On the Mechanism of Drag Reduction of Near-Wall Turbulence by Wall Oscillation*

Yutaka MIYAKE**, Koichi TSUJIMOTO**
and Masayuki TAKAHASHI***

It is intended to investigate the mechanism of drag reduction of a turbulent flow in a channel by wall oscillation normal to main flow, in this report. DNS is carried out in which one wall of a two-dimensional channel is stationary but the other is in sinusoidal oscillation normal to the mean flow. The most effective oscillation period is adopted and about 35% reduction in drag is confirmed. For this case, generation terms of quasi-streamwise vorticity are examined from various points of view. It is shown that quasi-streamwise vortices which play a key role in sustaining wall turbulence are most strongly affected in the buffer layer. Vorticity production rate fluctuates with the phase of wall oscillation and is enhanced at some definite favorable phase but suppressed as a whole, in one period of oscillation. The stretching effect as well as tilting effect is important. However, the latter affects mainly weak chaotic vortices and hence the role of the former which modulates coherent quasi-streamwise vortices is more substantial. The suppression of vorticity generation by stretching is due to the decrease of inclination angle of a vortex to a wall. It is demonstrated that the fall of production rate of quasi-streamwise vorticity due to stretching effect is substantial for the phenomenon. The periodical fluctuation of the attitude angle, i.e., the inclination angle to the wall and the slant angle of a vortex to mean flow, aggravates the production. This mechanism is a straightforward extension of the one commonly found in the usual near wall turbulence.

Key Words: Shear Flow, Turbulence, Flow Control, Drag Reduction, Oscillation, Quasi-Streamwise Vortex, Coherent Structure

1. Introduction

Many direct numerical simulations including those of present authors revealed that quasi-streamwise vortices which have their axis nearly in the mean flow direction play a key role for turbulence in the near wall region. The present authors investigated carefully the behavior of the quasi-streamwise vortices and found that they constitute a particular zig-zag pattern by repeated regeneration⁽¹⁾. They also found the mechanism of self-sustenance of quasi-streamwise vortices⁽²⁾. These findings are the basis of the discussion of modification of near-wall turbulence described in the following.

Control of turbulence, especially active control modifying the quasi-streamwise vortices has come up as one of the most prospective target of turbulence research, for which computer power allowing large scale direct numerical simulations of turbulent flows is crucially important.

The reduction of wall shear stress is the most primitive measure of turbulence control. Of several ideas to realize it, the one proposed by Jung et al.⁽³⁾ attracts much attention for the sake of its realizability in engineering application. This method is to apply wall oscillation normal to the main flow. i. e. in a channel flow, a wall is oscillated in the spanwise direction. The mechanism of this reduction of friction drag is not well understood until now but it is expected that it includes the key of controlling wall shear stress.

The present work has been carried out to resolve this problem using direct numerical simulation. It turns out that the reduction mechanism exists on the extension of the present authors' findings concerning

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** Department of Mechanical Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565, Japan

*** Toshiba Electronic Corporation, 2-4 Suehiro-cho, Tsurumi-ku, Yokohama 230, Japan

the sustenance of quasi-streamwise vortices.

2. Numerical Methods

A direct numerical simulation of a turbulent flow is carried out in a channel of half width H whose one wall is stationary but the other oscillates in the spanwise direction with the speed

$$w_w = \bar{W}_0 \cos(2\pi t/T) \quad (1)$$

where $\bar{W}_0$ means the amplitude and T , the period, as shown in Fig. 1. Numerical procedures are given in previous work⁽⁴⁾ in which periodic boundary conditions are assumed both in streamwise and in spanwise directions and no-slip condition is applied on the walls. The Reynolds number based on the mean friction velocity on the walls $\bar{u}_\tau$ and H is kept constant through out the simulation at $Re_\tau = 150$. Friction velocity $\bar{u}_\tau$ is defined as $\bar{u}_\tau = \sqrt{(\bar{\tau}_L + \bar{\tau}_U)/2\rho}$, where τ_U , τ_L are wall friction stress on the upper oscillating and the lower stationary wall, respectively. A spectral method is used with grid number $128(x) \times 129(y) \times 64(z)$. The oscillation of upper wall normal to the mean flow is applied after calculation of non-oscillating channel flow long enough to reach statistically steady state and the time t in the following is that measured from the instant of start of oscillation.

