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Skin-friction drag reduction in turbulent channel flow based on streamwise shear control

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ABSTRACT

It is known that stretching and intensification of a hairpin vortex by mean shear play an important role to create a hairpin vortex packet, which generates the large Reynolds shear stress associated with skin-friction drag in wall-bounded turbulent flows. In order to suppress the mean shear at the wall for high efficient drag reduction (DR), in the present study, we explore an active flow control concept using streamwise shear control (SSC) at the wall. The longitudinal control surface is periodically spanwise-arranged with no-control surface while varying the structural spacing, and an amplitude parameter for imposing the strength of the actuating streamwise velocity at the wall is introduced to further enhance the skin-friction DR. Significant DR is observed with an increase in the two parameters with an accompanying reduction of the Reynolds stresses and vorticity fluctuations, although a further increase in the parameters amplifies the turbulence activity in the near-wall region. In order to study the direct relationship between turbulent vortical structures and DR under the SSC, temporal evolution with initial eddies extracted by conditional averages for Reynolds-stress-maximizing Q2 events are examined. It is shown that the generation of new vortices is dramatically inhibited with an increase in the parameters throughout the flow, causing fewer vortices to be generated under the control. However, when the structural spacing is sufficiently large, the generation of new vortex is not suppressed over the no-control surface in the near-wall region, resulting in an increase of the second- and fourth-quadrant Reynolds shear stresses. Although strong actuating velocity intensifies the near-wall turbulence, the increase in the turbulence activity is attributed to the generation of counter-clockwise near-wall vortices by the increased vortex transport.

1. Introduction

Turbulent coherent structures play a crucial role in the momentum transport of wall-bounded turbulent flow and generation of skin-friction drag (Robinson 1991). The low-speed streaks induced by quasi-streamwise vortices are often populated in the buffer layer with a typical spanwise spacing of approximately $100\nu/u_\tau$, and hairpin or horseshoe vortices with a range of scales with a minimum height of $100\nu/u_\tau$ are prevalently observed above the buffer layer (Kline et al., 1967; Adrian et al., 2000). Here, u_τ is the friction velocity, and ν is the fluid kinematic viscosity. The individual hairpin vortex is a simple and common coherent structure that explains second- and fourth-quadrant fluctuations, spanwise vortex core with inclined shear layer and stagnation point in the wall-bounded flows. In addition, the hairpin model provides quite accurate predictions of the velocity statistics in boundary layer (Perry and Marusic 1995). With this simple model, quasi-streamwise vortices in the buffer layer are considered as the legs of the hairpin, and the low-speed streaks in the buffer layer are attributed to low-momentum fluid lifted up by the induction of the hairpin vortices (Adrian et al., 2000). The successive alignment of hairpin vortices in an organized manner in the streamwise direction creates larger-scale hairpin vortex packet (Smith et al., 1991; Adrian et al., 2000), and the hairpin packet contributes to more than 25% of the Reynolds shear stress associated with the skin-friction drag, although occupying less than 4.5% of the total area (Lee and Sung 2011). The large contribution of the packet is due to cooperative transfer of momentum between the hairpins in a packet (Adrian et al., 2000).

Regarding formation of hairpin vortex packet, Smith et al., (1991) argued that hairpins can be formed from an existing vortex under the appropriate conditions based on visualization of H_2 bubble patterns. Furthermore, in a direct numerical simulation (DNS) study of a turbulent channel flow at low Reynolds number, Zhou et al., (1999) found that if an initial vortical structure, that is qualitatively similar to a hairpin vortex in a mean turbulent field, is

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sufficiently strong, the evolution of the initial structure generates multiple hairpins both upstream and downstream of the structure, creating a packet. The primary cause for the auto-generation mechanism is delicate balance between self-induced and mutually induced motions of the quasi-streamwise vortex legs which tend to lift the vortex up and back (Zhou et al., 1999). In addition, more importantly, mean velocity shear plays a significant role to continuously stretch the initial vortex along the streamwise direction during the process, and as a result the vortex strength is intensified sufficiently higher to generate subsequent hairpin vortex. Because the aim of the present study is to achieve a high efficient skin-friction DR by control, one of effective way for DR is to inhibit the formation of hairpin vortex packet by suppressing the velocity shear.

Turbulence control in an attempt to suppress the velocity shear has been recently observed in flows over superhydrophobic surfaces (SHSs). Numerical studies for turbulent flows over SHSs with models of either a shear-free condition or a slip length for idealized air-water interface have consistently shown that turbulent drag is dramatically decreased over SHSs (Min and Kim 2004; Park et al., 2013; Rastegari and Akhavan 2015; Seo et al., 2015). However, because the solid-liquid interface in practice is not self-maintained without extra energy input and characteristics of air pockets are influenced by many factors, such as interface width, impact velocities, vibrations, contamination effects and two-phase thermodynamic interactions (Perkins 2014; Seo et al., 2015), it is nearly impossible to sustain the solid-liquid interface as designed, e.g., no air loss and a flat solid-liquid interface (Park et al., 2014).

