Abstract In order to understand the time dependent local flow behaviors of a dielectric barrier discharge (DBD) plasma actuator placed in quiescent air, a novel two-component laser Doppler velocity profile sensor (LDV-PS) is applied. The sensor is able to capture the wall-normal as well as wall-parallel velocity component simultaneously while achieving a very high temporal and spatial resolution. The aim is to acquire the whole time-dependent flow field in order to be able to evaluate the body force induced by the plasma actuator. Spatially highly resolved wall-normal distributions of the two-component velocity are measured at different phases of the 9.5 kHz harmonic current driver signal. A phase resolution of 60° was achieved which equals a temporal resolution of 17.5 µs. The measurement system was able to resolve the flow field down to 100 µm close to the actuator surface. On the basis of the Navier-Stokes equations the resulting, time-dependent body force is calculated. The measurement results reveal a clear dependency between induced body force and phase angle of the driver signal. Moreover, it is demonstrated that the force acts in alternating directions (upstream-/downstreamwise) in dependency of the phase which supports the push/pull-theorie. Nevertheless, a resulting average force in the downstream direction can be observed which is responsible for the created wall jet.

1. Introduction

Active flow control is a highly relevant topic in order to reduce drag, damp turbulence or improve the efficiency of e.g. turbo machines. That is why dielectric barrier discharge (DBD) plasma actuators, which seem to be an appropriate tool, have intensively been investigated for the purpose of flow control in the last time [1, 2]. During the operation in quiescent air, the actuator induces a local body force which manifests as a wall jet near the surface. This aspect is of high interest for various flow control applications. Plasma actuators have already been applied for active flow control of external flows, such as separation control [3], transition control [4] and internal flows, e.g. diffuser flows [5] or turbo machines [6]. However, the physical background of the actuation mechanism is not completely understood yet. One very important aspect is the relation between induced body force, flow behavior and phase angle of the driver signal. This question could not be answered satisfactorily up to now though it is of high importance for the application of plasma actuators.

Since most of the actuators are operated with an alternating current one would also expect an alternating behavior of the flow direction due to the change of the electrical field. Nevertheless, recent time-resolved velocity measurements did not confirm this behavior [7]. Hence, the details of the actuation mechanism are still a riddle which must be investigated in detail in order to understand the working principle of plasma actuators completely. Two theories about the force behavior exist right now. One is the push/pull-theory which states that an alternating force is acting in dependency of the phase [8]. On the other hand, the measurements of Enloe et al. [9] did not observe such alternating behavior and support the push/push-theory which suggests that no alternation of the force direction occurs during one period.

Different techniques for the evaluation of the induced body force have been suggested in the last
years including experiments as well as simulations. A two-dimensional numerical simulation was carried out by [10] without a comparison to experimental results. Another approach was proposed by [9] who suggested a model based on a two-stage mechanical system and combined it with experimental observations. It was shown, that a majority of the momentum coupling occurred during the negative-going part of the discharge cycle. Force balances have been used for evaluating the time-averaged body force as thrust while an insight into the temporal variation was not possible with this approach [11, 12]. Recently, new approaches have been taken by using time-resolved two-dimensional velocity data captured with particle image velocimetry (PIV) [13, 14]. Wilke suggested a technique based on the Navier-Stokes Equations under the assumption of a two-dimensional flow. Moreover, the pressure gradient is assumed to be much smaller compared to the induced body force, and can therefore be neglected. Albrecht et al. suggested an approach based on the use of vorticity transport equation under assumptions of a two-dimensional flow and a negligibly small magnitude of the wall-normal force [13]. The streamwise component of the time-dependent body force was obtained by integrating the vorticity transport equation. The method worked in a test made in an electrolyte flow controlled by Lorentz-force, however, it may not work at plasma actuators operated in the kHz range. A critical aspect of this approach is the resolution and uncertainty of the measurement system since it is based on the 3rd order derivative of the velocity. Hence, the evaluation of the force acting on the air remains a challenge, while it is of great interest for the consideration of the momentum induced to the flow.