A field data, which means velocity and pressure at every computational grid, is stored at every 64 step ($\Delta t^+ = 7.7$). In the following, overbar ($\bar{}$) denotes quantities averaged in a plane parallel to the wall (x - z plane) at each instant, superscript ($'$), fluctuation from this mean and superscript ($^+$), non-dimensionalized quantities by $\bar{u}_\tau$ which is mean friction velocity on the wall without wall oscillation and ν .

3. Mean Properties of Flow Field

In this simulation, most effective period of oscillation T which is known to be $T^+ (= T\bar{u}_\tau^2/\nu) = 100$ by Jung et al.⁽³⁾ is specified. The amplitude of spanwise velocity $\bar{W}_0$ of upper wall oscillation is given to be $\bar{W}_0 = 0.4Q/H = 12$ (Q : bulk flow rate), also referring to the data by available data⁽³⁾.

First, variation of mean property of flow field subjected to spanwise oscillation of one wall is described.

In figure 2, time evolution of wall shear stress τ_w on the walls, non-dimensionalized by that before oscillation is turned on or that at $t^+ = 0$. Wall shear stress on the oscillating wall is reduced as time marches, and five period of oscillation after, the reduction attains about 35% of normal channel flow case without oscillation.

Since the mean pressure gradient which is always kept constant throughout the present simulation,

Fig. 1 Coordinate system

Fig. 2 Time evolution of wall shear stress τ_w after the start of wall oscillation

remarkable reduction of shear stress on oscillating wall causes acceleration of the fluid in the passage, thus increase in bulk flow rate. Therefore, sum of shear stresses on two walls is smaller than that before the start of oscillation, though the wall shear stress on the opposite side stationary wall is gradually increasing.

Corresponding to the modulation of wall shear stresses, strong streamwise vortices which contribute most to generate high shear stress strongly attenuate in near wall region of oscillating wall side.

Mean streamwise velocity $\bar{u}$ expressed in non-dimensional form divided by instantaneous mean friction velocity on the oscillating wall goes up more from the line for normal channel flow case as the time proceeds and approaches to laminar flow distribution of $u^+ = y^+$, as shown in Fig. 3(a). As for instantaneous mean spanwise velocity, it becomes almost coincident with a steady stokes solution which is obtained by solving

$$\frac{\partial \bar{w}_{st}}{\partial t} = \frac{1}{Re_\tau} \frac{\partial^2 \bar{w}_{st}}{\partial y^2} \quad (2)$$

after $t/T \geq 0.5$, as shown in Fig. 3(b).

Although Stokes-layer thickness $l^+ (= \bar{u}_\tau \sqrt{T/\pi\nu})$ is 5.8, the effect of oscillation reaches up to $y^+ \sim 30$ from the wall. Jung et al.⁽³⁾ conducted similar simulations as the present one in the range $l^+ = 2.8 \sim 12.6$. Their simulations demonstrate that at both $l^+ = 2.8$ and 8.0, reduction in wall shear stress is small and less than 10%, and at $l^+ = 12.6$, shear stress even increases.

This suggests that optimum oscillation period exists which can bring suppression of turbulence. The present authors' findings by visualizing evolution of quasi-streamwise vortices whose main body are located at $y^+ = 10 \sim 30$ are that those vortices at growing and grown-up stage are self-sustained by generating

(a) Mean streamwise velocity

(b) Mean spanwise velocity

Fig. 3 Time evolution of mean velocity in near the oscillating wall region

new streamwise vorticity mainly at layer close to the wall, in particular, at their upstream part and that their life time t^+ is a couple of hundreds in average.

In case that Stokes layer is thin enough, wall oscillation affects to the flow only in the closest part of viscous sublayer and no effect on streamwise vortices is expected. Meanwhile, if Stokes layer thickness is large and the oscillation period is long enough to cause quasi-steady disturbance to streamwise vortices, no suppression effect is expected. This is the reason why limited range of oscillation period exists.

The period that we adopted here $T^+=100$ gives the best compromise.

4. Mean Property of Quasi-Streamwise Vortex under the Oscillation

Properties of quasi-streamwise vortices are discussed on the basis of various mean quantities.

