Suppression of turbulence in wall-bounded flows by high-frequency spanwise oscillations

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The response of wall-flow turbulence to high-frequency spanwise oscillations was investigated by direct numerical simulations of a planar channel flow subjected either to an oscillatory spanwise cross-flow or to the spanwise oscillatory motion of a channel wall. Periods of oscillation, $T^+_{\text{osc}} = T_{\text{osc}} u_\tau^2/\nu$, ranging from 25 to 500 were studied. For $25 \leqslant T^+_{\text{osc}} \leqslant 200$ the turbulent bursting process was suppressed, leading to sustained reductions of 10% to 40% in the turbulent drag and comparable attenuations in all three components of turbulence intensities as well as the turbulent Reynolds shear stress. Oscillations at $T^+_{\text{osc}} = 100$ produced the most effective suppression of turbulence. The results were independent of whether the oscillations were generated by a cross-flow or by the motion of a channel wall. In the latter case, suppression of turbulence was restricted to the oscillating wall while the flow at the other wall remained fully turbulent. Spanwise oscillations may provide a simple and effective method for control of turbulence in wall-bounded flows.

Several recent experiments and numerical studies[1–3] have shown that when a two-dimensional turbulent boundary layer is suddenly subjected to a spanwise pressure gradient, production of turbulence in the flow is temporarily suppressed, leading to transient reductions in all turbulence quantities including the turbulent Reynolds shear stress and the turbulence kinetic energy. These changes have been attributed to fundamental modifications in the flow structures responsible for the bursting process as a result of the sudden transverse strain.[1,3] For a constant imposed spanwise pressure gradient, the reduction in turbulence activity is only temporary, since the flow must eventually return to a new two-dimensional state with a new orientation and a higher Reynolds number.

In this study, we explore the possibility of sustained control of turbulence in wall-bounded flows by spanwise oscillations. The studies are based on direct numerical simulations of a planar turbulent channel flow which has been subjected either to an oscillatory spanwise cross-flow (equivalently, a spanwise pressure gradient), or to the spanwise oscillatory motion of one of the channel walls.

Simulations were done with standard Fourier/Chebyshev pseudospectral methods,[4] implemented in parallel on a 32-node iPSC/860 Intel hypercube.[5] The computational domain was a doubly periodic channel, $1.6\pi h$ (1010 wall units) long in each of the streamwise (x) and spanwise (z) directions and $2h$ wide in the normal (y) direction. Calculations were done with $64 \times 129 \times 128$ dealiased modes in the x, y, and z directions, respectively, to resolve all the essential scales of the turbulent motion. A fully developed turbulent flow at a mean Reynolds number, based on half-channel width and bulk velocity, of 3000 ($\text{Re}_\tau = 200$) was established in the channel by perturbing an initially laminar state with a combination of two- and three-dimensional least stable eigenmodes of the Orr–Sommerfeld equation, and carrying out the simulations until the flow had reached a stationary turbulent state with one- and two-point statistics in good agreement with known results. The influence of an oscillatory spanwise strain on the dynamics of the turbulent state described above was then studied. The primary interest lies in determining whether spanwise oscillations can lead to a substantial reduction in turbulence production and the turbulent drag.

The time evolution of the streamwise component of the wall shear stress subsequent to the start of oscillations is shown in Fig. 1 for a variety of oscillation periods ranging from $T_{\text{osc}} = 25\nu/u_\tau^2$ to $T_{\text{osc}} = 500\nu/u_\tau^2$, where u_τ is the wall friction velocity in the unperturbed turbulent channel. In each case the oscillations were turned on at $t=0$ in a flow that was fully developed and turbulent with statistics in good agreement with experimental results. With the exception of the case $(100, W)$, in all the runs shown in Fig. 1, the oscillations were produced by superimposing a spanwise cross-flow with specified flow rate (per unit width) equal to $0.8Q_x \sin \omega t$ on the base turbulent flow. Here Q_x is the flow rate (per unit width) in the streamwise direction, which was kept fixed at its unperturbed value in all the simulations. In the last case (curve $100, W$), the oscillations were produced by moving one of the channel walls in the spanwise direction with prescribed velocity $W_{\text{wall}} = 0.8(Q_x/2h)\sin \omega t$ and period $T^+_{\text{osc}} = 100$. As seen in Fig. 1, a net reduction in the streamwise wall shear stress is obtained for $25 \leqslant T^+_{\text{osc}} \leqslant 200$. The size of the reduction is strongly dependent upon the oscillation frequency. The largest drop is obtained at $T^+_{\text{osc}} = 100$, for which the streamwise wall shear stress is reduced by 40% compared to the unperturbed turbulent channel. These reductions are not transient phenomena, but are sustained in the long term after the flow has reached a statistically periodic steady state. Similar reductions were obtained for the case $T^+_{\text{osc}} = 100$ when the oscillating cross-flow was replaced by oscillations of one of the channel walls. In the latter case, however, the reduction in turbulence activity was observed only near the oscillating wall, while the flow at the other wall remained fully turbulent.