In the following, we present the phase-resolved behavior of the streamwise and wall-normal local flow velocities using a novel, two-component laser Doppler velocity profile sensor (LDV-PS). Our objective is to obtain physical insight into the time-dependent flow acceleration related to the body force, which is induced to the fluid in the proximity of the plasma actuator.

2. Measurement System

Two measurement setups were applied for two different measurement campaigns. The first setup consisted of a 1D1C laser Doppler velocity profile sensor [15, 16]. In contrast to conventional laser Doppler anemometry systems, the fringe spacing \( d \) is not constant but purposely misaligned in order to achieve a diverging and a converging fringe system, respectively (see Fig. 1). That is why, a burst signal of a tracer particle passing the measurement volume consists of two characteristic Doppler frequencies \( f_i \) \( (i=1, 2) \), belonging to each fringe system, which are used to determine not only the velocity \( u \) but also the position of the particle along the optical axis \( y \). In order to evaluate the acceleration \( a_y \) with a low uncertainty, a third fringe system with constant fringe spacing is superposed. The optical setup is depicted in Fig. 2. In the intersection region of the ellipsoids formed by the 3 pairs of laser beams, the measurement volume is formed. The resulting measurement volume has a size of ca. 400 \( \mu \)m along the optical axis, i.e., the y-axis, and a diameter of approximately 40 \( \mu \)m.

In order to estimate the body force originating from the DBD plasma actuator, the wall-normal as well as the wall-parallel velocity components have to be acquired simultaneously. Hence, a second setup was prepared in order to measure both velocity components. The evaluation of the wall-normal component becomes possible by tilting one of the fringe systems relative to the others. This third fringe system is tilted by 60° and exhibits a carrier frequency due to the application of an acousto-optic modulator (AOM). Hence, a directional discrimination is possible in order to capture possible occurring changes in the flow direction. This aspect is very important since the dependency of the force magnitude and direction on the phase angle is in the focus of our study. Again, two fringe systems are used to form the 1D1C LDV-PS as described above. The complete optical setup is depicted in Fig. 3. Due to the large tilting angle, the effective measurement volume only covers
region of ca. 50 µm along the y-direction. Its diameter is approximately 50 µm.

**Fig. 1:** Two superposed fringe systems of the 1D1C LDV-PS for the evaluation of \( u(y) \)

**Fig. 2:** Optical setup forming 3 fringe systems for the spatially resolved evaluation of \( u(y) \) & \( a_y(y) \)

In order to distinguish between the fringe systems, a wavelength division multiplexing (WDM) technique was applied. This means that three different wavelengths are applied (\( \lambda_1 = 532 \) nm, \( \lambda_2 = 561 \) nm and \( \lambda_3 = 658 \) nm) from which each is forming one fringe system. The superposition of the laser beams as well as the separation of the different light colors of the scattered light is achieved by dichroic mirrors.

For the calibration of the 1D1C LDV-PS, a pinhole mounted in a rotating wheel with the constant tangential velocity \( u \) is used to determine the quotient \( q(y) \) out of the two Doppler frequencies \( f_1 \) and \( f_2 \) as follows

\[
q(y) = \frac{f_2(u, y)}{f_1(u, y)} = \frac{u/d_2(y)}{u/d_1(y)} = \frac{d_1(y)}{d_2(y)}. \tag{1}
\]

With the known velocity during the calibration the fringe spacing functions follow as

\[
d_i(y) = \frac{u}{f_i(u, y)}. \tag{2}
\]

Afterwards, the velocity \( u \) of a particle can be calculated during measurements with the help of the known fringe spacing \( d_i \) (\( i = 1, 2 \)) by

\[
u(y) = f_1(u, y) \cdot d_1(y) = f_2(u, y) \cdot d_2(y). \tag{3}
\]

The same calibration tool is used to set up the third fringe system in order to adjust a constant fringe spacing. As a result, a fringe spacing variation of less than 0.1 % was achieved which, considering the small effective measurement area due to the intersection with the other ellipsoids, does not influence the velocity estimation significantly, and can therefore be neglected.