In order to overcome the limitations presented in the passive control using SHSs for DR, an active flow control with feedback loop to both sense and manipulate the flow structures can be utilized as a more practical and efficient method to suppress the velocity shear at the wall. Obviously, the great advantage of the active flow control approach compared to the passive approach is that input velocity at the wall for the control is freely provided by actuator to further enhance the DR rate. However, it should be noted that although the actuating velocity at the wall can easily be obtained from shear stress sensors due to significant development of MEMS fabrication technologies (Sun et al., 2015), it is extremely difficult to install many small-scale sensors and actuators over a wide range of wall area in real experiments. Nevertheless, an active flow control concept for DR provides useful information for how wall turbulence responds to the input condition with structural modification to devise an effective active flow control strategy in future. As an active turbulence control of dynamically significant coherent structures for DR, Choi et al., (1994) devised opposition control for wall-normal and spanwise velocity components (v- and w-controls) to suppress the energetic near-wall streamwise vortices, reporting DR up to 20%−25%, whereas in-phase control of the wall-normal and spanwise velocities leads to drag increase. Because the sensors within the flow can disturb the upcoming flow, Lee et al., (1997) conducted out-of-phase v-control based on the wall-shear stress and reported 20% DR, similar to that of Choi et al., (1994). In addition to the flow schemes, a wide variety of different control methods have been developed over the years including temporal or spatial wall oscillations (Skote 2013), streamwise/spanwise travelling waves (Quadrio et al., 2009).

In the present study, we perform DNSs of fully developed turbulent channel flows to explore an active flow control concept using streamwise velocity shear control at the wall. This work is based on the fact that the development of coherent structures, in particular hairpin vortex packet, is largely attributed to the velocity shear in the wall layer. We here assume that the actuators and sensors are arranged in an alternative longitudinal pattern (e.g., no-control and control surfaces) through the wall region while varying structural spacing of the pattern. Furthermore, in order to enhance the DR, we introduce amplitude parameter for imposing the strength of the actuating velocity at the wall. By varying the two parameters, we estimate the DR rate, net power savings rate and associated turbulent statistics. To shed new light on modification of turbulent coherent structures under the SSC, we present results based on quadrant analysis, the instantaneous view of vortical structures, analysis of vortex stretching and transport terms and conditionally averaged flow fields. Furthermore, single-eddy simulations are conducted to provide a clear picture of the mechanism of DR in the presence of the SSC in the near-wall and outer regions.

2. Numerical method

For an incompressible flow, the nondimensional governing equations are

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re_c}\frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

$$\frac{\partial u_i}{\partial x_i} = 0$$

where x_i denotes the Cartesian coordinates and u_i represents the corresponding velocity components. All variables are nondimensionalized by the laminar centerline velocity ($U_{c,o}$) and the channel half height (h). The equations are integrated over time using the fractional step method along with the implicit velocity decoupling procedure (Kim et al., 2002). A Block LU decomposition based on approximate factorization is applied to achieve both velocity-pressure decoupling and the decoupling of the intermediate velocity components. In this approach, the terms are initially discretized in time using the Crank-Nicholson method, and then the coupled velocity components are solved without iteration. All terms are resolved using a second-order central difference scheme in space with a staggered mesh. The mean pressure gradient is dynamically adjusted to maintain a mass flow rate constant.

The notation adopted is that x, y, and z denote the streamwise, wall-normal, and spanwise coordinates, respectively, and that u, v, and w denote the corresponding velocity components. The computational domain in each direction (L_x x L_y x L_z) is 6 h x 2h x 3h, and the corresponding mesh size is 192 × 129 × 128, resulting in grid resolutions of $\Delta x^+ = 5.5$, $\Delta y_{min}{}^+ = 0.29$, and $\Delta z^+ = 4.1$, respectively. Non-uniform grid distributions are employed in the wall-normal direction using the hyperbolic tangent function and a uniform grid distribution in both the streamwise and spanwise directions. Periodic boundary conditions are applied along the streamwise and spanwise directions. On the bottom and top walls, the boundary condition for $u(x,z)$ is prescribed to be $u(x,z)$ at the nearest wall-normal grid point from the wall with $v(x,z)=w(x,z) = 0$ in a control area (i.e., in-phase control), and thus streamwise velocity shear at the wall is almost zero due to continuous feedback control loop. Although not shown here, a grid sensitivity study with higher resolutions in time and space for computational feasibility indicated that the influence of the mesh resolution, including wall-normal grid, is negligible on our results. The boundary condition for the other area (no-control surface) on the bottom and top walls is provided using a no-slip condition. The initial velocity field for the flow control is obtained using DNS data for a fully developed turbulent channel flow with regular wall. The Reynolds number is Re_c $(=U_{c,o}h/\nu) = 4200$, and the corresponding Kármán number is Re_τ $(=u_{\tau,o}h/\nu) = 180$ based on the friction velocity on a regular channel wall ($u_{\tau,o}$). The subscript 'o' indicates the value for a regular channel wall.

In the present study, the flow is assumed to be actively controlled on limited longitudinal surfaces for simplicity (Fig. 1). The control surface of width L-L_w (grey) is repeatedly arranged in the spanwise direction with a no-control surface of width L_w (white),