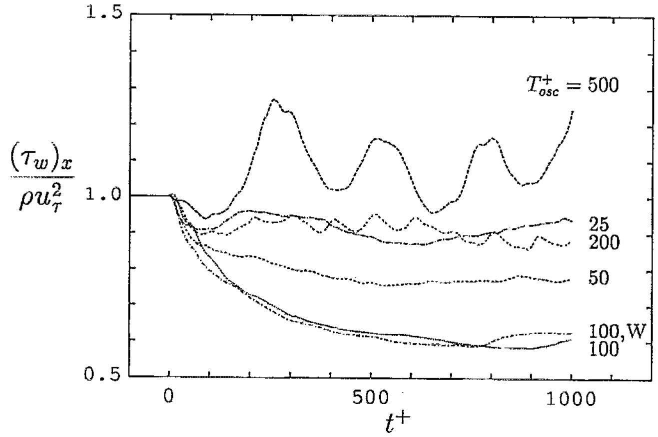

FIG. 1. Time evolution of the streamwise wall shear stress subsequent to the start of oscillations at various frequencies.

The spanwise component of the flow remained in agreement with laminar theory throughout the course of the simulations. Both the spanwise velocity profiles and the spanwise component of the wall shear stress were in close agreement with laminar predictions, while the spanwise component of the Reynolds shear stress remained small [see Fig. 2(b)]. As a consequence, no significant contribution to turbulence production was made by the spanwise flow. The reduction in the streamwise wall shear stress described above, therefore, represents the overall reduction in the turbulence activity.

Similar trends were observed when the spanwise cross-flow was replaced by one at a lower amplitude of $Q_z=0.4Q_x \sin \omega t$. The major difference from the results shown in Fig. 1 was that the magnitude of the drop in streamwise wall shear stress was at all frequencies significantly lower; on the order of 10% for $T^+_{\rm osc}=50$ and 100, and close to zero for $T^+_{\rm osc}$ of 25. The two cases $T^+_{\rm osc}=500$ and $T^+_{\rm osc}=200$ produced net increases in the streamwise component of the wall shear stress at this lower amplitude of oscillation.

A summary of the one-point statistics of the flow with cross-flow oscillations at $T^+_{\rm osc}=100$ and $Q_z=0.8Q_x \sin \omega t$ is shown in Fig. 2. The statistics for $t^+=0$, corresponding to the unperturbed channel, and the experimental data of Wei and Willmarth[6] for turbulent flow in a two-dimensional channel are also shown for reference. All the statistics are based on spatial averaging from a single realization of the flow at the indicated instant in time. In addition, the averaged quantities were reflected about the channel centerline and the data from the two halves of the channel were averaged together. The wall friction velocity u_τ in the unperturbed channel has been used as the velocity scale for nondimensionalizing all quantities in Fig. 2. The statistics shown are from the ninth period of oscillations, when the flow has reached a statistically periodic steady state. Profiles of mean velocity, Reynolds shear stresses, and turbulence intensities are shown in intervals of $T_{\rm osc}/4$, representing the extremes of the spanwise motion during a period of oscillation. None of the statistics show a significant varia-

