Detection of near-wall streamwise vortices by measurable information at wall

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Abstract. The relationship between near-wall streamwise vortices and flow quantities that can be measured at wall, i.e., streamwise and spanwise wall shear stress \( \tau_{wx} \) and \( \tau_{wz} \), and fluctuating wall pressure \( p'_w \), is studied using the DNS databases of fully developed turbulent channel flow. It is found that all the three quantities \( \tau_{wx} \), \( \tau_{wz} \) and \( p'_w \) are closely related with near-wall streamwise vortices. \( \tau_{wx} \) corresponds to the sweep and ejection motion induced by the downstream streamwise vortex. \( \tau_{wz} \) is the spanwise footprint of the overhead vortical structure. Compared with the wall shear stresses, the relationship between \( p'_w \) and the near-wall streamwise vortex is more complex. In the upstream of the detecting point, the high pressure region \( (p'_w > 0) \) corresponds to the sweep motion on the down-wash side of the streamwise vortex, while the low pressure region \( (p'_w < 0) \) corresponds to the ejection on the up-wash side of the structure; at the detecting point, a low pressure region is formed just underneath the streamwise vortex; in the downstream, the correspondence between \( p'_w \) and the sweep/ejection motion is in opposite to that in the upstream. Considering the practical requirement of turbulence control, a random blowing/suction at the wall is introduced to examine the robustness of the relationship. The results show that \( \tau_{wx} \) is greatly contaminated, while \( p'_w \) and \( \tau_{wz} \) still exhibit an excellent correspondence with near-wall streamwise vortices.

1. Introduction

Streamwise vortices, which are directly related with sweep and ejection motions, play dominant roles in the self-sustaining process of near-wall turbulence (Hamilton et al., 1995). Hence it is suggested that turbulence suppression and drag reduction can be achieved via active manipulation of these organized structures. This idea was confirmed by the initiative work of Choi et al. (1994), who first applied blowing/suction at the wall just in opposite to the vertical velocity at a small distance from the wall. By the so-called "opposition control", they found that the near-wall streamwise vortices were greatly attenuated, accompanied by a substantial skin-friction reduction. The great potential of the active turbulence control has attracted a vast amount of following researches to construct more practical control schemes based on wall information. For example, the spanwise wall shear stress has been used by Lee et al. (1997) to construct an adaptive controller based on a neural network. Wall shear stresses and pressure were employed by Lee et al. (1998) to construct the suboptimal control scheme. Hence the relationship between near-wall streamwise vortices and wall information is a crucial issue for the development of the practical active control schemes.
Streamwise and spanwise wall shear stress and fluctuating wall pressure are the measurable information at the wall, and have been considered as the possible "footprint" of the near-wall streamwise vortices. Kravchenko et al. (1993) studied the relationship between streamwise wall shear stress and near-wall streamwise vortices using database of fully developed turbulent channel flow by direct numerical simulation (DNS). It was found that higher streamwise wall shear stress was closely associated with the downstream streamwise vortices located near the wall. About ten years later, the close relationship between wall pressure and the near-wall streamwise vortices was disclosed by Kim et al. (2002) in a spatially developing turbulent boundary layer. By these works, we can not say that the complete scenario is already clear. For example, Lee et al. (1998) found that the suboptimal control scheme based on streamwise wall shear stress failed to yield any skin-friction reduction, while the scheme based on spanwise wall shear stress can obtain a similar amount of drag reduction to that by the opposition control. The explanation is still needed.

In present study, the relationship between near-wall streamwise vortices and wall information is investigated systemically by two-point correlation and conditional average with the aid of the DNS database of turbulent channel flow. The robustness of the relationship is also explored by performing DNS of turbulent channel flow under the influence of random blowing/suction at the wall.

2. DNS database of turbulent channel flow

The turbulent channel flow of incompressible Newtonian fluid is directly simulated by Fourier-Galerkin and Chebyshev-Tau method. The Reynolds number based on wall friction velocity $u_r$ and half channel width $H$ is 180. The computational domain spans $4\pi H \times 2H \times 2\pi H$ in the streamwise $(x, u)$, wall normal $(y, v)$ and spanwise $(z, w)$ directions, in accordance with the $128 \times 128 \times 128$ grids, respectively.

