DIRECT NUMERICAL SIMULATION OF TURBULENT WALL FLOWS AT CONSTANT POWER INPUT

Yosuke Hasegawa[1], Bettina Frohnapfel [2] & Quadrio Maurizio [3]
[1] *Institute of Industrial Science, University of Tokyo, Meguro-ku, Tokyo, Japan*
[2] *Institute of Fluid Mechanics, Karlsruhe Institute of Technology, Germany*
[3] *Dipartimento di Scienze e Tecnologie Aerospaziali - Politecnico di Milano, Italy*

Abstract We propose a new flow condition for conducting DNS of internal flows: Instead of keeping either a flow rate or a pressure gradient constant the new simulation approach is to maintain the *total power input*, at a constant value. This new condition is closer to a practical situation where the power input, i.e. the product of flow rate and pressure drop (and not flow rate or pressure drop independently), is given by a pump for example. From the flow control point of view, the constant power input approach is the most suitable approach for an energetic analyses of flows with/without control.

BACKGROUND & OBJECTIVES

Typically direct numerical simulations (DNS) of turbulent wall flows are carried out while keeping constant in time either the flow rate (CFR) or, less often, the pressure gradient (CPG), under the generally acknowledged assumption that the statistics of the flow are insensitive to this arbitrary choice. However, this apparently uninfluential choice becomes critical when drag-redution techniques are applied to turbulent channel or pipe flows. Under the CFR condition, a successful drag reducing technique reduces friction drag, which immediately translates into a reduction of the pumping power. One important drawback of the CFR constraint is that the wall shear stress, which is a dominant factor in near-wall turbulence dynamics, is changed due to the applied control, so that it is difficult to extract the essential effects of a control input itself owing to superimposed Reynolds number effects. On the other hand, when the CPG condition is used, friction drag is unchanged by design, and 'drag reduction' manifests itself through an increase of the flow rate, which implies an increase in the power required to drive the flow.

Recently, we introduced a novel way of assessing the energetic performance of flow control techniques by explicitly accounting for the total power spent for pumping and control (Frohnapfel et al. (2012)). The presented energy-convenience plane allows the designer to weight the energetic cost of the applied control against the increased performance, that is observed through an increased flow rate. This evaluation plane graphically emphasizes that besides CFR and CPG, many different routes link an uncontrolled turbulent state to the laminar flow state, which is the ultimate goal in drag reduction control. Among these various routes, the one of constant power input (CPI) is an alternative that puts the energetic advantage of laminarizing the flow into an interesting perspective: at a Reynolds number of 75000 relaminarisation corresponds to the total energy savings of 86% for CPI while stunning 50 times larger flow rate will be reached for CPG. In addition to this novel evaluation perspective that might be useful in judging the potential economical benefit of (active) flow control techniques, the CPI approach provides an interesting tool for the fundamental analysis of turbulent flows and their control. If we assume that an analysis of the energy flow through the system and its modifications in flow control can teach us something about the physics of turbulence itself and possibly allow generalized statements on how to efficiently control a flow, we need to be able to compare different flow control scenarios at the same energy flux and dissipation rate. This is basically impossible to realize with CFR or CPG but straightforward to implement with the CPI approach.

The aim of the present study is thus to introduce CPI as a physically sound strategy to carry out numerical experiments. We show how the CPI approach naturally leads to identifying a characteristic velocity scale, based on the power consumption, and thus a related Reynolds number. In this way it becomes natural and easy to carry out DNS under the CPI condition. First results for CPI in controlled flows are presented.

