BRIEF COMMUNICATIONS

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Observed mechanisms for turbulence attenuation and enhancement in opposition-controlled wall-bounded flows

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(Received 2 September 1997; accepted 20 May 1998)

Opposition control is a simple method used to attenuate near-wall turbulence and reduce drag in wall-bounded turbulent flows [H. Choi, P. Moin, and J. Kim, J. Fluid Mech. **262**, 75 (1994)]. This method employs blowing and suction at the wall in opposition to the wall-normal fluid velocity a small distance from the wall. Results from direct numerical simulations of turbulent channel flow indicate that, when the control at the wall is based on detection of the wall-normal velocity in a plane sufficiently close to the wall, the opposition control strategy establishes a ''virtual wall,'' i.e., a plane that has approximately no through flow, halfway between the detection plane and the wall. As a consequence, drag is reduced about 25%. When the detection plane is at a greater distance from the wall, a virtual wall is not established, and the blowing and suction increase the drag significantly.
 [S1070-6631(98)02209-0]

One of the dominant features of the turbulent boundary layer is the presence of streamwise vortices located a small distance above the wall (vortex center at $y^+ \approx 20$ on average).[1–3] These vortical structures enhance momentum transport near the wall by bringing relatively high speed fluid down close to the wall and low speed fluid away from the wall. The presence of streamwise vortices and the associated impingement of high speed fluid on the wall is correlated with an increase in skin friction.[4–6] Turbulent flow control has been attempted by a variety of passive and active techniques; one type of active control makes use of blowing and suction at the wall.[7,8] When Choi *et al.* performed direct numerical simulations of active wall control in turbulent channel flow, they found that a detection plane close to the wall ($y^+ \approx 10$) provided drag reduction ($\approx$25%), while a control plane slightly further from the wall ($y^+ \approx 26$) increased drag.[6] These results motivated the present investigation to determine the reasons for this significant difference in behavior.

In this study, data from a direct numerical simulation of turbulent channel flow at Reynolds number $\mathrm{Re}_c \approx 3240$ based on the centerline velocity, $U_c (\approx 18 u_\tau)$, and the channel half-width, δ, was analyzed. The velocity, distance, and time were nondimensionalized using wall units where the wall shear velocity, $u_\tau = (\tau_w / \rho)^{1/2}$, is determined from the average wall shear stress τ_w for the uncontrolled flow. The computational domain was periodic in the streamwise, x, and spanwise, z, directions, and had dimensions of $4\pi\delta$ and $2\pi\delta$, respectively, with 256 grid points along these axes. Dealised Fourier transforms were used to compute spatial derivatives in x and z. In the wall-normal direction, y, a conservative second-order finite difference scheme with 130 grid points was used. Time advancement was accomplished with a third order Runge Kutta scheme. A constant mass flow rate and identical, fully developed turbulent flow initial conditions were used for all cases studied; the control applied zero net mass flux at all times.

The v velocity at the wall was set to be the opposite of its value in a detection plane located a small distance from the wall. No slip boundary conditions were applied at the wall for the u and w components. When the detection plane was located at $y^+ \approx 15$, drag was reduced by about 25%, but when the detection plane was located at $y^+ \approx 25$, drag was

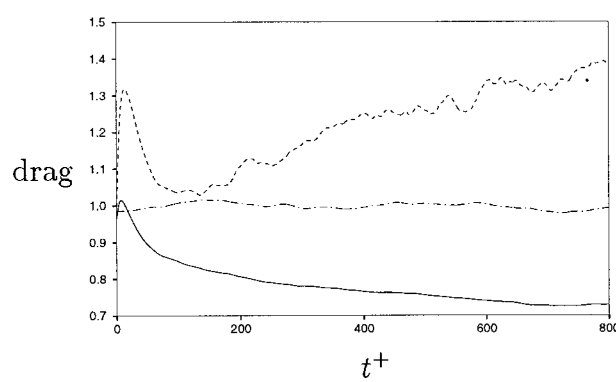

FIG. 1. Drag evolution for the uncontrolled case (dot–dash), detection plane at $y^+ \approx 15$ case (solid), and control detection plane at $y^+ \approx 25$ case (dash).

