Active Control of Wall Turbulence with Wall Deformation*

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The performance of an active feedback control with wall deformation was tested by direct numerical simulation of a fully developed turbulent channel flow. The local wall movement is determined based on the flow condition detected by virtual sensors distributed in the vicinity of the wall, i.e., the wall velocity is made opposite to the wall-normal velocity at $y/\delta=0.1$. The turbulent friction drag is reduced by 10% on average. The gain in the pumping power reaches about 28 times the energy consumption for actuating the wall. The primary mode of the resultant wall velocity distribution, which should be most effective in the present drag reduction scheme, is found to have wavelengths of about 300 and 50 viscous wall units in the streamwise and spanwise directions, respectively, while the time period is of the order of the time scale of the quasi-coherent vortical structure of near-wall turbulence. The effects of active wall deformation on quasi-coherent structures are investigated by a conditional averaging technique. In the present control scheme, the Q2 vortex is displaced away from the wall and the wall-normal and spanwise velocity fluctuations associated with the Q2 event are decreased. On the other hand, the location of the Q4 vortex from the wall remains unchanged while the vorticity of the Q4 vortex is substantially decreased. In the region downstream of the Q2 event, the wall is deformed in the shape of a shallow groove, which stabilizes the near-wall streaky structures along the groove.

Key Words: Wall Turbulence, Active Feedback Control, Wall Deformation, Drag Reduction

1. Introduction

An advanced control technique for turbulence and heat transfer phenomena is expected to be developed by a new technology related to a wide range of fields, such as transportation, energy, environment and bionics, through the free control of detachment, transition, noise and diffusion. Formerly, passive control techniques such as riblet surfaces were used; however, an active feedback control system⁽¹⁾ has attracted considerable attention, in which a control responding to the fluid situation is employed, and shows a

greater control effect.

Recently, a highly intelligent control algorithm which is a fusion of fluid dynamics and control theories, such as suboptimal control theory⁽²⁾ and neural networks⁽³⁾, has been applied and shows a high control efficiency. However, it is pointed out that the large burden of calculation to determine the control input results in a time delay of the control input, which may cause instability of the system for practical use. On the other hand, simple algorithms with small calculation loads have been developed with the physical argument of wall turbulence⁽¹⁾. It is well known that the turbulent coherent structures near the wall, especially quasi-streamwise vortices (QSV hereafter) play an important role in fluid dynamics, i.e., on the turbulence and the production of wall shear stress^{(4),(5)}. Choi et al.⁽⁶⁾ recently showed that about 30% drag reduction is obtained by interfering with QSV through local blowing/suction from the wall, determined from the velocity information near the wall. This result shows that highly efficient control is possible with a simple algorithm which requires a small calculation

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load.

A wall flow such as a boundary layer over an airplane wing or a pipe flow in the pipeline is assumed, in which the active feedback control of turbulence is applied. The elements of turbulence control system (i.e., sensor, controller, and actuator) used in this system should have similar dimensions to those of turbulent coherent structures, i.e., they should be of relatively small orders of microns up to hundreds of micrometers. Although it was not possible to construct such small elements in the past, the recent development of microelectromechanical systems (MEMS)⁽⁷⁾ makes it possible to design a highly intelligent control system, on which a number of sensors and actuators are distributed.

It is desirable that the actuator mode used in turbulence control should be continuous and have a small wall deformation, from the necessity of securing the validity and durability under a hostile environment. Carlson and Lumley⁽⁸⁾ employed a deformable bump on a channel wall, which moves with a predetermined mode, and reported that the friction drag is reduced by elevating the high-speed streaks away from the wall. They showed the possibility of turbulence control with wall deformation as an actuator.

In the present study, turbulent channel flow, which is relatively easy to calculate and has been studied extensively, is used as a verification flow field, and a direct numerical simulation (DNS hereafter) of turbulent channel flow with wall deformation is performed. The objective of the present study is to evaluate the active feedback control of wall turbulence with an actively deformable wall as an actuator. The influence of wall deformation upon the turbulent coherent structures is investigated by conditional sampling based on the quadrant analysis. An optimal spatiotemporal dimension required from the deformable actuators is evaluated for its contribution towards the progress of leading design of Smart Skin, on which deformable actuators are distributed regularly.