DNS AT CONSTANT POWER INPUT (CPI)

We consider one of the simplest canonical flows, namely a fully developed turbulent plane channel flow. For a given total input power P_t^*, the corresponding mass flow rate becomes maximum when the streamwise velocity profile becomes the laminar parabolic profile. In this case, the upper limit U_p^* of the bulk mean velocity is given by:

$$U_p^* = \frac{1}{3\mu^*}\left(-\frac{dp^*}{dx^*}\right)\delta^{*2}. \tag{1}$$

In a fully developed flow state, the total power input to the flow system balances the dissipation rate of the total kinetic energy of the flow. This leads to the following relationship between P_t^* and U_p^*:

$$P_t^* = \int_{-\delta^*}^{\delta^*} \mu^* \left(\frac{du^*}{dy^*}\right)^2 dy = \frac{6\mu^* U_p^{*2}}{\delta^*}, \tag{2}$$

so that the maximum achievable flow rate with the given total power input is given by:

$$U_p^* = \sqrt{\frac{P_t^* \delta^*}{6\mu^*}}. \tag{3}$$

Hence, the objective of flow control under the CPI condition is to increase the bulk mean velocity towards U_p^*.
Considering that Eq.(3) provides a unique velocity scale at given P_t^*, it is straightforward to normalize all quantities by U_p^* and the channel half width δ^*. Then, a newly-defined Reynolds number is given by $\mathrm{Re}_p = U_p^* \delta^* / \nu^*$, where ν^* is the kinematic viscosity of fluid.
Accordingly, the dimensionless total power input is given by:

$$P_t = \frac{P_t^*}{\rho^* {U_p^*}^3} = \frac{6}{\mathrm{Re}_p}. \tag{4}$$

In a CPI simulation P_t^* (and thus Re_p) is prescribed. In case of actively controlled flows, the sum of the pumping power and the control power, i.e., $P_t^* = P_p^* + P_c^*$, must be adjusted so as to satisfy Eq.(4) at every time step. The bulk mean velocity and the mean pressure gradient are obtained as a result of the computation. The ratio between the resulting U_b^* and U_p^* will be smaller or (in the ideal case) equal to unity and the increase of U_b^* can be used as a measure of the control performance.
One important parameter characterizing a control regime is the ratio of the control and pumping power inputs, i.e., $\gamma = P_c^*/P_p^*$. As an application of the CPI concept to flow control, we consider the well-known spanwise oscillating wall technique. The resultant flow rate at different γ under a constant oscillation frequency is shown in Fig. 1. The oscillation frequency is determined based on the optimal value under the CFR condition reported in Quadrio & Ricco (2004), and the oscillation amplitude is systematically increased to scan a wide range of γ. The oscillation wall is confirmed to possess a parameter range where the optimal share between pumping and control power yields an increase in the flow rate. This range, which is $0 < \gamma < 0.3$, identifies the region in parameter space where the oscillating wall yields positive gain. The optimum region covers a range centered around $\gamma \approx 0.1$, meaning that the optimal use of a given power is to employ 90% of the available amount for pumping and the reminding 10 % for the control. The maximum control-induced increase of the flow rate is rather small, of the order of 3 %, and this is in agreement with previous information that the maximum net power saving is about 7 % (Quadrio & Ricco, 2004). Note that other control schemes have higher net power savings and are therefore expected to further increase the bulk mean velocity if the control mode is properly chosen. In the final paper, the control performance of various flow control schemes will be reevaluated and their drag reduction mechanisms will be investigated through energy flow analysis.

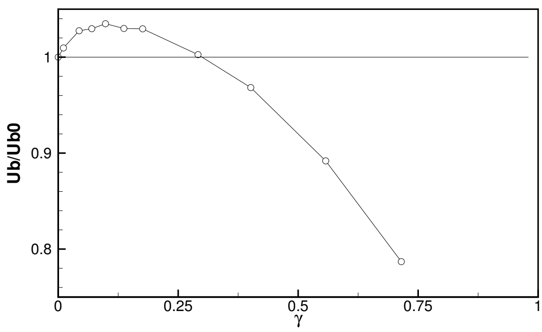

Figure 1. Variation of the flow rate U_b over the uncontrolled value U_{b0} as a function of the share γ of the available power between pumping power and control power provided to the oscillating walls.

References

[1] B. Frohnapfel, Y. Hasegawa, and M. Quadrio. Money versus time: evaluation of flow control in terms of energy consumption and convenience. *Journal of Fluid Mechanics* **77**: 406–418, 2012.
[2] M. Quadrio, and P. Ricco. Critical assessment of turbulent drag reduction through spanwise wall oscillation. *Journal of Fluid Mechanics* **512**: 251–271, 2004.