



**AIAA 93-3282**

**Control of Wall Turbulence by High  
Frequency Spanwise Oscillations**

R. Akhavan, W. Jung, N. Mangiavacchi  
The University of Michigan  
Ann Arbor, MI

**AIAA**  
**Shear Flow Conference**  
July 6-9, 1993 / Orlando, FL

# CONTROL OF WALL TURBULENCE BY HIGH FREQUENCY SPANWISE OSCILLATIONS

R. Akhavan\*, W. Jung† & N. Mangiavacchi‡  
*The University of Michigan*  
*Ann Arbor, MI 48109-2125*

A new technique for the control of turbulence in wall-bounded flows is discussed. Turbulence control is achieved by disrupting the spatial coherence of turbulence structures in the near-wall region using spanwise forcing. The feasibility of the control scheme has been demonstrated by direct numerical simulations of a turbulent channel flow which is subjected either to an oscillatory spanwise crossflow or to the spanwise oscillatory motion of one of the channel walls. In either case, oscillations at  $T_{osc}^+ = T_{osc} u_\tau^2 / \nu = 100$  are seen to result in a 60% reduction in overall turbulence production and a 40% reduction in the turbulent drag. Alternative methods for the implementation of these concepts in practical applications are discussed.

## 1. Introduction

Control of wall turbulence is of great interest in a wide variety of technological applications. Over the years a number of passive and active techniques for the control of wall turbulence have been proposed<sup>1</sup>. Nevertheless, a generally accepted practical and effective control scheme for wall-bounded flows does not yet exist.

Research on wall flow turbulence over the past twenty years has revealed that the production of turbulence in wall-bounded flows is accomplished by organized structures in the near wall region in a repeatable and regenerative cycle of quasi-periodic events. The emergence of such a structural picture has opened up new possibilities for the control of turbulence. If one could disrupt the internal organization of the flow such that the inherent feedback mechanism in the regenerative cycle of turbulence production is interrupted, significant reductions in turbulence production and turbulent skin friction drag may be within reach.

In this study we explore the possibility of control of wall turbulence by an imposed spanwise strain which is optimized to disrupt the spatial coherence of the turbulence structures in the near wall region. The studies were motivated by results from a number of recent experimental and numerical investigations<sup>2,3,4</sup>, which have shown that when a two-dimensional turbulent boundary layer is suddenly subjected to a spanwise strain it experiences temporary but significant reductions in its turbulence level. The objective of the present study is

\* Assistant Professor, Department of Mechanical Engineering, Member AIAA

† Graduate Student Research Assistant, Department of Mechanical Engineering

‡ Copyright © American Institute of Aeronautics and Astronautics, Inc., 1993. All rights reserved.

to determine whether it is possible to achieve a sustained suppression of turbulence by preventing the turbulence from ever reaching an equilibrium state using an imposed external spanwise strain. In the present study, this strain is imposed using either an oscillatory spanwise crossflow or by the oscillatory spanwise motion of the wall. The conclusions, however, are general and should not be dependent on the particular manner in which the strain is introduced. A number of alternative schemes for imposing the spanwise strain in practical applications is discussed in §4. A brief account of some of the results reported here has been previously given in [5].

## 2. Numerical Simulations

Direct numerical simulations were performed of a fully developed planar turbulent channel which was subjected either to an oscillatory spanwise crossflow (equivalently a spanwise pressure gradient) or to the spanwise oscillatory motion of one of the channel walls. Computations were done using standard Fourier/Chebyshev pseudospectral methods, implemented in parallel on a 32-node iPSC/860 Intel hypercube<sup>6</sup>. A fully-developed turbulent flow at a mean Reynolds number of 3000 based on half channel width and bulk velocity ( $Re_\tau = 200$ ) 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 computational domain (Figure 1) was  $1.6\pi h$  (1010 wall units) long in each of the streamwise (x) and spanwise (z) directions and  $2h$  wide in the normal (y) direction, and the calculations were done with  $64 \times 129 \times 128$  de-aliased modes in the x, y

and  $z$  directions, respectively, to resolve all the essential scales of the turbulent motion.

