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ON-OFF PUMPING FOR DRAG REDUCTION IN A TURBULENT CHANNEL FLOW

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INTRODUCTION

A set of demanding Direct Numerical Simulations is employed to assess whether a pulsating pressure gradient with a simple on/off waveform can yield energetic advantages with respect to its steady counterpart.

The steady injection of power into a pumping system is only one of the possibilities available to force a fluid flow into a duct, and not necessarily the most convenient. Since periodically driven currents are frequently found in nature, we are lead to wonder if those may provide some energetic advantage. The assessment of such an advantage — that we call drag reduction for short — requires care, as the very concept of drag reduction becomes elusive in this context: a clear reference flow to compare to is lacking. Inspired by the work of Frohnapfel, Hasegawa and Quadrio [1], we therefore introduce a proper metric to quantify the savings derived from the use of an unsteady on/off forcing.

A family of step-wise wave-forms, generated varying the amplitude, the duty-cycle of the pump and the period of the on/off cycle, is explored. Few similar studies exist, and it has been recently proven [4] that the parameters above are crucial for the effectiveness of the control. In general such wave forms are described by three parameters, but we reduce their number to two by linking the duty cycle ξ and the amplitude of the "on" stage, which is set at $1/\xi$. Even within this limitations, we unequivocally demonstrate that a net gain is possible: significant energy savings may be achieved by driving the flow through intense but brief surges of pumping power, followed by much longer periods of deceleration in which the pump is turned off. The flow alternately visits the turbulent and the laminar regimes, and this is the key reason for the energetic advantage.

A preliminary understanding of the turbulent structures governing the unsteady dynamics of the cyclic transition process is fundamental for the success of the control, which would otherwise remain at an empirical level. Similar structures have already been analysed [2]: after a quasi-step-wise increase of the flow rate, the usual low-speed streaks undergo a significant stretching, followed by the appearance of new turbulence in concentrated spots. However, to the best of our knowledge, no one has ever considered an acceleration that ends before the appearance of such spots. This is the scenario that we are set to investigate.

METHODS

Our numerical experiments simulate the flow of an incompressible Newtonian fluid among the walls of a planar channel. Such flow is described by the classic Navier–Stokes equations, here made dimensionless with the flow variables of a turbulent uncontrolled reference channel flow at $Re_\tau = 180$.

The external forcing is an homogeneous, time-dependent streamwise pressure gradient $\Pi(t)$. Its waveform (represented in figure 1) is a simple on/off step-wise pulsation. That is completely determined by three parameters, namely the period, T, the duty-cycle, ξ, and the amplitude, which becomes $\frac{1}{\xi}$ under the additional constraint that the integral of the pressure gradient over one period equals that of the steady reference case.

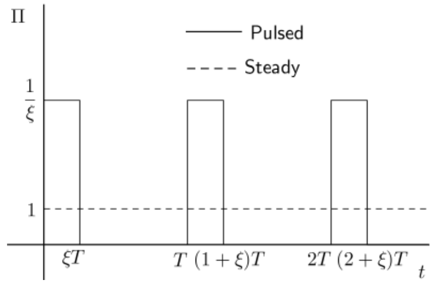

Figure 1: Pictorial representation of the forcing employed

The equations of motion are solved with an efficient in-house code (named Fujin), capable of second-order accuracy thanks to central finite-differences in space and Adams-Bashfort's method in time. Key results of this code are validated by re–running the relevant cases with a different DNS code [5], which uses mixed discretization, employs Fourier modes in the homogeneous directions and integrates in time with different schemes.

Having defined the forcing and its parameters, a proper metric is now needed to evaluate its performance. In order to carry out a meaningful analysis, a single controlled case needs to be compared not only to the steady-state reference one, but also to all the turbulent uncontrolled cases possible. Such idea lays at the base of the approach suggested in [1]. There, the authors represent in the so-called money-time plane the pumping energy E required to drive a certain amount of flow through a straight duct versus the quantity $1/U_b$, which represents the time for a fluid particle to travel a unit length, referring the first variable as "money" and the (inverse of) the second as "time" or "convenience". A natural turbulent flow is described by a point on this curve, which moves depending on the Reynolds number. The curve can be drawn by e.g. choosing the Blasius' correlation to relate the friction coefficient C_f with the Reynolds number, so that $C_f \propto U_b$ and $E \propto U_b^{7/4}$. By adding the laminar line, for which $C_f \propto 1/U_b$ and $E \propto U_b$, the plane is partitioned in three regions (as in figure 2). Theoretical arguments ensure that it is impossible (even with active flow control, if control power is accounted for) to reach below the laminar line, and the goal of flow control becomes achieving a flow represented by a point that sits below the turbulent line.

