It is when the high speed fluids related to this circulation approach closer to the wall that new streamwise vortex, i.e., new isosurface of $II$, emerges in the wall vicinity. However, thus generated tiny streamwise vortices are not accompanied by low-speed fluids and ejection, and soon attenuated.

Then, the mechanism of vortices attaching to wall vicinity is studied. The comparison between the vortices attaching and not attaching to wall vicinity shows that when the vortical structure is shifted into wall vicinity, it is accompanied by intense sweep, which is attributed to a definite inrush motion of fluids toward the wall on the side of the vortex. The inrush motion toward the wall is driven by the vorticity of the opposite sign on the sweep side of the vortex. Moreover, thus generated downward shift of the vortex is also related to vortex stretching in the streamwise direction.

This numerical simulation is performed at the low Reynolds number, where flow becomes easily laminarized sporadically and temporarily. In contrast, in the steady channel flow at higher Reynolds number, there must be a concentration of streamwise vortices in the wall vicinity, which also contributes to generating new vortices there. Hence, the results and conclusions we obtained in this numerical simulation may not be identical with steady channel
flow especially at higher Reynolds number. In addition, in the flow where the no-slip boundary condition is switched on and off in the streamwise direction, accelerating and decelerating flow effects related to pressure gradient may not be negligible. Such effects must be considered in future study.

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