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DNS OF TURBULENT CHANNEL FLOW WITH DIFFERENT TYPES OF SPANWISE FORCING

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The present work aims at establishing the effectiveness of drag-reduction techniques based on wall manipulation through spanwise forcing in the range of Reynolds numbers close to practical applications. It is known [6] that control strategies based on spanwise motion are quite effective in altering the near-wall coherent structures responsible for the cycle of wall turbulence self-sustainment, with subsequent friction relief. A spatially non-uniform spanwise forcing technique was proposed by Viotti *et al.* [8], in the form of longitudinal travelling waves, namely $w = A\sin(k_x x - \omega t)$, where w is the spanwise velocity component at the wall. At low Reynolds number, drag reduction up to about 50% was found via DNS for waves with moderate amplitude, travelling more slowly than the convection velocity of the near-wall eddies. Further support for drag reduction strategies based on the streamwise travelling waves concept has come from pipe flow experiments [1], in which case the spatio-temporal variations required to enforce the waves were obtained through a time- and space-varying azimuthal (rotational) speed of the pipe wall. A possible practical implementation of the spanwise actuation concept consists in the use of arrays of wall flush-mounted discs, which are made to rotate at constant angular velocity [7]. Maximum drag reduction of about 25% and net power saving of about 10% was observed for discs with diameter $D^+ = 1000$ and tip velocity $W^+ = 9$ (in wall units). A sensitive issue of these control techniques is the possible loss of efficiency at higher Reynolds number. Current evidence is that the control effectiveness of travelling waves is moderately affected by increasing Re_τ, with drag reduction decaying as small negative powers of Re_τ [3, 4]. No information is to date available on the high-Re behavior of control devices based on the rotating discs concept. Herein we carry out a series of direct numerical simulations (DNS) of manipulated turbulent plane channel flow, to more firmly establish the applicability of the above control strategies at high Reynolds number.

We numerically solve the incompressible Navier-Stokes equations in an orthogonal coordinate system (x, y, z denote the streamwise, wall-normal and spanwise directions) using staggered central second-order finite-difference approximations, so as to guarantee that kinetic energy is globally conserved in the limit of inviscid flow. Time advancement is carried out by means of a hybrid third-order low-storage Runge-Kutta algorithm coupled with the second-order Crank-Nicolson scheme. The fractional-step method is employed, whereby the convective and the diffusive terms are treated explicitly and implicitly, respectively. The Poisson equation stemming from the incompressibility condition is efficiently solved through Fourier transform-based methods. A spatially uniform pressure gradient is dynamically adjusted in time to maintain a constant mass flow rate, hence controlled and uncontrolled simulations are carried out at the same bulk Reynolds number. A full description of the numerical method is provided in Orlandi [5]. The DNS have been carried out in a $(L_x \times L_y \times L_z) = (6\pi h \times 2h \times 2\pi h)$ computational box, which based on previous extensive simulations [2] with channel flow with no actuation is expected to be sufficiently large to prevent any spurious effect due to numerical confinement.

Flow case	Control	Re_b	Re_τ	$\Delta C_f\%$
P1000	NA	39600	995	0
T1000	TW	39600	815	−32.9
D1000	RD	39600	898	−18.5
P2000	NA	87067	2017	0
T2000	TW	87067	1686	−30.1
D2000	RD	87067	1846	−16.2

Table 1: List of parameters for controlled turbulent channel flow cases. $Re_b = 2hu_b/\nu$ is the bulk Reynolds number, and $Re_\tau = hu_\tau/\nu$ is the friction Reynolds number. $\Delta C_f\%$ is the percent friction reduction with respect to the uncontrolled cases.

The results of DNS carried out at $Re_\tau = 1000, 2000$ (referred to the uncontrolled case) are hereafter presented for actuation with travelling waves (TW), and with rotating discs (RD), and compared with uncontrolled DNS. Regarding TW actuation, a slightly suboptimal configuration has been selected, corresponding to standing waves (i.e. $\omega = 0$) with streamwise wavelength $\lambda_x^+ = 1042$ ($k_x = 2\pi/\lambda_x$), and amplitude $A^+ = 13.55$. The flow parameters for RD actuation have