Figure 4 shows the time-wise variation of integrated vorticity $\Gamma^+ = \int \omega_x^+ dV/\nu H$ in half computational volume of oscillating wall side for various vorticity range of ω_x^+ , after the start of oscillation up to 6 periods. Solid, chained, broken and dotted lines mean total Γ , Γ due to vorticity of $|\omega_x^+| \leq 0.2$, of $|\omega_x^+| \leq 0.15$, and of $|\omega_x^+| \leq 0.10$, respectively and thick

Fig. 4 Time evolution of total streamwise vorticity Γ^+ integrated in the upper- and lower-half computational box. (solid lines: whole vorticity, chained lines: $|\omega_x^+| \leq 0.2$, broken lines: $|\omega_x^+| \leq 0.15$, dotted lines: $|\omega_x^+| \leq 0.10$, thick lines: $\omega_x^+ > 0$, thin lines: $\omega_x^+ < 0$)

lines are for positive vorticity and fine line, negative one. Strong vorticity ($|\omega_x^+| \geq 0.2$) attenuates fast at the early stage and the weaker the vorticity, the slower the attenuation. Since strong vorticity ($|\omega_x^+| > 0.2$) is found in coherent structure in normal non-oscillating channel, above attenuation property suggests that wall oscillation affects strongly coherent structure. However such a coherent structure does not totally disappear, but survives long. That is, coherent structures with weak vorticity ($|\omega_x^+| = 0.1$) are found sparsely in space in a visualized picture even at 6 periods after, though not shown here.

Figures 5 show the time evolution of integrated ω_x in a plane at $y^+=16$, $\Gamma^+ = \int \omega_x^+ dx dz/\nu$. Solid line denotes Γ^+ of whole vorticity and chained one, that of limited integration for $0 < \omega_x^+ < 0.2$. Similarly to Fig. 4, strong vortex attenuates fast at the initial stage of oscillation as shown in Fig. 5(a). The attenuation process depends on the direction of rotation as shown in Fig. 5(b) where solid line is for positive vorticity and dotted one, for negative one. The fluctuation of positive vorticity is in phase lag by π to that of negative one.

Time evolution of the wall-normal distribution of Γ^+ at the early stage of oscillation $t/T = 0.5 \sim 1.0$ when fastest attenuation of total vorticity takes place is given in Fig. 6(a) for positive vorticity and in Fig. 6(b), for negative one. Solid lines are for whole vorticity and broken ones are for limited vorticity of $|\omega_x^+| < 0.2$. Comparing the solid line with broken one, it is found that strong vorticity in the layer within buffer layer, $y^+ = 10 \sim 20$, is enhanced strongly in some time interval and that the location of vorticity peak moves to away from the wall in attenuation stage.

In previous works^{(1),(2)}, authors discussed the

Fig. 5 Time evolution of total vorticity I^+ integrated in plane parallel to the wall at $y^+=16$. [(a) solid line: whole vorticity, chained line: $0 < \omega_x' < 0.2$, (b) solid line: $\omega_x' > 0.2$, dotted line: $0 < \omega_x' < -0.2$]

Fig. 6 Time evolution of wall-normal distribution of streamwise vorticity integrated in constant y^+ -plane, I^+ . [(a) $\omega_x' > 0$, (b) $\omega_x' < 0$, solid line: whole, broken lines: $|\omega_x'| < 0.2$]

mechanism of generation and/or sustenance of quasi-streamwise vortices by analyzing the transport equation of ω_x . In the present case of oscillating wall side, the transport equation of turbulent streamwise vorticity ω_x' should be modified as

$$\frac{D\omega_x'}{Dt} = \omega_x' \frac{\partial u}{\partial x} + \omega_y \frac{\partial u}{\partial y} + \omega_z \frac{\partial u}{\partial z} + \frac{1}{Re_\tau} \nabla^2 \omega_x' - v \frac{\partial \bar{\omega}_x}{\partial y} + \bar{\omega}_x \frac{\partial u}{\partial x} \quad (3)$$

where u, v, w are velocity components in x, y, z direction, respectively and $\bar{\omega}_x$ is the streamwise vorticity of

Fig. 7 The wall normal distribution of mean absolute value of production rate terms $\bar{P}_{\omega_x}^+$ for strong vorticity ($|\omega_x'| > 0.2$)

the flow induced by wall oscillation averaged in plane parallel to the wall. Since the second and third terms in right-hand side of above equation include the same term $(\partial u / \partial z)(\partial u / \partial y)$ with opposite sign, it is re-arranged as follows.

