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TOWARDS ENERGY-EFFICIENT TURBULENT DRAG REDUCTION THROUGH ENHANCING THE INTER-SCALE COUPLING

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Prediction and control of skin friction drag has long been a primary motivation behind the scientific investigation of turbulent wall-bounded flows, which began over a century ago. Despite such concerted efforts from the community, achieving even moderate levels of drag reduction for commercial vehicles such as airplanes and ships has remained a challenge. Some of the primary reasons behind the poor efficacy of drag reduction schemes are associated with the complex flow physics through which the turbulent flow generates drag. This includes (but is not limited to): (i) contribution from a broadband range of turbulent scales or 'eddies', the span of which increases with the friction Reynolds number ($Re_{\tau_o} = \delta U_{\tau_o}/\nu$) of the wall-bounded flow, and (ii) changes in the percentage contribution from these eddies with Re_{τ_o} [5]. Figures 1(b,c) gives an evidence of the former, by depicting the premultiplied energy spectra ($f\phi_{\tau^+\tau^+}$) of the wall shear stress fluctuations (τ_w) over a broadband range of non-dimensional time scales T^+ ($= 1/f^+ = U_{\tau_o}^2/(f\nu)$), for zero-pressure gradient (ZPG) turbulent boundary layers (TBL) at two different Re_{τ_o}. Here, f is the frequency of turbulent scales, δ is the boundary layer thickness, ν is the kinematic viscosity and U_{τ_o} is the skin-friction velocity of the unactuated flow, with the latter two used to normalize the flow in viscous units (indicated by superscript '+'). At low Re_{τ_o} ($\lesssim \mathcal{O}(10^3)$), eddies corresponding to small time scales ($T^+ < 350$; henceforth referred as small eddies), which are associated predominantly with the viscous-scaled near-wall turbulence cycle, are the dominant contributors to the drag [5]. This scenario, however, changes with the increase in Re_{τ_o}, which leads to a logarithmic increase in contribution from the inertia-dominated large eddies ($T^+ > 350$; [4]). This makes both the viscous and inertial-eddy contributions statistically significant when considering the net skin-friction drag generated over a ship or an airplane ($Re_{\tau_o} \gtrsim \mathcal{O}(10^5)$). Thus, the success of a flow control scheme for the transportation industry depends on its ability to attenuate τ_w-fluctuations across such a broad range of scales. Further to that, the control mechanism should be able to deliver net power savings, i.e. the power spent in actuating/controlling the flow should be less than that saved by reducing the drag.

One flow control mechanism that promises net power savings for high Re_{τ_o} wall-bounded flows is through the spanwise oscillation of the wall elements [3], wherein the oscillating wall elements are synchronized in a manner to produce an upstream traveling wave with respect to the mean flow direction. Figure 1(a) presents a schematic of the control strategy employed by Marusic et al. [3], where the instantaneous spanwise velocity (w_s) imposed on the wall can be defined as: $w_s(x,t) = A \sin(\kappa_x x - 2\pi f_{osc} t)$. Here, f_{osc} and A are respectively the frequency and amplitude of the spanwise oscillation and $\kappa_x = 2\pi/\lambda$ is the streamwise wavenumber of the traveling wave generated by the synchronized oscillation of the wall elements. In the present study, we denote u, v and w as the velocity fluctuations along the streamwise (x), wall-normal (y) and spanwise (z) directions, respectively, while t denotes time. This control mechanism has been investigated extensively in the past [6] predominantly for its ability to achieve drag reduction (DR) through actuation of the viscous-scaled small eddies, which we will refer to here as the viscous-eddy actuation strategy (VEA; figures 1(b,d)). However, oscillating the wall elements at such small time periods incurs a significantly large power requirement (i.e. no net power savings), thereby making it unsuitable for implementation at high Re_{τ_o}. Based on the premise that the large-scale inertial contributions to the turbulent skin-friction increases with Re_{τ_o} [4], Marusic et al. [3] recently discovered that spanwise wall-actuation targeting these large-scales can also yield DR in case of a high Re_{τ_o} flow (figures 1(c,e)). More importantly, the power requirement to actuate at the corresponding large T^+ is significantly smaller, which makes this 'inertial-eddy actuation strategy' (IEA) energy efficient (i.e. net power savings are feasible). Interested readers can attend the accompanying talk of Chandran et al.[1] for a comprehensive description of the novel experimental set-up and measurements reported in [3]. It is to be noted here that the VEA and IEA strategies defined here were originally referred to as the 'small-eddy' and 'large-eddy' actuation strategies, respectively by Marusic et al.[3]. However, we believe that this new terminology is more precise in terms of description of the eddies being targeted by the actuation.

Interestingly, Marusic et al. [3] also noted that the turbulent DRs achieved from both the VEA and IEA strategies are associated with energy attenuation across a broadband range of scales (figures 1(b,c)). This scale range overlaps with the energy containing hierarchy in a high-Re_{τ_o} TBL, spanning from the viscous-scaled small eddies to the inertial large eddies. This observation suggests that the spanwise wall-actuation, although enforced at a specific frequency f_{osc}, 'activates' a mechanism that facilitates enhanced coupling between the inertial and viscous-scaled eddies in the flow, thereby making this broadband attenuation possible. The percentage attenuation of energy, however, can be noted to be varying from scale to scale for each strategy (figures 1(d,e)). Interestingly, in case of IEA, a significant portion of the DR is in fact associated with the attenuation of the viscous-scales ($\sim$ 40% at $T^+ \sim 100$) as compared to that for the inertial eddies ($\sim$ 20% at $T^+ \sim 600$). One can thus infer that the enhanced inter-scale coupling is key to the success of the IEA strategy, since it facilitates a substantial attenuation of major drag contributing viscous-scales despite the flow being actuated at the large scales (at much less power).

