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LARGE-SCALE FRICTION CONTROL IN TURBULENT WALL FLOW

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Abstract

The present study reconsiders the control scheme proposed by Schoppa & Hussain [Phys Fluids **10**:1049–1051 (1998)], using new sets of numerical simulations in a turbulent channel at a friction Reynolds number of 180. In particular, it is aimed at better characterising the physics of the control as well as investigate the optimal parameters. Results indicate that a clear maximum efficiency in drag reduction is reached for the case with a viscous-scaled spanwise wavelength of the vortices of 1200, which yields a drag reduction of 18%, contrary to the smaller wavelength of 400 suggested as the most efficient vortex in Schoppa & Hussain.

INTRODUCTION

There is a significant cost both for the environment and economy, associated with overcoming the drag exerted on streamlined bodies moving through fluids. At typical speeds and sizes encountered in transportation (as for instance airplanes, cars, pipelines) the Reynolds number is always so high such that the flow needs to be considered fully turbulent. Therefore, classical schemes to delay transition are not applicable in such circumstances, but rather the drag caused by the turbulent flow needs to be reduced directly. The literature contains a number of successful technique to achieve this goal, mostly by modifying the immediate near-wall region, *e.g.* by uniform or intermittent blowing (Kametani *et al.*, 2015), opposition control via localised blowing and suction or volume forces (Choi *et al.*, 1994), wall oscillations or traveling waves (see for instance Du & Karniadakis, 2000). As opposed to these active schemes, also passive measures such as the well-known riblets modifying the wall surface have been used. For all these methods, at least for lower Reynolds numbers drag reduction of 10% or more could be achieved, both in simulations, but also in practical implementations (Gad-el Hak, 2007).

During recent years, the large-scale structure of turbulent wall-bounded flows has received considerable attention (see *e.g.* Jiménez, 1998; Marusic & Adrian, 2013). Similarly, Schoppa & Hussain (1998) showed that artificially creating and strengthening such large-scale, essentially streamwise oriented vortices, can be an effective method to reduce the frictional drag in channel flows. They considered a number of cases, both decaying and frozen vortices, and could obtain sustained reduction of the drag by approximately 15%. The interesting feature of the latter control scheme is that the control is not imposed directly in the near-wall region, but rather further away from the wall, on correspondingly much larger scales. Therefore, this scheme appears to be a good candidate of practical relevance, even for higher Reynolds numbers which are characterised by very small near-wall scales of turbulence.

It is thus the aim of the present work to further study the control scheme proposed by Schoppa & Hussain (1998), using new sets of numerical simulations, in order to better characterise the physics of control and the optimal parameters. The influence of the Reynolds number, and the potential application also in open boundary layer flows are left for future studies.

NUMERICAL SIMULATIONS

In the following, channel flows at fixed bulk Reynolds number $Re_b = 4200$, based on half-width h and bulk velocity u_b are considered; the corresponding friction Reynolds number $Re_\tau \approx 180$. Periodicity in the wall-parallel directions x and z is imposed; all simulations are performed using a fully spectral code (Chevalier *et al.*, 2007). The control is achieved by imposing large-scale vortices on top of the turbulent flow. These are implemented by adding a volume force of the form (Schoppa & Hussain, 1998)

$$F_y = -A\beta\cos(\beta z)(1+\cos(\pi(y/h-1))) \qquad (1)$$
$$F_z = -A\pi\sin(\beta z)\sin(\pi(y/h-1))\ . \qquad (2)$$

The forcing amplitude A is varied, and the strength of the vortices in the resulting flow is measured by the maximum amplitude of the wall-normal mean velocity $\max|\langle v\rangle_{x,t}|$. Note that this quantity vanishes in the uncontrolled case.