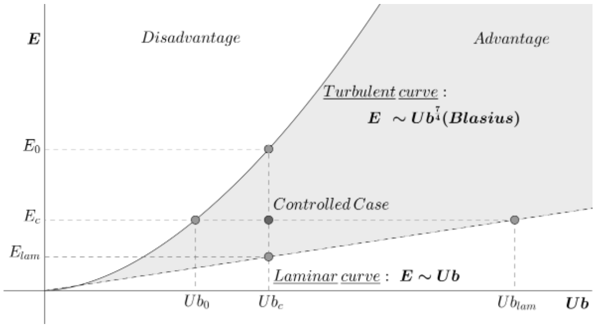

Figure 2: The money-time plane. Adapted from [1].

RESULTS

Our parametric study covers three values for the period and six values for the duty cycle, hence a total of 18 parameter pairs. Inspired by the work of Iwamoto et al.[3], we have set them to $T^+ = 3600, 10800, 14400$ and $\xi = 0.005, 0.0125, 0.025, 0.0375, 0.05, 0.1$.

Results computed on the largest domain, which provide the most interesting performance and have all been checked for spurious discretization effects, are first plotted as circles in figure 3. There, a non-dimensional version of the money-time plane is employed: energy, represented by $C_f Re_b^2$, is plotted against Re_b. Squares, instead, refer to the results obtained in [3] and [4]. The results correspond to a configuration where 512 points are employed in the homogeneous directions and 160 in the wall-normal one, distributed in a domain of size $6\pi \times 3\pi \times 2$. All the simulations at $T^+ = 14400$ with $\xi \geq 1.25\%$ denote savings both in terms of energy and time.

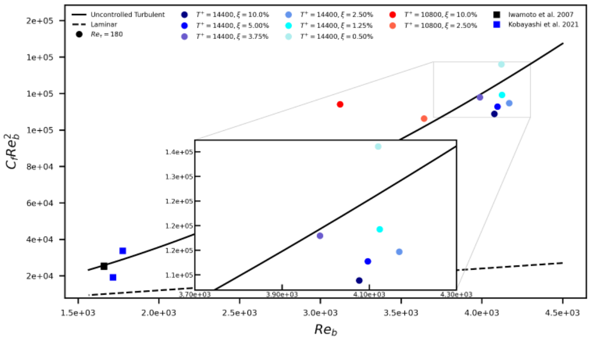

Figure 3: Results plotted in the money-time plane.

The success of our control descends from the repeated transition among a quasi-laminar and a fully turbulent state. The random breakdown to turbulence is marked by a sharp change in the decrease rate of the instantaneous U_b during the "off" period of the forcing, where no pressure gradient is driving the flow (point B in figure 4). A partial re-laminarization is attained at the end of the acceleration phase (point A in figure 4). Between A and B, the flow dynamics is dominated by intense anomalous streaks, whose instability and sudden breakup leads to turbulence. The ability to control their lifetime and intensity is essential to achieve successful control.

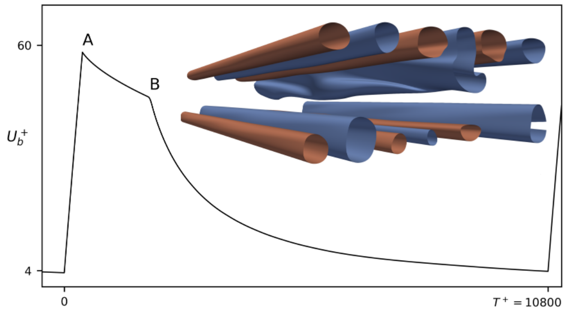

Figure 4: Bulk velocity during one forcing period. Inset: positive (red) and negative (blue) contours of the streamwise velocity fluctuations in the early decay (between A and B).

Our results are relevant as a proof of concept, to unequivocally demonstrate that it is possible to do better than injecting pumping power steadily into the system. So many possible choices exist for the control parameters, that it is currently difficult to comment on the true potential of the technique. At the Meeting, we will describe our results in full and elaborate on their scaling. We will also provide details on the flow structures that appear in the re-transition process and grow through a peculiar instability mechanism, in the hope that their understanding will be essential to drive further research in this subject.

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