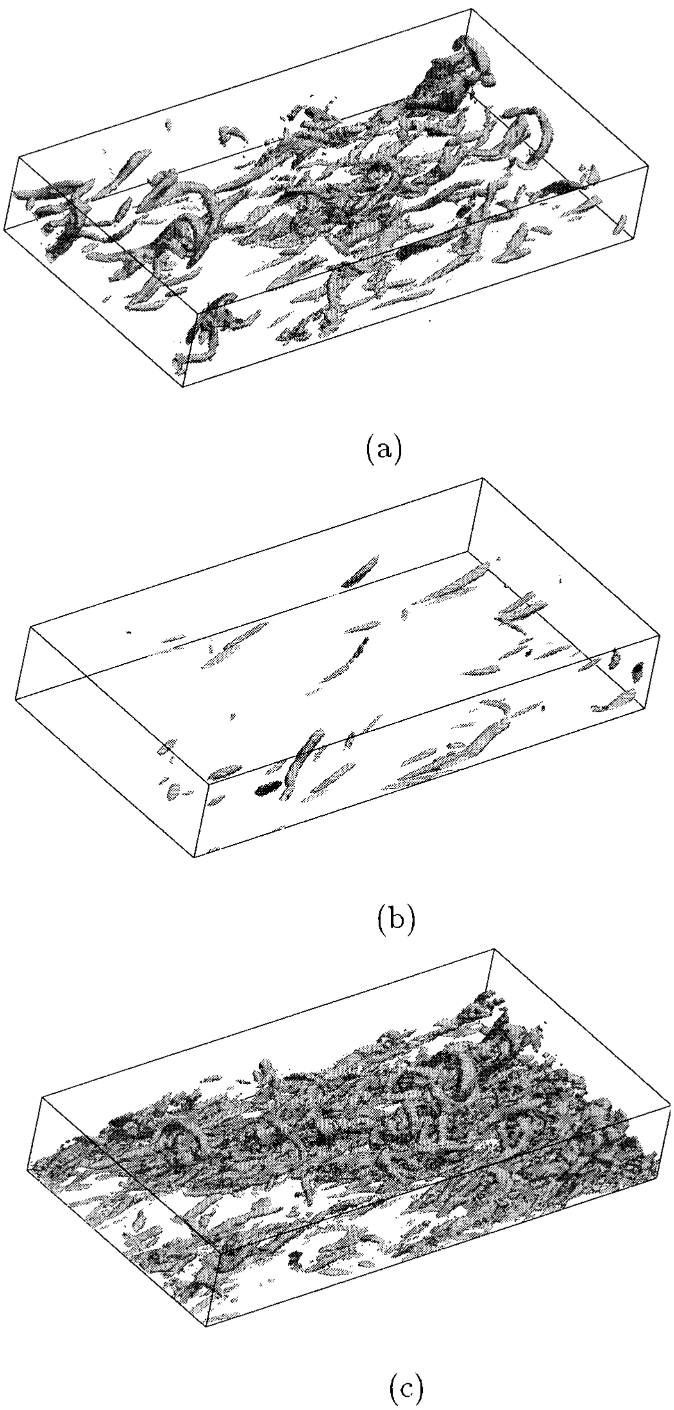

FIG. 2. Isosurfaces of the discriminant of the velocity gradient tensor for (a) uncontrolled baseline case; (b) detection at $y^+ \approx 15$ scheme at $t^+ \approx 280$; (c) detection at $y^+ \approx 25$ scheme, also at $t^+ \approx 280$. For clarity, only one-quarter of the lower half of the computational domain is shown. Flow is from left to right; the same value of the discriminant was used for (a)–(c).

drastically increased (Fig. 1). This is consistent with the results of Choi *et al.* The detection plane at $y^+ \approx 15$ gave better drag reduction than opposition schemes based on detection at $y^+ \approx 10$ and $y^+ \approx 20$, which are not shown here.