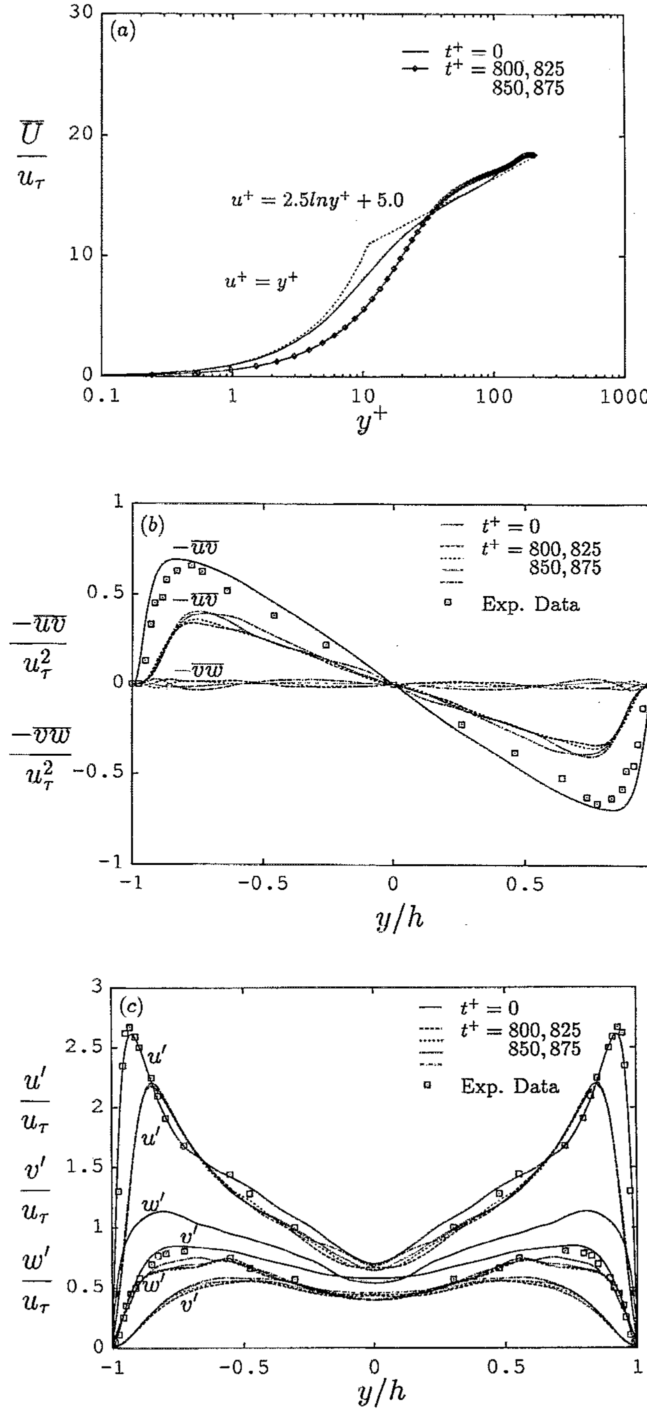

FIG. 2. Profiles of (a) mean streamwise velocity, (b) the Reynolds shear stress, and (c) turbulence intensities in a channel with cross-flow oscillations at $T^+_{\rm osc}=100$ compared to the unperturbed channel (solid lines) and to the experimental data of Wei and Willmarth[6] for flow in a two-dimensional channel (symbols).

tion as a function of the phase in the cycle. The profiles of mean streamwise velocity for the oscillated channel show a significant deviation from the regular law of the wall [see Fig. 2(a)]. This remains the case even if the wall friction velocities in the oscillated channel are used for nondimensionalizing the velocities. The oscillations give rise to a 40% reduction in the streamwise component of the Rey-

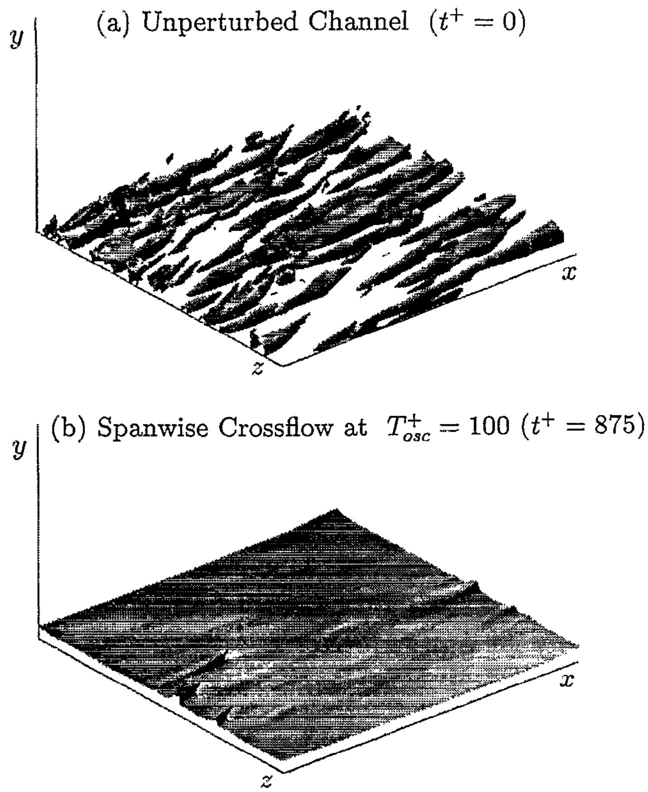

FIG. 3. Turbulence structures in the unperturbed channel compared to the structures in a channel with cross-flow oscillations at $T^+_{osc} = 100$. The turbulence structures are represented by contour surfaces of constant vorticity magnitude; $|\omega| = 1.1 u_\tau^2/\nu$.

nolds shear stress, $-\overline{uv}$, with no significant increases in the spanwise component of the Reynolds shear stress, $-\overline{vw}$ [see Fig. 2(b)]. The three components of turbulence intensities also experience significant reductions [see Fig. 2(c)]. Quite unexpectedly, however, the percentage drops in w'(35%) and v'(30%) are significantly larger than the drop in u'(14%). In addition to the drop in the magnitudes of turbulence intensities, the peaks of these quantities have also moved closer to the center of the channel.

These reductions in various turbulence quantities occur because of a decrease in the number and intensity of turbulent bursts in the oscillated channel compared to the unperturbed flow. Figure 3 shows the near-wall turbulence structures in the two flows. The vorticity isosurface plots shown in each case have a magnitude 10% higher than the average wall vorticity in the unperturbed channel. Both the number and intensity of the turbulent events have been dramatically reduced in the oscillated channel. Note that the bursts in the oscillated flow continue to be in the streamwise direction, even though the structures shown in Fig. 3(b) are from the time $t^+ = 875$ for which the spanwise cross-flow takes on a peak amplitude. The detailed mechanism of how this reduction in turbulence production is brought about is currently under study. An understanding of these mechanisms may pave the way for effective control of turbulence in wall-bounded flows.

ACKNOWLEDGMENTS

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