The two-point correlation coefficient between wall measurable quantity $\theta_w$ and streamwise vorticity $\omega_x$ is first considered in present study. It is defined as

$$R_{\theta_w \omega_x}(\Delta x^+, y^+, \Delta z^+) = \frac{\langle \theta_w(x^+, z^+)\omega_x(x^+ + \Delta x^+, y^+ + \Delta y^+, z^+ + \Delta z^+) \rangle}{\theta_{w rms} \omega_{x rms}(y^+)}$$

in which $\theta_w$ stands for either of the two components of wall shear stress, $\tau_{wx} = \mu(\partial u'/\partial x)_w$ and $\tau_{wz} = \mu(\partial w'/\partial y)_w$, or the fluctuating wall pressure $p_w'$. $\langle \rangle$ represents the averaging over the streamwise and spanwise directions, and time. It should be noted that the function $R_{\theta_w \omega_x}$ depends on the three dimensional coordinates, and reflects the relationship between $\theta_w$ on the detecting point and the streamwise vorticity all over the domain for performing statistics.

The relationship between near-wall streamwise vortices and wall information can also be depicted by the conditionally averaged flow field around strong streamwise vortices. For flow quantity $\phi(x, y, z)$, its conditional average associated with positive streamwise vortices is defined as

$$\langle \phi(\Delta x^+, y^+, \Delta z^+) \rangle^P = \frac{1}{N_P} \sum_{m=1}^{N_P} \phi^{(m)}(\Delta x^+, y^+, \Delta z^+)$$

where $\phi^{(m)}(\Delta x^+, y^+, \Delta z^+)$ is the sampled flow quantity satisfying $\omega_x(x^{(m)}, y^+ = 15, z^{(m)}) > \omega_{x rms}(y^+ = 15)$, and $N_P$ is the number of samples. $\Delta x^+ = x^+ - x^{(m)}$ and $\Delta z^+ = z^+ - z^{(m)}$.

The conditional average associated with negative streamwise vortices can be similarly defined as

$$\langle \phi(\Delta x^+, y^+, \Delta z^+) \rangle^N = \frac{1}{N_N} \sum_{n=1}^{N_N} \phi^{(n)}(\Delta x^+, y^+, \Delta z^+)$$
where $\phi^{(n)}(\Delta x^+, y^+, \Delta z^+) = \omega_x(x^+(n), y^+ = 15, z^+(n)) < -\omega_{x rms}(y^+ = 15)$, and $\Delta x^+ = x^+ - x^{+(n)}$ $\Delta z^+ = z^+ - z^{+(n)}$.

3. Relationship between wall information and near-wall streamwise vortices

3.1. Correlation between streamwise wall shear stress and streamwise vorticity

The relationship between streamwise wall shear stress and near-wall streamwise vortices is elucidated by $R_{\tau_{wx} \omega_x}$, as is shown in Fig.1. Fig.1(a) shows the iso-surface of $R_{\tau_{wx} \omega_x} = \pm 0.15$, which appears in the form of two pairs of streamwise elongated structures with alternate sign in the downstream of the detecting point of $\tau_{wx} (\Delta x^+ = 0, \Delta z^+ = 0)$. The pair of structures adjacent to the wall is attributed to the vorticity due to the presence of the near-wall streamwise vortices under the effect of non-slip condition at the wall. It is the upper pair of structures that is directly related to the near-wall streamwise vortices. The maximum correlation occurs at $\Delta x^+ = 90$, which is in accordance with the analysis of Kravchenko et al. (1993). Contours of the correlation coefficient in $y-z$ plane across $\Delta x^+ = 90$ is shown in Fig.1(b). The distribution of the contours is anti-symmetrical relative to $\Delta z^+ = 0$, and reaches maximum around $y^+ = 20$, which is regarded as the statistical location of the streamwise vortex core (Kim et al., 1987). If $\tau_{wx} > 0$ at the detecting point, the positive and negative regions around $y^+ = 20$ correspond to positive (clockwise rotating) and negative (counterclockwise rotating) streamwise vortices, respectively, and the fluid moves toward the wall at the detecting point. This suggests that the high streamwise wall shear stress at the detecting point is closely related with the sweep motion induced by the counter-rotating vortex pair. Similarly, if $\tau_{wx} < 0$ at the detecting point, the fluid moves away from the wall, indicating the close relationship between low streamwise wall shear stress and the ejection motion induced by the vortex pair.