2. Control Algorithm

In the first stage of the present study, a simple control algorithm similar to that proposed by Choi et al.⁽⁶⁾, is employed in order to evaluate the effect of wall deformation. Choi et al. showed in their turbulence control with local blowing/suction from the wall, that a maximum friction drag reduction is obtained when the detection plane to capture QSV is placed at $y_d^+ = 10 \sim 20$. However, we placed the detection plane at $y_d/\delta = 0.1$ ($y_d^+ \approx 15$), to avoid the physical unreasonableness of the detection plane being buried inside the deformable wall. Namely, as shown in Fig. 1, the wall normal velocity component v_s is sensed to

Fig. 1 Schematic diagram of control algorithm

detect QSV at time t_n on the detection plane which is placed at $y_d/\delta = 0.1$ from the basis of the wall. The wall velocity v_w at the next time step t_{n+1} is determined from the following Eq. (1). Here, x , y , and z denote the streamwise, wall-normal, and spanwise directions, respectively.

$$v_w^+(t_{n+1}) = \alpha(v_s^+(t_n) - \langle\langle v_s^+(t_n) \rangle\rangle) - \beta y_w^+(t_n), \quad (1)$$

where $\langle\langle v_s \rangle\rangle$ denotes an ensemble average of wall normal velocity component v_s in the x - z plane at each time step. The second term on the right-hand side is a damping term to avoid an excess of wall deformation. The integration of the first term of the right-hand side of Eq. (1) on the wall is zero. In the present study, $\alpha = \pm 1$ is assumed for the deformation mode, to enhance/suppress the rotation of QSV, respectively. The time constant $(1/\beta)$ estimated from $\beta = 0.31$ used in the present study, is approximately twice that of Kolmogorov's time scale near the wall $\tau^+ \equiv \sqrt{1/\varepsilon^+} \approx 1.6$, at the present Reynolds number.

3. Numerical Procedure

The governing equations are incompressible Navier-Stokes equations and the continuity equation for the moving boundary⁽⁹⁾. Wall deformation is represented with a boundary-fitted coordinate system for a moving boundary⁽¹⁰⁾. A modified Crank-Nicolson type fractional-step method⁽⁹⁾ is used for the time advancement, while a second-order central difference scheme⁽¹¹⁾ is employed for the spatial discretization. The pressure Poisson equation is solved with the multi grid method, and three levels of meshes are used to accelerate the convergence, in which a successive over relaxation (SOR) method is adopted for the finest and medium meshes, whilst an incomplete LU decomposition conjugate gradient squared method (ILUCGS) is used for the coarsest mesh. The Reynolds number Re_b based on the bulk mean velocity U_b and the channel width 2δ , is 4 600 ($Re_\tau = u_\tau \delta / \nu \sim 150$; u_τ is friction velocity), and the flow rate is kept constant throughout the present study. The volume of the computation domain is approximately four times larger than that of the minimal flow unit⁽¹²⁾, i.e., $L_x \times L_y \times L_z = 1.25\pi\delta \times$

Fig. 2 Temporal evolution of mean pressure gradient

$2\delta \times 0.375\pi\delta (L_x^+ \times L_y^+ \times L_z^+ \sim 590 \times 300 \times 177)$. The number of grid points is 48, 97 and 48 in the x -, y - and z - directions, respectively. Grid spacings in the x - and z - directions are constant, and are $\Delta x^+ = 12.3$, $\Delta z^+ = 3.7$. A non-uniform mesh with a hyperbolic tangent distribution is employed in the y - direction, and the first mesh point away from the wall is given at $y^+ = 0.25$. The computational time step is chosen to be $\Delta t^+ = 0.33$. Periodic boundary conditions are employed in the x - and z - directions, while a non-slip boundary condition is imposed on the channel walls. Both top and bottom walls are deformable, of which each grid can move only in the y - direction.

