Flow morphing by coaxial type plasma actuator

S Toyoizumi\textsuperscript{1}, H Aono\textsuperscript{2} and H Ishikawa\textsuperscript{2}

\textsuperscript{1} Graduate School of Engineering, Tokyo University of Science, Tokyo, JAPAN
\textsuperscript{2} Department of Mechanical Engineering, Tokyo University of Science, Tokyo, JAPAN,

E-mail: 4515635@ed.tus.ac.jp

Abstract. The purpose of study is to achieve the fluid drag reduction of a circular disk by Dielectric Barrier Discharge Plasma Actuator (DBD-PA). We here introduced “Flow Morphing” concept that flow around the body was changed by DBD-PA jet, such as the body shape morphing. Coaxial type DBD-PA injected axisymmetric jet, generating the vortex region on the pressure side of the circular disk. The vortex generated by axisymmetric plasma jet and flow around circular disk were visualized by tracer particles method. The fluid drag was measured by compression type load cell. In addition streamwise velocity was measured by an X-type hot wire probe. The extent of fluid drag reduction by coaxial type DBD-PA jet was influenced by the volume of vortex region and the diameter of plasma electrode.

1. Introduction

There is a problem of energy resources depletion in recent years and the necessity of saving energy is increasing in various fields. Certainly, energy saving devices of fluid machinery are also required. The fluid drag reduction is important; however it is an unsolved problem. The fluid drag reduction of a circular disk, as a typical example of three-dimensional bluff bodies, has been researched by many researchers. Igarashi et al. have proposed two methods of changing the circular disk shape to control the flow field around disk. One was applying a spherical surface to side wall of disk, the other was cut to a stepwise shape with smaller diameter\textsuperscript{[1][2]}. They reported the stepwise shape disk can reduce the fluid drag by about 75 percent. Other active flow active researches, such as an electromagnetic actuator\textsuperscript{[3]}, a synthetic jet\textsuperscript{[4]} and laser-pulse\textsuperscript{[5]} were reported. Bigger et al. have proposed that a symmetrical actuation by the electromagnetic actuators in disk produced effective reduction in the recirculation region length of 10 percent. The problems with the electromagnetic actuators are complication of mechanism and noise.

A Dielectric Barrier Discharge Plasma Actuator (DBD-PA) has actively studied as a promising flow control device\textsuperscript{[6]}. Figure 1 shows the schematic diagram of typical DBD-PA. DBD-PA consists of two electrodes and a dielectric material. When a high alternating current voltage is applied between two electrodes, DBD occurs on the surface of a dielectric material. This induces the plasma jet along the wall surface. In this study, the fluid control around the body to use an axisymmetric jet by the coaxial type DBD-PA was investigated. Figure 2 shows the schematic of structure of the coaxial type DBD-PA. The advantages of DBD-PA are easy installation due to simple structure, excellent responsiveness, active controllable and instantaneous controllable due to electrically control.

We here proposed “Flow Morphing” concept\textsuperscript{[7]} that flow field around the body was changed by DBD-PA jet, just as the shape morphing technology. The shape continuously change by morphing is one of
the control method. However, several problems of shape morphing are devices to be heavier and complication of mechanism. In this study, we visualizing the vortex changed by axisymmetric jet and flow around circular disk by tracer particles method. The fluid drag was measured by compression type load cell. In addition streamwise velocity was measured by the X-type hot wire probe.

2. Experimental Setup and Methods
In present study, experiments were carried out in the suction-type wind tunnel that has cylindrical measuring section. Circular disk (Diameter: $D=50$ [mm], Thickness: $t=5$ [mm]) was supported by a strut ($d=3$ [mm]) from downstream side. The strut was supported vertically on linear bush with low friction. The circular disk was fixed vertically to mainflow. Considering the general blockage ratio, less than 5% seems reasonable. The circular disk ($D=20$ [mm], $t=5$ [mm]) was chosen because the blockage ratio is 3%. However this disk has three problems, the influence of the electrical noise form PA, the scattering of measurements and PA shape pattern was restricted by the small surface area of the disk. Therefore the circular disk ($D=50$ [mm], $t=5$ [mm]) was chosen. The fluid drag are influenced of the blockage effect. Figure 3 shows the different diameters of coaxial type DBD-PA. The coaxial type DBD-PA was chosen in order to induce the axisymmetric jet. We used 4 different diameters of PA from generating plasma diameters ($D_p=10$, 20, 30 and 40 [mm]). The dielectric of PA is polyimide film that has a thickness of 125 [$\mu$m]. The both electrodes of PA are copper foils that have a thickness of 12 [$\mu$m]. Top and bottom electrodes are connected to a high voltage and frequency power source. In this study, the applied voltage is 5.0 [k V$_{p-p}$] (subscript p-p means the value between a peak to peak) with the frequency of 6.0 [kHz]. The Reynolds number ($Re$) based on the mainflow velocity and disk diameter was calculated to be 5,000 and 10,000. The PA in static air generated plasma jet velocity of 0.4–0.7 [m/s].
2.1. Flow visualization
Figure 4 shows the schematic of the flow visualizing experiment. The flow was visualized by the tracer particle method. The photograph was taken using the high-speed camera (PHOTRON, FASTCAM-SA3) and the YAG laser as the illumination. The frame rate was 1,000 [fps]. The main flow velocity \( U_\infty \) was 1.7 and 3.3 [m/s].

