TOWARDS TURBULENT DRAG REDUCTION WITH PLASMA-BASED SPANWISE FORCING – A COMPARISON OF ACTUATION CONCEPTS

Marc T. Hehner[1], Jochen Kriegseis*[1], Nicolas Benard[2], Marios Kotsonis[3], Bettina Frohnapfel[1] and Davide Gatti[1]
[1] Institute of Fluid Mechanics (ISTM), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[2] PPrime Institute, University of Poitiers CNRS, Poitiers, France
[3] Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands

Summary Three distinct concepts of spanwise flow forcing using plasma actuators are synthesised, implemented and compared in terms of their respective advantages and limitations. The three concepts involve either temporal or spatial oscillation of the plasma forcing, ultimately aimed at turbulent drag reduction. All experimental characterization efforts of the respective concepts are discussed in reference to the ISTM duct-flow facility in order to provide the comparison in physical dimensions (as relevant for actuator development and operation) and furthermore in viscous units (as relevant for the control concept in a turbulent channel flow).

BACKGROUND

Across the board of external and internal flow scenarios, the skin-friction drag is one of the key factors to determine the energy expenditure required to perform respective engineering applications. Consequently, numerous research efforts addressed the successful reduction of this contribution of drag and thus achieved meaningful energy savings. Among the different techniques towards turbulent drag reduction [1], Streamwise Traveling Waves (StTW) of spanwise wall velocity have established as one successful approach [2]. StTWs impose a transverse fluid motion on the mean flow by periodic oscillation of the surface, as shown in figure 1 (a). Additionally, the oscillation is periodically modulated along the streamwise direction. The achievable amount of drag reduction can be visualized for particular conditions of Re_τ in a (oscillation-) frequency (f), -streamwise wavelength (λ_x) plane [3]. Experimental studies have shown that StTWs favourably interact with near-wall turbulence and attain great potential for turbulent drag reduction and net energy savings (see e.g. [4-7]). However, the so-far proposed devices mainly involve physical oscillation of the wall, achieved through various mechanical means. These yield high complexity and limited control ability. Resonant effects or mechanical inertia of physically oscillating walls bound the maximum oscillation frequency, thus limiting applicability to a narrow range of typically relatively low Re_τ.

Plasma actuators are a type of electrical flow-control device of less complex structure than their mechanical alternatives. They can be configured to mainly induce wall-parallel momentum in the vicinity of the surface, providing a promising alternative to pure in-plane wall movement. Finally, they are based on electrical rather than mechanical principles, thus having the potential for high-frequency operation. Pioneering efforts by Wilkinson [8] and Jukes *et al.* [9] have laid the necessary foundations for advanced concepts to accomplish plasma-based drag reduction. Recent experimental proof-of-concept studies by Hehner *et al.* [10, 11] and Benard *et al.* [12] demonstrated the feasibility of concepts to produce particular kinds of virtual StTWs by a spanwise forcing; see figures 1 (b) and (c), respectively.

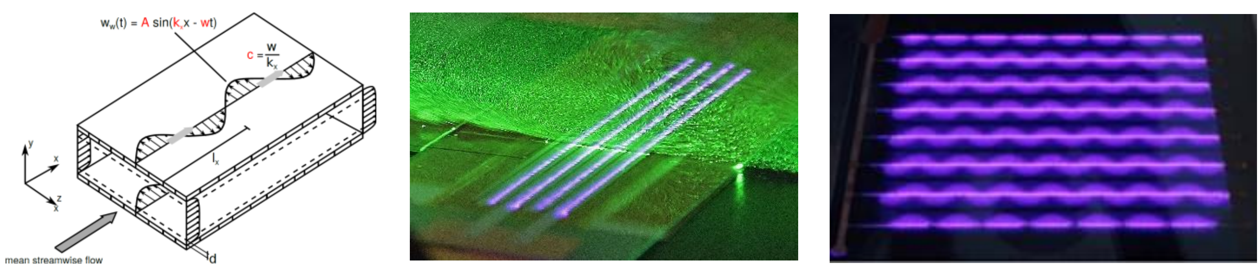

Figure 1: StTW of spanwise wall velocity. (a) Duct section and wall-velocity profile $w(x)$ of StTW. Reproduced from [6]. Spanwise forcing in (b) for virtual wall oscillation [10,11] and in (c) for (streamwise) standing waves [12] of virtual spanwise wall velocity.

OBJECTIVES

Due to the flexibility and large parameter space of plasma actuators, several concepts for efficient and effective StTW generation have been brought forward recently. The objective of the current work is to draw a comparison of the available actuation concepts for plasma actuators [10-12] through a well-documented common test case and elaborating advantages and disadvantages, relevant concept characteristics and Re_τ limitations. The drag-reduction map (f, λ_x-plane), presented by Gatti & Quadrio [6], spans two degrees of freedom for StTWs, which particularly lead to two special cases of (i) a purely temporal oscillation with $\lambda_x \rightarrow \infty$ and (ii) a standing wave in space without temporal oscillation, i.e. $f = 0$.

On the one hand this map provides a clear guideline for promising parameter combinations for successful flow control – on the other hand, however, this parameter space scales in viscous units, which closely relies on the considered test case

*Corresponding author E-mail: kriegseis@kit.edu

and, furthermore, requires a careful translation to physical dimensions, since the latter is the relevant parameter space for development, operation and control of either plasma-actuator concept. As such, the present contribution particularly elaborates the proper choice of control parameters from either perspective: flow requirements (in viscous units) and the actuator requirements (in physical units). This combined evaluation leads to a clear guideline for promising parameter combinations, which match the requirements from both perspectives. It is foreseen that all concepts are eventually applied, tested and evaluated in the ISTM duct-flow facility [6].

