Drag Reduction by Spanwise Oscillatory Wall motions and Related Near-Wall Turbulence Mechanisms

E. Touber, L. Agostini, S. Lardeau and M.A. Leschziner

Oscillatory spanwise wall motion is known to cause a substantial reduction in streamwise friction drag. This is of particular interest in civil aviation where fuel efficiency of major importance. Given optimum actuation conditions, reductions of almost 50% can be achieved in channel flow at relatively low values of the Reynolds number - although the effectiveness declines with increasing Reynolds number.

Understanding the fundamental mechanism at play, rather than identifying the optimum forcing conditions quantifying the level of drag reduction, has been the principal objective of several strands of research by the authors over several years [1-6], based on own DNS performed for channel flow and boundary layers. Most simulations have been done for the friction Reynolds number $Re_\tau = 500$ and $Re_\tau = 1000$, in an effort to observe trends the Reynolds-number dependence of the drag-reduction margin and its origin. Current information for channel flow, derived from both DNS and highly resolved LES, indicates that the decline in the drag-reduction level, given a close-to-optimal forcing period and spatially-homogeneous conditions, follows $DR_\% \approx 1.2 Re_\tau^{-0.2}$ **(Fig. 1)**.

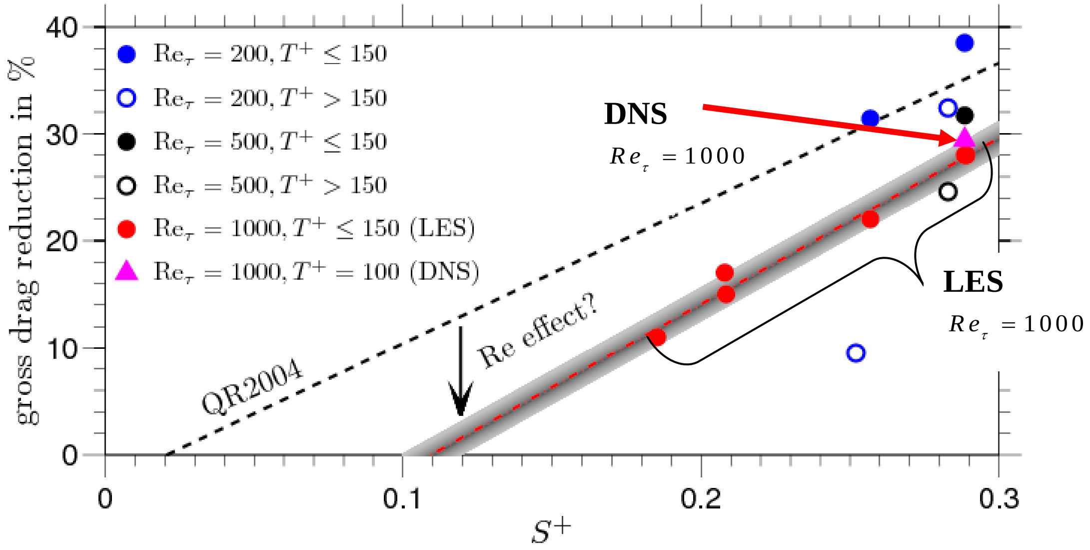

Fig. 1: Drag-reduction margins for different wall-scaled forcing periods, T^+ and friction Reynolds number values. The ordinate S^+ is a composite parameter combining T^+, the wall-scaled maximum wall velocity and several properties extracted from the Stokes layer induced by the spanwise wall motion. "QR2004" is a correlation reported by Quadrio & Ricco, based on low-*Re* simulations.

A range of statistical data have been derived, including second-moment budgets of the stochastic turbulence (i.e. with periodic components excluded), **Fig. 2(a)**, joint-probability-density functions, **Fig. 2(b)**, enstrophy and energy-spectra maps.

Structural features have also been investigated by reference to the response of streak properties to the oscillatory forcing. The unsteady cross-flow straining in the buffer layer is shown to cause major spanwise distortions in the streak near-wall structures, leading to a pronounced reduction in the wall-normal momentum exchange in the viscous sublayer, hence disrupting the turbulence contribution to the wall shear stress. The response of the streaks, in terms of their periodic reorientation in wall-parallel planes, the decline and recovery of their intensity during the cyclic actuation, and their wall-normal coherence, is shown to be closely correlated with the temporal variation of the shear-strain vector.

