A NEW STRATEGY OF TURBULENCE CONTROL: PLANE COUETTE FLOW

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Abstract A new strategy of shear flow turbulence control is proposed. It can be realised by the following steps: (i) a specially designed, non-symmetric in spanwise direction seed perturbations are imposed at the walls of the flow; (ii) the configuration of these ensures a gain of shear flow energy and the breaking of turbulence reflection symmetry – generates spanwise mean flow; (iii) the generated flow changes the self-sustaining dynamics of turbulence and considerable reduces its level and kinetic energy production. The generated spanwise mean flow is an *intrinsic, nonlinear composition* of the forced turbulence and not directly introduced in the system. First of all, a model weak near-wall forcing was designed to impose in the flow the perturbations with the required characteristics. Then the efficiency of the proposed scheme has been demonstrated by the direct numerical simulation using plane Couette flow, $\mathbf{U} = (Ay, 0, 0)$, as a representative example.

A wide variety of active and passive, linear and nonlinear flow control mechanisms for drag reduction have been developed over the years [2, 3, 1]. It is now recognised that the organised turbulence structures play an important role in wall-layer dynamics and that the most high skin-friction regions in near-wall turbulent layers are induced by nearby streamwise vortices [6, 4]. Common features of all drag-reduced flows are weakened near-wall streamwise vortices and streaks. Recently efforts have been made to control turbulence through different spanwise wall-based forcing methods directly creating a spanwise flow [5] using the simplified models of shark-skin riblets [4], wall oscillations [7], etc. However, there could be another, indirect way of a spanwise mean flow generation by a week near-wall forcing that initiates the breaking of turbulence spanwise reflection symmetry that, in turn, leads to the turbulence control. The scheme of this control strategy is the following: (i) a specially designed near-wall weak forcing (non-symmetric in spanwise direction) generates the seed velocity perturbations that draw shear flow energy and undergo substantial transient growth; (ii) these perturbations lead to the breaking of turbulence reflection symmetry and the generation of mean spanwise flow (iii) which, in turn, changes the statistics of the turbulence and considerable reduces its level.

Transient growth of perturbations due to the non-normality of the linearised operators of shear flows is the basis of the dynamical activity in these flows that for sufficiently high Reynolds numbers support a set of (optimal) perturbations that undergo large transient growth during the dynamical time of turbulence ($\mathcal{O}(1/A)$). A robust growth of 3D perturbations satisfies the following conditions: their streamwise and spanwise characteristic scales are the same order and larger than the viscous dissipative length scale, $\ell_x \simeq \ell_z \gg \ell_\nu$, or, in terms of wavenumbers, $k_x, k_z \ll k_\nu$ (here, $k_\nu \equiv \sqrt{Re} \approx 1/\ell_\nu$); they are tilted with the background shear, $k_y/k_x < 0$.

Based on these conditions the model of the helical forcing presented in Figure 1 was desined and studied the dynamical characteristics of the turbulence numerically using pseudo-spectral code. We consider forced incompressible plane Couette flow with shear parameter A and Reynolds number $Re \equiv UL/\nu = AL^2/\nu = 750$, based on the wall velocity U, the channel half-width L, and the kinematic viscosity ν. Simulation box and resolution were $L_x \times L_y \times L_z = 8\pi \times 2 \times 4\pi$ and $\Delta x^+ = 5,\ \Delta y^+ = 0.03 - 1.6, \Delta z^+ = 5$ correspondingly.

