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COHERENT NEAR-WALL STRUCTURES AND DRAG REDUCTION BY SPANWISE FORCING

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The aim of the present work is to study the effect of streamwise-traveling waves of spanwise wall velocity (StTW) on the quasi-streamwise vortices (QSV) populating the near-wall region of a turbulent channel. This study estends the analysis of [4], where the particular case of spatially uniform wall oscillation (OW) is considered and studied by conditional-averaging of DNS data.

The travelling waves are enforced as a spanwise wall velocity of the form:

$$w_w\left(x,t\right) = A\sin\left(\omega t - \kappa_x x\right) \tag{1}$$

being $w_w\left(x,t\right)$ the spanwise velocity, which periodically varies according to the phase $\phi = \omega t - \kappa_x x$, function of both the time t and the streamwise coordinate x. The control parameters are the maximum wall velocity A, the wavenumber κ_x and the angular frequency ω. These, in turn, determine the wavelength $\lambda_x = 2\pi/\kappa_x$, the period $T = 2\pi/\omega$ and the phase speed $c = \omega/\kappa_x$ of the wall velocity wave. The law 1 contains the two limiting cases of the stationary wave when $\omega = 0$ and the spanwise oscillating wall (OW) when $\kappa_x = 0$.

The application of StTW results in the formation of a periodic and streamwise-varying crossflow called generalised Stokes layer (GSL). The GSL interacts with quasi-stramwise vortices and longitudinal low-speed streaks which are essential in the near-wall turbulence regeneration cycle. Altering this cycle through a perturbation of the structures is generally recognised as the foundation of the drag-reducing effect of the GSL. However, the details of the interaction between the wall forcing and the near-wall turbulent structures remain partially unclear.

Similarly incomplete is the research of a predictive correlation, based on physical or empirical arguments, to estimate the drag reduction as a function of the control parameters.

The goal of this work is therefore twofold: we first extend the conditional analysis of [4] to the general case of StTW and we developed a new predictive correlation to arrive at a satisfactory drag-reduction prediction based upon GSL quantities alone.

The data are provided by five incompressible Direct Numerical Simulations (DNS) of a fully developed turbulent channel flow: one DNS provides the reference case, whereas for each control technique two configurations are simulated, one with good performance and the other that performs weakly (smaller drag reduction for OW and drag increase for StTW).

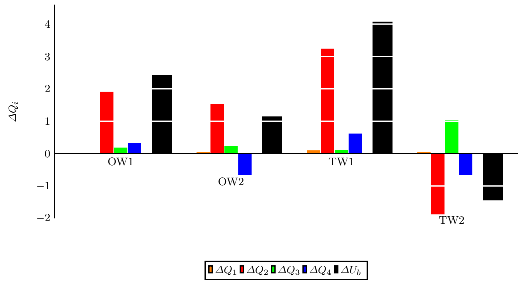

Figure 1: Changes ΔQ_i of the quadrant contributions to U_b, from Eq.3. The sum of the four ΔQ_i equals the total change ΔU_b (shown with a black bar) from the uncontrolled case.

The variation of bulk velocity $\Delta U_b = U_b - U_{b,Ref}$ is used to quantify the friction drag changes induced by the control, where $U_{b,Ref} = 15.90$ is the bulk velocity of the reference case. The variation of bulk velocity can be rearranged in the case of Constant Pressure Gradient (CPG) as derived in [2]:

$$U_b = \frac{Re_\tau}{3} - \int_0^{Re_\tau} \left(1 - \frac{y}{Re_\tau}\right)\left(-\overline{u'v'}\right) dy^+. \tag{2}$$

where the overbar is the temporal mean, and the prime indicates a fluctuating turbulent quantity according to the Reynolds decomposition.

This equation can be written as:

$$U_b = \frac{Re_\tau}{3} + \sum_{i=1}^{4} Q_i, \tag{3}$$

where Q_i is the event contribution of quadrant i to the weighted integral of the Reynolds shear stresses (see Ref. [3]). The laminar term remains unchanged between controlled and uncontrolled flows, so the change of bulk velocity is the sum of the changes of quadrant contributions to the shear stress: $\Delta U_b = \sum_{i=1}^{4} \Delta Q_i$.

The results of the quadrant analysis for the considered cases are presented in Fig.1. OW results are in agreement with the previous results of [4] and it can be observed as the variation of Q2 events is the dominant mechanism for the travelling waves too, bearing a suppression of Q2 events in TW1 case, whereas in the drag-increasing TW2 case they are significantly enhanced. TW2 presents other peculiarities: similarly to OW2, control performances are decreased by a negative ΔQ_4, but this is compensated by the large $\Delta Q_3 > 0$.

The extraction procedure for the QSV is based on the swirling strength criterion, introduced by Zhou et al. [5], and the conditional average process follows the steps of [4].