The influence of an additional spanwise strain on the dynamics of the turbulent state described above was then studied. The oscillations were generated either by a spanwise crossflow with specified flow rate per unit width equal to  $Q_z = (0.4 \text{ or } 0.8 \text{ or } 1.2) Q_x \sin \omega t$ , or by the motion of one of the channel walls according to  $V_{wall} = 0.8(Q_x/2h) \sin \omega t$ . The flow rate per unit width in the streamwise direction  $Q_x$  was kept fixed at the unperturbed turbulent channel value in all the runs. Calculations were made for non-dimensional periods of oscillation  $T_{osc}^+ = T_{osc} u_\tau^2 / \nu$  ranging from 25 to 500, where  $u_\tau$  is the wall friction velocity in the unperturbed channel.

### 3. Results

The time evolution of the streamwise component of the wall shear stress subsequent to the start of oscillations is shown in Figure 2. With the exception of the case 100W, in all the runs shown in Figure 2 the oscillations were generated by a crossflow with flow rate per unit width equal to  $0.8Q_x \sin \omega t$ . The case 100W demonstrates the effect of oscillation of one of the channel walls with velocity  $V_{wall} = 0.8(Q_x/2h) \sin \omega t$  and period  $T_{osc}^+ = 100$ . As seen in Figure 2, oscillations with  $25 \leq T_{osc}^+ \leq 200$  result in reductions of 10 to 40% in the streamwise wall shear stress. The size of the reduction is strongly dependent upon the oscillation frequency. The largest drop is obtained at  $T_{osc}^+ = 100$ , 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. The reductions are independent of whether the oscillations are produced by a crossflow or by the motion of one of the channel walls, as can be seen from a comparison of the two curves 100 and 100W in Figure 2. For oscillations produced by the motion of a channel wall, however, the reduction in turbulence activity is restricted only to the channel half which is adjacent to the oscillating wall. The flow in the other channel half remains fully turbulent.

A summary of the one-point statistics of the flow in the presence of crossflow oscillations at  $T_{osc}^+ = 100$  and  $Q_z = 0.8Q_x \sin \omega t$  is shown in Figure 3. The shown statistics are from the 9th period of oscillations, when the flow has reached a statistically periodic steady state. The statistics for  $t^+ = 0$ , corresponding to the unperturbed channel, and the experimental data of Wei and Willmarth<sup>7</sup> for turbulent flow in a two-dimensional channel are also shown for reference. The oscillations re-

sult in a 65% reduction in the overall turbulence production and comparable reductions in the Reynolds shear stress and the turbulence intensities. The oscillations give rise to a 40% reduction in the streamwise component of the Reynolds shear stress,  $-\overline{u'w'}$ , with no significant increases in the spanwise component of the Reynolds shear stress,  $-\overline{v'w'}$ . The three components of turbulence intensities  $\sqrt{\overline{u'^2}}$ ,  $\sqrt{\overline{v'^2}}$ ,  $\sqrt{\overline{w'^2}}$  experience reductions of 14%, 35% and 30% in their peak magnitudes, respectively. 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.

Analysis of the dynamics of the turbulence structures in the presence of the oscillations (Figure 4) reveals that the suppression of turbulence observed in these studies is due to a continuous shift of the near wall streamwise vortices relative to their associated wall layer streaks as a result of the imposed oscillations. This shift significantly reduces the efficiency of the turbulence production cycle and results in the all the observed reductions in turbulence quantities. Note in Figure 4 that the turbulence structures are extremely robust in responding to the imposed spanwise strain, and in re-aligning themselves to resume production of turbulence. Eventually (Figure 5) the flow reaches a periodic steady state, in which the turbulence structures are much wider and weaker. The success of  $T_{osc}^+ = 100$  in suppressing the production of turbulence lies in its ability to continuously displace the near-wall streamwise vortices (located at  $z^+ \sim 15$ ) relative to the wall layer streaks (located at  $0 < z^+ < 15$ ) in the spanwise direction. This relative displacement of the two structures is brought about by the gradients of the spanwise velocity in the oscillatory boundary layers near the wall. At  $T_{osc}^+ = 100$  these oscillatory boundary layers are located at  $0 < z^+ < 15$ , thus maximizing their influence on the near wall structures. If the oscillation frequency is too high ( $T_{osc}^+ < 50$ ), the sharp gradients associated with the spanwise flow remain embedded within the viscous sublayer ( $z^+ < 5$ ), while in the remainder of the channel ( $z^+ > 5$ ) a nearly uniform flow is established. In the presence of such a flow, both the wall layer streaks and the buffer layer streamwise vortices move back and forth in the spanwise direction. However, both structures experience identical spanwise displacements. Hence their spatial coherence is not affected, and the production of turbulence remains unchanged. On the other hand, when the oscillation frequency is too low ( $T_{osc}^+ > 200$ ), the oscillatory boundary layers extend to the buffer layer and beyond. Both the wall-layer streaks and the streamwise vortices experience a re-orientation under the influence of the imposed oscillations. However, the oscillations are slow enough to allow the turbulence structures to get re-aligned and