Isosurfaces of the discriminant of the velocity gradient tensor were used in the visualizations. A positive value of the discriminant indicates a spinning fluid motion.[9] Isosurfaces of the discriminant clearly show the changes in the structure

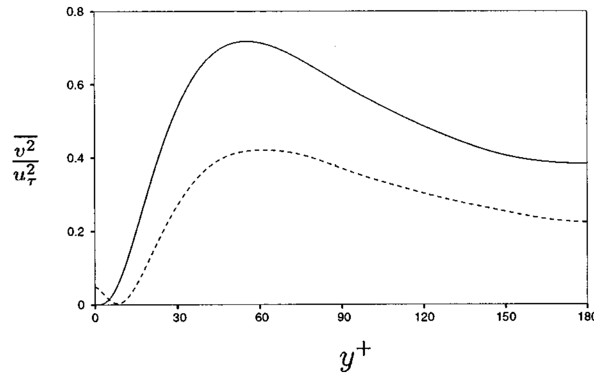

FIG. 3. Turbulent intensities in the wall-normal direction averaged over time and x and z directions. The solid line is for the baseline uncontrolled case, and the dashed line represents the control scheme based on detection at $y^+ \approx 15$. The peak magnitudes of $\overline{u^2}$ and $\overline{w^2}$ are reduced by the control by a similar proportion to the reduction of peak magnitude of $\overline{v^2}$ shown here.

of the channel flow (i.e., vortices) due to application of active control (Fig. 2).

With the control detection plane at $y^+ \approx 15$, the active control effectively counters the sweep and ejection events and establishes a ''virtual wall'' in the fluid halfway between the physical wall and the detection plane. The vertical velocity fluctuations are nearly zero in the plane of the virtual wall, as shown in Fig. 3. The control reduces the interaction between the flow near the wall and at the wall by mitigating the vertical transport of high momentum fluid towards the wall and the low momentum fluid away from the wall. Convective transport of momentum no longer occurs across the plane of the virtual wall, and the only mechanism for transport of momentum in the wall normal direction is diffusion by viscosity.

The reduction in drag by approximately 25% due to the $y^+ \approx 15$ control is consistent with a simple control volume analysis of the time-averaged, uncontrolled flow. A momentum balance in the x direction indicates the drag is balanced by the pressure gradient, the shear in the mean flow, and the Reynolds stress. When these components are evaluated at $y^+ \approx 7.8$, the contributions of these three terms to the wall stress are found to be $\tau_w \approx \rho u_\tau^2 (0.043 + 0.728 + 0.229)$. If the vertical velocity fluctuations v' are nearly eliminated at $y^+ \approx 7.5$, then the Reynolds stress term, $-\rho\overline{u'v'}$, is made approximately zero, and the value of τ_w will be reduced by 22.9%. Therefore, the bulk of the drag reduction may be explained simply by a reduction of vertical transport of streamwise momentum very near the wall.

Flow visualization indicates that, with the control detection plane at $y^+ \approx 25$, the active control scheme does not effectively counter the streamwise vortices seen in Fig. 2(c). The inability to establish a virtual wall may be considered an essential reason for the failure of this control scheme. The detection plane is far enough away from the wall that it allows high momentum fluid to be drawn into the region between the detection plane and the wall. This high momentum fluid can then be drawn towards the wall on a skewed path via suction below a nearby ejection event.

An instantaneous picture of the near-wall flow located at one of the unstable regions is shown in Fig. 4(a), demonstrat-

