Body Force Produced by Plasma Actuator Using PIV and Pressure Measurements

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The body force distribution on a quiescent air induced by a slender uniform plasma actuator is calculated using the Navier-Stokes equations and the measured velocity and pressure distributions in order to study the contribution of the pressures. Both velocity distribution and pressure distribution over a perpendicular plane situated in the middle of the actuator are measured simultaneously with a two-dimensional particle image velocimetry and a thin flat static pressure board, respectively. The convergences of time-averaged velocity components and static pressures versus the sampling time are verified. The pressure distribution over the PIV grid is obtained by the bilinear interpolation. The body-force distribution is calculated assuming that the flow is steady, two-dimensional, incompressible and laminar. The body force calculated by neglecting the pressure terms in the Navier-Stokes equations is presented for comparing with that including the pressures. The total body forces over four control volumes of different sizes are calculated from the body-force distribution to facilitate the presentations. A parametric study on body force is conducted for the peak-to-peak ranging from 5.5 kV to 12.3 kV at the carrier frequency of 13.5 kHz.

Nomenclature

| abcda | = control volume boundary in plane perpendicular to actuator length |
| F    | = total body force per unit length of actuator over abcda, mN/m, or carrier frequency, kHz |
| \( F_x, F_y \) | = \( x, y \)-component of total body force per unit length of actuator over abcda, mN/m |
| \( f_x, f_y \) | = \( x, y \)-component of body force per unit volume, mN/m³ |
| \( \Delta p \) | = pressure increment from atmospheric pressure. Pa |
| \( p_x \) | = partial derivative contour of \( \Delta p \) with respect to \( x \). |
| \( p_y \) | = partial derivative contour of \( \Delta p \) with respect to \( y \). |
| \( t \) | = time, s |
| \( U \) | = velocity, m/s |
| \( u, v \) | = \( x, y \)-component of velocity, m/s |
| \( V_{p-p} \) | = peak-to-peak voltage of a.c. voltage source, kV |
| \( \rho \) | = air density |
| \( \mu \) | = air dynamic viscosity |

I. Introduction

Plasma active flow control has received growing attention in recent years because of the advantages of not having mechanical parts, zero reaction time, broader frequency bandwidths and relatively low energy.
consumption. What is most important, the plasma actuators can be arranged conveniently on the parts surface of the vehicle. Plasma actuators have been used in several studies aiming at separation control\cite{1,2}, turbulent drag reduction\cite{3}, noise reduction\cite{4}, boundary layer control\cite{5,7} and transition delay\cite{8}. Excellent reviews on plasma actuators for aerodynamic flow control have been published recently\cite{9,10}.

Many researchers choose the single dielectric barrier discharge (SDBD) as the plasma actuation type. The effect of the SDBD actuator is to impart momentum to the flow, much like flow suction or blowing but without the mass injection. The plasma results in a body force distributed in the ambient air, which has been derived from first principles and implemented in numerical flow simulations\cite{11}.

In recent years, PIV (Particle Image Velocimetry) measurements in close proximity to SDBD actuator have been conducted to determine the spatial distribution of the body force using the Navier-Stokes equations or the like (Ref.12-13). In most studies, the pressure gradients over the entire flow field are neglected without proof.

In this paper an investigation on the body force of the plasma is performed. A prediction technique is proposed by combining the PIV and pressure measurement to accurately and efficiently measure the body force magnitude, spatial distribution and orientation in the vicinity of the actuator. After a description of the experimental setup is given which is followed by a discussion on the results. Finally some conclusions and future work are presented.

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II. Experimental Setup

The determination of the induced body force can be done experimentally in several ways. In our test, 2D PIV technique and pressure measurements are used to estimation the body force induced by SDBD plasma actuator. The experimental setup comprises two separate systems for the measurements of static pressure and induced velocity field, as shown in Figures 1. The pressure scanning and PIV measurements are carried out at the same time for each test case.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{experimental_setup.png}
\caption{Sketch of the experimental setup.}
\end{figure}

A. Design Concept of Single Dielectric Barrier Discharge Plasma Actuator

One slender strips of asymmetric SDBD plasma-actuator are placed on a plexiglass plate. The plasma actuator consists of two copper electrodes each of 0.03 mm thickness. A thin Kapton dielectric film separates the covered electrode from the exposed electrode. The length of the electrodes is 100 mm, the width of the exposed and covered electrode is 5 mm and 10 mm, respectively. There is no gap or overlap between the exposed and covered electrode. The actuators are hand-made and attached directly to the plate surface. An overview of the actuator parameters for all measurements is shown in table 1.