This presentation discusses the mechanism that enhances

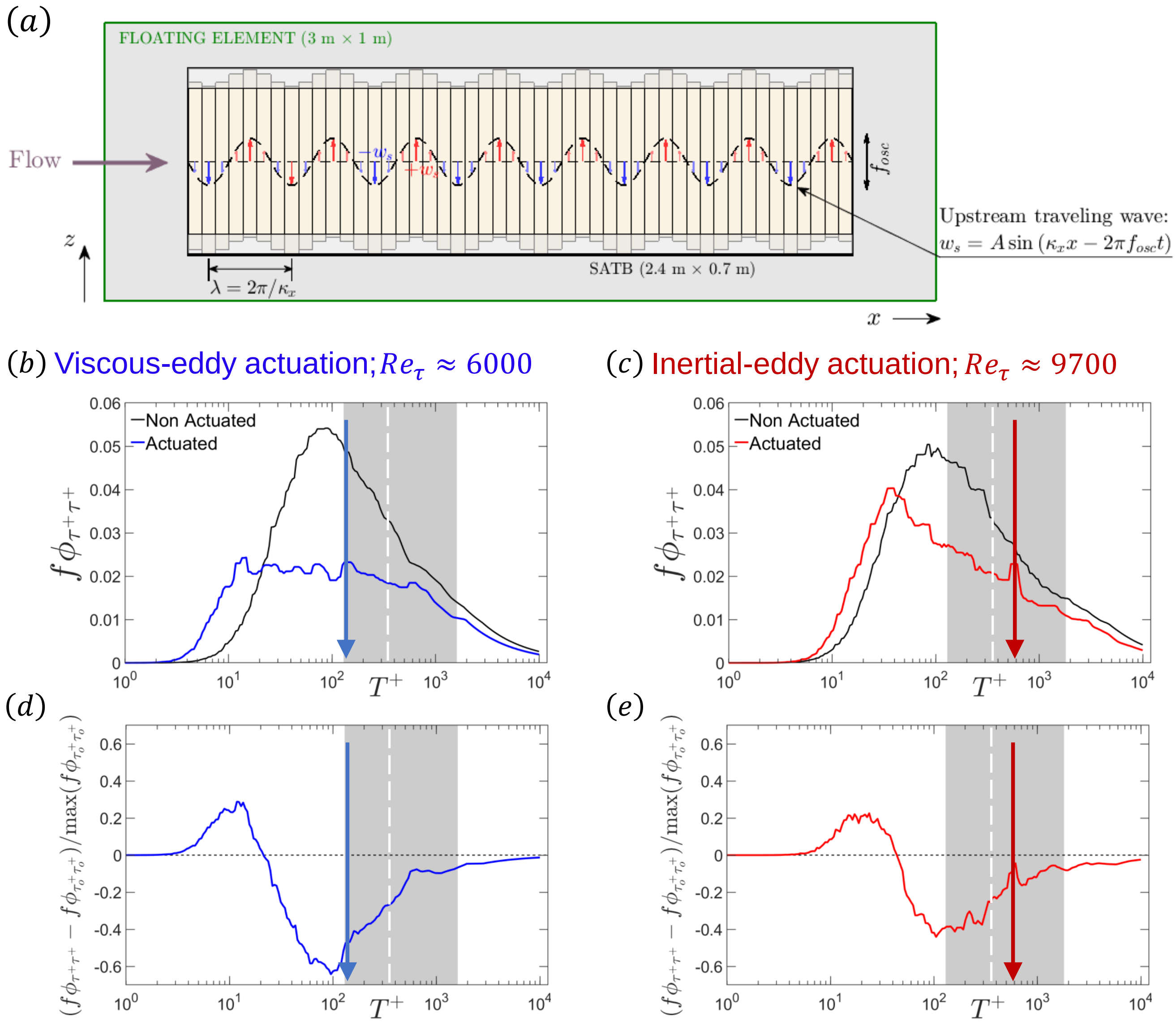

Figure 1: (a) Schematic of the spanwise wall-actuation scheme employed by Marusic et al. [3]. (b,c) Premultiplied spectra of the τ_w with (in color) and without (in black) wall-actuation, as reported in [3]. The spectra has been normalized by the skin-friction velocity of the corresponding non-actuated case, U_{τ_o}. (d,e) shows the difference between the two curves in (b,c) respectively, normalized by the spectra from the unactuated case. (b,d) corresponds to VEA with parameters: $T^+_{osc} \approx 140$, $A^+ \approx 12$, $k^+_x \approx 0.0014$ for a ZPG TBL at $Re_{\tau_o} \approx 6\,000$, while (c,e) corresponds to IEA with parameters: $T^+_{osc} \approx 604$, $A^+ \approx 4.6$, $k^+_x \approx 0.0008$ for a ZPG TBL at $Re_{\tau_o} \approx 9\,700$. Grey background in (b-e) represents the hierarchy of energy-containing scales between the inner (viscous) and outer (inertial) spectral peak at the respective Re_{τ_o}. Dashed white line indicates nominal demarcation between viscous and inertial-eddy time-scales, $T^+_c = 350$ while the arrow indicates the wall-oscillation time scale, T^+_{osc}.

this inter-scale coupling for both the VEA and IEA spanwise wall actuation strategies. The investigation follows the framework laid out in the literature by McKeon and co-workers[2], who studied the changes in the inter-scale coupling for a ZPG TBL perturbed by spatially impulsive dynamic wall roughness. This effort forms the first step towards a broader and more ambitious goal of leveraging the inter-scale interactions to optimize the energy-efficient turbulent DR, via the newly discovered IEA strategy.

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