RESULTS

The most important quantity is the drag reduction DR, measured as the relative reduction in the necessary pressure gradient to achieve a certain bulk flow. This is shown in Fig. 1 for a number of cases considered in this study: Five different spanwise wavelengths of the vortices, $\beta = 2\pi/\Lambda$, were chosen, and for each vortex size, the amplitude is varied. The wavelengths, expressed in viscous units, ranges from $\Lambda^+ = 200$ to $\Lambda^+ = 1800$. Fig. 1 (top) clearly shows that the friction is not changed for very low amplitudes of the imposed vortcies (say below 1%). Consistent results are also obtained for very strong amplitudes (above 10%); all cases show significant negative DR, *i.e.* drag increase. Inspection of the flow fields clearly shows that this increase is due to the strong shear created by the vortices in the near-wall region, rather than increased turbulence. In fact, for the strongest amplitude of the forcing, turbulence disappears altogether, but the drag is very high.

However, more relevant for the present study is the intermediate region, for which all vortex sizes (except $\Lambda^+ = 200$) show at least DR = 10%. A clear maximum efficiency is reached for the case with $\Lambda^+ = 1200$, which peaks at DR = 18%. It is interesting to note that in the paper by Schoppa & Hussain (1998) a smaller wavelength of $\Lambda^+ = 400$ is suggested as the most efficient vortex.

Similarly, the necessary forcing amplitude A (normalised with β) for all cases is shown in the bottom panel of Fig. 1. It turns out that the resulting vortex strength (measured in wall-normal velocity amplitude) is essentially linearly dependent on the forcing amplitude, a results that is perhaps not surprising. However, evaluating the energy saving achieved by the drag reduction is much more relevant than the control input which in general is negligible.

For the remainder of this paper, only the most efficient vortex, *i.e.* wavelength $\Lambda^+ = 1200$ with $\max v = 0.04$ is considered. Fig. 2 shows typical turbulence statistics for

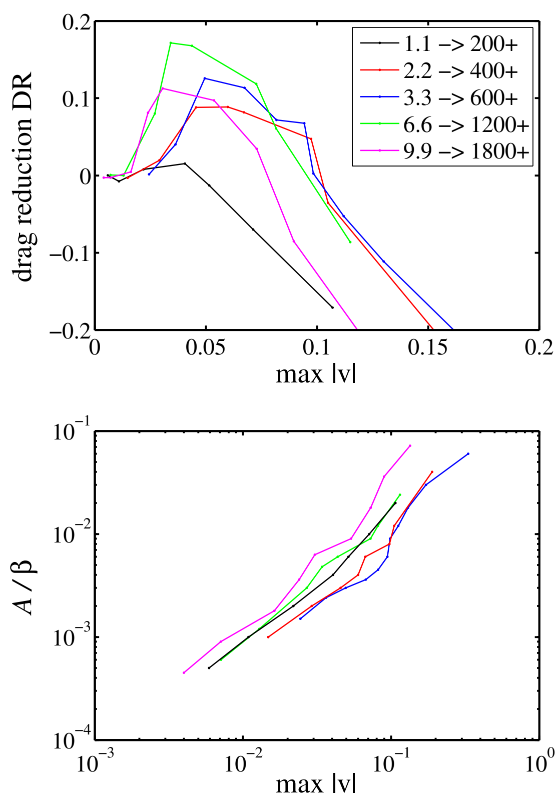

Figure 1. *Top:* Drag reduction (DR) as a function of vortex strength, measured in $\max|\langle v\rangle_{x,t}|$, for 5 different vortex wave lengths $\Lambda = 2\pi/\beta$. *Bottom:* Forcing amplitude A/β necessary for a vortex of certain strength.