2.2. Fluid drag measurement
Figure 5 shows the fluid drag measurement setup. The drag is measured by compression type load cell (KYOUWA, LMB-A-10N-P). The load cell was installed to the linear bushing and can only measure the force to the mainflow direction. The sampling frequency was 1.0 [kHz], the number of sampling points are 16,384, low pass filter is 10 [Hz]. The measurements were carried out 20 times for each main flow velocity. The measuring time was about 16 seconds. The PA power source is turned on in 8 seconds. Considering the effect of hysteresis, interval time needs 30 seconds.

2.3. Streamwise velocity measurement
The streamwise velocity behind the disk was measured by the X-type hot wire probe. The hot wire probe was connected to constant temperature anemometer (KANOMAX, Model 1010) and the linearizer (Model 1013). The velocity profiles depending of plasma edge diameters were obtained by the X-type hot wire probe at \( x/D=3, r/D=0.16~0.9 \) (at 0.04 space).

3. Results and Discussion
3.1. Flow visualization
Figure 6 shows flow structure of induced jet from the coaxial type DBD-PA. Large vortex structure was generated on the pressure side of circular disk. The yellow symbol indicates ejected position of induced plasma jet (i.e, the edge of plasma electrode). For no control case (Figure 6 (a)), in-coming flow passed though along the surface of disk. With the induced plasma jet case (Figure 6 (b)–(e)) it showed the vortex structure growth. The shape of generated vortex was observed in conical shape when \( D_p \) of 10, 20 [mm] case. The generated vortex has conical shape when \( D_p \) were 10 and 20 [mm]. On the other
hand, shape of vortex generated region in $D_p = 30$ and 40 [mm] case were observed as ring structures. From these instantaneous images, the size of vortex generated region was not proportion to $D_p$. The vortex generated region showed the maximum size when $D_p$ was 20 [mm]. As the $D_p$ decreased, plasma jet collided near the centre of circular disk. As the $D_p$ was increased, the ring type vortex region generated. In the case of $D_p=20$ [mm] the vortex yielded largely changes of flow structure than the case of $D_p=10$ [mm] because induced jet velocity was enough large. In that there was no steady vortex region, repeating vortex generating and collapsing at 5 [Hz] intervals. Figure 8 suggested that flow morphing effects were weak when this unsteady process was occurred.

![Flow visualization of vortex region on the pressure side of circular disk](image)

(a) Without PA jet  (b) $D_p= 10$ [mm]  (c) $D_p= 20$ [mm]  (d) $D_p= 30$ [mm]  (e) $D_p= 40$ [mm]

**Figure 6.** Flow visualization of vortex region on the pressure side of circular disk

![Vortex growth process](image)

(a) Vortex generation  (b) Vortex development  (c) Vortex collapse

**Figure 7.** Vortex growth process

### 3.2. Fluid drag measurement

Figure 8 shows the drag coefficient in all $D_p$ cases. The error bar shows standard error that measured by 20 times (Standard error is standard deviation devided by the square root of sample size). The drag coefficient was calculated by formula (1). The reducing effect by plasma jet cases was shown in Table 1. Due to inducing plasma jet, the fluid drag reduction is about 6~11% lower than that of without PA case. The case of $D_p=20$ [mm] is lowest of all $D_p$ cases of drag reduction.

$$C_D = \frac{2D}{\rho S V_o^2} \quad (D: Drag, \rho: flow density, S: Representative area)$$ (1)
3.3. Streamwise velocity measurement
Figure 9 shows the streamwise velocity distributions in Reynolds number of 5,000. Increment of streamwise velocity in the wake behind the circular disk without PA jet was confirmed in all $D_p$ cases. Above all, the velocity increasing effect in the center of disk wake was greater than that of the outside region of disk. Streamwise velocity defect behind the circular disk became smaller by inducing plasma jet. This suggested that the reverse flow region and the drag acting on the circular disk were decreased.

![Figure 8. Relationship of $C_D$ and PA edge diameter](image)

![Figure 9. Time mean velocity distributions with plasma jet](image)

| $D_p$ [mm] | $Re = 5,000$ |
|------------|--------------|
| $D_p=10$ [mm] | 10.9 [%] |
| $D_p=20$ [mm] | 6.5 [%] |
| $D_p=30$ [mm] | 7.8 [%] |
| $D_p=40$ [mm] | 10.6 [%] |
4. Conclusions

We have performed wind tunnel experiments in order to clarify the drag reduction mechanism by flow morphing with coaxial type DBD plasma actuator. Flow morphing by the coaxial type DBD-PA achieved about 10% drag reduction compared with no PA in this study. Flow visualization showed the growth process of vortex by induced plasma jet on the pressure side of circular disk. The hot-wire probe measurement showed that the streamwise velocity in the wake behind the disk was accelerated by generated vortex induced by the coaxial type DBD-PA. In the case of the disk diameter of $D_p = 20$ [mm], the vortex generation, development and collapse process were repeated with low frequency. This unsteadiness affected the effects of drag reduction and streamwise velocity distribution. This suggested that time independency of flow structure played a role in favorable effect of flow morphing.

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