The statistics and instantaneous velocity fields of the unmanipulated and forced turbulence were compared. The forcing imposes in the flow at each simulation time step a specially designed seed velocity perturbations. Right plot in Figure 1

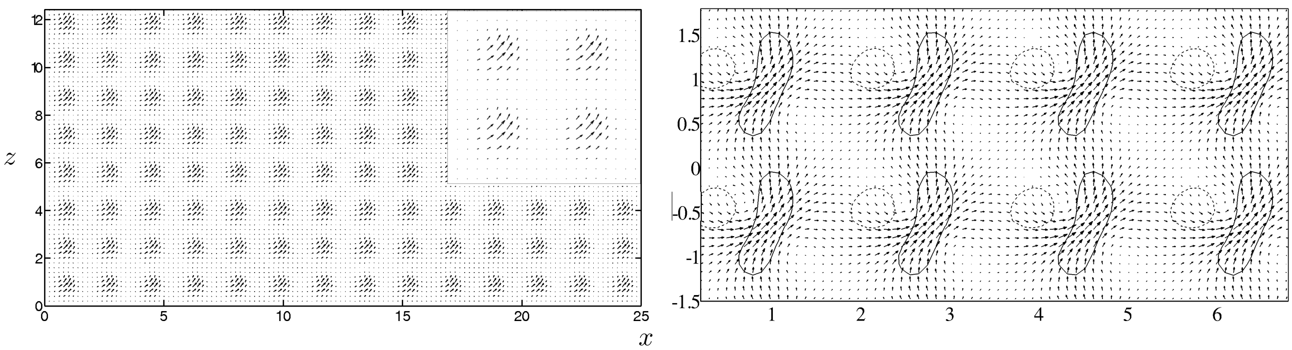

Figure 1. Left plot: the desigh of the helical forcing in xz-plane at $y = -0.95$; Right plot: the related seed velocity field imposed at each action of the forcing in the same plane with contours of positive (0.0005 ——) and negative (-0.0001 - - -) spanwise velocity.

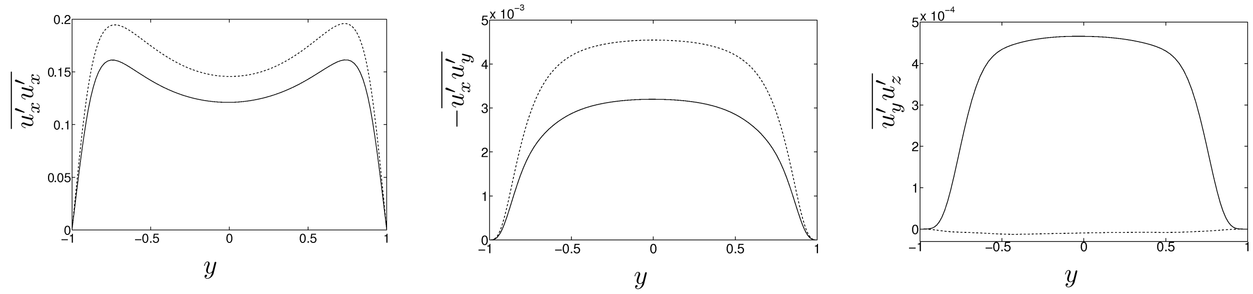

Figure 2. Reynolds stress tensor components for unmanipulated turbulent (– – –) and controlled (——) flows.

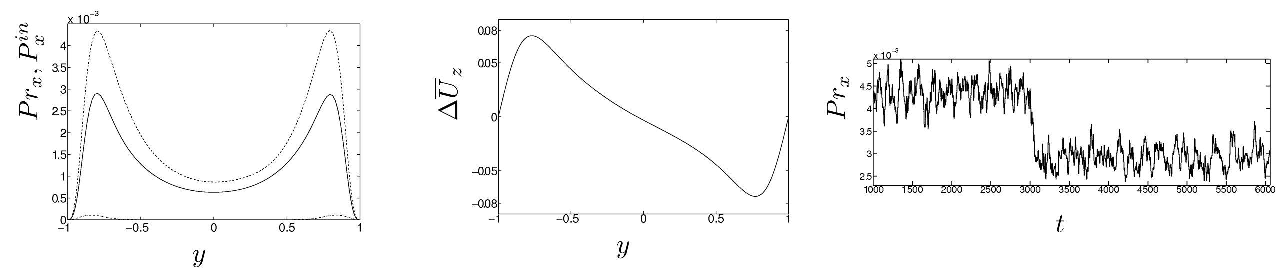

Figure 3. Left plot: Time averaged productions of turbulent kinetic energy (Pr_x) for the turbulent (– – –) and controlled (——) flows and input power, P_x^{in}, (— · —); Middle plot: The deviation of the controlled flow mean spanwise ($\Delta\overline{U}_z$) velocity profiles from the unmanipulated turbulent flow ones; Right plot: Time evolution of Pr_x for the unmanipulated ($t < 3000$) and controlled ($t > 3000$) flows (right plot).