The LDV-PS provides a high spatial resolution in the wall-normal direction of around \( \sigma_y = 3 \) µm and a low relative velocity uncertainty less than 0.1 % at a typical signal-to-noise ratio (SNR) of 5 dB. These values have been determined by test measurements with the calibration tool. During the post processing of the measurement data a spatial as well as temporal slotting technique was applied in order to gather enough data in each position/phase-slot. As a result, the effective spatial resolution of the sensor was 10-20 µm in the y-direction and 50 µm in the x- and z-directions.

Sideward detection was applied in order to suppress the influences of wall reflections and measure as close as possible to the actuator surface. Furthermore, the measurement system consists of an
A/D converter cards (4 channels, 16-bit, 200 MS/s, 125 MHz bandwidth, 1 GS memory depth) which records the detected signals of the avalanche photo detectors (APDs) as well the driver signal of the plasma actuator. This allows for phase resolved measurements and enables the high temporal resolution of the measurement setup.

![Fig. 3: Optical setup forming 3 fringe systems for the spatially resolved, two-component measurement of \( u(y) \) & \( v(y) \)](image_url)

![Fig. 4: Photo (left) and schematic drawing (right; top: top view, bottom: side view) of the applied ceramic DBD plasma actuator](image_url)

### 3. DBD plasma actuator

The measurements have been carried out on a DBD actuator. The actuator is made of a ceramic dielectric which is manufactured using the Low Temperature Co-Fired Ceramics (LTCC) technology. The width of the upper, air-exposed and lower, ground electrode is 2.5 mm and 10 mm, respectively. Both have a thickness of around 50 µm and are placed without a separating gap as depicted in Fig. 4 on the right. A photo of the examined ceramic plasma actuator is also shown in Fig. 4 on the left side.

In order to ensure a two-dimensional flow, the electrodes span 65 mm in \( z \)-direction so that the flow is actuated homogeneously along the spanwise direction. The dielectric surrounds the ground electrode completely despite of a small contact pad at the bottom. This manufacturing principle yields an actuator which is very durable and long lasting and hence enabled experiments over several weeks. During this time no significant change of the working parameters of the actuator has been observed. This is a big advantage compared to conventional plasma actuators which apply Kapton tape as dielectric material. As a perspective, applications in harsh environments, e.g. at turbo machines, become possible with these kinds of actuators.

The actuator is driven by a harmonic high voltage signal \( (U_{pp} = 8 \text{ kV}) \) at a frequency of 9.5 kHz. The generated cold plasma covers a region of ca. \( x = 0...5 \text{ mm} \) with approximately 0.4 mm in height, i.e., the expansion along the \( y \)-direction.

### 4. Tracer Particles

Since the excitation frequency of the DBD plasma actuator is very high, attention has to be paid to the seeding particles, which are necessary for the optical measurements. The particles have to be selected carefully in order to insure that they are able to follow the local flow motions. That is why poly-dispersed diethylhexyl sebacate (DEHS) particles with a mean diameter of 0.85 µm were used. According to [17] the seeding particles exhibit a relaxation time of 2.4 µs at 20 °C. As a result, the
characteristic particle cut-off frequency \( f_c \), up to which the particles are able to follow with a maximum slip of 1\% is approximately 9.5 kHz and hence equals the driver frequency of the DBD actuator. As a result, the tracer particles should represent the behavior and local accelerations of the flow induced by the plasma actuator very well.

5. Body force estimation

As explained, a two-dimensional DBD plasma actuator in quiescent fluid is considered in the present study. Fig. 4 (right) shows the actuator geometry with \( x, y, z \) being the streamwise, wall-normal and spanwise direction respectively.

The flow motion induced by the actuator is considered two-dimensional and laminar near the actuator surface. Hence, only the streamwise \( u \) and wall-normal \( v \) velocity components have to be considered. Thus, the Navier-Stokes equation for the flow around the actuator leads to

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = f_x - \frac{\partial p}{\partial x} + \eta \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right)
\]

