PLASMA-INDUCED OSCILLATORY FORCES AS A CONCEPT FOR SMALL-SCALE TURBULENCE CONTROL

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INTRODUCTION

Near-wall turbulence manipulation via spanwise wall forcing [1] is a class of effective techniques to reduce skin-frition drag in turbulent flows. It attracts large interest because of the challenging understanding of the drag reduction mechanisms, its conceptual simplicity and promising control performance. The most beneficial technique in the class is streamwise traveling waves of spanwise wall velocity [2], which theoretically achieves a sizeable net-power saving and whose drag reduction capabilities have been confirmed both numerically [3] and experimentally [4]. Spanwise-wall oscillations are the simplest method that is based on periodic in-plane motions of a solid boundary in the spanwise direction. The oscillation generates a spanwise periodic shear layer that favourably interacts with near-wall turbulence and yields drag reduction [5, 6]. To date, most experimental implementations of such techniques either rely on the mechanical movement of the wall or require complex mechanical actuation devices [4, 7, 8]. A notable exception is the work by Ghebali *et al.* [9], who tried to reproduce the shear profile introduced by the wall motion via a particular undulated surface.

Plasma actuators (PAs) promise a comparably simpler design approach, since a mainly wall-parallel momentum [**?** 10] is imparted to the flow without any moving parts.free of moving parts. Accordingly, PAs have lately established in the field of aerodynamic flow control [11]. Furthermore, first successful attempts to mimic wall oscillations with PAs have been shown by Choi *et al.* [12] by means of a series of tri-electrode configurations.

Even though promising as a proof of concept, the chosen arrangement featured a remarkable gap between adjacent actuators, resulting in individually exerted oscillations instead of a coherent spanwise fluid movement. Near-wall turbulence intensity was reduced, however no supporting drag measurements were performed. Thus, the present work aims at developing a novel PA configuration for turbulent drag reduction, which reduced the spanwise inhomogeneity. It is hypothesized that this in turn improves the control authority of the induced periodic spanwise shear layer and consequently leads to an advanced flow control concept to mimic spanwise wall forcing.

PLASMA-ACTUATION CONCEPT

In the present stage of the current project a novel plasma-actuation concept has been developed. Its design reduces the unavoidable spanwise wavelength of the forcing by adjacently placing electrodes on both sides of the dielectric, as presented in figure 1 (a). The AC-DBD plasma actuator is made up of a polyethylene terephthalate dielectric and $10\,\mu$m thick silver electrodes [13]. It requires three high-voltage transformers to power the electrodes (HV1, HV2, HV3) according to the timing diagram in figure 1 (b). This new concept reduces the spanwise wavelength of the forcing by $50\,\%$ compared to [12].

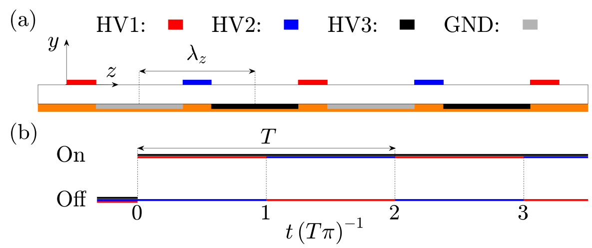

Figure 1: (a) Cross-section view of AC-DBD plasma actuator configuration. High-voltage (HV1, HV2, HV3) and grounded (GND) electrodes are indicated in corresponding color. (b) Signal of electrode power control versus time.

FLOW-FIELD ANALYSIS

The velocity fields from high-speed particle image velocimetry of two distinct opposing phases of one oscillation cycle, indicate an oscillatory motion in the yz-plane; see figure 2. Since the experiment was conducted in quiescent air, the impact of external airflow remains yet to be considered [14]. Any assessment of the flow characteristics with respect to control of small-scale turbulence has, therefore, to be elaborated with carefulness.

For the applied oscillation frequency of 50 Hz, the selection of an air channel flow at $Re_\tau = 250$ (channel height $0.025\,m$) [8] is selected, matching the optimal oscillation period of $T^+ = 125$ [3]. This allows for a non-dimensionalisation to viscous units. From the velocity fields, wall-normal profiles of spanwise velocity $w^+(y^+)$ and shear $\partial w^+/\partial y^+$ were extracted, as shown in figures 3 (a), (b). The profiles reveal both inherent Stokes-layer and shearing action importantly occurring within the sublayer region ($y^+ = 5$). Figures reffig:three (c) and (d) still indicate spatio-temporal distribution of the spanwise velocity. However, a new concept leads to a significantly reduction of such spanwise variations as compared to previous experimental efforts [12]. Furthermore, time, velocity and length scales are found favourable for turbulent flow control.

Magnitude and influence of the wall-normal flow are not

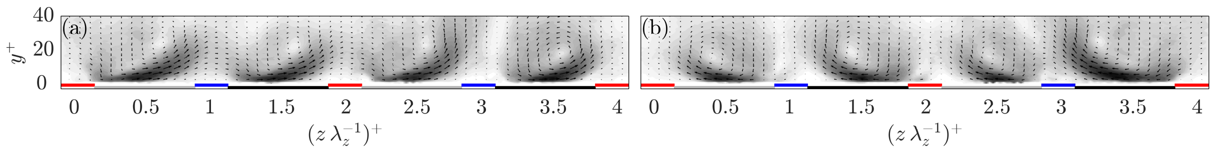

Figure 2: PIV mean fields of spanwise velocity magnitude (0 to 3.5, 29 levels from white to black). (a) $\varphi = \frac{11}{12}\pi$. (b) $\varphi = \frac{23}{12}\pi$.

