Phase-resolved body-force estimation of AC-DBD plasma actuator at various airflow speeds

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In the field of active flow control, plasma actuators feature competitive characteristics compared to various strategies, e.g. suction or blowing systems. Minor complexitiy and a wall-parallel momentum impact yield advantages that demonstrated to cover applications in laminar-flow control, separation control and turbulent boundary-layer control. Even though very powerful, in order to improve the physical understanding of a plasma actuator, influential performance-changing effects have to be profoundly investigated.

Alternate-current dielectric-barrier-discharge (AC-DBD) plasma actuators, as the most prominent feature, impart a time-dependent force [1], [2] - in direct correlation to the discharge - that was partially considered as quasi steady [3], [4] which turned out to be an oversimplification of more complex scenarios. The spatial distribution of the body force was mainly based on the assumption of a negligible pressure gradient [5] - valid in quiescent air - within the plasma or on the vorticity transport equation [6]. Direct numerical simulations (DNS), compared the methods by Wilke [5] and Albrecht [6] in both quiescent and airflow environment on the gorunds of an empirical quiescent-air model. Similar force fields were obtained for both approaches in quiescent air, wheareas the neglection of the pressure gradient in the plasma [5] led to a significant deformation of the simulated force distribution in a boundary-layer flow. In contrast, for the vorticity-bases [6], a constancy in the force was found. Dörr & Kloker [7] thus recommended to apply the vorticity transport equation for calculations of the plasma body force in non-zero conditions, due to an anticipated influential pressure gradient. On the experimental side Pereira *et al.* [8] used a load cell to measure the plasma body force in external flow environment. An enhanced force was measured with increasing free-stream velocity, when the actuator was oriented along the mean-flow direction (co flow). However, the increase in force was mainly attributed to change of skin-friction, due to the plasma wall jet. An increase of the measured force for U=50 to 60 m/s was also registered, but could not be readily explained. For the power consumption Pereira *et al.* [8] found no variation with an externally imposed flow, whereas it weakly decreased in the case of Kriegseis *et al.* [9].

To tackle this seeming paradox more rigorously and to interrelate it to the body-force models, the objective of the present work revolves around an in-depth investigation of the immediate interplay of outer airflow and actuator body force. Phase-resolved PIV measurements were performed to determine the time-dependent locally manipulated velocity field by an AC-DBD plasma actuator in co-flow forcing configuration, in a laminar boundary-layer flow of a range of $U = 0$ to 30 m/s. The plasma actutor is equivalent to Kriegseis *et al.* [9] and is made from Kapton and copper as dielectric and electrode material, respectively. The initial analysis was performed according to Debien *et al.* [1] and Kuhnhenn *et al.* [2], considering the available force-determination models [5], [6]. In addition, the discharge capacitance of the actuator (at f = 10 kHz) is directly related to the strength of the integrated plasma body force per actuator length in two Lissajous figures for a free-stream velocity $U = 0$ and 30 m/s.

Figure 1 (a) depicts a slight decrease in the effective capacitance for a constant peak-to-peak voltage, hence a reduction in power consumption, in compliance with the outcomes of Kriegseis *et al.* [9] for that particular actuator assembly. The power consumption, determined by the enclosed area of the Lissajous figure, yields a drop of about 4 % at an airflow velocity of 30 m/s. For statistical signifcance, the cycle-to-cycle standard deviation of the area integral was determined to 1.5 % in maximum amongst all runs. The integral forces per actuator length produced by the plasma actuator were calculated according to a constant rectangular control volume and are shown at 8 phase angles of one AC cycle in Figure 1 (b) for the methods of both Albrecht [6] and Wilke [5]. For Wilke [5] a significant decrease of the force is depicted comparing 30 m/s to quiescent conditions. Only at the initiation of the positive half cycle a minor increase of the force results. For Albrecht [6], similarly, there is a reduction of the integral force, however much less decisive. Furthermore, the increase of the force in the positive half cycle is more distinctive. In rough correspondance to the findings of Dörr & Kloker, the approach of Albrecht suggests a force that is weakly dependent on the outer airflow, whereas for Wilke a strong change in the force integrals amongst all phases is observed. The accuracy of the approach by Wilke remains still unclear, due to the neglected pressure gradient in the plasma. In order to relate the results to the work of Pereira *et al.* [8] a deeper analysis of the time-averaged force integrals remains to be performed in order to accomplish a comparison.

As a final remark this work presents PIV-based results of the phase-resolved body force generated by a plasma actuator in an external airflow that allows to compare the available force-determination models on the basis of experimental data.

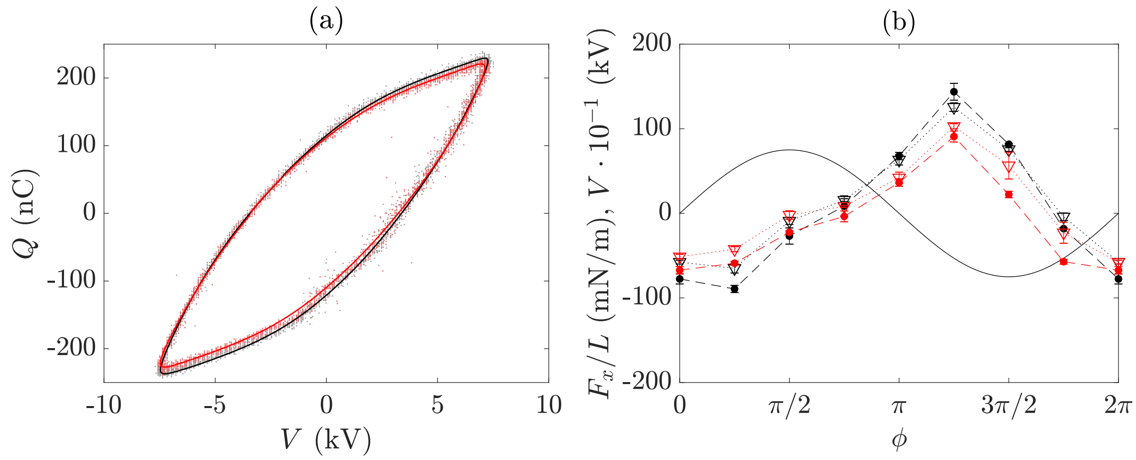

Fig. 1 (a) Lissajous figure for $U = 0$ (black) and 30 m/s (red). (b) Force integral per actuator length for 0 (black) and 30 m/s (red), method of Wilke [5] (solid circles) and Albrecht [6] (open triangles).

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