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The turbulence vorticity as a window to the physics of friction-drag reduction by oscillatory wall motion

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ABSTRACT

DNS data for channel flow, subjected to spanwise (in-plane) wall oscillations at a friction Reynolds number of 1025, are used to examine the turbulence interactions that cause the observed substantial reduction in drag provoked by the forcing. Following a review of pertinent interactions between the forcing-induced unsteady Stokes strain and the Reynolds stresses, identified in previous work by the present authors, attention is focused on the equations governing the components of the enstrophy, with particular emphasis placed on the wall-normal and the spanwise components. The specific objective is to study the mechanisms by which the Stokes strain modifies the enstrophy field, and thus the turbulent stresses. As such, the present analysis sheds fresh light on the drag-reduction processes, illuminating the interactions from a different perspective than that analysed in previous work. The investigation focuses on the periodic rise and fall in the drag and phase-averaged properties during the actuation cycle at *sub-optimal* actuation conditions, in which case the drag oscillates by around ±2% around the time-averaged 20% drag-reduction margin. The results bring out the important role played by specific strain-related production terms in the enstrophy-component equations, and also identifies vortex tilting/stretching in regions of high skewness as being responsible for the observed strong increase in the spanwise enstrophy components during the drag-reduction phase. Simultaneously, the wall-normal enstrophy component, closely associated with near-wall streak intensity, diminishes, mainly as a result of a reduction in a production term that involves the correlation between wall-normal vorticity fluctuations and the spanwise derivative of wall-normal-velocity fluctuations, which pre-multiplies the streamwise shear strain.

1. Introduction

There is considerable interest, both from fundamental and long-term practical perspectives, in active-control methods that aim to reduce the friction drag of turbulent boundary layers on walls. This applies to long-haul civil aviation, in particular, in which case even very modest reductions in skin friction can have an economically and environmentally important impact on fuel consumption and CO_2 emissions.

It is generally accepted that the effectiveness of any control method targeting turbulent skin friction must be rooted in its ability to disrupt and suppress the mechanisms responsible for sustaining the transport of momentum across the viscosity-affected near-wall layer – a process that is associated with quasi-organised streamwise vortices and streaks. One effective strategy, in general, is to impose a periodically varying transverse strain onto the viscosity-affected near-wall layer by means of wall oscillations or body forces (see Karniadakis and Choi (2003) for a broad review). If the forcing parameters are chosen appropriately, the response of the turbulence to the unsteady strain is a reduction in the time-averaged turbulent stresses and hence skin friction.

Several recent computational and experimental studies, both for channel flow (e.g. Quadrio and Ricco (2004), Ricco and Quadrio (2008), Quadrio et al. (2009), Touber and Leschziner (2012), Agostini et al. (2014)) and for spatially evolving boundary layers (e.g. Choi (2002), Di Cicca et al. (2002), Ricco (2004), Skote (2011), Skote (2013), Lardeau and Leschziner (2013)) demonstrate that oscillatory spanwise wall motion, either spatially homogeneous or in the form of in-plane waves, results in a substantial decline in skin friction, if the actuation period and wave length are chosen judiciously. One particularly important constraint to respect is that the unsteady layer generated by the wall motion remains confined to the viscous sublayer – that is, the actuation has to result in an unsteady *Stokes* layer. In the case of streamwise-homogeneous wall motion, the skin friction is observed to drop by a maximum of around 35% at the friction Reynolds number

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$Re_\tau = \mathcal{O}(200)$, a wall-velocity amplitude $W_m^+ = W_m/u_\tau = 12$ and oscillation period $T^+ = Tu_\tau^2/\nu \approx 100$, although this maximum margin appears to decrease roughly in proportion to $Re_\tau^{-0.2}$, a rate based on simulations by Quadrio and Ricco (2004), Ricco and Quadrio (2008), Touber and Leschziner (2012) and Chung and Hurst (2014) in the range $Re_\tau = 200$—1500. Quadrio et al. (2009) show that even higher gross margins – around 45% at $Re_\tau = \mathcal{O}(200)$ – can be achieved if the wall motion is imposed in the form of streamwise stationary or travelling waves. More importantly, from a practical perspective, is the fact that this actuation mode results in a material energetic *net* gain, when the expenditure of actuation power is accounted for – a subject reviewed in broad terms by Ricco and Quadrio (2008), Quadrio et al. (2009) and Frohnapfel et al. (2012).