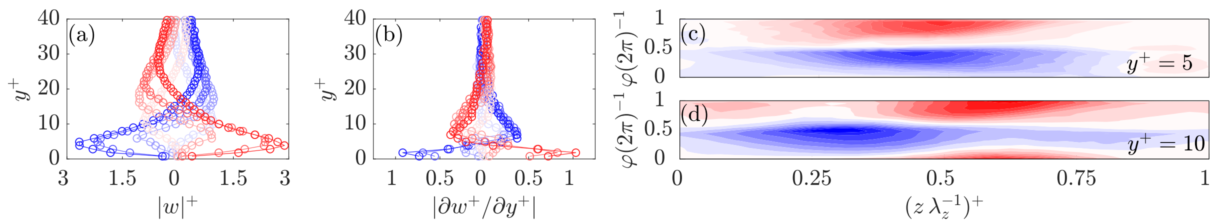

Figure 3: (a), (b) Phase-averaged profiles of spanwise velocity $w^+(y^+)$ and shear $\partial w^+/\partial y^+$ extracted in the center of the encapsulated electrode for eight phase positions. (c), (d) Velocity distribution in the φz-plane for $y^+ = 5$, 10 ($-3.5 < w^+ < 3.5$, 29 level from blue to red).

further evaluated for the quiescent air case, since any external flow will immediately change this weak impact to the overall topology. This airflow influence is foreseen to be investigated in future studies.

CONCLUDING REMARKS

A first estimation of the successfully introduced actuation concept for spanwise plasma oscillation from PIV data in quiescent conditions, is carried out with respect to turbulence control, and gives promising insights into the induced flow characteristics, aimed at mimicking a spanwise-oscillating wall. Near-future campaigns will include another characterisation experiment that involves the effect of external airflow on the oscillation, in order to rate the control mechanism more rigorously.

REFERENCES

[1] M. Quadrio. Drag reduction in turbulent boundary layers by in-plane wall motion. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1940):1428–1442, 2011.

[2] M. Quadrio, P. Ricco, and C. Viotti. Streamwise-travelling waves of spanwise wall velocity for turbulent drag reduction. *Journal of Fluid Mechanics*, 627:161–178, 2009.

[3] D. Gatti and M. Quadrio. Reynolds-number dependence of turbulent skin-friction drag reduction induced by spanwise forcing. *Journal of Fluid Mechanics*, 802:553–582, 2016.

[4] J. Bird, M. Santer, and J. F. Morrison. Experimental control of turbulent boundary layers with in-plane travelling waves. *Flow, Turbulence and Combustion*, 100(4):1015–1035, 2018.

[5] A. Yakeno, Y. Hasegawa, and N. Kasagi. Modification of quasi-streamwise vortical structure in a drag-reduced turbulent channel flow with spanwise wall oscillation. *Physics of Fluids*, 26(8):085109, 2014.

[6] L. Agostini, E. Touber, and M. A. Leschziner. The turbulence vorticity as a window to the physics of friction-drag reduction by oscillatory wall motion. *International Journal of Heat and Fluid Flow*, 51:3–15, 2015.

[7] K. Gouder, M. Potter, and J. F. Morrison. Turbulent friction drag reduction using electroactive polymer and electromagnetically driven surfaces. *Experiments in fluids*, 54(1):1441, 2013.

[8] D. Gatti, A. Güttler, B. Frohnapfel, and C. Tropea. Experimental assessment of spanwise-oscillating dielectric electroactive surfaces for turbulent drag reduction in an air channel flow. *Experiments in Fluids*, 56(5):110, 2015.

[9] S. Ghebali, S. I. Chernyshenko, and M. A. Leschziner. Can large-scale oblique undulations on a solid wall reduce the turbulent drag? *Physics of Fluids*, 29(10):105102, 2017.

[10] N. Benard, A. Debien, and E. Moreau. Time-dependent volume force produced by a non-thermal plasma actuator from experimental velocity field. *Journal of Physics D: Applied Physics*, 46(24):245201, 2013.

[11] J. Kriegseis, B. Simon, and S. Grundmann. Towards in-flight applications? a review on dielectric barrier discharge-based boundary-layer control. *Applied Mechanics Reviews*, 68(2):020802, 2016.

[12] K.-S. Choi, T. Jukes, and R. Whalley. Turbulent boundary-layer control with plasma actuators. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1940):1443–1458, 2011.

[13] S. Yadala, M. T. Hehner, J. Serpieri, N. Benard, P. C. Dörr, M. J. Kloker, and M. Kotsonis. Experimental control of swept-wing transition through base-flow modification by plasma actuators. *Journal of Fluid Mechanics*, 844, 2018.

[14] J. Kriegseis, S. Grundmann, and C. Tropea. Airflow influence on the discharge performance of dielectric barrier discharge plasma actuators. *Physics of Plasmas*, 19(7):073509, 2012.