resume effective production.

#### 4. Discussion

The results presented in this paper demonstrate that the spanwise forcing of the turbulence structures in the near wall region is a very effective means of control of turbulence in wall-bounded flows. In the present study, this spanwise strain was maintained by temporal spanwise oscillations. This is not the most economical way of suppressing the turbulence if one is concerned about the overall energy savings, since the power savings obtained as a result of the suppression of turbulence is offset by the power required to oscillate the flow (or the wall). However, the concepts underlying the suppression mechanism discussed in this paper can be implemented in a number of other passive and active techniques, in which little or no penalty is paid in way of the power requirements of the control scheme. In way of passive techniques, one can envision guiding vanes or surface grooves which force the flow to be turned in alternating spanwise directions during the course of its downstream path along a wall. Since the optimal geometry of such vanes would depend on the free stream flow speed, it may be more efficient to use actuators which push the flow in alternating spanwise directions to achieve control. A similar effect may be achieved using wall jets that are issued in the spanwise direction. The common thread in all of these schemes, is the concept of turning of the near wall fluid in the spanwise direction relative to the rest of the flow to achieve turbulence suppression. Efforts to implement these more practical schemes are currently under way in our laboratory.

#### Acknowledgments

This work was supported by a grant from the University of Michigan Rackham School of Graduate Studies and in part by AFOSR grant #91-0402. The computations were performed on the San Diego Supercomputer Center Intel iPSC/860 hypercube.

#### References

- 1 Bushnell, D. M., "Turbulent drag reduction for external flows," AIAA Paper 83-0227, 1983.
- 2 Bradshaw, P. and Pontikos, N., "Measurements in a turbulent boundary layer on an infinite swept wing," *J. Fluid Mech.*, vol. 159, pp. 105-130, 1985.
- 3 Anderson, S. D. and Eaton, J. K., "Reynolds stress development in pressure-driven three-dimensional turbulent boundary layers," *J. Fluid Mech.*, vol. 202, pp. 263-294, 1989.
- 4 Moin, P., Shih, T., Driver, D., Mansour, N., "Direct numerical simulation of a three-dimensional turbulent boundary layer," *Phys. Fluids A*, vol. 2 (10), pp. 1846-1853, 1990.
- 5 Jung, W. J., Mangiavacchi, N. and Akhavan, R., "Suppression of turbulence in wall-bounded flows by high-frequency spanwise oscillations," *Phys. Fluids A*, vol. 4(8), pp. 1605-1607, 1992.
- 6 Mangiavacchi, N. and Akhavan, R., "Direct Numerical Simulations of Turbulent Shear Flows on Distributed Memory Architectures", *Proc. Sixth SIAM Conf. Parallel Proc. Sci. Comp.*, vol. 1, pp. 61-64, 1993
- 7 Wei, T. and Willmarth, W. W., "Reynolds number effects on the structure of a turbulent channel flow," *J. Fluid Mech.*, vol. 204, pp. 57, 1991.