![Figure 1](image_url)  
Figure 1. (a) Iso-surface and (b) contours of $R_{\tau_{wx} \omega_x}$. Red for $R_{\tau_{wx} \omega_x} = 0.15$ and blue for $R_{\tau_{wx} \omega_x} = -0.15$, solid lines for positive value and dashed lines for negative value.

The conditionally averaged streamwise wall shear stress associated with strong streamwise vortices is depicted in Fig.2. It can be seen that the iso-surface of positive (negative) $\omega_x$ tends to tilt to negative (positive) $z$ direction. Both positive and negative streamwise vortices leave a region with significant high streamwise wall shear stress on the wall at their downwash side in upstream when they propagate downstream. A much smaller region with low streamwise wall shear stress is formed at the up-wash side of the streamwise vortices, indicating that the correlation between low streamwise wall shear stress and near-wall streamwise vortices is much weaker than that between high streamwise wall shear stress and near-wall streamwise vortices. The above analysis shows that in turbulent channel flow, $\tau_{wx}$ is closely linked with the downstream near-wall streamwise vortices. The high streamwise wall shear stress can be considered as the footprint of the sweep motion induced by the overhead vortical structure.
Figure 2. Top view of iso-surface (hatched) of (a) $\langle \omega_x \rangle_P = 1.0$ and (b) $\langle \omega_x \rangle_N = 1.0$ and contours of $\tau_{wx}$ on the wall (colored).

3.2. Correlation between spanwise wall shear stress and streamwise vorticity
Spanwise wall shear stress $\tau_{wz}$ is one of the most important wall information that has been successfully used in the construction of active control scheme for turbulence drag reduction. Lee et al. (1998) developed the suboptimal control method based on $\tau_{wz}$ and reported about 20% drag reduction in turbulent channel flow. The spanwise gradient of $\tau_{wz}$ has been adopted by Kasagi et al. (2009) to control the ”see-saw” actuator, and about 6% drag reduction has been obtained experimentally. It was also found that selecting $\tau_{wz}$ to construct the cost function in neural network control of turbulence is much more effective than selecting streamwise wall shear stress $\tau_{wx}$ (Lee et al., 1997). To get a more clear scenario on the relationship between spanwise wall shear stress and near-wall streamwise vortices, the correlation between $\tau_{wz}$ and $\omega_x$ is first studied.

$R_{\tau_{wz}\omega_x}$ gets its maximums just above the detecting point $\Delta x^+ = 0$, $\Delta z^+ = 0$. Fig.3 shows the contours of $R_{\tau_{wz}\omega_x}$ in $y-z$ plane across $\Delta x^+ = 0$. The positive correlation region adjacent to the wall is a kinematic consequence of the presence of streamwise vortices above the wall and the no-slip boundary condition imposed at the wall, and hence our focus is on the upper negative correlation region which is directly related to near-wall streamwise vortices. If $\tau_{wz} > 0$ at the detecting point, the negative correlation around $y^+ = 15$ indicates the existence of streamwise vortices with negative streamwise vorticity (counterclockwise rotating) there, and vice versa. Because the streamwise vortices tend to appear in counter-rotating pairs, there are two symmetrical positive correlation regions formed on both sides of the negative correlation region. At about $y^+ = 15$, $R_{\tau_{wz}\omega_x}$ reaches maximum amplitude of 0.41, which is much higher than that of $R_{\tau_{wx}\omega_x}$ (about 0.28). This suggests that spanwise wall shear stress is much more strongly correlated with near-wall streamwise vortices than streamwise wall shear stress.

Figure 3. Contours of $R_{\tau_{wz}\omega_x}$ in $y-z$ plane at $\Delta x^+ = 0$. Solid lines for positive value and dashed lines for negative value with contour level increment of 0.05.
Fig. 4 shows the distribution of the conditionally averaged spanwise wall shear stress associated with strong streamwise vortices. Just beneath the streamwise vortices with positive (negative) streamwise vorticity, a region with negative (positive) spanwise wall shear stress is formed, accompanied on both sides by two regions with positive (negative) spanwise wall shear stress. Superior to $\tau_{uw}$, the rotating direction of the streamwise vortices can be identified by $\tau_{uwz}$.

![Figure 4](image-url)

**Figure 4.** Top view of iso-surface (hatched) of (a) $\langle \omega_z \rangle^P = 1.0$ and (b) $\langle \omega_z \rangle^N = 1.0$ and contours of $\tau_{uwz}$ on the wall (colored).

