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SPANWISE WALL OSCILLATION IN A DAMPED CHANNEL FLOW FOR TURBULENT DRAG REDUCTION

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INTRODUCTION

Turbulent skin friction drag reduction is a longstanding objective in fluid mechanics research. Over the years, various flow control techniques, both active and passive, as well as open-loop or closed-loop, have emerged. Among all the possible techniques, the oscillating wall (OW) stands out for its effectiveness. OW is an active method that is capable of positive net energy savings. Moreover it is conceptually simple as requires no feedback from the flow.

With OW, the wall moves periodically, with period T, in the spanwise direction according to $w_w(t) = A\cos(\omega t)$, where w_w is the spanwise velocity at the wall, A the oscillation amplitude and $\omega = 2\pi/T$ the oscillation frequency. This wall oscillation is able to create the so-called Stokes layer, whose interaction with the near wall turbulence reduces friction drag.

There is broad consensus that an optimal oscillation period exists which maximizes drag reduction. For simulations at constant flow rate, this optimal period is $T^+_{opt} \approx 100$, when scaled with the viscous units of the uncontrolled flow. However there is no shared view to interpret this optimal value and the drag reduction mechanism in general. However, several ideas regarding the working mechanism of the OW technique suggest that turbulent structures may play a central role. For instance, the optimal period may be linked to characteristic timescales of near-wall turbulence. T^+_{opt} could be related to a convective time scale derived from the ratio between the typical length of near-wall streaks and their convection velocity. In an unmodified channel flow, these values are approximately $\lambda^+_x = O(10^3)$ and $U^+_{conv} = O(10)$ at a location consistent with the location of the streaks. This would result in $T^+_{opt} \approx \lambda^+_x / U^+_{conv} \approx 100$. Whether or not the coincidence of this time scale with the optimum forcing period is physically significant remains an open question [5]. This time scale is obviously not the only option, several others are possible, for instance [1] calculated the streak amplification time and tried to relate it to the optimal period of the forcing.

In this work, we take inspiration from the work by [2], where the longest turbulence structures in a turbulent channel flow were artificially damped to understand the importance of long streaks in near-wall turbulence dynamics. The OW technique is applied here to a damped channel flow, characterized by an altered turbulence in terms of length scales and time scales, in an attempt to elucidate the role of near wall turbulence time scales in the working mechanism of the OW.

METHODS

We consider DNS of a channel flow at $Re_b = U_b h/\nu = 10000$, where U_b is the bulk velocity, h half the height of the channel and ν the kinematic viscosity. This corresponds to $Re_\tau = u_\tau h/\nu \approx 550$ for the unmodified and unforced case, where u_τ is the friction velocity. In the following x, y and z represent respectively the streamwise, wall-normal and spanwise directions, while u, v, w represent the corresponding velocity components. The employed code solves the Navier–Stokes equations in the $v - \omega_y$ formulation, employing Fourier expansion in the homogeneous directions x and z and compact finite differences in y.

To damp the system a filter, similar to the one employed in [2], is used. At each time step, the filter explicitly zeroes all the Fourier modes of the wall-normal vorticity, $\hat{\omega}_y$, characterized by a streamwise wavelength above a threshold $\lambda_{x,f}$ as

$$\hat{\omega}_y(k_x, y, k_z) = \hat{\omega}_y(k_x, y, k_z)F(y) \quad \forall k_z, \quad k_x < 2\pi/\lambda_{x,f} \quad (1)$$

where $F(y)$ is a function that is either 0 or 1 and allows to control the y location where the damping is applied.

The OW technique is applied in comparative form to the reference damped/undamped case: the oscillation amplitude is kept fixed at $A^+ = 12$, while the oscillation period is varied from $T^+ = 25$ to $T^+ = 200$. Two different sets of experiments of damped turbulence are performed. In one case, only the near-wall flow is damped, i.e. $F(y) = 0$ for $y^+ < 60$ and $F(y) = 1$ otherwise. In the other, only the outer flow is damped. The specific wall distance $y^+ = 60$ is chosen after [3], who showed that below $y^+ = 60$ wall turbulence survives autonomously. Multiple simulations are performed by varying the parameter $\lambda_{x,f}$ in (1), e.g. by filtering modes with different wavelengths. The obtained modified turbulence is then characterized via relevant time scales for the streamwise velocity component u. In particular, following [4], we compute the space-time autocorrelation function to extract the typical Eulerian and Lagrangian time scales of the flow at the y position where the streamwisse velocity fluctuations are most intense. These two time scales will be referred respectively as $T^{+,E}_u$ and $T^{+,L}_u$, these will be always expressed in + units but the superscript will be dropped in the following for clarity. T^E_u and T^L_u can be interpreted respectively as the time a turbulent structure take to completely pass over a fixed point and as the life-time of a turbulent structure itself.

Since damping by itself reduces the turbulent friction, it is important to point out that the superscript + indicates, as usual, scaling in viscous units computed with the friction velocity of the case without OW, and additionally that the friction velocity is the one of the damped simulation itself.

RESULTS

One reference undamped simulation was carried out, while six damped simulations without OW were performed, three cases filtered near the wall and the remaining three far from the wall. Table 1 summarizes all the results for the reference simulations in terms of Re_τ and time scales. It reports also the value of $\lambda_{x,f}$ for the damped simulations. Ref indicates the reference undamped simulation, I-2, I-3 and I-4 are the simulations where the inner flow at $y^+ < 60$ is damped, and $\lambda_{x,f}$ is chosen to damp the second, third and fourth longitudinal wavenumber. Correspondingly, O-2, O-3 and O-4 are the simulations where the outer flow is damped.