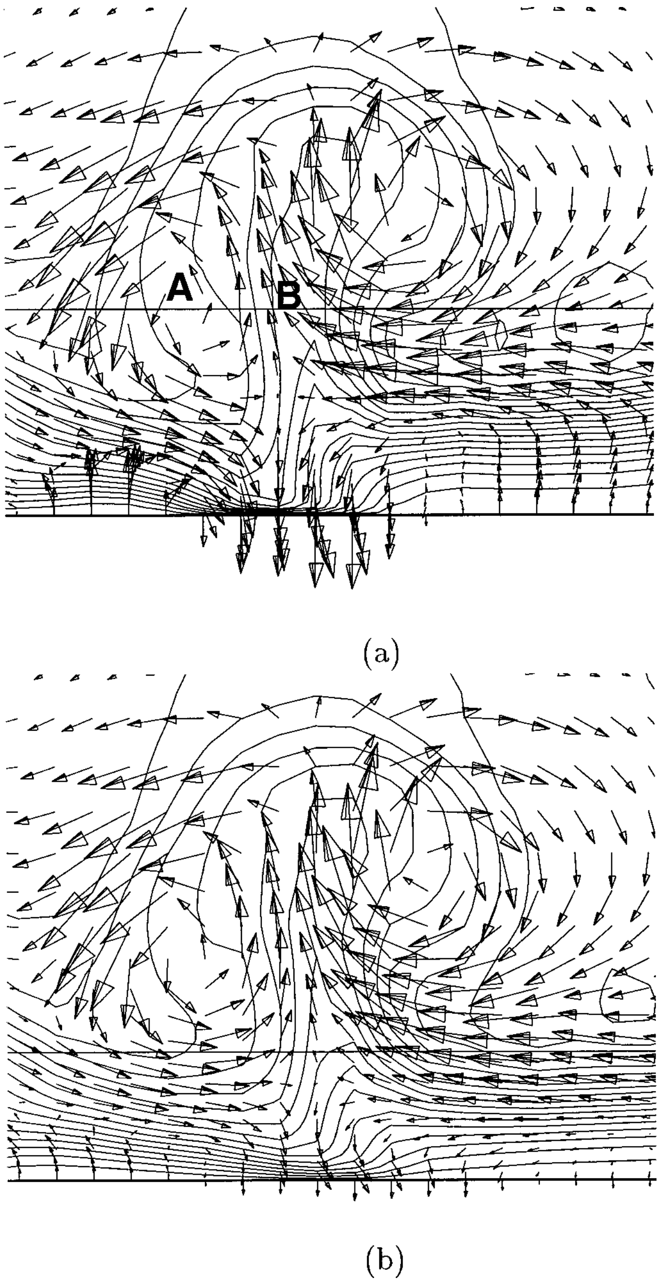

FIG. 4. Instantaneous images of a cross-flow plane near the wall; flow is out of the page. The heavy bottom horizontal line is the wall, and the horizontal line in the midst of the flow is the detection plane for the respective case; (a) detection plane at $y^+ \approx 25$ case at $t^+ \approx 10$; (b) detection plane at $y^+ \approx 15$ case at $t^+ \approx 10$. The contour lines are of streamwise velocity, u; the same contour levels are used in (a) and (b). Similarly, the cross flow vectors for v and w are to the same scale; for clarity, only every other grid point is shown in the wall-normal direction.

ing this mechanism. A streamwise vortex (approximate center at **A**) that is just above the detection plane is bringing high momentum fluid from the bulk flow into the gap on the left-hand side of Fig. 4(a). An adjacent ejection event (approximate location marked by **B**) causes the control at the wall to react with strong suction; the high momentum fluid is drawn close to the wall, which increases the skin friction greatly. Note the concentration of u contour lines at the area of suction; this control scheme fails to keep the high momentum fluid from reaching the wall. In comparison, control with the detection plane at $y^+ \approx 15$ does not react as strongly, and high momentum fluid from the nearby sweep event does not reach the wall, as shown in Fig. 4(b). The mismatch of the blowing and suction with the sweep and ejection events and the suction of high momentum fluid towards the wall cause relatively large $\partial u / \partial y$ gradients. Thus, additional spanwise vorticity is introduced which can then be stretched and tilted into the streamwise direction, increasing the turbulence in the channel.

Active control of turbulent channel flow can significantly decrease drag, up to approximately 25% with a simple opposition scheme. A detection plane that is close enough to the wall allows the formation of a virtual wall halfway between the physical wall and the detection plane. The diminished convective vertical transport of momentum reduces the interaction between the wall and the core region of the channel flow. Control based on a detection plane placed too far from the wall responds too strongly to sweep and ejection events and creates unstable, skewed paths by which the opposition scheme fails to inhibit vertical transport of core fluid and near-wall fluid. The result is churning of the channel flow and an increase in drag. Animations of the different cases are available in the web page of the Center for Turbulence Research (http://www-fpc.stanford.edu/CTR/gallery).

ACKNOWLEDGMENTS

This work was sponsored by the Air Force Office of Scientific Research under Grant No. F49620-93-1-0078. The authors thank the NASA Ames Research Center and the Large-Scale Interactive Visualization Environment for use of their computational resources.

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