In summary, $\tau_{uwz}$ can be considered as the footprint left by near-wall streamwise vortices in spanwise direction under the constraint of no-slip condition at the wall. Compared with streamwise wall shear stress, $\tau_{uwz}$ has a better correspondence with the near-wall streamwise vortices.

### 3.3. Correlation between wall fluctuating pressure and streamwise vorticity

Kim *et al.* (2002) has examined the relationship between wall pressure and near-wall streamwise vortices in a spatially developing turbulent boundary layer. They found that $p'_w$ is closely correlated with the upstream streamwise vortices, and the maximum correlation occurs at about $\Delta x^+ = -20$. In the upstream, the high pressure region ($p'_w > 0$) corresponds to the sweep motion while the low pressure region ($p'_w < 0$) corresponds to the ejection motion. Just above the detecting point, the correlation between $p'_w$ and $\omega_z$ is very weak.

Different from wall shear stress, pressure is a scalar, by which the rotating direction of the vortices can not be identified. For example, low pressure region at wall is closely linked with overhead streamwise vortices satisfying $\omega_z(x^+, y^+ = 15, z^+) > \omega_{x rms}(y^+ = 15)$, and similarly $R^N_{p'_w, \omega_z}$ is obtained for negative streamwise vortices satisfying $\omega_z(x^+, y^+ = 15, z^+) < -\omega_{x rms}(y^+ = 15)$. The correlation between fluctuating wall pressure and streamwise vortices rotating in different directions can be represented by $R^P_{p'_w, \omega_z}$ and $R^N_{p'_w, \omega_z}$, respectively.

$R^P_{p'_w, \omega_z}$ and $R^N_{p'_w, \omega_z}$ are antisymmetric about $z$ coordinate, hence only $R^P_{p'_w, \omega_z}$ is analyzed in the following. Compared with the unconditional correlation function $R^P_{p'_w, \omega_z}$ (Kim *et al.*, 2002), the magnitude of the conditional correlation $R^P_{p'_w, \omega_z}$ is much larger than $R^N_{p'_w, \omega_z}$. The iso-surfaces of $R^P_{p'_w, \omega_z}$ are also in the streamwise elongated appearance, but not symmetric anymore about $z$.
Figure 5. Contours of $R_{p'w'}^P$ in $y-z$ plane at different $\Delta x^+$. Solid lines for positive value, dashed lines for negative value with contour level increment of 0.1.

and tend to tilt to the $-z$ direction downstream. Fig.5 shows the contours of $R_{p'w'}^P$ in $y-z$ planes at different $\Delta x^+$. In the streamwise direction, the conditional correlation is strongest at the detecting point of $p'_w$, and gradually weakened in upstream and quickly weakened in downstream. In the upstream of the detecting point of $p'_w$, at $\Delta x^+ = -72$, a positive correlation region appears around $y^+ = 15, \Delta z^+ = -20$, and a negative correlation region occurs around $y^+ = 15, \Delta z^+ = 20$. At $\Delta x^+ = -36$, the center of the positive region moves to $\Delta z^+ = -25$, and that of the negative region moves to $\Delta z^+ = 15$. At $\Delta x^+ = 0$ and 36, the detecting point is just underneath the negative region. The distribution of the correlation indicates that in upstream, the high wall pressure ($p'_w > 0$) corresponds to the sweep motion induced by the above streamwise vortices, while the low wall pressure ($p'_w < 0$) is linked to the ejection motions; around the detecting point, the low wall pressure region is located just beneath the streamwise vortices; in downstream, the correspondence between wall pressure $p'_w$ and the ejection/sweep motions is just in opposite to that in upstream.

The distribution of the conditionally averaged wall pressure associated with strong streamwise vortices is exhibited in Fig.6. It can be seen that a low pressure region is formed at the wall just beneath the streamwise vortices represented by the iso-surface of streamwise vorticity, with two high wall pressure regions accompanied on both sides. The iso-surface of positive (negative) streamwise vorticity tends to deviate to positive (negative) $z$ direction from the axis of the low wall pressure region. Because of the deviation, the correspondence between wall pressure and the sweep/ejection motion is opposite to each other in the upstream and downstream of the detecting point. In upstream, the high pressure region appears at the up-wash side of the streamwise vortices, while that appears at the down-wash side in downstream.