$$\frac{D\omega_x'}{Dt} = \omega_x' \frac{\partial u}{\partial x} - \frac{\partial w}{\partial x} \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \frac{\partial u}{\partial z} + \frac{1}{Re_\tau} \nabla^2 \omega_x' - v \frac{\partial \bar{\omega}_x}{\partial y} + \bar{\omega}_x \frac{\partial u}{\partial x} \quad (4)$$

The right-hand side members of above equation are the production rate terms representing effects of stretching, tilting, twisting, viscous diffusion in the order from left to right. The last two terms EX1 and EX2 are extra terms added to non-oscillatory wall cases. EX1 means the augmentation of ω_x' due to the entrainment of $\bar{\omega}_x$ by wall-normal velocity fluctuation induced by streamwise vortices and EX2 means that due to stretching of vorticity of Stokes flow or $\bar{\omega}_x$.

Figure 7 shows wall-normal distribution of the mean absolute value averaged in time between $t/T = 0.5 \sim 1.5$, of production rate $\bar{P}_{\omega_x}^+$ averaged in a plane parallel to the wall, of strong streamwise vorticity of $|\omega_x'| > 0.2$. In the figure, $y = -1$ is the stationary wall and $y = 1$ is oscillating one. It is observed in the figure that in attenuating period of strong streamwise vortex, production rate due to Ex1, $-v(\partial \bar{\omega}_x / \partial y)$, becomes significant and that the terms other than this term in oscillating wall side shows basically similar distribution as in the stationary wall side, although the strength of production rate terms is weaker in oscillating wall side than in stationary one. It is also found that in the oscillating wall side, the major terms are also due to stretching and tilting. Of these big terms, Ex1 serves to swing the upstream-end portion of quasi-streamwise vortices located close to the wall, synchronously with the wall oscillation, as will be mentioned later. The distributions of production rate terms due to stretching and tilting are shown in Figs. 8(a), (b), in the similar manner as in Figs. 6. In the figures, the upper one is for positive vorticity and the lower, for negative one. Comparing production rate $\bar{P}_{\omega_x}^+$ for $|\omega_x'| \geq 0$ with that for $|\omega_x'| < 0.2$, it is found

Fig. 8 Time evolution of wall-normal distribution of mean production rate integrated in constant y^+ -plane, $\bar{P}_{\omega_x}^+$. [(a) stretching, (b) tilting, solid line: whole, broken lines: $|\omega_x'| < 0.2$]

that production rate due to stretching is mostly responsible for the strong vorticity. As for the production rate due to tilting, it contributes much for relatively weak vortices, although its magnitude is much larger than stretching production. The layer where the production due to stretching is modified seriously is up to $y^+ \sim 35$ which is farther away from the wall than the distance to where the wall oscillation reaches, as the thickness of the Stokes layer in this case is $l_{\text{stokes}}^+ (= \bar{u}_{\tau 0} \sqrt{T/\pi\nu}) = 5.8$. This suggests that the modification of turbulence due to wall oscillation is not by direct modulation of Stokes flow oscillation.

As reported in a separate report⁽⁵⁾, the production due to stretching and due to tilting in a normal channel flow show different features, when they are analyzed with respect to direction angle of vorticity vector. This analysis is applied to this case. Figures 9 show the iso-contour map in a plane β and $\omega_x'^+$, of production rate of ω_x' at $t/T = 1.38$, where β is the angle of vorticity vector projected on a plane parallel to the wall from positive z axis, i.e.,

$$\beta = \tan^{-1}(\omega_x'/\omega_z). \quad (5)$$

Production rate at each point of $(\beta, \omega_x'^+)$ in the figure is obtained by summing up the production rate multiplied by $\omega_x'^+$ at the grid points having the combination of $(\beta, \omega_x'^+)$ in the layer between $y^+ = 10 \sim 35$, and $P_{\omega_x, \text{str.}}$ due to stretching, $P_{\omega_x, \text{tilt.}}$ due to tilting and

Fig. 9 The iso-contour map of production rate of ω_x' in the plane of ω_x' and angle β . [(a) stretching, (b) tilting, (c) stretching-tilting, solid lines: positive, dotted lines: negative]