presents the imposed at each action of the forcing seed velocity field in the xz-plane at $y = -0.95$ and contours 0.0005 (solid line) and -0.0001 (dashed line) of spanwise velocity component. The velocity field in the area of the solid contour initiates the breaking of the spanwise symmetry. The imposed velocity configuration, for the set of parameters presented in Figure 1, leads to the generation of mean spanwise velocity and, finally, to substantial reduction of the turbulent kinetic energy production.

The statistics of Reynolds stress tensor components in unmanipulated (dashed lines) and forced (solid lines) cases are shown in Figure 2. These plots show that the level of turbulence decreases significantly in the latter case.

The terms characterising the energetics of the control process are presented in Figure 3. Turbulent kinetic energy production $Pr_x = -\overline{u'_x u'_y} d\overline{U}_x/dy$ is presented on the left plot in Figure 3. The forcing also inputs additional power in the flow: $P^{in} \simeq P_x^{in} + P_z^{in}$ (the power in the wall-norman direciton, P_y^{in}, is negligible). The left plot displays P_x^{in} (dashed-dotted line) and Pr_x for the unmanipulated (dashed line) and controlled (solid line) flows. The figure shows that $P_x^{in} \ll Pr_x$ and the turbulent kinetic energy production is substantially reduced in the controlled case. This result is confirmed by the middle and right plots in Figure 3. Middle plot shows the deviation of the controlled flow mean spanwise ($\Delta\overline{U}_z = \overline{U}_z^{contr} - \overline{U}_z^{turb}$) velocity profile from the unmanipulated turbulent flow. For the unmanipulated turbulent flow, the mean spanwise velocity is zero, consequently, $\Delta\overline{U}_z = \overline{U}_z^{contr}$. Right plot on the same figure displays the time evolution of averaged in all directions production of turbulent kinetic energy. The time region $t \leq 3000$ corresponds to the unmanipulated turbulent flow, at $t = 3000$ the forcing was switched on and $t > 3000$ corresponds to the manipulated flow. As a result, the reduction of the level of turbulence about 35% was obtained.

Conclusion The aim of this study was to propose and analyse a new strategy of the flow control by imposition in the flow a specially designed seed perturbations that have potential of transient growth and gives to the turbulence helical nature – creates spanwise mean flow. The results are of the control are promising: the applied forcing considerably reduces the turbulent kinetic energy production.

References

[1] T. R. Bewley. Flow control: new challenges for a new renaissance. *Progress in Aerospace Sciences*, **37**:21–53, 2001.

[2] H. Choi, P. Moin, and J. Kim. Direct numerical simulation of turbulent flow over riblets. *J. Fluid Mech.*, **255**:503–539, 1993.

[3] M. Gad-el-Hak. *Passive, Active and Reactive Flow*. Cambridge Univ. Press, Cambridge, UK, 2000.

[4] R. Garcia-Mayoral and J. Jimenez. Hydrodynamic stability and breakdown of the viscous regime over riblets. *J. Fluid Mech.*, **678**:317–347, 2011.

[5] G. E. Karniadakis and K.-S. Choi. Mechanisms on transverse motions in turbulent wall flows. *Annu Rev. Fluid Mech.*, **35**:45–62, 2003.

[6] J. Kim. Physics and control of wall turbulence for drag reduction. *Phil. Trans. R. Soc. A*, **369**:1396âĂŞ1411, 2011.

[7] P. Ricco, C. Ottoneli, Y. Hasegawa, and M. Quadrio. Changes in turbulent dissipation in a channel flow with oscillating walls. *J. Fluid Mech.*, **700**:77–104, 2012.