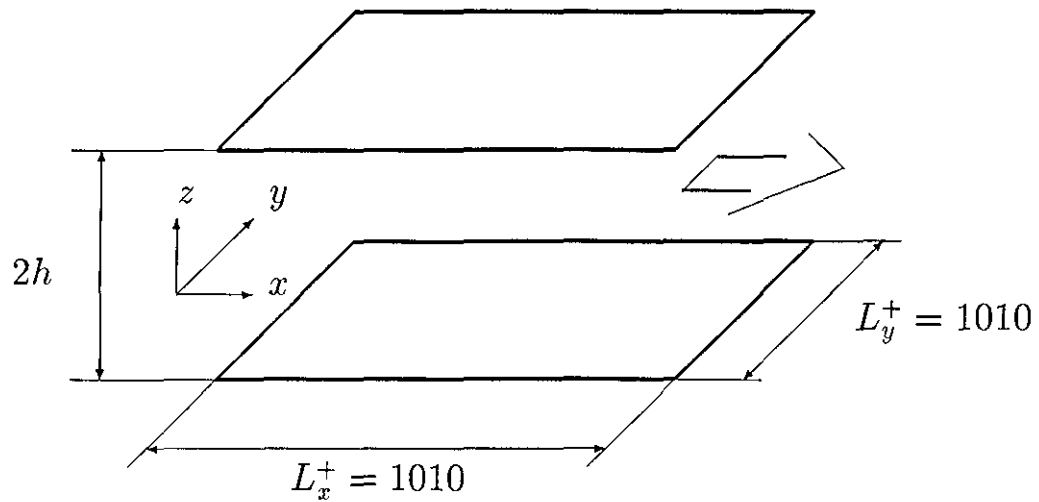


Figure 1. Schematic of the channel and the coordinate system.