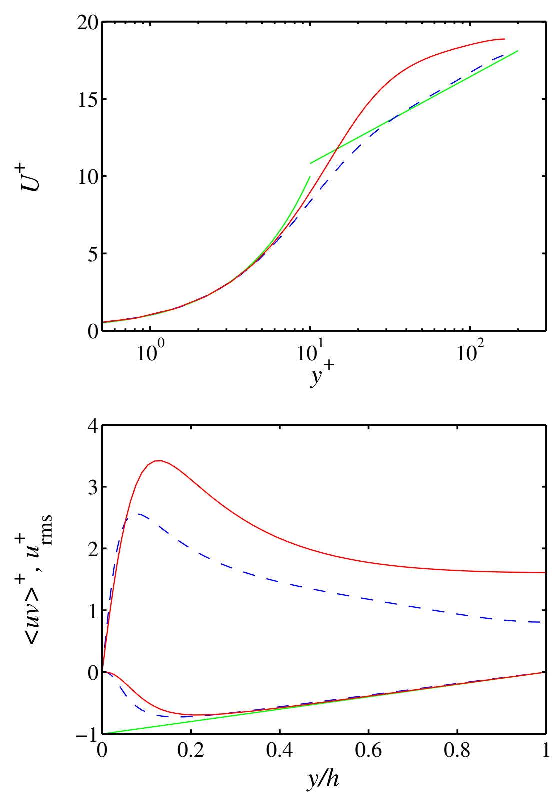

Figure 2. Mean velocity profile $U^+(y^+)$ and selected stresses. Uncontrolled channel flow at $Re_\tau = 180$ (dashed), highest drag reducing case ($\Lambda^+ = 1200$, solid). The green solid line denotes law of the wall and linear shear stress relation. Scaled in respective plus units.

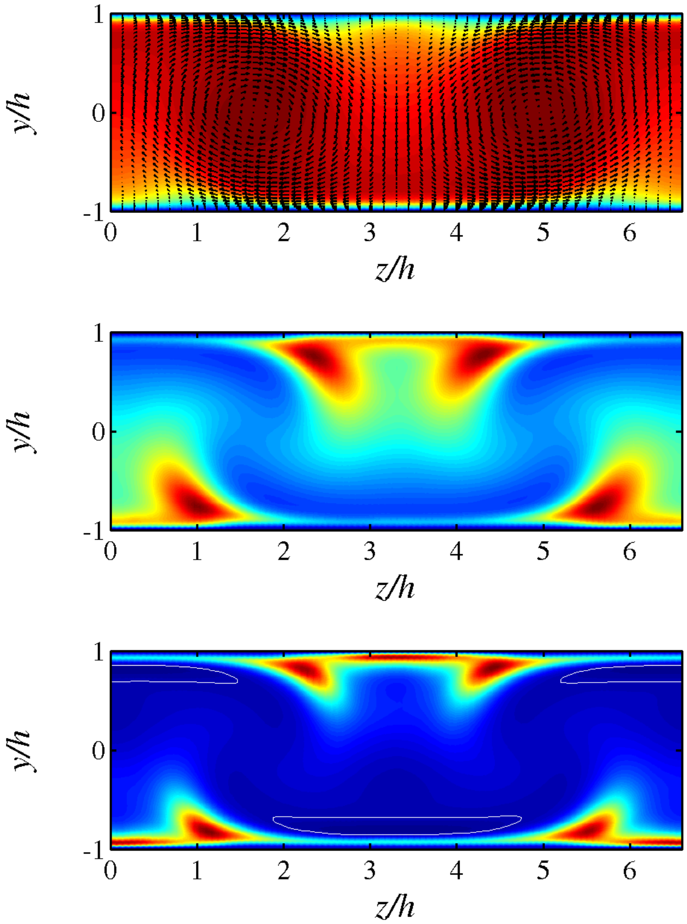

Figure 3. Two-dimensional $y-z$ planes showing (*top*) streamwise velocity and superimposed in-plane vectors, (*middle*) turbulent kinetic energy k, (*bottom*) turbulent production $\mathscr{P}$; the white contour encloses negative $\mathscr{P}$.

both controlled and uncontrolled case. The velocity profile becomes more uniform in the channel centre (indicated by a lower slope for high wall distances), which is clearly due to the increased wall-normal momentum exchange induced by the vortices. At the same time, the inner-scaled fluctuations are increased by the control, but pushed further away from the wall. The same effect can also be seen in the Reynolds shear stress $\langle uv \rangle$, which is still approaching the linear relation, but only for larger wall distances; close to the wall the shear stress is clearly lower.