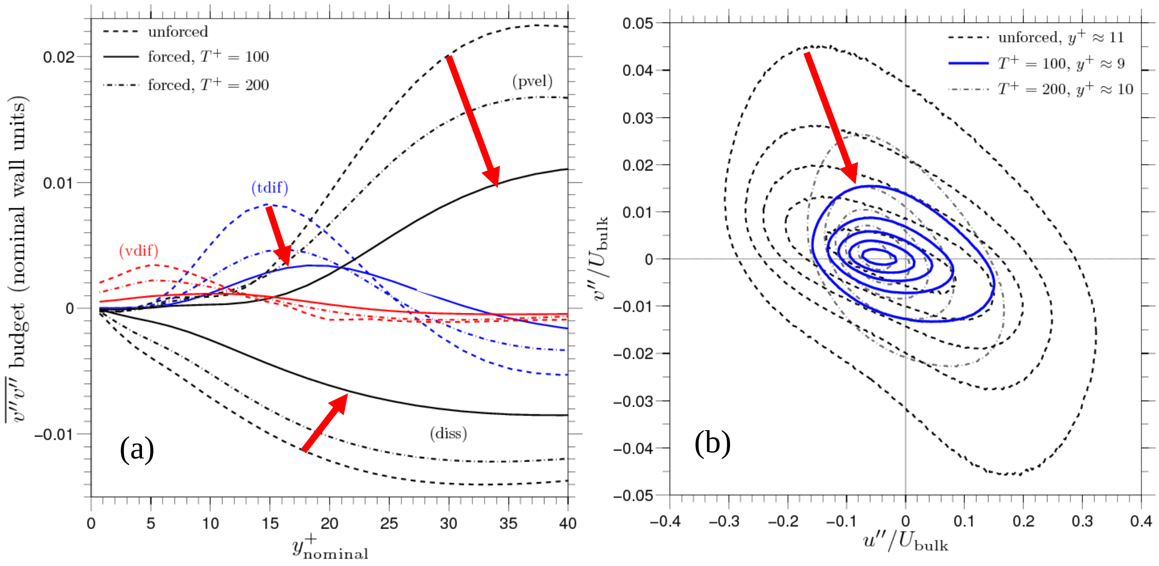

Fig. 2: (a) Budgets of the stochastic wall-normal second moment, with and without forcing, (b); Joint PDFs in the viscous sublayer, with and without forcing. $Re_\tau = 500$. Note the substantial decline in turbulence activity induced by forcing.

Additional factor playing important roles in the drag reduction scenario are velocity skewness in the viscous sublayer (see ref [6]) and the streak-regeneration time scale (see ref [2]), which implies a delay in the re-establishment of streaks following their attenuation by the unsteady Stokes strain.

In an effort to gain insight into the Reynolds-number dependence of the drag reduction margin, the top-to-bottom foot-printing and “modulating” effect, associated with large-scale outer-layer structures, has been studied. This is highlighted in **Fig. 3**. Recent observations at $Re_\tau = 1000$ add support to the interpretation of the role played in the drag-reduction scenario by the interaction between outer structures and the near-wall streaks. This area of research is covered by the following research brief on the **Response of small-scale near-wall turbulence to large-scale outer motions**.