The conditionally-averaged flow fields for cases OW1, OW2 and TW1 (not shown for brevity) qualitatively confirm the picture of [4], with Q_2 and Q_4 contributions possessing an evident phase dependency and drag reduction mostly related to

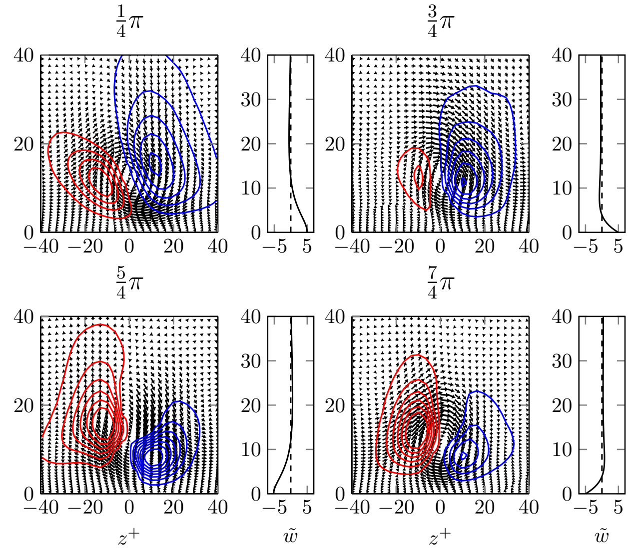

Figure 2: Four phases of the conditionally-averaged flow field (TW2) with QSV extracted at $y_c^+ = 11.3$. The additional right panels plot the phase-averaged mean velocity profile.

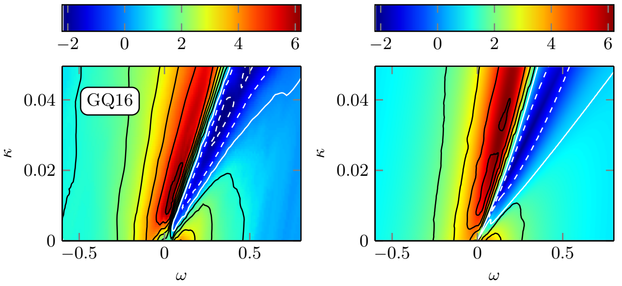

Figure 3: Left: drag-reduction map from the database of [1] at $Re_\tau = 200$. Right: drag changes predicted by Eq.6.

a reduction of Q_2. The drag-increasing TW2 case displayed in Fig. 2, however, behaves differently, showing a considerable variation in Q_2 values along the cycle, varying from the minimum at $\phi = 3/4\pi$ to larger values, with a significant maximum at $5/4\pi$. Changes of Q4 events are of lesser evidence, as expected from Fig. 1, but generally sweeps do appear as more intense in controlled cases than in the uncontrolled one.

A peculiar feature of the TW cases, visible in figures in Fig. 2, is the phase-related vertical shift of Q_2 and Q_4 conditional fields around the vortex center: the center of the Q_2- and Q_4-structures appears to move vertically during the forcing cycle. The angle β formed by the straight line connecting the maxima of the Q_2 and Q_4 fields at the center of the QSV has been found to be in agreement with the angle α formed by the direction of the second eigenvector of the phase-averaged strain-rate tensor $\langle S \rangle_{ij}$ evaluated at $y^+ = 12$. The structure of $\langle S \rangle_{ij}$ is indeed modified between OW and StTW by the introduction of a x dependance on the phase ϕ. We observe as both α and β are larger in modulus for the TW2 case, supporting the idea that large wall-normal excursion of the Reynolds shear stress structures relate to drag increase.

Existing strategies for drag reduction prediction are mostly restricted to OW: they can be extended to the TW cases leading to satisfactory results. The drag reduction predicion formula proposed in [4]:

$$\Delta U_b = a \left.\frac{\partial \widetilde{w}}{\partial y}\right|^{rms}_{y^+=10} - b \left.\frac{\partial \widetilde{w}}{\partial y}\right|^{rms}_{y^+=15}. \qquad (4)$$

has been extend to include the effects of the travelling waves. In particular, we we augmented the original formulation to include the rms value of the α angle evaluated at $y^+ = 12$, $\alpha^{rms}_{y^+=12}$, and the parameter S':

$$S'(\omega, \kappa_x) = \int_0^\ell a_m(\omega, \kappa_x, y) dy. \qquad (5)$$

being S' the maximum over the forcing cycle of the GSL acceleration integrated over its penetration depth l. This expression for S' reflects the speed difference of turbulent structures and the travelling wave and the ensuing forcing timescale $2\pi/\omega_{eq}$, while $\alpha^{rms}_{y^+=12}$ is used to take into account for the drag increase effect of StTW. The prediction formula 4 is modified as:

$$\Delta U = S' \left(a\tau_z|^{rms}_{y^+=10} + b\tau_z|^{rms}_{y^+=15} \right) - c\alpha^{rms}_{y^+=12}. \qquad (6)$$

where a, b, c are empirical coefficients determined with a least square fit to the dataset available from Ref. [1]. Despite being obtained through simple observations, the prediction produces a strikingly similar map compared to the numerical results, and it performs significantly better than the alternative predictive formulas. This result confirms that (this type of) drag reduction is mostly a linear phenomenon, albeit non-linear effects need to be included for a quantitatively accurate prediction. The empirical coefficients appearing in the formula reflect our current inability to relate the properties of the GSL with the vertical dynamics/bouncing of the QSV, which could be the direction for further work.

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