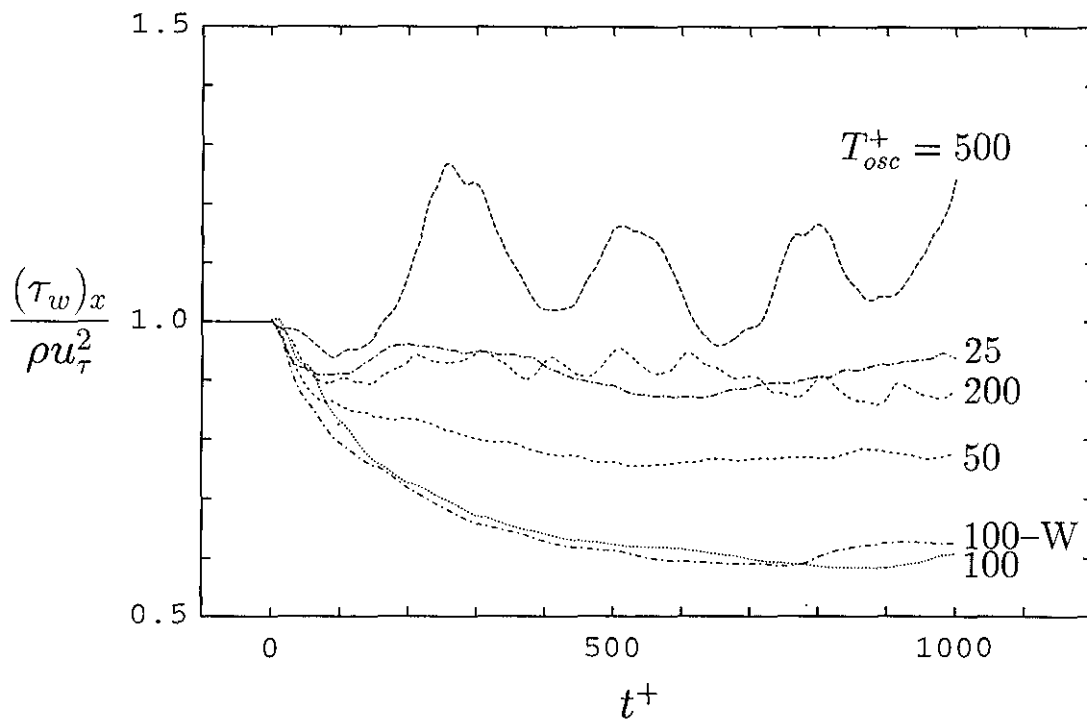
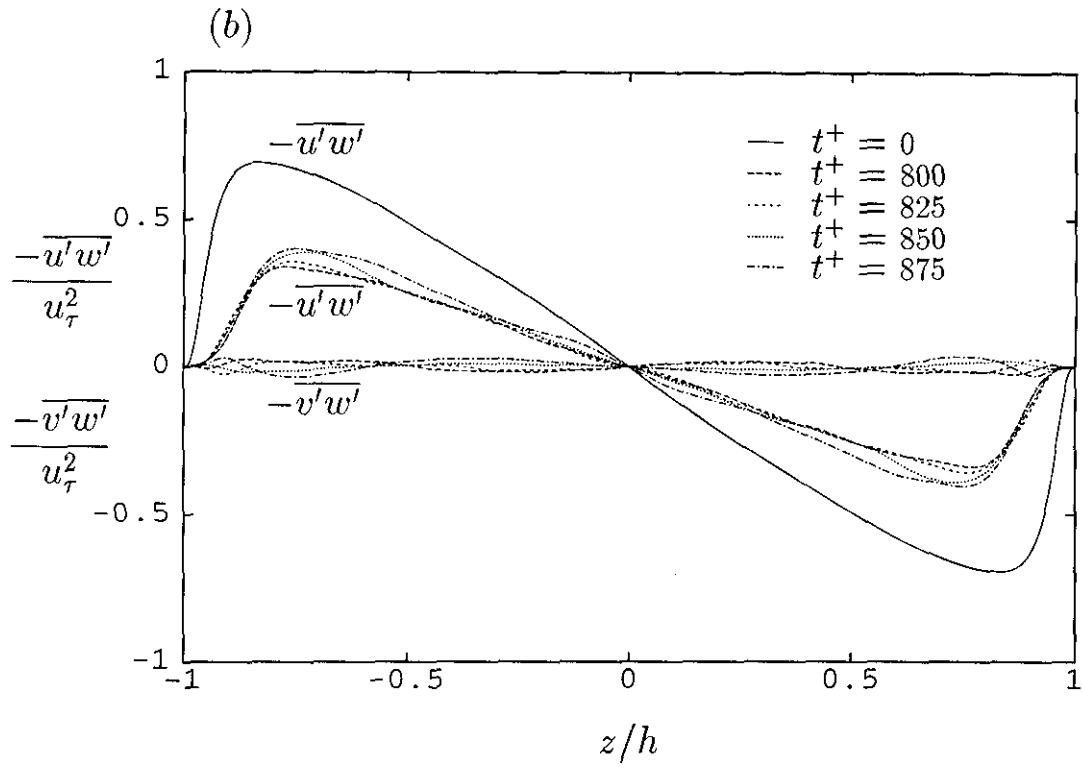