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = f_y - \frac{\partial p}{\partial y} + \eta \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right),
\]

with \( f_x \) and \( f_y \) being the volume force densities acting in the streamwise and wall-normal direction, \( \rho \) being the density, \( p \) being the pressure and \( \eta \) being the viscosity. Since the pressure gradient terms remain difficult to obtain from velocity measurements, i.e., (4) provides only two equations for the three unknowns \( f_x, f_y, \) and \( p \), further assumptions and/or simplifications are required. Wilke [13] assumed that the absolute value of the force \( f_i \) is much larger compared to the according pressure gradient \( \left| f_i \right| \gg \frac{\partial p}{\partial x_i} \). Hence, the latter one can be neglected and the volume force densities follow as

\[
f_x = \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) - \eta \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right)
\]

\[
f_y = \rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) - \eta \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right),
\]

Finally, the total body force is calculated by integrating the volume force densities according to [13]

\[
F_x = \iint_A f_x dA \\
F_y = \iint_A f_y dA.
\]

Note that the viscous terms are usually small compared to other terms of the Navier-Stokes equation except in the wall vicinity.

Another approach is presented by Albrecht et al. [14]. By calculating the rotation of the Navier-Stokes equation it becomes

\[
\frac{1}{\rho} \left( \frac{\partial f_x}{\partial y} - \frac{\partial f_y}{\partial x} \right) = \frac{\partial \omega}{\partial t} + u \frac{\partial \omega}{\partial x} + v \frac{\partial \omega}{\partial y} - \eta \left( \frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right),
\]

with: \( \omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \).

Due to the curl operator the pressure terms are eliminated and the force is finally calculated under
the assumption that \[
\left( \frac{\partial f_x}{\partial y} \right) \gg \left( \frac{\partial f_y}{\partial x} \right)
\] by [14]

\[
F_x = - \int_{-\infty}^{0} \rho \psi (x, y) dy.
\] (8)

6. Experimental Setup

For the measurements, the plasma actuator was mounted on two translation stages which allowed the positioning and traversing of the actuator in the \(x\)- and \(y\)-direction. The experiments were performed in a closed containment in order to achieve a high seeding concentration. The LDV-PS setup was placed in front of the chamber and a glass window granted access from the side. The experimental setup is depicted in Fig. 5.

![Fig. 5: Top view of experimental setup with two-component LDV-PS.](image)

The detection optic was positioned above the experimental setup and observed the measurement volume through the acrylic glass cover of the chamber. Due to the sideward detection, the light scattering from the wall could be reduced significantly and hence measurements close to the actuator surface were possible.

7. Measurement Results

Two measurement campaigns were performed, one with a single-component and a second one with a two-component LDV-PS setup.

At first the single component LDV-PS was applied in order to capture the velocity and acceleration profiles along three lines of the plasma actuator (see Fig. 4 for coordinate reference). Therefore, the plasma actuator was traversed along the \(y\)-direction with 200 \(\mu\)m steps in order to secure a 50% overlap of the consecutive measurement data. All measurements are performed at a central \(z\)-position so that the assumption of a two-dimensional flow is fulfilled and boundary effects are negligible. The measurements at the front edge of the upper electrode (\(x = 0\) mm) exhibit only a very low velocity \(u\) of 0.8 m/s in maximum (see Fig. 6, left). Since this is the region where the plasma starts to develop and the surrounding air is entrained by the plasma, this behavior is reasonable. Further downstream, i.e., at \(x = 1\) mm and \(x = 3\) mm, the development of the wall jet is clearly visible (see Fig. 6, center & right).

During the post processing the phase has been separated into four quarter circles according to the driver signal, which allows identifying the characteristic behavior of the momentum transfer at reasonable temporal accuracy. Moreover, the velocity and acceleration profiles are divided into 20
µm slots in order to gather enough data, i.e., more than 400 values each.

**Fig. 6:** Phase-resolved velocity profiles at three different \( x \)-positions along the plasma actuator.

The results of the acceleration measurement show a direct relation between its magnitude and the four different phase intervals at any measurement position. Again, at \( x = 0 \) mm a relatively small acceleration \( a_x(y) \) is measured due to the same reasons as explained above (see Fig. 7, left). Further downstream, at \( x = 1 \) mm and \( x = 3 \) mm a much stronger acceleration occurs (see Fig. 7, center & right), namely \( 1.8 \times 10^4 \) m/s\(^2\) and \( 1 \times 10^4 \) m/s\(^2\), respectively. The results clearly show that the strongest acceleration is present in the third interval, i.e., between 180° and 270° at all times. Additionally, there is always a negative acceleration present in the first half-period, pointing at a negative force in this time interval. The scatter of the measurement results near the actuator surface (\( y = 0 \) mm) is caused by strong light reflections which reduce the SNR and amount of evaluable measurement data. Hence, the closest measurements results have been achieved 100 µm apart from the surface.

