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NEAR-WALL ENSTROPHY GENERATION IN A DRAG-REDUCED TURBULENT CHANNEL FLOW WITH SPANWISE WALL OSCILLATIONS

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We study the turbulent drag reduction technique of sinusoidal spanwise wall oscillations, first introduced by [1], by direct numerical simulations of a turbulent channel flow. This flow has been studied mainly through turbulence statistics, flow visualizations, and models attempting to explain the mechanism behind drag reduction [2, 3]. However, the answers to fundamental questions, such as of why the turbulent kinetic energy (TKE) and the friction drag decrease, still remain elusive. Our objective is therefore to gain further insight into the physics of this flow. The focus is on how the energy transfer between the mean flow and the turbulent fluctuations is affected by the wall motion and on the role played by the modified turbulent enstrophy. Another important point is to study the energy transfer during the temporal evolution from the start-up of the wall motion with the aim of explaining the decrease of skin-friction coefficient. Our paper [4] presents the results in detail. The simulations are carried out with a constant mean streamwise pressure gradient and henceforth the quantities are expressed in viscous inner units.

After decomposing the velocity and the vorticity fields as $\mathbf{U}=\left\{\widehat{U}(y,t),0,\widehat{W}(y,t)\right\}+\{u,v,w\}$ and $\mathbf{\Omega}=\left\{\widehat{\Omega}_x(y,t),0,\widehat{\Omega}_z(y,t)\right\}+\{\omega_x,\omega_y,\omega_z\}$ (where the hat $\widehat{\ }$ indicates averaging over the homogeneous directions x,z), the dynamics of the *turbulent enstrophy*, $\omega_i\omega_i$, is studied through the turbulent enstrophy equation:

$$\begin{aligned}\underbrace{\frac{1}{2}\frac{\partial\widehat{\omega_i\omega_i}}{\partial t}}_{1} = \underbrace{\widehat{\omega_x\omega_y}\frac{\partial\widehat{U}}{\partial y}}_{2} + \underbrace{\widehat{\omega_z\omega_y}\frac{\partial\widehat{W}}{\partial y}}_{3} + \underbrace{\widehat{\omega_j\frac{\partial u}{\partial x_j}}\frac{\partial\widehat{W}}{\partial y}}_{4} - \underbrace{\widehat{\omega_j\frac{\partial w}{\partial x_j}}\frac{\partial\widehat{U}}{\partial y}}_{5} - \underbrace{\widehat{v\omega_x}\frac{\partial^2\widehat{W}}{\partial y^2}}_{6} + \underbrace{\widehat{v\omega_z}\frac{\partial^2\widehat{U}}{\partial y^2}}_{7} + \\ \underbrace{\widehat{\omega_i\omega_j\frac{\partial u_i}{\partial x_j}}}_{8} - \underbrace{\frac{1}{2}\frac{\partial}{\partial y}\left(\widehat{v\omega_i\omega_i}\right)}_{9} + \underbrace{\frac{1}{2}\frac{\partial^2\widehat{\omega_i\omega_i}}{\partial y^2}}_{10} - \underbrace{\widehat{\frac{\partial\omega_i}{\partial x_j}\frac{\partial\omega_i}{\partial x_j}}}_{11}.\end{aligned} \tag{1}$$

In the oscillating-wall case, the vorticity production term 3, $\widehat{\omega_z\omega_y}\partial\widehat{W}/\partial y$, is dominant in the proximity of the wall, $y<10$, over terms 4 and 6, and over the production and transport terms already present in the fixed-wall case, i.e. terms 2, 5, 7, 8, 10. This is the key term producing turbulent enstrophy (and dissipation). It peaks at $y\approx 6$ and distinctly affects term 11, the dissipation of turbulent enstrophy, at the edge of the viscous sublayer and in the lower part of the buffer region. Flow visualizations indicate that regions of high values of $\omega_z\omega_y$, which is dominated by the product $(\partial u/\partial y)(\partial u/\partial z)$, appear sporadically near the wall and always occur at the sides of pockets of high-speed streaks. While the streaks are less energetic, the number, the amplitude, and the spatial size of the $\omega_y\omega_z$ pockets strongly increase during the wall motion, in line with the observed intensified enstrophy fluctuations. The physics of term 3 can be exemplified as the underlining vortical structures cyclically being stretched and compressed by the large-scale action of the viscous spanwise layer $\widehat{W}$. A model based a simplified version of equation (1) elucidates this enstrophy-production mechanism and the balancing action of the turbulent enstrophy dissipation.