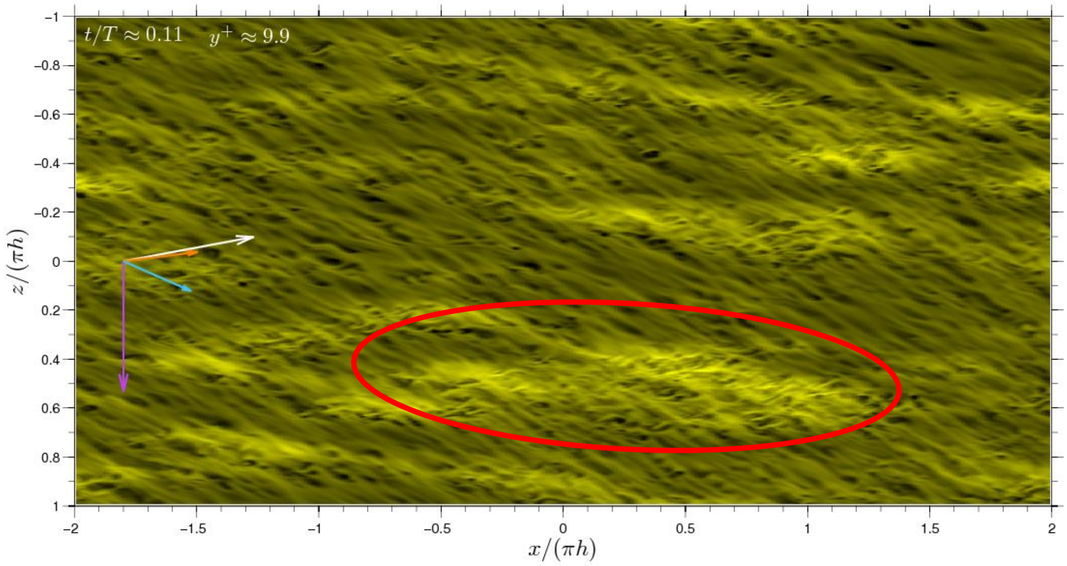

Fig. 3: Alterations of the near-wall streaks by the action of turbulent-velocity excess associated with large-scale structures, separated roughly by the channel half height (600 wall units). The streak orientation is about to flip from the downward to the mirror upward state, and this flipping is pre-empted in patches of large-scale footprints imposing extra straining

Studies on boundary layers [3] indicate that the drag-reduction effectiveness of spanwise motion is somewhat lower than in channel flow. Moreover, as shown in **Fig. 4**, drag reduction sets in quicly after the onset of the actuation and returns quickly to the unforced state upon removing the actuation.

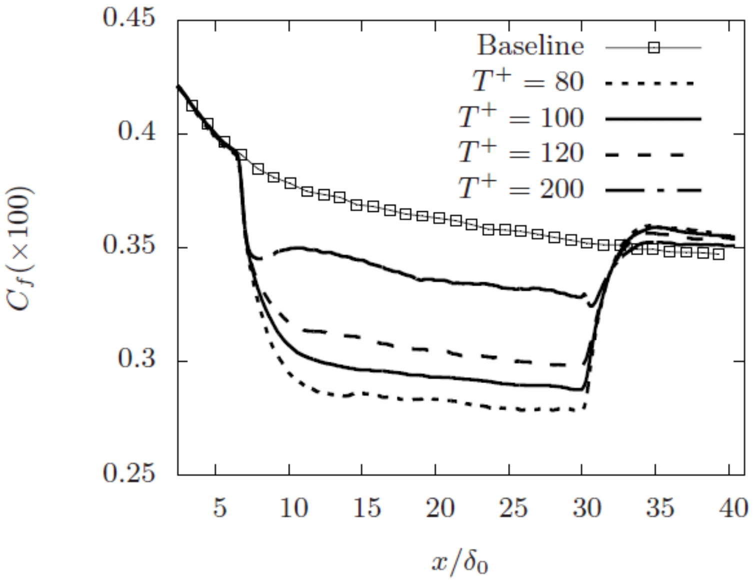

Fig. 4: Drag reduction in a spatially developing boundary layer at different actuation frequencies with forcing over a limited spanwise extent.

References

1. Touber, E and Leschziner, M A (2012) Near-wall streak modification by spanwise oscillatory motions and relationship to friction-drag reduction, J. Fluid Mechanics, 693, pp. 150-200.
2. Blesbois, O, Chernyshenko, S I, Touber, E and Leschziner, M A (2013), Pattern prediction by linear analysis of turbulent flow with drag reduction by wall oscillation, J. Fluid Mechanics, 607, pp. 607-641.
3. Lardeau, S and Leschziner, M A (2013), The streamwise drag-reduction response of a boundary layer subjected to a sudden imposition of transverse oscillatory wall motion, Physics of Fluids, 25, paper 075109.
4. Agostini, L, Touber, E and Leschziner, M A (2014), Spanwise oscillatory wall motion in channel flow: drag-reduction mechanisms inferred from DNS-predicted phase-wise property variations at Re_t=1000, J. Fluid Mechanics, 743, pp. 606-635.
5. Agostini, L., and Leschziner, M A (2014), On the influence of outer large-scale structures on near-wall turbulence in channel flow, Physics of Fluids, 26, paper 075107.
6. Agostini, L, Touber E & Leschziner, M A (2015), The turbulence vorticity as a window to the physics of friction-drag reduction by oscillatory wall motion, Int. J. Heat and Fluid Flow, 51, pp. 3-15.