4. Results and Discussion

Figure 2 shows a time trace of the mean pressure gradient $\langle -\partial P / \partial x \rangle$ normalized by that without control $\langle -\partial P / \partial x \rangle_c$. Hereafter, the superscript $*$ denotes the nondimensionalization by the friction velocity without control $u_{\tau c}$, and the kinematic viscosity ν .

In the case of $\alpha=1$, both the turbulence and the friction drag are increased, and the calculation is diverged at $t^*=88$, since the scale of turbulence becomes smaller and the calculation mesh used in the present DNS is not fine enough to analyze it. On the other hand, the friction drag is substantially reduced in the case of $\alpha=-1$, and the maximum friction drag reduction rate reaches about 28% at $t^*=2190$. From this finding, it is suggested that the efficient control of wall turbulence is possible with wall deformation. Note that, the mean drag reduction rate during $t^*=0 \sim 5000$ is about 10% and the friction drag shows fluctuation with a long period of about $1000\nu/u_{\tau}^2$. This phenomena is also seen in the DNS conducted by Mito and Kasagi⁽¹⁰⁾, and a slight tendency is observed in the DNS conducted by Choi et al.⁽⁶⁾. The calculation domain used in the present study is relatively small because of its high computational load, and the small computational domain is expected to relate to the phenomenon⁽¹²⁾. However the details are unclear still,

Fig. 3 Temporal evolution of root-mean-square values of wall displacement and velocity

and this will be a future subject of study.

When $\beta=0$ in Eq. (1), the algorithm is similar to that proposed by Choi et al.; however, it is necessary to damp the wall deformation by setting $\beta>0$ in the present study, for the security of stable calculations as well as in the sense of physics. For this, the correlation of v_s and v_w is about -0.75 , and QSV is sometimes increased against to the purpose of control.

Figure 3 shows root-mean-squared (rms) values of the wall displacement $\langle \langle y_w^{*2} \rangle \rangle^{(1/2)}$, and the wall velocity $\langle \langle v_w^{*2} \rangle \rangle^{(1/2)}$. The orders of the wall deformation and wall velocity are $1.0\nu/u_{\tau}$ and $0.15u_{\tau}$, respectively. These values are much smaller than the maximum wall deformation value of $12.0\nu/u_{\tau}$, and the maximum wall velocity value of $1.0u_{\tau}$ given in Carlson and Lumley⁽⁸⁾, and the present control is more efficient. These values become small in the period when the friction drag is decreased and the turbulence becomes inactive ($t^* \sim 400, 2000$). On the other hand, during the period of $500 < t^* < 1500$, QSV near the wall is regenerated, the turbulence becomes active again, and the drag is increased.

From the ratio of the power input for the wall deformation W_{in} and the reduction of the pumping power G , the performance of the present control η ($\equiv G/W_{in}$) is investigated. G and W_{in} are defined by Eqs. (2) and (3), respectively. After Mito and Kasagi⁽¹⁰⁾, (i) the pressure work, (ii) the work of convecting turbulent kinematic energy, and (iii) the stress work, are taken into account as energy input, although the work for stretching the wall material is neglected.

$$G = \left[\left(-\frac{\partial p}{\partial x} \right)_{\text{No-control}} - \left(-\frac{\partial p}{\partial x} \right)_{\text{Control}} \right] \cdot U_b L_x L_y L_z, \quad (2)$$

$$W_{in} = \int_{\Gamma_w} \left[\underbrace{p'_w \times v_n}_{(i)} + \underbrace{k \times v_n}_{(ii)} + \underbrace{\left(-\frac{1}{Re} \frac{\partial k}{\partial n} \right)}_{(iii)} \right] d\Gamma_w, \quad (3)$$

where Eq. (3) gives the surface integration over the deformable wall, and n denotes the wall-normal direction/component. The terms k , p'_w and Q denote the

Fig. 4 Temporal evolution of reduction in pumping power and power input for wall deformation

Fig. 5 Two-dimensional spectrum of wall displacement

turbulent kinetic energy, wall pressure fluctuation, and flow rate, respectively. Note that (ii) is much smaller, and is of the order of 1/10 of (i) and (iii).