	$\lambda_{x,f}/h$	$\lambda^+_{x,f}$	Re_τ	T_u^E	T_u^L
Ref	-	-	545	20.9	80.8
I-2	3.14	1624	517	6.2	28.7
I-3	2.09	1043	498	4.9	24.2
I-4	1.57	742	473	4.0	20.3
O-2	3.14	1494	476	15.7	51.6
O-3	2.09	913	437	15.7	51.6
O-4	1.57	602	384	13.6	46.0

Table 1: Results in terms of Re_τ and time scales for all the seven reference simulations. Ref is the reference undamped simulation. For the reference damped simulations I-2, I-3, I-4 (filtered near the wall) and O-2, O-3, O-4 (filtered far from the wall) also the value of the threshold $\lambda_{x,f}$ is reported.

As expected [2], increasing the number of damped modes, i.e. reducing $\lambda_{x,f}$, leads to a reduction of Re_τ, yet all cases remain fully turbulent. Damping far from the wall results in a lower Re_τ compared to damping near the wall. This can be explained by the greater volume damped if the filter is applied far from the wall.

Calculated values for of T_u^E and T_u^L for the reference flow are in accordance with [4]. Damping has a significant effect on the time scales: T_u^E and T_u^L are reduced, especially for the inner damping. Indeed, directly filtering the near-wall region reduces the streamwise extent of near wall turbulent structures, that must be shorter than $\lambda^+_{x,f}$, which immediately translates in a decrease of T_u^E for the inner damping. Instead, outer damping shows a minor effect on the time scales.

Moving on to the application of the OW, Figure 1 plots the results of the small parameter studies carried out for each of the seven cases discussed above, in terms of the percentage drag reduction $DR\%$ obtained at various oscillation periods T^+. $DR\%$ is defined as $DR\% = 100\frac{C_{f0}-C_f}{C_{f0}}$, where C_{f0} is the skin friction coefficient of the reference simulation and C_f is the one of the forced simulation.

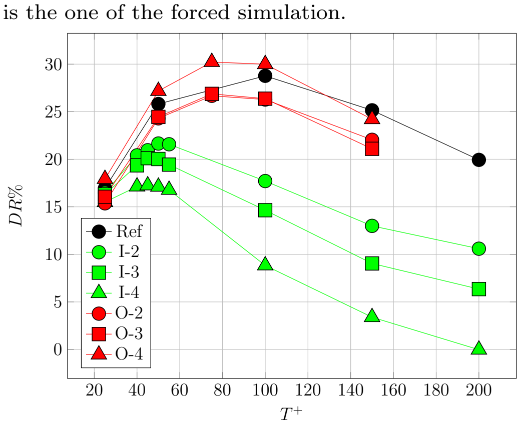

Figure 1: $DR\%$ as a function of the forcing period T^+.

The optimal forcing period T^+_{opt}, as visible from Figure 1, shifts towards smaller periods, if the reference simulation is damped. As expected, for the undamped case $T^+_{opt} \approx 100$. The inner damping decreases it to $T^+_{opt} \approx 50$, while outer damping yields $T^+_{opt} \approx 80$. Another relevant change is the maximum $DR\%$ attainable. Compared to the undamped case, $DR\%_{max}$ is always smaller for inner damping, as part of the drag reduction margin is already taken away from the damping. Differently, with outer damping $DR\%_{max}$ tends to increase. This may be linked to a Reynolds effects, as the decrease in Re_τ causes the OW to become more effective.

The shift of T^+_{opt} towards shorter periods may be linked to the decrease in the time scales of turbulent structure near the wall. As shown in Figure 2 there is a general trend of decreasing of T^+_{opt} accompanied by a reduction in both Lagrangian and Eulerian time scales.

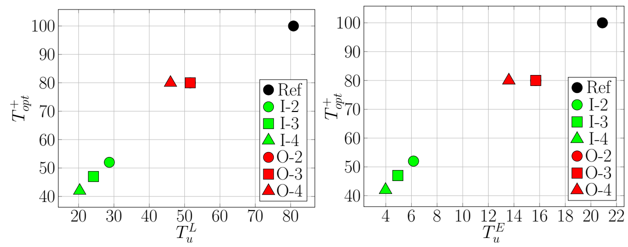

Figure 2: Left: trend of T^+_{opt} against the Lagrangian time scale T_u^L. Right: trend of T^+_{opt} against the Eulerian T_u^E. O-2 and O-3 markers are superimposed.

As illustrated in Figure 3, this trend does not follow a linear pattern. The ratio between T^+_{opt} and the time scales increases as the life scale decreases, suggesting that faster dynamics of near-wall turbulence require a slower control.

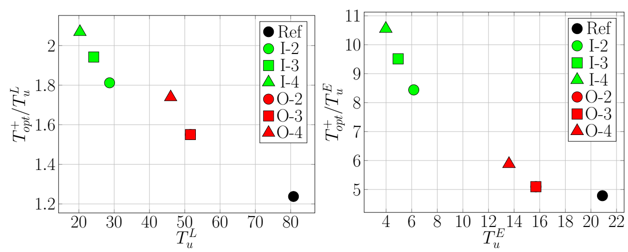

Figure 3: Left: trend of T^+_{opt}/T_u^L against the Lagrangian time scale T_u^L. Right: trend of T^+_{opt}/T_u^E against the Eulerian time scale T_u^E. O-2 and O-3 markers are superimposed.

Further research is ongoing to clarify the physical relevance of the presented patterns and whether one time scale (Lagrangian or Eulerian) prevails over the other.

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