SCALE ENERGY FLUXES IN TURBULENT CHANNELS WITH DRAG REDUCTION AT CONSTANT POWER INPUT

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We analyse how conceptually different strategies for turbulent skin-friction drag reduction modify the energy transport processes from production to dissipation in wall turbulence, as means to access the physics of drag reduction. Direct numerical simulations (DNS) are performed with the recently-proposed Constant Power Input (CPI) approach [3, 5], in which the power transferred to the flow – through pumping and imposition of control – is kept constant at a power-based Reynolds number of $Re_\Pi = U_\Pi h/\nu = 6500$, corresponding in the reference unmanipulated channel, to $Re_\tau = u_\tau h/\nu = 199.7$ and $Re_b = U_b h/\nu = 3176.8$. In the previous definitions, U_Π is the bulk velocity of a laminar flow driven by the given total power Π_t, u_τ and U_b are respectively the friction and the bulk velocity, h the channel semi-height and ν is the kinematic viscosity of the fluid. The turbulent energy transport phenomena are described through the generalized Kolmogorov equation (GKE) [4, 2], a budget equation for the second order structure function $\langle \delta u^2 \rangle$, where $\delta u^2 = \delta u_i \delta u_i$ and δu_i is the increment of the i-th velocity component at position $\mathbf{X_c}$ and separation $\mathbf{r}$, i.e. $\delta u_i = u_i(\mathbf{X_c} + \mathbf{r}/2) - u_i(\mathbf{X_c} - \mathbf{r}/2)$. $\langle \delta u^2 \rangle$ can be interpreted as the amount of energy at a *scale* (smaller than) $\mathbf{r}$ and in a channel flow is a function of space through the wall-normal position Y_c only and of scale through the separation vector $\mathbf{r}$. In its most compact notation the GKE reduces to:

$$\frac{\partial \Phi_c(Y_c, r_i)}{\partial Y_c} + \frac{\partial \Phi_{r_i}(Y_c, r_i)}{\partial r_i} = \xi(Y_c, r_i),$$

in which Φ_c and Φ_{r_i} are the scale energy fluxes in space and among scales, while ξ is the scale energy source, budget between production and dissipation of scale energy. The equation above, stemming from the Navier-Stokes equation, describes the path in space and among scales between the production and dissipation of scale energy.

In the present study, we compute the GKE spanning for the first time the whole 4-dimensional space (Y_c, r_i) for turbulent channels in which drag reduction has been achieved by two active means (wall oscillations [6] and opposition control [1]) chosen for their different energy requirements. The modification of the scale energy source and fluxes induced by the control, an example of which is given in figure 1, is used to explain the mechanisms of drag reduction.

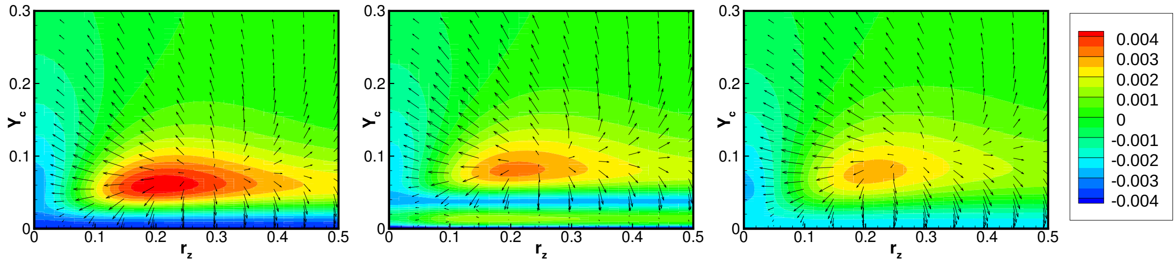

Figure 1. Contour maps of the scale energy source ξ for a reference channel (left), a channel controlled by opposition control [1] (center) and by oscillating wall [6] (right) as a function of the wall normal distance Y_c and the spanwise separation r_z for $r_x = r_y = 0$. The vectors represent the fluxes among scales r_z and in space Y_c. All values are nondimensionalized by the velocity U_Π and the channel semi-height h.

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