$P_{\omega_x, \text{str.}} - P_{\omega_x, \text{tilt.}}$, the difference of these two, are shown in (a) through (c). In the figures, all the vortices are reduced to positive ones, making equivalent conversion. In this sense, β is to be understood as absolute value. It is observed in Figs. 9 that strong vortex oriented in nearly streamwise direction acquires vorticity ω_x by stretching, and the spanwise oriented weak vortex does by tilting. This confirms the result of Figs. 8. But in some situation, even the strong vortex is largely sustained by tilting. On the basis of Fig. 9(c), two categories of streamwise vorticity are separately discussed. That is, one group labeled category I is the ones having $P_{\omega_x, \text{str.}}$ larger than $P_{\omega_x, \text{tilt.}}$. This group is expected to represent vorticity composing core of strong quasi-streamwise vortex. The other group, labeled category II is the ones having $P_{\omega_x, \text{str.}}$ smaller than $P_{\omega_x, \text{tilt.}}$, with additional condition that second invariants of velocity gradients $Q^{(6)}$ is positive. This group is expected to represent vorticity surrounding vortex core. Volume density of streamwise vorticity $\gamma^+ (= \int \omega_x'^+ dV/V)$ of each group varies with time as in Fig. 10. where solid line are for positive vorticity ($\omega_x'^+ > 0$) and dotted ones, for negative one ($\omega_x'^+ < 0$), and lines with $\bullet$ are for category I and lines without symbols are for category II. It is to be noted that two groups of vorticity respond differently to wall oscillation. Namely, the phase of vorticity fluctuation of these two categories

Fig. 10 Time evolution of mean vorticity γ^+ of category I and II (solid lines: $\omega'_x > 0$, dotted lines: $\omega'_x < 0$)

Fig. 11 Time evolution of circulation intensity Γ and production rate due to various sources for vortices of kind (a): I and (b): II. [St: stretching, Ti: tilting, Tw: twisting, Vi: viscous diffusion, Ex1, Ex2: extra term due to Stokes flow]

is not synchronized, although the mechanism for this is not clarified yet. Figures 11 show the time evolution of each production rate terms in Eq. (4) for (a) category I and for (b) category II. In the figures, the lines show total quantities integrated in buffer layer ($y^+ = 10 \sim 35$) for positive ω'_x . Similar results are obtained for negative vorticity, though not shown here. Corresponding to variation of production rate

Fig. 12 Top view of quasi-streamwise vortices and production rate due to stretching and due to tilting. [(a) $\omega'_x \geq 0.2$, (b) $P^+_{\omega_x, str.} > 0.015$, (c) $P^+_{\omega_x, tilt.} > 0.015$]

due to stretching and/or tilting, total vorticity Γ^+ (integration of γ^+ in buffer layer) also varies. While production rate due to stretching generate the vorticity with time lag, that due to tilting does with no time lag, which suggests that the latter does affect little to coherent structures.

Figures 12 show the top view of areas of (a) strong streamwise vorticity $\omega'_x \geq 0.15$, (b) strong production rate by stretching $P^+_{\omega_x, str.} > 0.015$ and (c) that by tilting $P^+_{\omega_x, tilt.} > 0.015$ in the layer $y^+ = 10 \sim 35$, respectively. Although figures show the distribution at $t/T = 0.8$ and these patterns change depending on time, it is always true that areas of high- $P^+_{\omega_x, str.}$ are coincident with those of high vorticity areas. Meanwhile, high- $P^+_{\omega_x, tilt.}$ areas are not always those of high-vorticity areas and at the instant of Figs. 12, areas of $P^+_{\omega_x, tilt.} \leq -0.015$ are found at pretty different from those of $\omega'_x \leq -0.15$. This suggests that tilting effect is not of vital importance for coherent structures.

As shown in Figs. 9, tilting effect contributes more to weak vortices than to strong one. That is, for strong streamwise vortices which are crucially important in near wall turbulence, production rate due to stretching is most important than other one. Although areas in Figs. 12 includes vortices of both categories I and II, the areas of high- $P^+_{\omega_x, tilt.}$ shown in Fig. 12(c) are nearly coincident with those of vortices of category II.