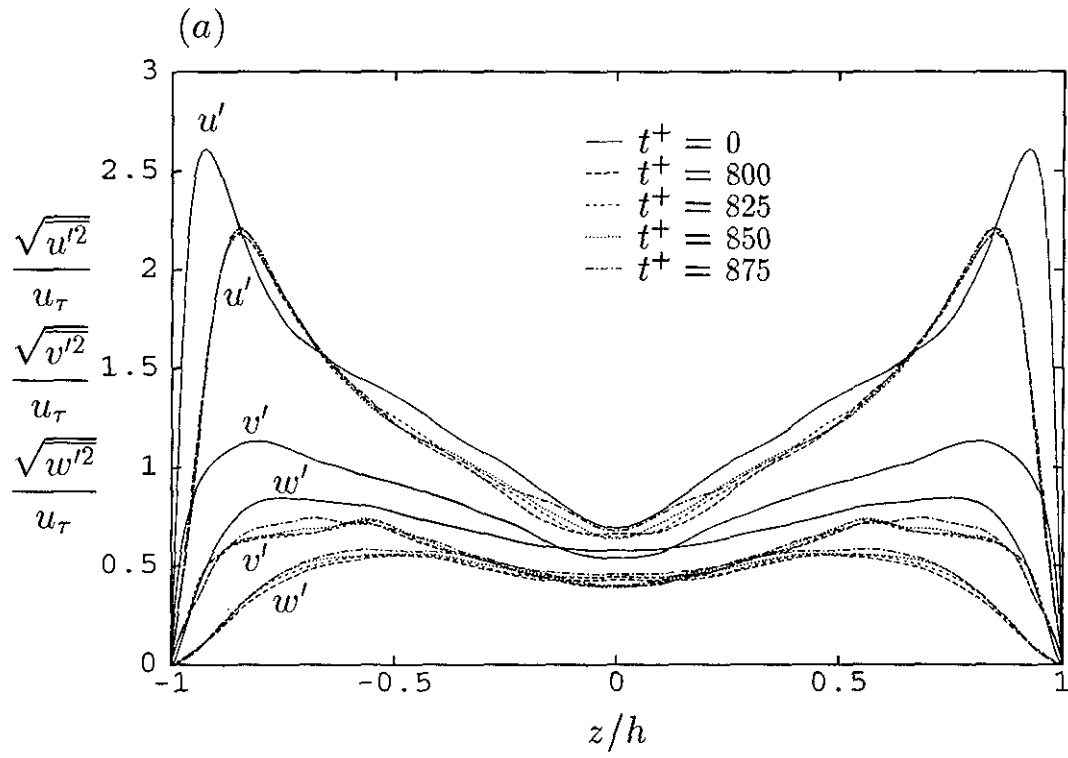