Figure 4 shows time traces of G and W_{in} . W_{in} shows almost the same behavior with the wall velocity $(\langle\langle v_w^{*2} \rangle\rangle)^{1/2}$ shown in Fig. 3, and the short-period fluctuation of W_{in} is also seen in (i) and (iii). This indicates that the wall pressure fluctuation p'_w and the kinematic energy k are supplied a short-period fluctuation by the wall deformation. G is about a 10 times larger order of W_{in} , although there is a period when G becomes negative, and an average value of $\eta=28$ is obtained. Since Choi et al.⁽⁶⁾ reported that $\eta=30$ is obtained in their turbulence control with local blowing/suction, it is shown that the present control with wall deformation has almost the same control efficiency as that of blowing/suction.

Figure 5 shows a contour plot of a two-dimensional spectrum in the x and z directions of wall displacement during the period $t^*=0\sim 2000$. The horizontal and vertical axes denote the wave numbers κ_x and κ_z in the x and z directions, respectively. The peak is observed at $\kappa_x=0$, $\kappa_z=1\sim 2$, which corresponds to the wavelength of $m_x=L_x/(2\kappa_x)=580\nu/u_\tau$, $m_z=L_z/(2\kappa_z)=45\sim 90\nu/u_\tau$. The wall deformation with a wave number above 10 in the streamwise direction is quite weak.

Fig. 6 Two-dimensional spectrum of wall velocity

Fig. 7 Temporal spectrum of wall deformation

In the same manner, Fig. 6 shows a contour plot of a two-dimensional spectrum in the x and z directions of wall velocity v_w during the period $t^*=0\sim 2000$. A peak of the spectrum is at $(\kappa_{vx}, \kappa_{vz})=(1, 2)$, which corresponds to the spatial scales of wall velocity of $(m_{vx}, m_{vz})=(L_x/(2\kappa_{vx}), L_z/(2\kappa_{vz}))=(300\nu/u_\tau, 45\nu/u_\tau)$. Consequently, an efficient control is possible with a basic structure, of which the shape and the velocity are relatively long in the streamwise direction. According to Schlichting⁽¹³⁾, the wall roughness within $y^+=5$ is categorized as "hydraulically smooth." Therefore, the remarkable drag reduction obtained in the present study should be due to the wall-normal velocity of the fluid induced by the wall deformation rather than the deformed shape of the wall.

Figure 7 shows a temporal spectrum of wall displacement y_w , against the inverse of the deformation period T^* . The spectrum is obtained from the instantaneous data of $t^*=0\sim 2000$ with an interval of $\Delta t^*=5.0$, and is averaged in x - z directions. Since the peaks of the spectrum are at $1/T^*=0.0025\sim 0.003$, 0.019 , which correspond to $T^*=52, 332\sim 400$, it is shown that most of the wall deformation is relatively slow. In the same manner, a temporal spectrum of wall velocity is plotted against the inverse of wall velocity period T_v^* in Fig. 8. Since the spectrum takes a large value at $1/T_v^*>0.01$, it is shown that the wall velocity v_w fluctuates with a period shorter than $100\nu/u_\tau^2$. Note

Fig. 8 Temporal spectrum of wall velocity

Fig. 9 Mean velocity profile

that the peak is observed at $T_v^* = 47, 52$.

Kim and Spalart⁽¹⁴⁾ reported that the bursting period is $60\nu/u_\tau^2$, from the mean distance of bursting phenomena extracted by VISA technique, and the convection velocity. The characteristic periods $T^* = 52$ and $T_v^* = 52$ presently obtained are close to this value. Hamilton et al.⁽¹⁵⁾ showed that the period of regeneration cycle of the turbulent coherent structures near the wall is about $270\nu/u_\tau^2$, and the deformation period $T^* = 332, 400$ obtained from the present study is slightly longer than this. Although at present it is still difficult to obtain the physical interpretation of the correspondence with these time scales, an efficient control should be possible with a deformation mode, the period of which is close to the characteristic time scale of the turbulent coherent structure.