Due to the spanwise inhomogeneity of the imposed vortices, better insight can be gained by considering statistics averaged only in the streamwise direction and time. Such two-dimensional $y-z$ planes are shown in Fig. 3; featuring the mean flow (top panel), the turbulent kinetic energy k (middle) and the production (bottom). The reason for the increased turbulence activity in the near-wall region becomes now clear; the regions where the in-plane mean flow is directed *away* from the wall are characterised by two local k peaks each. However, the turbulence is lifted from the wall, meaning that these positions feature the lowest local drag. Conversely, the essentially relaminarised regions where the vortex is pushing fluid *towards* the wall exhibit the highest drag; again not due to turbulence, but because of the thin shear layer. It is interesting to note that the production $\mathscr{P}$ reaches moderately negative values (*i.e.* transport from fluctuations to mean) in exactly those regions.

Finally, Fig. 4 compares three-dimensional instantaneous visualisations of the controlled and uncontrolled flow. Whereas in the uncontrolled case the turbulence activity is homogeneously distributed along the channel walls, the introduction of the vortices leads to the specific regions already discussed. The turbulence activity (visualised by the presence of the vortical structures) is concentrated in the regions with positive wall-normal flow; the regions with splatting motion are void of turbulent fluctuations, but yet have the highest contribution to the wall friction.

The DR plot in Fig. 1 clearly shows that there is an ideal spacing of the vortices. From the results presented here, it becomes clear that this maximum is due to the balance between extending the upwelling regions as much as possible. However, a too large vortex distance establishes as the region between the two fluctuation maxima without noticeable drag reduction, *i.e.* normal wall turbulence.

OUTLOOK

The shown results extend the results by Schoppa & Hussain (1998) by a careful analysis of the whole parameter range (amplitude and wave length). In particular, it was shown that a clear maximum efficiency is reached for the case with $\Lambda^+ = 1200$, which yields a drag reduction of 18%,

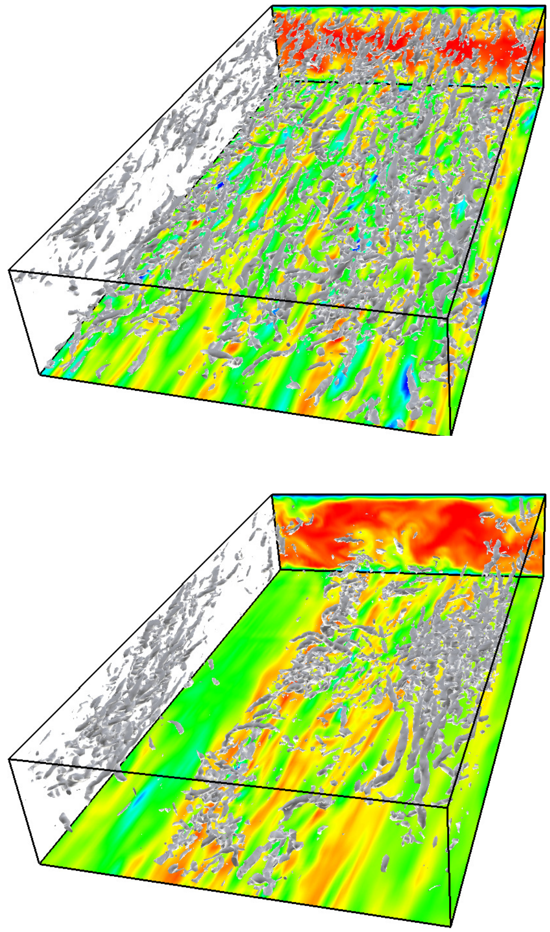

Figure 4. Instantaneous visualisation of the turbulent flow for *top:* uncontrolled and *bottom:* controlled case. The bottom plane shows the wall-shear stress, background plane streamwise velocity, and isocontours of $-\lambda_2$. Note that the lower plane corresponds to $y = 1$.

contrary to the smaller wavelength of $\Lambda^+ = 400$ suggested as the most efficient vortex in Schoppa & Hussain (1998). Future work is required to answer the question whether the present control scheme is also applicable for channel flows at higher Reynolds numbers, and how the optimal parameters change. However, the most important step towards practical usage of this large-scale control is by considering spatially developing boundary layers, which are modulated by such streamwise vortices.

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