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### Table 1. Actuator setup: dimensions and measured parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating voltages ($V_{pp}$, kV)</td>
<td>5.5, 6.3, 7.0, 10.0, 11.4, 11.8, 12.0, 12.3</td>
</tr>
<tr>
<td>Operating frequency ($f$, kHz)</td>
<td>13.5</td>
</tr>
<tr>
<td>Plasma actuator length (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Upper electrode width (copper, mm)</td>
<td>5</td>
</tr>
<tr>
<td>Lower electrode width (copper, mm)</td>
<td>10</td>
</tr>
<tr>
<td>Gap distance (mm)</td>
<td>0</td>
</tr>
<tr>
<td>Dielectric thickness (Kapton, mm)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### B. Pressure measurements system

The total 98 time-averaged pressure tappings are arranged in 3mm even increments, 7 row × 14 columns. These pressure taps are arranged in a plexiglass board which is set vertical to the plasma actuator, as shown in figure 1. The model of pressure taps is 9816 by the PSI Company with an accuracy of up to ±0.05% FS, where the full scale = 5000 Pa, which are read at frequency of 50 Hz and consecutive 10 seconds of sampling are performed for each case.

The maximum of $|\Delta p|$ for all test cases is about equal to the maximum measurement error of 2.5 Pa. However, a study of the convergence of the time-averaged $\Delta p$ validates the present measured results. See Subsection IV. B.

### C. PIV Facility

In addition to pressure measurements, two-dimensional PIV was performed, the laser sheet nearly coincides with the section of pressure measured station in order to make a comparison of the results gotten from the two different measurement technique. The PIV measurement plane was normal to the axis of the plasma actuator. Measurements were made with one Nd:YAG 200-mJ lasers. A CCD camera of 1200×1600 pixel is used to record the induced cross-flow image which has height and width 37 mm × 50 mm. The laser produces double pulses with a time interval of 30 $\mu$s. Data were processed in 32×32 pixel interrogation areas with 50% overlap. The repeat rate of the laser double-pulse is set at 13 Hz and consecutive 10 seconds of sampling are performed for each case.

The study is conducted inside a space formed by a rectangular cover, which is of 600 mm in length, 500 mm in width and 500 mm in height. All the five sides of the cover are made from 5 mm thick float glass to allow for optical viewing and access for the laser sheet. The plasma actuator is set inside the cover. The air under the cover at one atmosphere pressure is shielded from air flow within the laboratory room. The seeds are smoke particles of approximately 1 $\mu$m in diameter commonly used in cinema industry. The seeds would stay suspended for many hours and were only replenished when needed.

### III. Calculations

The coordinates xOy and control volume are shown Fig. 2. The origin lies at the downstream end of the exposed electrode and on the flat surface. Fig. 3 presents the four control volumes I-IV of different sizes for depicting the total body forces.

![Figure 2 Coordinates and control volume.](image)
The flow is two dimensional, steady, laminar and incompressible, the body force per unit volume is calculated using the Navier-Stokes Equations (1)-(3) with the measured velocity and pressure distributions.

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

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

\[ f = \left( f_x^2 + f_y^2 \right)^{1/2} \]  

where \( \Delta p \) = pressure increment from atmospheric pressure.

Total body force components are calculated by Eqs. (4) and (5). The field of integration \( S \) is the area enclosed by the boundary of control volume abcd.

\[ F_x = \iint_S f_x \, dx \, dy \]  

\[ F_y = \iint_S f_y \, dx \, dy \]  

For above equations, the pressure gradient terms are neglected in many literatures\(^\text{11-12}\). In the presented research, the static pressure is measured at the same time when the induced flowfield is measured. Now body force induced by DBD can be obtained. The partial differential derivatives are calculated using second accuracy finite difference and the integral operation via trapezoid formula.

IV. Results and Discussion

In order to show that the results presented in this paper are convergent, both the time averaged \( u \) and \( v \) induced by plasma and time averaged pressure are given in figure 4, 5 & 6. We can clearly see that the results are almost convergent with 10 seconds sampling time, except the \( u \) and \( v \) at highest induced speed zone, for example, \( x=15.9\)mm, \( y=2.05 \).

A. Convergence of Time-Averaged \( u \) and \( v \)
Figure 4 Convergence of Time-Averaged $u$ and $v$, $F = 13.5$ kHz, $V_{p-p} = 5.5$ kV, $x = 5.2$mm.

Figure 5 Convergence of Time-Averaged PIV, $F = 13.5$ kHz, $V_{p-p} = 12.0$ kV, $x = 15.9$mm.