The following explanation elucidates the turbulent statistics of the case $\alpha = -1$, averaged during $t^* = 0 \sim 5000$. Each statistic is calculated on the basis grid of the undeformed channel. When the basis grid exists within the deformable wall, no statistic is added to the sample. Hereafter, the superscript + denotes a non-dimensionalization with the friction velocity of each case u_τ , and the kinematic viscosity ν . Figure 9 shows the mean velocity profile. As often observed, the log-law region is shifted upwards, and it is confirmed that the viscous sublayer is thickened.

Fig. 10 Reynolds stresses

Fig. 11 Vorticity profile

Figures 10 and 11 show the nonzero components of the Reynolds stress and vorticity fluctuation profiles. Contrary to the usual channel flow with undeformed wall, each component of Reynolds stress takes a nonzero value at the wall. The peak of u_{rms} is away from the wall, and v_{rms} and w_{rms} are decreased. At the same time, the streamwise vorticity is suppressed, and its local minimum is away from the wall. Therefore, the mean position of QSV is further from the wall, and the rotation of QSV is suppressed.

The Q2 event (ejection event: $u' < 0, v' > 0$) and the Q4 event (sweep event: $u' > 0, v' < 0$) are extracted depending on the quadrant analysis⁽¹⁶⁾ from the instantaneous flow fields of $t^* = 0 \sim 2000$. The condition is given as

$$|u'v'| > H u_{rms} v_{rms}, \quad (4)$$

where, the detection point is at $y^* = 15$, and the threshold H is set to be unity. It is well known that there is frequently observed the asymmetry of the instantaneous coherent structures in the spanwise direction. Therefore, it is necessary to take the average by conserving the asymmetry of the structure in the spanwise direction, to grasp the coherent structure precisely. In the present study, an ensemble average is taken with the z coordinates of the velocity vector distribution reversed, depending on the sign of w' at the detection point⁽¹⁷⁾.

Fig. 12 Conditional-averaged velocity distribution with the Q2 event, (a) No-Control, (b) Control

Figures 12 and 13 show the velocity vector distributions in the y - z plane, accompanied by the Q2 and Q4 events with and without control. The cross section is observed from the upstream region, and shows about 100 viscous lengths in the spanwise direction with the detection point centered, and 65 viscous lengths from the wall in the wall-normal direction. A large and small vortex pair is clearly observed facing the spanwise direction across the detection point. Generally, the Q2 and Q4 events are brought about by an identical vortex, however, there are qualitative differences between the vortices near the Q2 and Q4 events which are conditionally detected by a fixed threshold. In the present study, we term the strong vortex observed at $z < 0$ near the Q2 event as the “Q2 vortex,” and that at $z > 0$ near the Q4 event as the “Q4 vortex.”

Figure 14 shows the streamwise vorticity ω'_x distribution in y - z plane accompanied by the Q2 event with and without control. The cross section in the figure is the same as that in Fig. 12. Under the present control, the Q2 vortex is lifted away from the wall and its vorticity is suppressed. Although it is not shown here, the vorticity of the Q4 vortex is also suppressed significantly, and the rotating motion is hardly ob-

Fig. 13 Conditional-averaged velocity distribution with the Q4 event, (a) No-Control, (b) Control

Fig. 14 Conditional-averaged streamwise vorticity with the Q2 event, (a) No-Control, (b) Control

(a)

(b)

Fig. 15 Conditional-averaged wall-normal velocity with the Q4 event, (a) No-Control, (b) Control

served.

Figure 15 shows the wall-normal velocity component accompanied by the Q4 vortex with and without the control. Under the present control, a virtual wall⁽¹⁸⁾ is formed by the interaction between the wall-normal velocity component accompanied by QSV and the wall velocity v_w , where the wall-normal velocity component is zero and the momentum transport at the near wall region is prevented. It is suggested that the rotation of the Q4 vortex is attenuated by the virtual wall.

Figure 16 shows the contribution profile of each event to the Reynolds shear stress $\overline{u'v'}$. It is clearly observed that both negative contributions of the Q2 and the Q4 events to Reynolds shear stress decline, which indicates that the production of Reynolds shear stress is suppressed.