The emphasis of many, if not most, previous computational studies has been on the quantification of the drag-reduction margins and the identification of the most effective sets of actuation parameters. In contrast, a minority of studies examine the details of the fundamental interactions underlying the drag-reduction mechanisms. Very recent studies in which these interactions take centre stage are those of Skote (2012), Touber and Leschziner (2012), Ricco et al. (2012) and Agostini et al. (2014). The last two are especially noteworthy for their focus on unsteady processes that are intended to reveal how the actuation drives the drag towards the quasi-steady minimum-drag state. However, they do so by reference to very different aspects of the unsteadiness. Ricco et al. (2012) consider the transient decline of the drag following the sudden imposition of spatially-homogeneous wall oscillations in a channel at $Re_\tau = 200$. In contrast, Agostini et al. (2014) examine the phase- averaged fluctuations in the drag and flow properties in a channel flow at $Re_\tau = 1025$ subjected to wall oscillations at a higher-than-optimal period, in which case the low-drag state is characterised by significant periodic fluctuations around the reduced – but not lowest possible – time-averaged level. Both consider a range of statistical indicators – notably, the enstrophy among them – in an effort to identify the key mechanisms at play. Remarkably, the two studies arrive at very different conclusions: Ricco et al. (2012) argue, by reference to the enstrophy-transport equation, that the drag decline is driven by an increase in the enstrophy during the initial portion of the transient phase, following the onset of the actuation, and hence by an increase in turbulence dissipation, while Agostini et al. (2014) observe the opposite, namely that the drag decreases and increases in harmony with declining and rising levels of enstrophy and dissipation, respectively. Agostini et al. (2014) argue, instead, that the principal mechanism that causes the drag to drop during a dominant portion of the actuation cycle is a suppression of strain-induced streak generation by a high rate of change in the *direction* of the strain in the upper part of the viscous sublayer, in combination with high velocity-vector skewness in the lower part of the Stokes layer. In addition, the tendency towards drag recovery during a relatively short portion of the cycle is suppressed when the actuation period is comparable to a streak-generation time scale that emerges from a linear *General Optimum Perturbation* analysis (Blesbois et al. (2013)). These interactions are reviewed in some detail in Section 3. The principal part of the paper then examines the effects of the unsteady Stokes strain on the turbulent vorticity field and, more specifically, on the phase-averaged stochastic enstrophy components and on key terms in the transport equations governing these components.

2. Computational conditions

The computational implementation is described in detail in Agostini et al. (2014). Here, only a few key facts are given.

The results arise from a DNS computation of a channel flow at $Re_\tau = 1025$ over a box of length, height and depth of $4\pi h \times 2h \times 2\pi h$, respectively, corresponding to approximately $12 \times 2 \times 6 \times 10^3$ wall units. The box was covered by $1056 \times 528 \times 1056 (= 589 \times 10^6)$ nodes. The corresponding cell dimensions were $\Delta x^+,\ \Delta y^+_{min},\ \Delta y^+_{max},\ \Delta z^+ = 12.2, 0.4, 7.2, 6.1$. The DNS code is forth-order accurate in respect of the fluxes and third-order accurate in time. The time step is chosen such that the maxim CFL number, based on streamwise velocity and grid distance, does not exceed 0.25.

The periodic actuation is restricted to a purely sinusoidal spanwise oscillation of the wall, namely:

$$W(t) = W_m \sin(2\pi t/T)$$

In the present study, $W_m^+ = W_m/u_\tau = 12$ and $T^+ = Tu_\tau^2/\nu = 200$, where u_τ is the friction velocity in the unforced (baseline) flow. The former value is the same as that used by Touber and Leschziner (2012) at $Re_\tau = 500$, as well as others reporting DNS studies on drag-reduction phenomena in channel flow at lower Re_τ values. The actuation period $T^+ = 200$ is approximately twice the optimum value at which the maximum drag-reduction margin of 30% is achieved, and has been deliberately chosen so as to give rise to significant periodic fluctuations around the low-drag state – a feature that does not arise at the optimum period.

3. Principal elements of previously described drag-reduction paradigm

This section summarises the major interactions that are held responsible for the behaviour shown in Fig. 1(a). The figure contains two time traces for the wall-averaged skin-friction reduction at $T^+ = 100$ and 200. The former value is close to the optimum period, insofar as it results in the maximum drag-reduction margin and the virtual absence of any actuation-related oscillations. At the latter non-optimal value, the skin friction settles down, after approximately two actuation cycles, to a mean drag-reduction value of -20%, around which periodic fluctuations of approximately ±2% are induced by the actuation. The long-time-scale undulations reflect foot-printing by outer structures residing in the log layer. These are clearly visible in Fig. 1(b) as large darker and lighter regions within which the small-scale near-wall streaks are embedded. The latter structures, visualised as contours of streamwise-velocity fluctuations at $y^+ = 13.5$, are inclined at an orientation that is closely aligned with the angle of the strain vector (comprising the streamwise-shear and Stokes-strain components) at the same wall-normal elevation. Agostini et al. (2014) show that the effects of the large-scale structures can be removed by a filtering process that separates the large-scale and small-scale motions.

Touber and Leschziner (2012) and Agostini et al. (2014) investigate the drag-reduction mechanisms based on an examination of streamwise-, spanwise- and phase-averaged stochastic properties, which are displayed in phase-space plots in which wall-normal property variations in the near-wall layer are traced over a representative (averaged) actuation cycle. The stochastic fluctuations arise from the triple decomposition,

$$U = \widetilde{U} + u'' = \overline{U} + \hat{u} + u'' \tag{1}$$

where $\overline{U}$ is the time-averaged value, $\widetilde{U}$ is the phase-averaged value, evaluated from

$$\widetilde{U}|_\varphi = \frac{1}{N}\sum_{n=1}^{N}\left(\frac{1}{IK}\sum_{i,k=1,1}^{I,K} U_{i,k}|_{\varphi+(n-1)T}\right) \tag{2}$$

where $\varphi \in \{0, T\}$, i, k are x, z grid indices, N is the number of cycles over which averaging is performed, $\widehat{u}$ is the periodic fluctuation and u'' is the stochastic (purely turbulent) contribution.

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