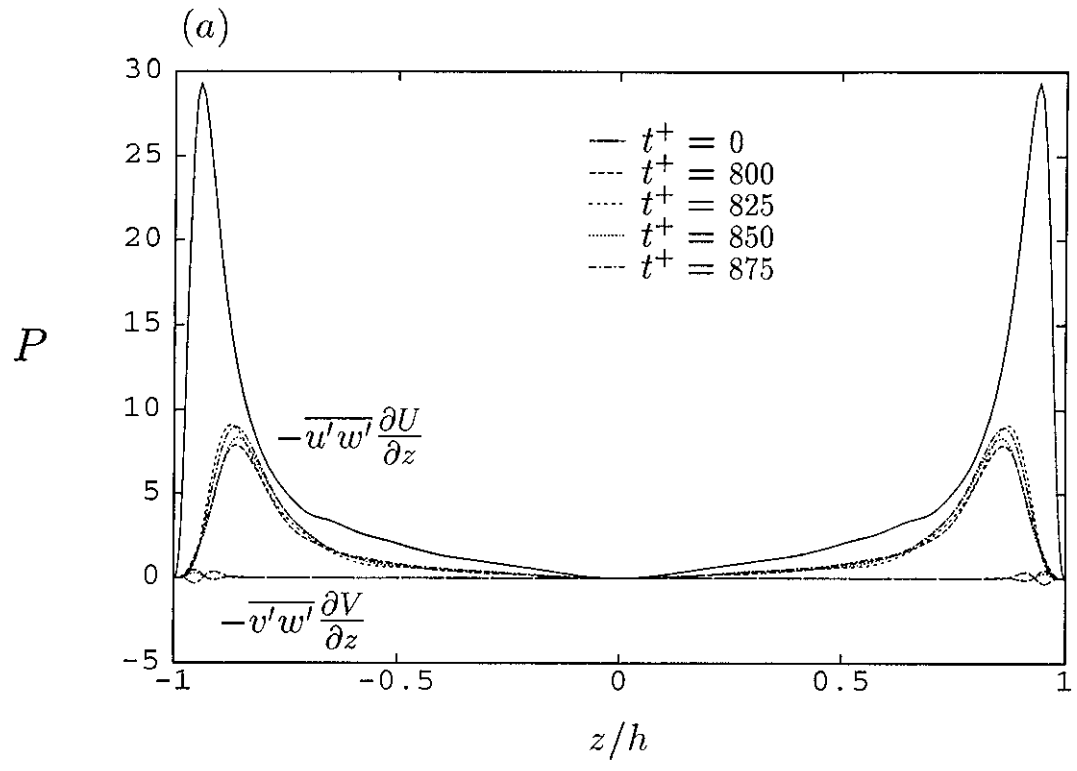
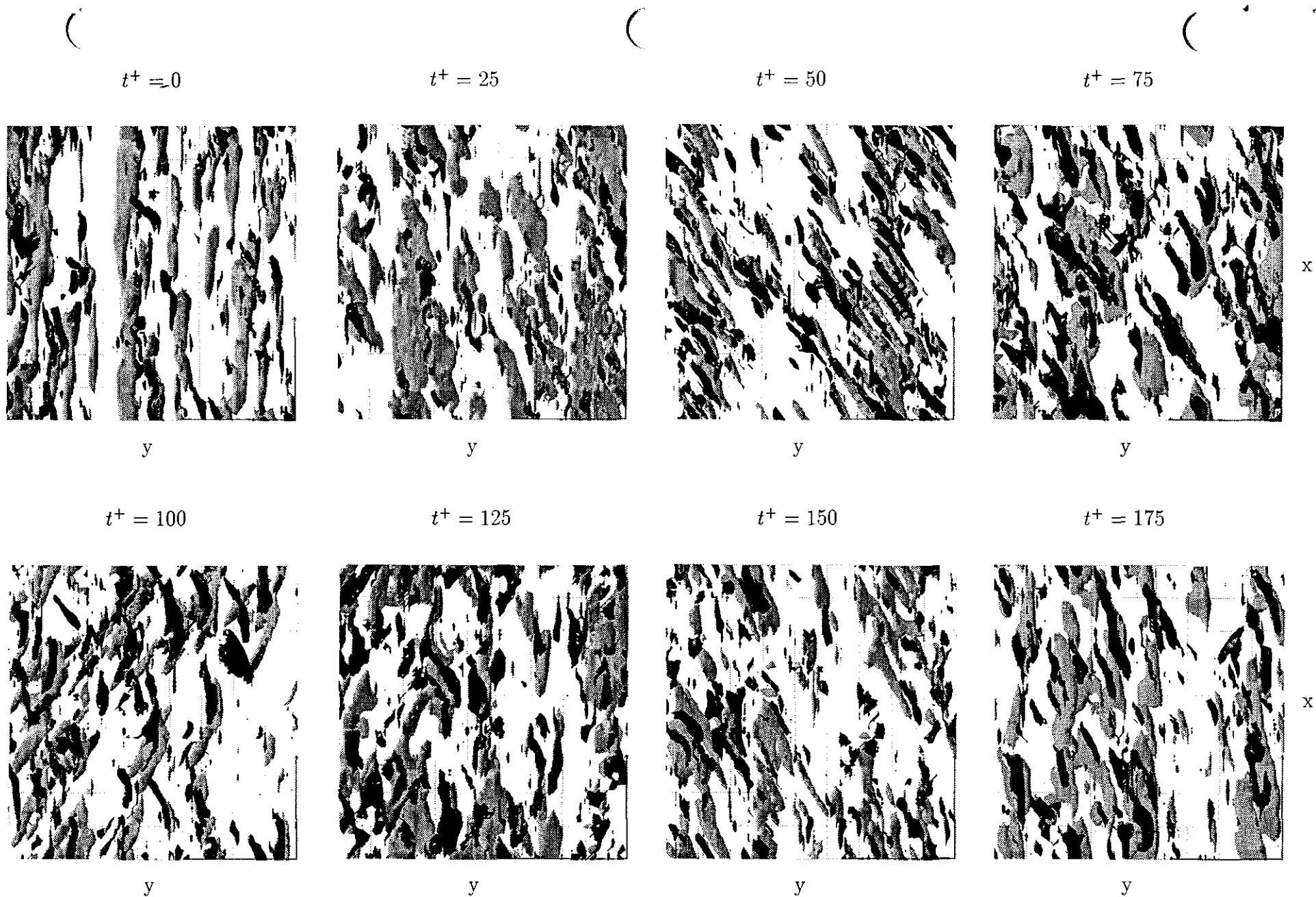


