# LETTERS

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## A large-scale control strategy for drag reduction in turbulent boundary layers

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Using direct numerical simulations of turbulent channel flow, we present a new method for skin friction reduction, enabling large-scale flow forcing without requiring instantaneous flow information. As proof-of-principle, $x$-independent forcing, with a $z$ wavelength of 400 wall units and an amplitude of only 6% of the centerline velocity, produces a significant sustained drag reduction: 20% for imposed counterrotating streamwise vortices and 50% for colliding, $z$-directed wall jets. The drag reduction results from weakened longitudinal vortices near the wall, due to forcing-induced suppression of an underlying streak instability mechanism. In particular, the forcing significantly weakens the wall-normal vorticity $\omega_y$ flanking lifted low-speed streaks, thereby arresting the streaks' sinuous instability which directly generates new streamwise vortices in uncontrolled flows. These results suggest promising new drag reduction techniques, e.g., passive vortex generators or colliding spanwise jets from $x$-aligned slots, involving durable actuators and no wall sensors or control logic. © *1998 American Institute of Physics.* [S1070-6631(98)00805-8]

Although numerous strategies have been developed to reduce the skin friction of turbulent boundary layers, their engineering application has remained notably scarce. Streamwise vortices are now known to dominate near-wall turbulence production and drag generation, but their physical nature poses some formidable obstacles: (i) small dominant lengthscales [O(0.1 mm) for aircraft], (ii) random $(x,z)$ locations, and (iii) apparently complex spatiotemporal dynamics.

The current state-of-the-art involves active wall control, via micro-electro-mechanical systems (MEMS)[1] for sensing and actuation. In response, recent control strategies[2,3] have focused on locally annulling the drag producing effect of individual streamwise vortices based on instantaneous flow information. For practical implementation, these strategies require sensing and actuation to be implemented at the sub-mm scale of the dominant near-wall vortices, necessitating a dense spatial array of MEMS. For engineering applications, durability limitations will obviously pose a formidable challenge for MEMS-based boundary layer control.

As an alternative, here we develop new bulk control approaches using large-scale, rugged actuators (i.e., whose spacing is much larger than the characteristic streak spacing), without wall sensors or control logic. In this way, more durable actuators would be permitted, each providing drag reduction over an extended spatial domain containing perhaps thousands of streamwise vortices. Although it is challenging to realize successful control under these restrictions, we feel that these constraints are necessary for feasibility of implementation.

In essence, our control is designed to suppress or prevent streamwise vortex formation in the first place. It has long been hypothesized that a major source of turbulence production near the wall is the instability of inflectional low-speed streaks.[4] Recently, we have found that the dominant longitudinal *coherent structures* (CS),[5] extracted from fully developed near-wall turbulence, are in fact created by a new sinuous instability of lifted, vortex-free streaks near a single wall (created by previous vortices, no longer present).[6]

We focus on new large-scale control techniques aimed at streak stabilization and hence suppressed vortex formation, using direct numerical simulations of the Navier–Stokes equations. Periodic boundary conditions are used in $x$ and $z$, and the no-slip condition is applied on the two $y$ walls; see Kim *et al.*[7] for the spectral algorithm details. The control simulations are initialized with fully developed channel flow turbulence[7] at $\mathrm{Re}=U_c h/v=1800$ and 3200 ($U_c$ is the centerline velocity of the $2h$ wide channel), with (48,65,48) modes in $(x,y,z)$ for Re=1800 and (192,129,192) modes for Re=3200 (before dealiasing). Actuation is represented by an applied control flow, either maintained at a constant amplitude or allowed to freely evolve, superimposed onto the turbulence. In particular, we investigate drag reduction by: (i) a spanwise row of counter-rotating, $x$-independent streamwise vortices, centered in the outer region (at the channel centerline) and (ii) $x$-independent, $z$-directed colliding wall jets.