In addition to β defined in Eq. (5), another inclination angle α which is the tilting angle from the wall,

$$\alpha = \tan^{-1} \left(\frac{\omega'_y}{\sqrt{\omega'^2_x + \omega'^2_z}} \right) \quad (6)$$

is introduced. Time evolution of mean α and β averaged in buffer layer of vortices of category I and II is shown in Fig. 13. Solid lines are for positive

vortices $\omega_x^+ > 0$ and dotted lines, for negative ones but the lines for negative vorticity are shown in the form equivalently converted to positive vorticity. In the figure, numbers attached to the symbols denote time t/T .

Corresponding to Figs. 9, vortices of category II are tilted more toward spanwise direction and are nearly parallel to the wall. Meanwhile, β of the vortices of category I is $100^\circ \sim 120^\circ$ which is slightly larger than inclination of quasi-streamwise vortices. This is because the inclination angle of vortex line is usually larger than that of axis of quasi-streamwise vortices defined by concentration of ω_x' . Most of vortices having this property are found in the core region of a quasi-streamwise vortex. Mean values of angle β of two categories of vortices I and II are quite different but they fluctuate largely in one period of wall oscillation. So does angle α varies largely. Namely, attitude angle of quasi-streamwise vortices changes largely with motion of the wall. Since the tilting term represents variation of vorticity component in a specified direction, high production rate due to tilting shown in Figs. 8 can be interpreted to demonstrate large variation of attitude angle with wall motion.

Next, the mechanism of the attenuation of

Fig. 13 Variation of inclination angle to the wall ($|\alpha|$) and to the streamwise direction ($|\beta|$) for vortices of category I and II. (solid lines: $\omega'_x > 0$, broken lines: $\omega'_x < 0$)

Fig. 14 Time evolution of angle α versus mean production rate due to stretching and due to tilting in plane ($y^+=16$) for the vortices of category I. (solid line: stretching, dotted line: tilting)

production rate due to stretching is discussed in the following.

Distinctive property of vortices of category I is that they change tilting angle α largely in one period of wall oscillation. Comparing variation of α of positive vorticity in Fig. 13 with production rate of due to stretching $P_{\omega_x, \text{str.}}$ in Fig. 11(a), one finds that larger the α , larger $P_{\omega_x, \text{str.}}$ and vice versa. Figure 14 which shows time evolution of mean production rate P_{ω_x} and tilting angle α of vorticity of category I in the plane of $y^+=16$ supports this conclusion. Namely, when the inclination angle α of a vortex line is small, the difference of height of highest point and lowest one of the vortex line becomes less and accordingly, stretching of vortex line by wall-normal gradient of streamwise velocity is reduced as was reported in authors' previous paper⁽²⁾ related with self-sustenance mechanism of a vortex. So, a possible interpretation is that the production of streamwise vorticity due to stretching can not be effective for some interval within one period of wall oscillation to recover diffusion by viscosity, because within this time interval, attitude angle of a vortex line stays unfavorable. It is to be added that in Fig. 14, production rate due to tilting contributes negatively while α is decreasing, consistently with the known physical mechanism taking place in the core region of a vortex. Figures 15 show time evolution of mean production rate due to stretching $\bar{P}_{\omega_x, \text{str.}}^+$ averaged in some planes parallel to the wall in the time interval of $t/T=0.5 \sim 1.5$ where upper is stationary wall side and lower, oscillating one. Obviously, time-wise integration is smaller in oscillating wall side than in stationary one.

(a) Stationary wall side

(b) Oscillating wall side

Fig. 15 Time evolution of production rate $P_{\omega_x, \text{str.}}^+$ integrated in a plane parallel to the wall for strong vortices $\omega_x^+ < -0.2$

5. Dynamics of Each Quasi-Streamwise Vortex

An example of evolution of configuration of a streamwise vortex is discussed in the following. Figure 16 shows top view of a typical negative quasi-streamwise vortex varying its configuration consecutively in time in the growing interval of $t/T=0.54 \sim 0.73$. As observed in the figure, a quasi-streamwise vortex starts to change its direction from its upstream-end portion which is located close to the wall, following the wall motion, then this change propagates to the downstream portion of further away from the wall. Cross sectional distribution of strong production rate and strong vorticity at the section labeled A in Fig. 16, at $t/T=0.62$ is shown in Fig. 17. Solid line is strong vorticity region of $\omega_x^+ < -0.2$ and it contains area of strong production rate due to stretching $P_{\omega_x, \text{str.}}^+ < -0.02$ (chained line).