Figure 2. Time evolution of the streamwise component of the wall shear stress subsequent to the start of crossflow oscillations with  $Q_y = 0.8Q_x \sin \omega t$  and  $25 \leq T_{osc}^+ \leq 500$  or wall oscillations with  $V_{wall} = 0.8(Q_x/2h) \sin \omega t$  and  $T_{osc}^+ = 100$ .



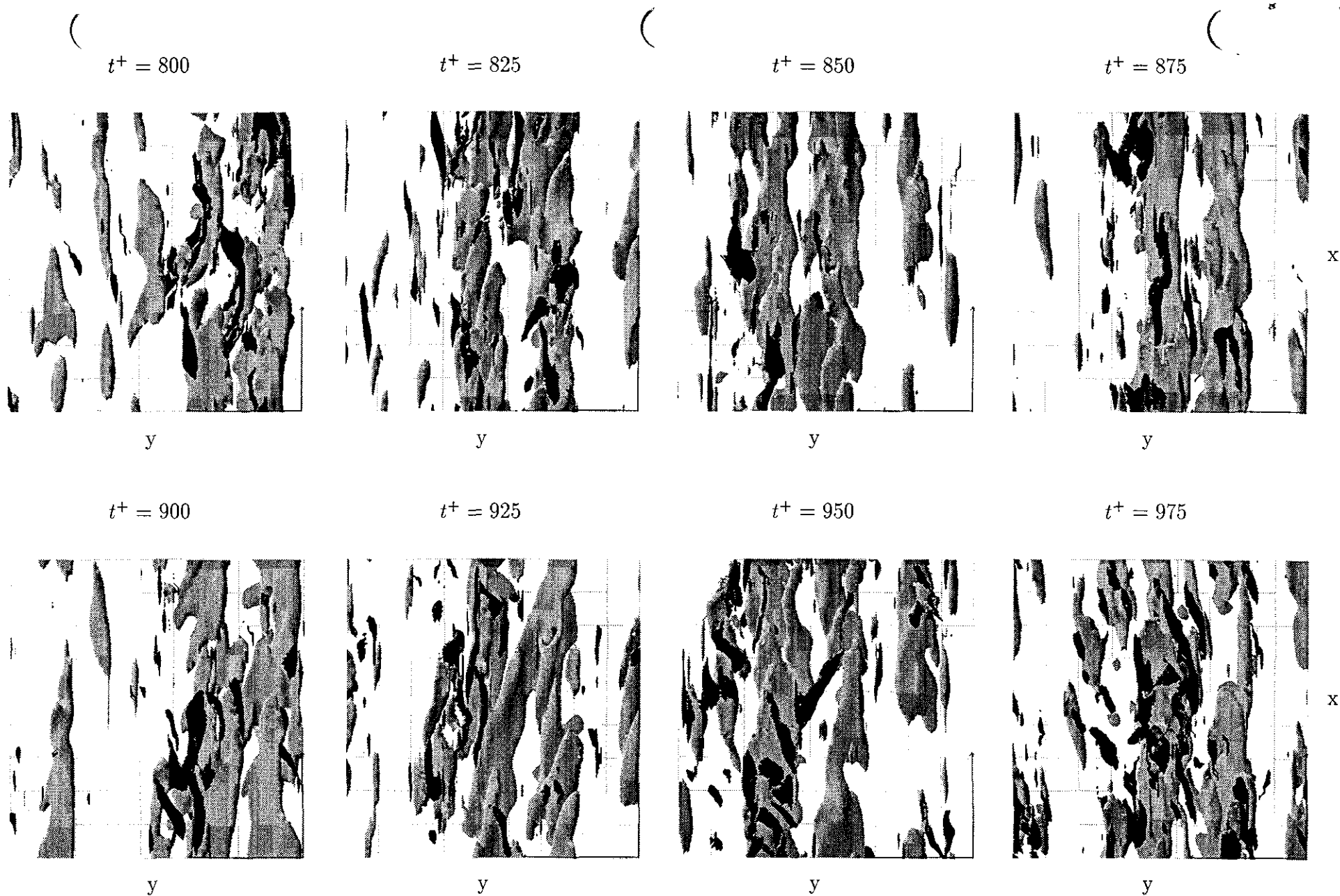


**Figure 3.** Profiles of (a) Reynolds shear stress, (b) turbulence intensities and (c) turbulence production in the presence of crossflow oscillations at  $T_{osc}^+ = 100$  compared to the unperturbed channel (solid lines).



**Figure 4.** Plan view of the channel showing the evolution of turbulence structures during the first two periods immediately following the start of crossflow oscillations at  $T_{osc}^+ = 100$ . The structures are represented by isosurfaces of  $\omega_y = 1.15(\tau_w)_x/\mu$  (high speed streaks, gray) and  $\omega'_x = 0.275(\tau_w)_x/\mu$  (streamwise vortices, black). Note that since  $(\tau_w)_x$  decays as a function of time, these isosurfaces represent progressively weaker structures as  $t^+$  increases.





**Figure 5.** Plan view of the turbulence structures in the oscillated channel after the flow has reached a periodic steady state, for crossflow oscillations at  $T_{osc}^+ = 100$  (iso-surfaces as in figure 4).