As a simple model of streamwise vortex generators or spanwise slot jets, we consider a control flow of the form

$$\begin{aligned} &U_{\mathrm{con}}=0,\\ &V_{\mathrm{con}}(y,z)=-A\beta\cos(\beta z)(1+\cos\pi(y/h-1)),\\ &W_{\mathrm{con}}(y,z)=-A\pi\sin(\beta z)\sin\pi(y/h-1), \end{aligned} \tag{1}$$

 

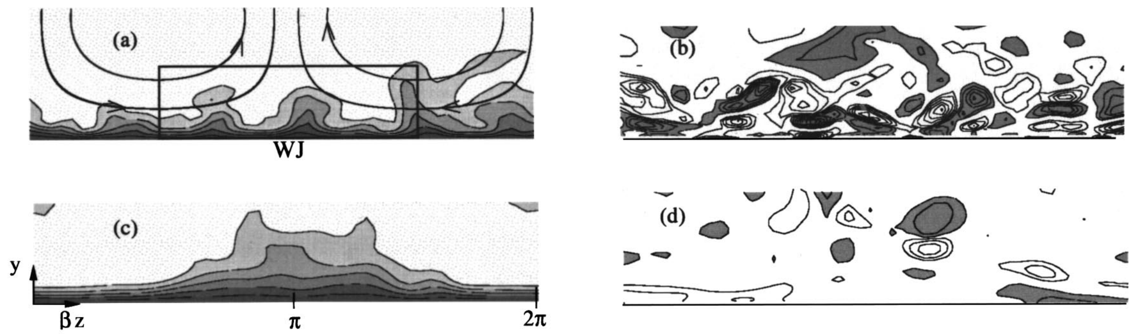


FIG. 1. Distributions of $u(y,z)$ in (a,c) and $\omega_x(y,z)$ in (b,d) near one wall of turbulent channel flow at Re=1800, without (a,b) and with (c,d) an imposed large-scale control flow. The controlled flows, shown at $t_0^+=500$ (after control starts), have a frozen forcing amplitude of 6%. Note the disruption of streaks and the attenuation of streamwise vortices near the wall by control.

which satisfies the continuity equation and the no-slip condition on the channel walls (at $y=0,2h$), where $A$ is the control amplitude and $2\pi/\beta^+\cong 400$. To demonstrate proof-of-principle for large-scale forcing, the $z$ wavelength of the control flow is four times the characteristic streak spacing of approximately 100 wall units; even much larger-scale control (although computationally prohibitive) may be possible in practice. As illustrated in Fig. 1(a), the control flow (1) has a much larger scale than local minima of $u(y,z)$ near the wall, representing lifted low-speed streaks. For simplicity, we focus on the lower half of the channel (i.e., $y\in[0,h]$) in this and other figures; the upper half yields similar results. For a full period in $z$, (1) represents an array of counter-rotating 2D streamwise vortices [Fig. 1(a)], termed *vortex control*. Over the half period $\beta z\in[\pi/2,3\pi/2]$, (1) resembles colliding, spanwise-directed 2D wall jets [region *WJ* in Fig. 1(a)], referred to as *wall jet control*. Thus, we actually simulate a single control flow, distinguishing vortex and wall jet control by the region of $z$ considered. In practice, the relative extents of diverging (outside *WJ*) and converging (inside *WJ*) wall jets can be adjusted to reduce the former.

To assess potential drag reduction, the time evolution of wall-integrated strain rate, given by

$$\Omega_w=\frac{1}{L_x(z_2-z_1)}\int_0^{L_x}\int_{z_1}^{z_2}\frac{\partial u}{\partial y}\bigg|_{y=0}dx\,dz \qquad (2)$$

is shown in Fig. 2 for several control cases. Note that $(z_1,z_2)$

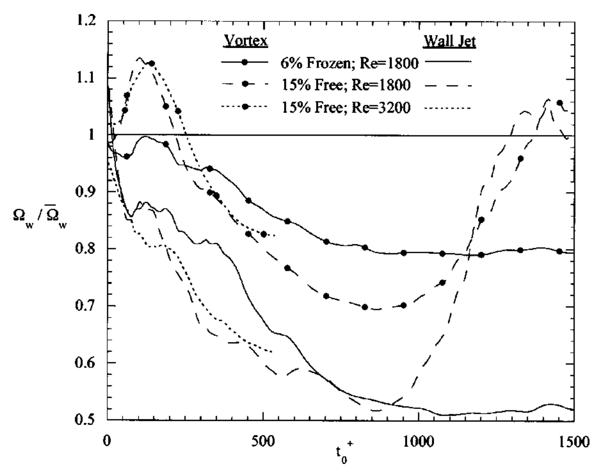


FIG. 2. Time evolution of wall-integrated shear stress (normalized by the time-mean of the uncontrolled flow), illustrating significant drag reduction by large-scale control.

