Large-eddy simulations of turbulent drag reduction by spanwise wall forcing up to $Re_\tau = 4000$

A. Rouhi[*], M. K. Fu[†], D. Chandran[‡], A. Zampiron[§], A. J. Smits[¶] and I. Marusic[‡]

We study turbulent drag reduction by spanwise wall forcing $w_s(x,t) = A\sin(\kappa_x x - \omega t)$, where w_s is the spanwise surface velocity that generates a travelling wave with amplitude A, wavenumber κ_x and frequency ω. Most studies have investigated this mechanism up to friction Reynolds number $Re_\tau \simeq 2000$[1]. Marusic et al.[2] extended Re_τ to 12800 and discovered two pathways for drag reduction (DR): inner-scaled actuation (ISA) and outer-scaled actuation (OSA). Here, we investigate the ISA pathway, that actuates the near-wall scales. We perform wall-resolved large-eddy simulations in a channel flow with viscous-scaled actuation parameters $A^+ = 12, 0.00238 \leq \kappa_x^+ \leq 0.02, -0.2 \leq \omega^+ \leq +0.2$ at $Re_\tau = 951$ and 4000 (Fig.1a). We separate the Stokes layer stress $\langle \tilde{w}^2 \rangle_{xt}$ from the turbulent stress $\langle w''^2 \rangle_{xzt}$ through triple decomposition (Fig.1b), and quantify the Stokes layer protrusion through the lengthscale $\ell_{0.01}$, which is the height where $\langle \tilde{w}^2 \rangle_{xt} \simeq 0.01 \langle w''^2 \rangle_{xzt}$. The level of turbulence attenuation and hence DR, is found to change with $\ell_{0.01}$. We identify a parametric range where DR increases as $\ell_{0.01}$ increases up to 30 viscous units. In this range, the Stokes layer attenuates the near-wall turbulence, lifting up the cycle of turbulence generation and thickening the viscous sublayer. Outside this range, the strong Stokes shear strain enhances the near-wall turbulence, leading to a drop in DR with increasing $\ell_{0.01}$.

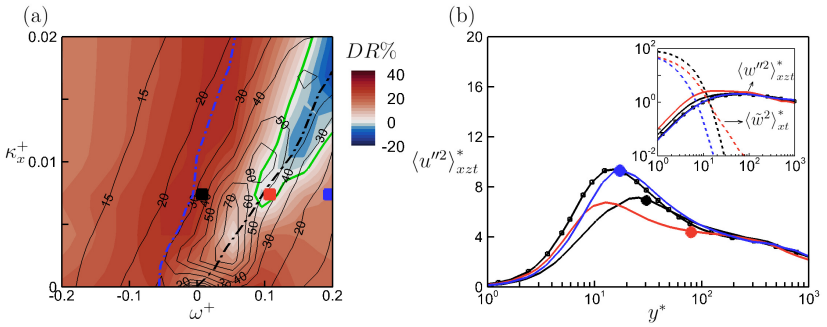

Figure 1: (a) Drag-reduction DR map (filled contour) at $Re_\tau = 4000$ overlaid by the Stokes layer protrusion height $\ell^*_{0.01}$ (contour lines). (b) Profiles of the streamwise and spanwise turbulent stress $\langle u''^2 \rangle^*_{xzt}, \langle w''^2 \rangle^*_{xzt}$, and Stokes layer stress $\langle \tilde{w}^2 \rangle^*_{xt}$ for some actuated cases as identified in (a). The bullet points in (b) locate $\ell^*_{0.01}$ for each case. '+' and '$*$' superscripts indicate scaling by the non-actuated and actuated friction velocity, respectively.

[*]Dep. Engineering, Nottingham Trent University, Nottingham NG11 8NS, United Kingdom
[†]Graduate Aerospace Laboratories (GALCIT), Caltech, Pasadena, CA 91125, USA
[‡]Dep. Mechanical Engineering, University of Melbourne, Victoria 3010, Australia
[§]School of Engineering, University of Aberdeen, Aberdeen AB24 3FX, United Kingdom
[¶]Dep. Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA
[1]Ricco et al., *Prog. Aero. Sci.* **123**, 100713 (2021)
[2]Marusic et al., *Nat. Commun.* **12**, 1-8 (2021)