In summary, the fluctuating wall pressure is closely linked to near-wall streamwise vortices. In the upstream of the detecting point, high wall pressure ($p'_w > 0$) is related to sweep motions due to near-wall streamwise vortices, while low wall pressure ($p'_w < 0$) corresponds to the ejection; around the detecting point, a low pressure region is formed just below the vortices; in the downstream, the correspondence between wall pressure and near-wall streamwise vortices is in opposite to that in the upstream.
4. Influence of random wall blowing/suction on the relationship between wall information and near-wall streamwise vortices

The analysis in the above section shows that all the three quantities that can be measured at the wall, $\tau_{wx}$, $\tau_{wz}$ and $p'_w$, are closely related with near-wall streamwise vortices in canonical turbulent channel flow. But for practical application in active turbulence control, near-wall streamwise vortices and wall information are both under the influence of active actuation determined by a certain kind of control scheme. Hence the robustness of their relationship explored previously must be further examined. In this section, random blowing/suction is introduced on the lower wall of the channel to check how the correlations between wall informations and near-wall streamwise vortices are affected.

Direct numerical simulation is performed to turbulent channel flow with all the computational settings consistent with the canonical channel except that a random vertical velocity is imposed at the lower wall,

$$v_w(x, z, t) = F(t) \cdot v_{dis}(x, z, t)$$  \hspace{1cm} (4)

In order to make the transition from solid wall to permeable wall smoothly, a time relaxing term $F(t) = 1 - e^{-t^2}$ is introduced. The root mean square of the random disturbance $v_{dis}$ is chosen at a level similar to the root mean square of the vertical velocity at $y^+ = 10$ in canonical turbulent channel flow.

4.1. Influence to the correlation between streamwise wall shear stress and streamwise vorticity

Affected by the random blowing/suction disturbance at the lower wall, the correlation $R_{\tau_{wx} \omega_x}$ still exhibits two pairs of streamwise elongated structures but the magnitude of the correlation is reduced dramatically. Fig.7 shows the contours of $R_{\tau_{wx} \omega_x}$ in $y-z$ plane across the streamwise maximum value position. Compared with Fig.1 for canonical channel flow, the maximum amplitude of the correlation around $y^+ = 15$ is reduced from 0.28 to about 0.1, indicating that the correlation between $\tau_{wx}$ and near-wall streamwise vortices is very sensitive to the random disturbance applied on the wall.

To examine how $\tau_{wx}$ response to the random disturbance, the two-point correlation between $\tau_{wx}$ and $v_w$, the blowing/suction velocity at the wall, is performed. Fig.8 shows the distribution of $R_{\tau_{wx} v_w}$ on the wall. It is found that $\tau_{wx}$ is closely associated with blowing/suction velocity at the wall, and the maximum correlation coefficient is about -0.7, which is reached at $\Delta x^+ = 15$ downstream from the detecting point. The results indicate that the ejection/sweep motions due to the upstream streamwise vortices can not affect the streamwise wall shear stress directly because of the presence of the blowing/suction on the wall. $\tau_{wx}$ is mainly determined by the local blowing/suction on the wall and the footprint left by the downstream vortical structures is

Figure 6. Top view of the iso-surface (hatched) of (a) $\langle \omega_x \rangle^P = 1.0$ and (b) $\langle \omega_x \rangle^N = 1.0$ and contours of $p'_w$ on the wall (colored).
destroyed by the disturbance at the wall. Therefore, under the random disturbance at the wall, \( \tau_{wx} \) can not reflect the evolution of the near-wall streamwise vortices any more.

Lee et al. (1998) has tried to select \( \tau_{wx} \) as an input information to construct the suboptimal control scheme for drag reduction. However, the control based on \( \tau_{wx} \) causes the drag increase in their numerical simulation. A simple negative feedback is built between \( \tau_{wx} \) and \( v_w \) in Lee’s test case because \( \tau_{wx} \) is only dominated by the initial velocity applied on the wall according to the control law. Hence, after the control begins, \( \tau_{wx} \) can no longer determine the locations of near-wall streamwise vortices, and the output of the control becomes a disturbance to the turbulent flow, and hence turbulence is activated instead of suppressed.