B. Convergence of Time-Averaged Pressure

Figure 6 Convergence of time-averaged $\Delta p$, $F = 13.5$ kHz, $x = 9.2$mm.
C. Time-Averaged Velocity Vectors and Contours

The time averaged induced flowfields with the tow different peak-to-peak operating voltages, 5.5 kV and 12.0 kV are shown in figure 7. It can clearly see that when \( V_{p-p} \) is equal and higher than 10.0kV, the velocity field measured by 2D PIV become discontinuity, there are main three reasons to explain this phenomena:

1. Particle is adsorbed to the actuator surface.
2. Reflection of the laser has a bad effect on results.
3. Sampling time is not enough to obtain a steady flow field.

D. Pressure Distributions

The pressure and velocity distributions are measured in different grids. The pressure measuring grid has the size of 3 mm × 3 mm. The PIV measuring grid has the size of 0.5 mm × 0.13 mm. It can be see that the PIV grids are much finer. The pressure derivatives are first calculated in the pressure measuring grids using the second-order accurate difference formulas, and, then, evaluated in the PIV measuring grids by the bilinear interpolation and linear extrapolation at the x axis.

Figs. 8 and 9 present \( \Delta p \) contour before and after interpolations at \( V_{p-p} = 5.5 \) kV and 12.0 kV, respectively. Figs. 10 and Figs. 11 present the partial derivative contour of \( \Delta p \) with respect to \( y \) before and after interpolations at \( V_{p-p} = 5.5 \) kV and 12.0 kV, respectively.
Figure 8. $\Delta p$ contour at $V_{p-p} = 5.5$ kV, before and after interpolation.
Figure 9 $\Delta p$ contour at $V_{pp} = 12.0$ kV, before and after interpolation.

Figure 10 The partial derivative contour of $\Delta p$ with respect to $y$ before interpolation, $V_{pp} = 5.5$ kV.
E. Body Force Contours with/without Pressures

The body force contours for $V_{pe} = 5.5$ kV and $V_{pe} = 12.0$ kV with/without pressures are presented in Figure 12 - Figure 13. It can clearly see that the body force distributions are totally different for $V_{pe} = 5.5$ kV, both x- and y-components with and without pressures.
Figure 12. $x$-component of body force distribution with/without pressures, $V_{pp} = 5.5$ kV.
Figure 13. $y$-component of body force distribution with/without pressures, $V_{pp} = 5.5$ kV.

Figure 14. $x$-component of body force distribution with/without pressures, $V_{pp} = 12.0$ kV.
Figure 15. y-component of body force distribution with/without pressures, $V_{pp} = 12.0 \text{ kV}$.

F. $F_x$ & $F_y$ vs. $V_{pp}$ with/without Pressures

The total body force per unit length of actuator for $x$, $y$-component over 4 different control volume with and without pressure are presented in Figure 16 and 17. We can see (1) $F_x$ reaches maximum value of 7.48 mN/m at $V_{pp}=11.4 \text{ kV}$ with pressure. (2) $F_y$ reaches maximum value of 2.71 mN/m at $V_{pp}=12.3 \text{ kV}$. (3) $F_x > 0$, $F_y > 0$ for $V_{pp}=5.5-12.3 \text{ kV}$, $F=13.5 \text{kHz}$. (4) Due to pressures, the increment of $F_x$ is generally 6 mN/m. (5) Due to pressures, the increment of $F_y$ is generally 2 mN/m. (6) The pressure terms can not be neglected in comparison with other terms of Navier-Stokes equations for finding the body force produced by plasma actuation.
Figure 16. $x$-component of body force vs $V_{pp}$ with/without pressures.
V. Conclusions

The body force distribution produced by a typical plasma actuator in quiescent air is calculated from the two-dimensional, steady, laminar and incompressible Navier-Stokes equations using the measured velocity and pressure distributions. The actuator consists of two electrodes, one exposed to the air and the other covered by a dielectric material. The electrodes are supplied with an ac voltage that at high enough levels, causes the air over the covered electrode to ionize. The ionized air, in the presence of the electric field produced by the electrode geometry, results in a velocity and pressure variations in the ambient air. The comparison of the body forces calculated with and without the pressure terms in the Navier-Stokes equations reveals that the pressure terms are, in general, negligible. For the peak-to-peak voltage ranging 5.5 kV to 12.3 kV and the carrier frequency of 13.5 kHz, from the largest control volume the maximum body forces are found at $V_{p-p}=11.4$ kV, where $F_x = 7.48$, $F_y = -0.08$, $F_z = 7.48$ mN/m, with pressures; and $F_x = 3.64$, $F_y = -0.29$, $F_z = 3.66$ mN/m, without pressures. Further investigations should be pursued to refine the present pressure and PIV measurements.

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References