ACTUATION CONCEPTS FOR SPANWISE FORCING

Hehner *et al*. recently introduced two concepts for virtual wall oscillations with plasma actuators [10,11], both of which maintain a spanwise oscillatory forcing to virtually mimic wall oscillations. The so-called *burst* concept [10] individually operated various groups of electrodes in pulsed mode, where the duty-cycle (DC) and corresponding oscillation frequency f, and the force magnitude F can be adjusted precisely. The major drawback of the *burst* concept is the comparably fast material degradation of the dielectric due to continuous switch-on and -off events. The so-called *beat* concept is applied with the identical electrode array, but operated in a totally different way. In order to minimize the dielectric wear, the *beat* concept avoids any duty cycles, where all groups of electrodes receive a high-voltage signal at slightly different plasma frequencies, such that the resulting beat frequencies between the electrode groups lead to an effective duty-cycle frequency f. The advantage of a "mild" plasma operation comes with the price that the formerly independent control parameters of effective DC and forcing magnitude F are inherently coupled to the supplied high voltage for the beat concept. Benard et al. [12] introduced a plasma actuator that is capable of producing a virtually standing wave of spanwise velocity in the streamwise direction, as shown in figure 1 (c). This effectively *convective* oscillation concept works with steadily operated plasma discharges and only one group of high-voltage electrodes. In contrast to the electrical simplicity of this concept (at least in comparison with the *burst* and *beat* concepts), an accurately designed electrode shape along the main flow direction is of utmost importance for a successful operation of the *convective* concept. Particularly, the actuator design and operation have to match the optimal wavelength λ_x and forcing magnitude F for the respective Re_τ.

For the *burst* and *beat* concept the applicable Re_τ reaches an upper limit when the decreasing oscillation period cannot be compensated with an increase of the forcing magnitude. For the *convective* concept, Re_τ is limited by both a constructive and flow-characteristic confinement. The decreasing λ_x may lead to either too small geometric dimensions of the plasma actuator or to collapse of the induced standing wave. The main difference in the applicability of the three concepts is the adaptability of the control to the flow conditions. While for the standing wave the range of Re_τ at which drag reduction can be achieved is predetermined by the locked streamwise wavelength λ_x, the frequency of oscillation can be individually tuned for the *burst* and *beat* concept. Therefore, variable flow conditions can be considered for the latter applications, where a change of the oscillation frequency additionally requires an adjustment of the forcing amplitude.

Since all actuator concepts are scheduled to be evaluated in the channel-flow facility at ISTM [6], the actuator-parameter space will be converted into viscous units as apply for this wind tunnel, where skin friction is determined accurately via pressure-drop measurements. The test-section half height is $h = 12.6$ mm and the possible Reynolds number range is $200 < Re_\tau < 2500$.

The interplay of the influencing factors and control parameters will be comparatively discussed and evaluated along the drag-reduction map [3] as function of the possible Re_τ range of the ISTM test facility.

References

[1] Corke, T. C., Thomas, F. O. "Active and Passive Turbulent Boundary-Layer Drag Reduction". *AIAA J.* **56**, 3835-3847, 2018.
[2] Quadrio, M., Ricco, P., Viotti, C. "Streamwise-travelling waves of spanwise wall velocity for turbulent drag reduction," *J. Fluid Mech.* **627**, 161-178, 2009.
[3] Gatti, D., Quadrio, M. "Reynolds-number dependence of turbulent skin-friction drag reduction induced by spanwise forcing," *J Fluid Mech* **802**, 553-582, 2016.
[4] Auteri, F., Baron, A., Belan, M., Campanardi, G., Quadrio, M. "Experimental assessment of drag reduction by traveling waves in a turbulent pipe flow," *Phys. Fluids* **22**, 115103, 2010.
[5] Bird, J., Santer, M., and Morrison, J. F. "Experimental control of turbulent boundary layers with in-plane travelling waves," *Flow, Turbul. Combust.* **100**, 1015-1035, 2018.
[6] Gatti, D., Güttler, A., Frohnapfel, B. Tropea, C. "Experimental assessment of spanwise-oscillating dielectric electroactive surfaces for turbulent drag reduction in an air channel flow," *Exp. Fluids* **56**, 110, 2015.
[7] Choi, K.-S., Clayton, B. R. "The mechanism of turbulent drag reduction with wall oscillation," *Int. J. Heat Fluid Flow* **22**, 1-9, 2001.
[8] Wilkinson, S. P. "Investigation of an oscillating surface plasma for turbulent drag reduction," *AIAA paper* **2003-1023**, 2003.
[9] Jukes, T., Choi, K.-S., Johnson, G., Scott, S. "Turbulent drag reduction by surface plasma through spanwise flow oscillation," *AIAA paper* **2006-3693**, 2006.
[10] Hehner, M.T., Gatti, D., Kriegseis, J. "Stokes-layer formation under absence of moving parts – A novel oscillatory plasma actuator design for turbulent drag reduction," *Phys. Fluids* **31**, 051701, 2019.
[11] Hehner, M.T., Gatti, D., Mattern, P., Kotsonis, M., Kriegseis, J. "Beat-Frequency-Operated Dielectric-Barrier Discharge Plasma Actuators for Virtual Wall Oscillations", *AIAA J.*, October 2020.
[12] Benard, N., Bayoda, K.D., Bonnet, J. P., Moreau, E. "Non Homogeneous Streamwise Wall Forcing by Surface Plasma Actuator," *EDRFCM*, 2019.