The study of the temporal evolution of the terms in equation (1) from the beginning of the wall motion is useful to understand how the flow evolves from the stationary-wall configuration to the new fully-developed drag-reduction regime. Upon the start-up of the oscillation, term 3 grows abruptly until $t = 25$, i.e. at a quarter of the oscillation period. It therefore gives a transient production of turbulent enstrophy; the turbulent dissipation is therefore enhanced, which causes the monotonic decrease of TKE. This feeds back onto the turbulent vorticity and onto term 3, which are both diminished because of the weakened turbulent activity. As a consequence of the attenuation of TKE, the streamwise mean flow accelerates, which is evident from the mean streamwise momentum equation,

$$-\Pi = \frac{\partial \widehat{U}}{\partial t} - \frac{\partial^2 \widehat{U}}{\partial y^2} + \frac{\partial \widehat{uv}}{\partial y}, \tag{2}$$

because $-\Pi$ is constant (and positive) and the term $\partial \widehat{U}/\partial t$ must be positive to balance the decay of the Reynolds stresses transport (which is larger than the mean viscous transport, given by $\partial^2 \widehat{U}/\partial y^2$). The TKE continuously decreases because, although the turbulent dissipation and production are both attenuated, the latter is proportionally smaller. As the streamwise flow accelerates, all the quantities decrease up to $t \approx 400$. The wall-shear stress, $\partial \widehat{U}/\partial y|_{y=0}$, drops initially as an immediate consequence of the acceleration of the mass flow rate, which is shown by integrating (2) along y,

$$-\Pi h = \frac{\partial}{\partial t}\left(\int_0^h \widehat{U} \mathrm{d}y\right) + \left.\frac{\partial \widehat{U}}{\partial y}\right|_{y=0}.$$

As $-\Pi$ is positive and the flow-rate term on the r.h.s. is positive, the wall-shear stress must be smaller than its steady-state value during the transient evolution. The wall-shear stress value eventually re-establishes itself in the new fully-developed regime to the value imposed by the constant Π. In the new quasi-equilibrium regime after the long transient, the flow thus requires a relatively lower level of turbulent dissipation because TKE is smaller. The schematic in figure 1 shows the crucial physical processes during the temporal flow evolution from the start-up of the wall motion to the new fully-developed regime. This last regime is indicated with ‘Drag reduction’, although one must recall that the turbulent drag eventually attains its stationary-wall value, and the beneficial effect of the wall oscillation is to increase the mass flow rate.

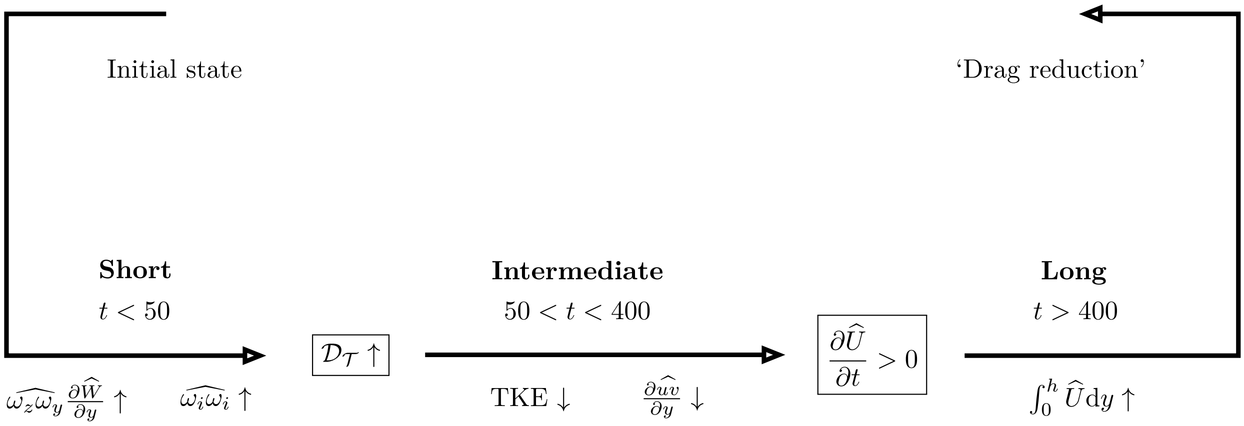

Figure 1: Schematic of the physical mechanism leading to skin-friction drag reduction by wall oscillations. The vertical arrows indicate whether the quantities increase or decrease.

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