**Fig. 7:** Phase-resolved acceleration profiles at three different \( x \)-positions along the plasma actuator.

The two-component LDV-PS setup was applied for the second measurement campaign. Due to the shorter length of the measurement volume along the \( y \)-direction, a traversing of only 20 µm was chosen so that more than 50 % overlap of consecutive measurements was achieved. The traversing distance along the \( x \)-direction varied between 50 µm over the plasma up to 500 µm further downstream, in order to capture the whole flow field in a reasonable time. Nevertheless, the whole measurement time was approximately 5 days.

Similar to the first set of data, the phase was separated into 60°-slots in the post processing which were processed with 50 % overlap. Hence, a further improvement of the temporal resolution was achieved. Again, a spatial slotting technique with a 10 µm step size was applied. Examples of the velocity fields of the \( u \) & \( v \) component for different phase angles are depicted in Fig. 8/9 and 10/11, respectively.

The development of the wall jet is clearly visible, where furthermore differences of the velocity distributions can be identified when comparing Figures 8 and 9. This difference is most salient in
Fig. 8: \( v \)-component velocity field at a phase angle of \( 0^\circ \pm 30^\circ \)

Fig. 9: \( v \)-component velocity field at a phase angle of \( 180^\circ \pm 30^\circ \)

The region \( 5 \text{ mm} < x < 10 \text{ mm} \). Since the wall jet is solely created by the plasma, this observation already suggests a periodical variation of the induced body force.

Fig. 10: \( v \)-component velocity field at a phase angle of \( 0^\circ \pm 30^\circ \)

Fig. 11: \( v \)-component velocity field at a phase angle of \( 180^\circ \pm 30^\circ \)

The measurement results of the \( v \)-component show the entrainment of the air above the actuator. Moreover, a significant fluctuation of the velocity is also noticeable in the region behind \( x = 5 \text{ mm} \) which, again, reflects the periodical variation of the induced body force.

On basis of the temporally resolved, two-component flow fields, the induced body force is calculated applying the approach of Wilke [13], as described in Sec. 5. The force in horizontal direction is computed applying Eq. 6 and the results are depicted in Fig. 12.

Fig. 12: Phase-resolved force in the \( x \)-direction.

The results exhibit a fluctuation of the induced body force in dependency of the phase angle. The highest amplitude of the force in the \( x \)-direction, i.e., \( F_x \) is observed around \( 180^\circ \). Though the
negative force $F_x$ is present in the second half-period, its magnitude is much lower compared to the positive portion. Hence, a positive force balance of $F_x$ is achieved with a mean value of $F_{x,mean} = 43$ mN/m.

The result confirms the allusion on the existence of an alternating force during one complete period.

8. Conclusion

Due to the application of the two-component LDV-PS measurement system with its high spatial and temporal resolution, new information about the body force behavior of plasma actuators could be gained. The measurement results clearly reveal that an alternating direction of the force is present during different parts of the period of the driver signal. It was demonstrated that, for the actuator geometry examined, the push/pull-theory is correct. To our knowledge, this behavior was evaluated and observed for the first time on a plasma actuator driven with almost 10 kHz. As a result, a deeper insight into the working principle of the actuator is achieved.

9. Outlook

Though the achieved results are very good and clearly show the temporal behavior of the flow around and force originating from the plasma actuator, the measurements took quite long and were only possible due to the long term stability of the actuator. Nevertheless, an improved measurement system which captures a larger area could reduce this measurement time significantly and should therefore be in the focus for the future. Moreover, the direct acceleration evaluation for both components, i.e., $a_x$ and $a_y$ on basis of the measurement system is another aim for future developments. The feasibility of this approach has already been presented here but should be extended to the two-component measurements.

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