Fig. 16 Time evolution of a quasi-streamwise vortex ($\omega_x^+ < -0.2$)

Fig. 17 Cross sectional distribution of production rate of quasi-streamwise vortex. (solid lines: $\omega_x^+ = -0.2$, chained line: $P_{\omega_x, \text{str.}}^+ = -0.02$, broken lines: $P_{\omega_x, \text{Ex1}}^+ = \pm 0.02$)

This suggests that quasi-streamwise vortex is enhanced by stretching. In the mean time, areas of high positive and negative value of $|P_{\omega_x, \text{Ex1}}^+| > 0.02$ are found on both sides of the vortex core. This production serves to bring the vortex core to the right ($z^+ < 0$). This why the upstream-end part of the vortex close to the wall follows the wall movement, the rest keeping its attitude unchanged. For the swing of upstream part of vortex, absorption of strong streamwise vorticity included in the Stokes layer flow by vertical flow that the vortex induces is responsible and viscous entrainment affects little.

An example of time evolution of streamwise distribution of cross-sectional integration of production rate $P_{\omega_x, \text{str.}}^+$ and circulation Ω_{ω_x} of streamwise vorticity are shown in Fig. 18, where cross-sectional integration means that of a concerned quantity in a cross section of the core of a vortex where $\omega_x^+ > 0.2$. The figure is for the vortex shown in Fig. 16. It is demonstrated that in the upstream end portion of this vortex, $P_{\omega_x, \text{str.}}^+$ is small because angle α is too small as mentioned earlier. In Fig. 19, the cross sectional vortex lines as well as high vorticity areas are shown for tail portion (section A in Fig. 18) where $P_{\omega_x, \text{str.}}^+$ is decreasing.

It is observed in the figure that most of the production rate due to stretching takes place in the area of $\omega_x^+ < -0.2$. In this section of $x^+ = 486$, the

Fig. 18 Time evolution of the streamwise distribution of (a) production rate of vorticity $P_{\omega_x, \text{str.}}^+$ and (b) circulation Ω_{ω_x} for vorticity $\omega_x^+ < -0.2$

Fig. 19 2-D vortex lines and the vorticity area. (dotted line: vortex lines, chained lines: $\omega_x^+ < -0.2$, $t/T = 0.69$, $x^+ = 486$)

vortex lines pass through the body of streamwise vortex so strongly tilted to horizontal plane that stretching by wall-normal gradient of mean flow becomes ineffective. This is to be compared with the upstream-end portion of a quasi-streamwise vortex found in usual non-oscillating wall whose center is at about $y^+ \sim 25$ where large enough velocity gradient to stretch vortex takes place.

Wall oscillation entrains this vortex to spanwise direction and brings it closer to the wall. That is, the vortex section becomes flattened and goes closer to the wall. This modification weakens the stretching effect.

Above observation suggests that the effect of wall oscillation is to modify the strength and the manner of winding of spanwise vortex layer. That is, the inclination of the vortex lines passing through the vortex cross section is modified by the wall oscillation and as the result, the efficiency of conversion of the spanwise vorticity to streamwise one due to stretching of the entrained vortex filament is modified. The inclination angle varies continuously from the most efficient one to the least one in one oscillating period and in average, aggravation is far larger than improvement.

6. Conclusion

In this work, the mechanism of the reduction of wall shear stress by spanwise wall oscillation is discussed by using direct numerical simulation.

1) The wall oscillation affects most strongly to the strongest vortices at the beginning and then gradually to weaker ones. The effect propagates with time

lag to away from the wall. In the near oscillating wall, strong streamwise vortex attenuates not straightforwardly but with periodic growth and attenuation synchronized with the period of wall oscillation but with phase lag depending on the direction of rotation.

2) In one period of oscillation, the layer at which both streamwise vorticity and its production are affected by the wall oscillation moves from a layer close to the wall to farther away from the wall with time.

3) The contribution of tilting term is larger than that of stretching term so far as its integrated amount is concerned. But stretching term contribute to the strong vortex in contrast with tilting term which contributes to the weak vortex.

4) The inclination angle of vorticity varies largely in one period. The production rate due to stretching strengthen the strong vorticity along with the inclination angle. But as the time mean, aggravation is far larger than improvement.

5) The upstream-end-part of the quasi-streamwise vortex is located close to the wall and follows the wall movement. This is caused by entraining vorticity of the Stokes flow by vertical flow of vortex itself.

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