Figure 17 shows the streamwise changes of the center positions of the Q2 and Q4 vortices. For simplicity, the center position of the vortex is estimated from the velocity vector distribution of the conditionally averaged flow field. Since all positions of vortices become higher in the streamwise direction, it indicates that QSV is inclined away from the wall in the streamwise direction. The small inclination region ($\Delta x^* < 0$) is termed leg⁽⁴⁾, and plays a dominant role in

Fig. 16 Contribution to Reynolds stress

Fig. 17 Wall distance of the center of the event vortex

Fig. 18 Wall displacement and velocity associated with the Q2 and Q4 events

the wall shear. The Q2 vortex under the present control is lifted away from the wall than without control. Although the center position of the Q4 vortex is difficult to detect since its rotation is suppressed, the center position of the Q4 vortex seems unchanged by the present control.

Figure 18 shows the distributions of the wall displacement y_w and the wall velocity v_w in the y - z cross section with the detection point centered. Although the wall displacement right beneath the center of the Q2 vortex ($\Delta z^* = -20$) is almost zero, the Q2 vortex is lifted away from the wall by the positive wall velocity there. On the other hand, there is a middle between the negative wall-normal velocity in the buffer layer accompanied by the Q4 vortex

Fig. 19 Low-speed streak associated with the Q2 event, (a) No-control, (b) control

and the positive wall velocity at $z^*=0$. However, the wall velocity right beneath the Q4 vortex center is negative. These two conflicting mechanisms are the reason why the position of the Q4 vortex is unchanged.

Figure 19 shows the low-speed region accompanied by the Q2 event ($u'^+ = -2.5$, white contour) and the wall velocity distribution. The figure shows the top view, and shows 325 and 100 viscous lengths in the streamwise and spanwise directions, respectively, with the detection point centered. The low-speed region accompanied by the Q2 event is short in the streamwise direction, and is about 120 viscous lengths. It is well known that the low-speed streak observed in instantaneous flow field, extends more than $1000\nu/u_\tau$ in the streamwise direction^{(19),(20)}, however, an image of the streak conditionally averaged is observed to be much shorter due to the meandering in the spanwise direction⁽¹⁹⁾.

On the other hand, the low-speed region under the present control system detected at the same threshold, is elongated to as much as $240\nu/u_\tau$ in the streamwise direction. This indicates that the meandering of low-speed streak is suppressed by the wall deformation, and the low-speed streaks are stabilized. The shape of wall deformation resembles a shallow trough, which is relatively long in the streamwise direction along the region of $v' > 0$ in the buffer layer accompanied by the Q2 vortex. The trough surrounds the low-speed region, and flows in the streamwise direction as the low-speed streak convects (not shown here).

5. Conclusion

DNS of feedback control of turbulent channel flow with actively deformable walls is performed, and the friction drag is reduced by about 10% on average, and by as much as 30% at the maximum. The gain in pumping work is about 28 times larger than the power input for the wall deformation, and it is shown that turbulence control for drag reduction using the wall deformation as an actuator is quite effective. It is also shown that an efficient control is possible with a deformable actuator, which has the deformation mode of about $300\nu/u_\tau$ and $50\nu/u_\tau$ in the streamwise and spanwise directions, and a period close to the time scale of the turbulent coherent structures near the wall. From the conditional sampling based on the quadrant analysis, the Q2 vortex is lifted away from the wall by the positive wall velocity right beneath the vortex, and its rotation is suppressed by the wall deformation. On the other hand, although the center position of the Q4 vortex appears unchanged, its rotation is significantly attenuated. Therefore, it is suggested that the present control affects the two typical production modes of Reynolds shear stress, with clearly different mechanisms.

It is also shown that the contributions of both the Q2 and the Q4 events to the Reynolds shear stress are suppressed. The wall deforms as a trough downstream of the Q2 event, and the low-speed region convects relatively stably along the trough. The low-speed region under the present control is longer in the streamwise direction than that without control, which indicates that the meandering of the low-speed streak is attenuated.

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