4.2. Influence to the correlation between spanwise wall shear stress and streamwise vorticity

Fig. 9 shows the contours of \( R_{\tau_{wz}\omega_x} \) in \( y-z \) plane at \( \Delta x^+ = 60 \) for turbulent channel flow with random wall disturbance, and can be compared with Fig. 3 for canonical turbulent channel flow. Just as \( R_{p'_w\omega_x} \), \( R_{\tau_{wz}\omega_x} \) exhibits a similar structure as that in the canonical turbulent channel flow and keeps a similar magnitude. So, it can be conclude that under the random wall disturbance, the correspondence between spanwise wall shear stress and near-wall streamwise vortices are almost unchanged, and \( \tau_{wz} \) can still be considered as an reliable wall information to reflect the locations of near-wall streamwise vortices.

4.3. Influence to the correlation between fluctuating wall pressure and streamwise vorticity

Since the conditional correlations \( R_{p'_w\omega_x} \) and \( R_{p'_w\omega_x}^N \) are antisymmetric about coordinate z, only the contours of \( R_{p'_w\omega_x} \) in \( y-z \) planes at different \( \Delta x^+ \) are given out in Fig. 10, which can be compared with Fig. 5 for canonical turbulent channel flow. Under the random wall disturbance,
Figure 9. Contours of $R_{\tau_{wx}, \omega_z}$ in $y - z$ planes at $\Delta x^+ = 0$ in turbulent channel flow with random wall disturbance. Solid lines for positive value and dashed lines for negative value with contour level increment of 0.05.

$R_{p'_{w}, \omega_z}$ exhibits a similar distribution to that for canonical turbulent channel flow, and the amplitude of the correlation is almost unchanged. The results confirms that, under random wall disturbance, the fluctuating wall pressure can still reflect the evolution of the near-wall streamwise vortices.

Figure 10. Contours of $R_{p'_{w}, \omega_z}$ in $y - z$ planes at different $\Delta x^+$ in turbulent channel flow with random wall disturbance. Solid lines for positive value and dashed lines for negative value with contour level increment of 0.1.

By now, the robustness of the relationship between wall information ($\tau_{wx}$, $\tau_{wz}$ and $p'_w$) and near-wall streamwise vortices is examined by introducing a random blowing/suction disturbance at the wall. It is found that the relationship based on $\tau_{wx}$ is destroyed extensively by wall disturbance, while $p'_w$ and $\tau_{wz}$ still exhibit an excellent coincidence with near-wall streamwise vortices. Therefore, in the practical active control of turbulence for drag reduction, the fluctuating wall pressure $p'_w$ and the spanwise wall shear stress $\tau_{wz}$ are more reliable than $\tau_{wx}$ to construct a control scheme.

5. Conclusions

With the aid of DNS database of turbulent channel flow at $Re_x = 180$, the relationship between wall information, i.e., streamwise and spanwise wall shear stress $\tau_{wx}$, $\tau_{wz}$ and wall
fluctuating pressure $p'_w$, and near-wall streamwise vortices is explored by two-point correlation and conditional average. It is found that all the three quantities $\tau_{wx}$, $\tau_{wz}$ and $p'_w$ are closely related with the near-wall streamwise vortices. $\tau_{wx}$ corresponds to the sweep and ejection motions induced by the downstream streamwise vortices. $\tau_{wz}$ is the footprint left by the overhead vortical structures in spanwise direction at the wall. Compared with the wall shear stresses, the correlation between $p'_w$ and near-wall streamwise vortices is more complex. In the upstream of the detecting point, the high pressure region ($p'_w > 0$) corresponds to the sweep motion on the down-wash side of the streamwise vortices, while the low pressure region ($p'_w < 0$) corresponds to the ejection on the up-wash side of the structure; around the detecting point, a low pressure region is formed just below the streamwise vortices; in the downstream, the correspondence between $p'_w$ and the sweep/ejection motions is just in opposite to that in the upstream.

Considering the practical application in active turbulence control, a random blowing/suction at the wall is introduced to examine the robustness of the relationship. The results show that $\tau_{wx}$ is mainly determined by the blowing/suction velocity at the wall, and the relationship based on $\tau_{wx}$ is destroyed. Under the influence of wall disturbance, $p'_w$ and $\tau_{wz}$ still exhibit an excellent correspondence to near-wall streamwise vortices, which can provide us an useful guidance to the selection of the information input for active control.

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