in (2) encompasses $(0,2\pi/\beta)$ for vortex control and $(\pi/2\beta,3\pi/2\beta)$ for wall jet control. For both, we consider two methods of forcing: (i) *free* forcing in which the control flow (1) is superimposed onto a turbulent flowfield at $t_0=0$ and allowed to freely evolve, and (ii) *frozen* forcing with the $x$-mean Fourier coefficients (denoted by a tilde) of the control flow maintained constant in time:

$$\left.\begin{aligned}\tilde{v}(k_x=0,k_z,y,t)&=\tilde{V}_{\rm con}(k_z,y)\\ \tilde{w}(k_x=0,k_z,y,t)&=\tilde{W}_{\rm con}(k_z,y)\end{aligned}\right\}k_z\neq 0. \qquad (3)$$

For frozen forcing, $V_{\rm con}$ and $W_{\rm con}$ are specified as the flowfield resulting after one turnover time of viscous, 2D evolution of the initial condition (1). In this way, relaxation of the control flow is permitted before it is frozen, since (1) is unsteady for both viscous and inviscid evolution.

Significantly, Fig. 2 reveals that substantial drag reduction, sustained in time for frozen forcing, is attainable—20% for vortex control and 50% for wall jet control. In both cases, a surprisingly weak control amplitude of 6% [i.e., $\max(V_{\rm con})=2A\beta=0.06U_c$] is most effective, in general desirable from the practical standpoint of low power consumption (active control) or parasitic drag (passive control) of actuators. The dependence of drag on the (frozen) forcing amplitude (not shown) indicates a cusp-like effect of the control amplitude; the control effect is insignificant for 2% or weaker forcing, while 15% or stronger forcing leads to increased drag for both vortex and wall jet control. The increased drag at higher amplitudes reflect direct generation of drag by the control flow itself, occurring even in the absence of turbulence. The optimum control is attained when the control is strong enough to stabilize near-wall streaks (discussed below), yet weak enough not to induce significant additional drag. Significant drag reduction is also observed for free forcing, at both Re=1800 and 3200 (Fig. 2). Although the control effect is temporary for free forcing, due to eventual dissipation of the control flow, significant drag reduction is observed for O(1000) wall time units. During this time, the control flow advects $(U_c^+)(\Delta t^+)\sim$16,000 wall units downstream, thus suggesting the practical feasibility of large-scale, effective control in both $x$ and $z$ (i.e., simultaneously many streaks, covering numerous wall vortices).

To understand these observed drag reduction phenomena, we first consider the control effect on lifted streaks, visualized in Figs. 1(a) and 1(c) by $u(y,z)$ before and after

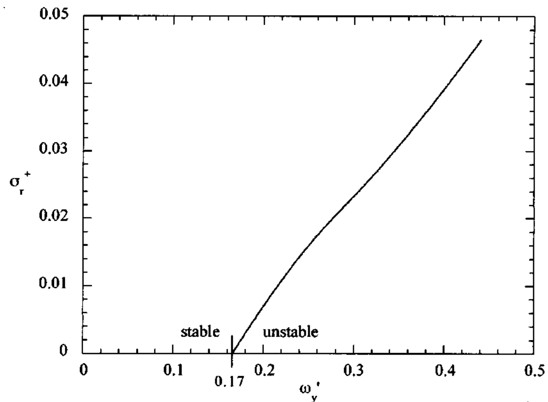


FIG. 3. Dependence of sinuous streak instability growth rate $\sigma_r^+$ on the streaks' $\omega_y'$, for the base flow (4).