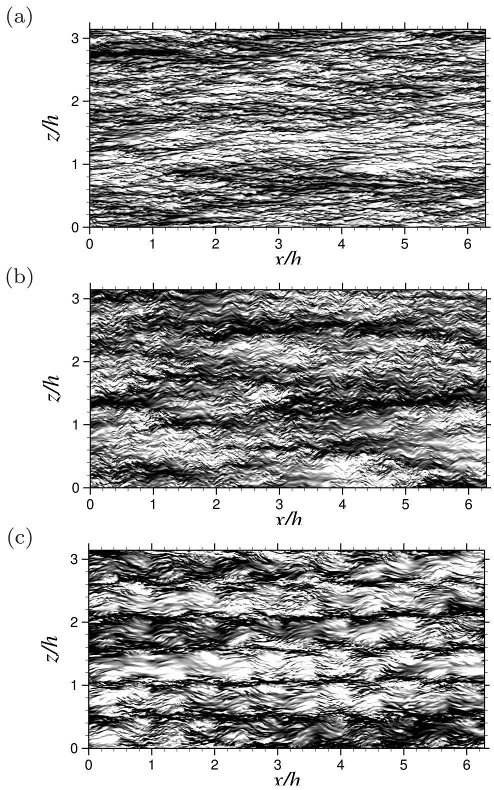

Figure 1: Instantaneous visualizations of u' at $y^+ = 15$ for flow case P2000 (a), T2000 (b), D2000 (c).

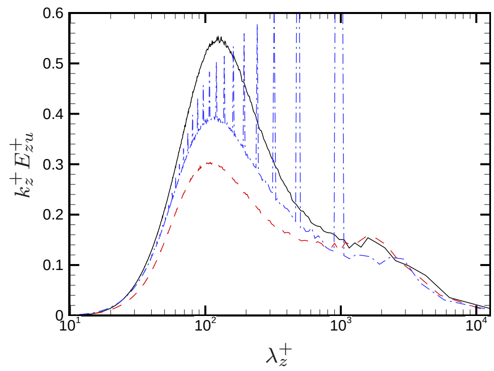

Figure 2: Spanwise spectra of streamwise velocity at $Re_\tau = 2000$. Solid: P2000, dashed: T2000, chained: D2000.

been selected to compare the two types of actuation directly. Hence, discs with diameter $D^+ = 1042$ have been used, with tip velocity $W^+ = 13.55$.

A qualitative perception for the change in the flow organization induced by the wall actuation is given by figure 1, where contours of streamwise velocity fluctuations in a wall-parallel near-wall plane are shown (note that only a small part of the computational box is shown). As expected, the flow in the absence of control (panel a) is dominated by high- and low-velocity streaks, whose typical spanwise spacing is about 100 wall units. On top of these small-scale streaks, the outer-layer larger superstructures impose a clear near-wall footprint at this relatively high Reynolds number. The typical spanwise spacing of this signature in the near-wall layer is $O(h)$. Actuation through TW (panel b) has a clear effect of inhibiting the streamwise coherence of the small-scale streaks, whereas it barely affects the superstructures, hence supporting the notion that their existence is intrinsically related to the outer-layer dynamics, rather than to the presence of the wall. Actuation through rotating discs (panel c) has a similar effect on the small-scale streaks, which undergo severe sinuous excursion in the spanwise direction. Differently from the TW case, the near-wall footprint of the outer structures is strongly influenced by the streamwise-elongated jets formed at the tips of the discs. This scenario is quantitatively supported by the analysis of the spanwise velocity spectra, shown in figure 2. Most energy in all flows is concentrated at wavelengths slightly in excess of 100^+, although wall control significantly decreases the amplitude of the spectral peak. Differences of spectra at larger scales are much smaller. The small spectral bump at $\lambda_z \approx h$ is almost unaffected by TW, whereas it is inhibited by RD actuation. The latter also exhibits a series of spectral peaks at discrete wavelengths corresponding to the size of the rotating discs, and subharmonics. These qualitative differences translate into differences in the friction coefficient as listed in table 1. The present database confirms that substantial skin friction reduction can be achieved with both control methods, also at high Reynolds number, and in large computational boxes. Although both types of actuation share similar features, it appears (not unexpectedly) that RD actuation is less effective with respect to TW actuation, while retaining the advantage of easier implementation. The present DNS also support very slight decrease of the friction reduction effect with the Reynolds number, hence strengthening the claim of Gatti & Quadrio [4] that wall actuation through spanwise forcing (at least in principle) does successfully extend to flows of relevance for the aeronautical industry.

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