control (at $t_0^+=500$). The numerous preexisting lifted streaks [Fig. 1(a)] are flattened by splatting where $V_{\text{con}}$ pushes fluid toward the wall and $W_{\text{con}}$ spreads it in $z$ (outside of $WJ$). Within the wall jet control region $WJ$, $V_{\text{con}}$ is directed away from the wall and $W_{\text{con}}$ converges in $z$, causing cross-diffusion of compressed streaks and hence weakening $\omega_y$. Along the entire wall, even very weak control drastically decreases the $\omega_y$ originally flanking streaks in the uncontrolled flow [cf. Figs. 1(a) and 1(c)]. The significance of this attenuation of $\omega_y$ lies in our recent results regarding formation of new streamwise vortices near the wall by streak instability,[6] when $\omega_y$ is above a threshold. Most importantly for control, we find that sufficient $\omega_y$ flanking streaks is required for instability and that the instability growth rate increases significantly with the $\omega_y$ magnitude (Fig. 3). The growth rate data in Fig. 3 are for sinuous instability modes (i.e., $z$ displacement of streaks, with sinusoidal $x$ variation) of the base flow family

$$U(y,z)=U_0(y)+(\Delta u/2)\cos(4\beta z)y\ \exp(-\sigma y^2);\quad V=W=0, \tag{4}$$

where $U_0(y)$ is the mean velocity. The spanwise wavenumber of $4\beta$ corresponds to a streak spacing of 100 wall units, and the parameter $\sigma$ is specified so that the maximum streak $\omega_y$, with normal circulation $\Delta u$, occurs at $y^+=30$. The base flow (4) is found to be an accurate representation of vortex-free low-speed streaks[6] (i.e., during the quiescent phase of regeneration) observed in uncontrolled near-wall turbulence. In essence, both vortex and wall jet controls break the near-wall vortex regeneration cycle by disrupting the naturally occurring (unstable) distributions of streaks generated by previous or pre-existing streamwise vortices. Recalling the necessity of sufficient streak $\omega_y$ for instability (Fig. 3) and hence vortex formation, the reduction of local streak $\omega_y$ peaks by control is expected to significantly attenuate near-wall streamwise vortex formation. A comparison of the near-wall $\omega_x$ with and without control [Figs. 1(b) and 1(d)] indicates that this is indeed the case. Without control [Fig. 1(b)], numerous compact, drag-producing vortices with strong $\omega_x$ are present immediately near the wall. In contrast, the reduction of $\omega_y$ across streaks by control significantly weakens $\omega_x$ in the controlled flow [Fig. 1(d)], with no compact vortices present near the wall. Statistics of $\omega_y'$ confirm a strong re-

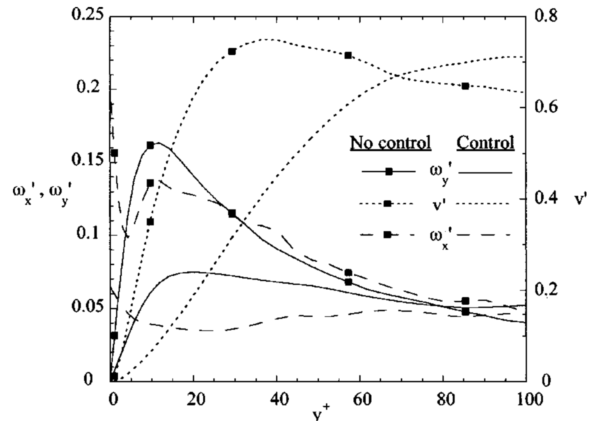


FIG. 4. Suppression of $v'$, $\omega_x'$, and $\omega_y'$ by large-scale control at $t_0^+=500$, with Re=1800 and frozen 6% forcing.

duction of local $\omega_y$ maxima by control, accompanied by large suppression of $\omega_x'$ and drag-producing $v'$ (Fig. 4). The latter occurs only after existing vortices, which eventually weaken by annihilation due to cross-diffusion and dissipate, are not replaced by equally strong and numerous vortices, due to the suppressed vortex formation mechanism by control-induced streak $\omega_y$ reduction.

Since streamwise vortex formation and the associated enhanced drag appears to be reliant on lifted low-speed streaks with strong $\omega_y$, large-scale (relative to the natural streak spacing) control of streaks is a potentially effective approach to drag reduction. We demonstrate here the feasibility of drag reduction via bulk forcing using either counterrotating vortex generators or colliding spanwise wall jets, requiring no instantaneous flow information (otherwise necessary for adaptive control). For implementation at very high Re, the physical scale of our control will likely decrease, but being significantly larger than the near-wall structures, will surely alleviate the micro-scale requirement for controllers and eliminate the need for sensors. Experiments are necessary at higher Re to realize the drag reducing effect of the control considered here.

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