Interaction of streamwise vortex pair induced by counter type plasma jet with flow past a circular cylinder

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Abstract
A streamwise vortex pair induced by a counter-type plasma actuator interacts with the separated shear layer from a circular cylinder. The spanwise array of the plasma actuator placed on the surface of the circular cylinder works in place of the vortex generator. Induced jets from the adjacent actuators interact with each other and produce streamwise vortex pairs. Flow visualizations in quiescent air and in the wake region of the cylinder were performed using a high speed camera and PIV analysis. The spanwise flow structure in the cylinder wake was investigated through hot-wire measurements. Flow visualization revealed that vortex pairs generated by the counter-type plasma actuator were effectively introduced into the separated shear layer. Hot-wire measurements showed that the interaction between the streamwise vortex pair with the shear layer enhanced the turbulent mixing, improving the velocity defect in the wake.

Key words: Flow control, Separation, Plasma actuator, Circular cylinder

1. Introduction

In flow around bluff bodies, airfoils, and other aerodynamic configurations, separation control is a long standing problem in spite of a technical advance in fluid mechanics. In order to prevent the separation, for example, the jet blown directly supplies the momentum into the separation region. On the other hand, high momentum fluid in the outer flow is introduced into the near-wall region and a separated shear layer by a streamwise (longitudinal) vortex. A vortex generator, which is a common flow control device, is used to generate a streamwise vortex. Spanwise array of the vortex generator, which consists of small plate vanes or delta wings, is embedded normal to the surface of the airfoil, enhancing the lift and retarding the flow separation. Shabaka, et. al (1985) have investigated the effect of vortex generators. They reported that the circulation generated by a half-delta wing vortex generator was preserved up to a considerable downstream distance. The cross-sectional area that was influenced by the streamwise vortex was increased in proportion to the local boundary layer thickness. The review by Lin (1985) also highlighted the effectiveness of vortex generators for improving airfoil performance. Pauley and Eaton (1988) classified different vortex pair configurations, which were common flow up, common flow down and co-rotating. They also discussed the diffusion of vorticity enhanced by neighbouring vortex interaction.

However, a vortex generator itself causes parasitic drag depending on the severity of the flow condition. A solid, fixed vortex generator becomes nothing more than an obstacle when the angle of attack increases significantly. The development of small turbomachinery such as micro gas turbines is currently being actively promoted. However, the internal flow in such small scale turbomachinery is problematic because pressure drop and flow separation easily occurs at low Reynolds number. The flow separation causes reduced efficiency in low Reynolds number flows. However there is not enough space to install solid, fixed vortex generators in such small turbomachinery.
An alternative method for generating streamwise vortices is the use of jets blown through holes in the surface of the airfoil and the wall. The vortex generator jet was blown up with the skew and pitch angles of the mainstream direction. The advantage of the vortex generator jet is that it allows active flow control. The circulation of the streamwise vortex by the vortex generator jet is changeable by adjusting the velocity of the blow jet. Johnston and Nishi (1990) employed a spanwise array of skewed and pitched jets in the surface of a wind tunnel. The vortex generator jet was effective in preventing flow separation by enhancing the cross-sectional mixing. The vortex generator jet equipment was primarily installed on the inside of the airfoil, so that parasitic drag was not caused even if the attack angle of the body changed.

Plasma actuator jets produced by dielectric barrier discharge (DBD) are expected to become new flow control devices (see Thomas, et al.(2009); Corke, et al. (2010); Segawa, et al. (2010); Jukes, et al.(2012)). Plasma actuators are able to be directly installed on the surfaces of airfoils because of their simple and thin structure. This advantage makes them easily installable in the narrow spaces of turbomachinery. Plasma actuators are flow control devices with a wide range of applications. Jukes and Choi (2012) conducted a study on the generation of streamwise vortices using plasma actuators in which they placed a DBD plasma actuator on the surface of a flat plate at a yaw angle to the mainstream of the oncoming flow. They succeeded in reducing flow separation from a trailing-edge ramp and revealed several advantages of the DBD plasma vortex generator over normal vortex generators.

In this paper, we propose that a counter type plasma jet actuator is able to generate a stronger streamwise vortex pair. Yamada (2012) developed a counter-type plasma jet actuator to control the separation from a flat plate wing. Colliding of the counter-jet from plasma actuators produces a streamwise vortex and introduces high momentum fluid into the separation region. Flow around a circular cylinder was employed as a separated flow model with a pressure drop. A spanwise array of these counter-type plasma jet actuators was placed on the surface of the circular cylinder. The effects of this counter-type plasma jet actuators on the streamwise flow structure were already discussed (Yamada, et al., 2011). We here focus attention on the spanwise structure under control of the spanwise plasma array. The behaviours of the streamwise vortex pair in quiescent air and in the intermediate wake generated by the counter-type plasma jet were investigated experimentally by flow visualization and hot-wire measurements.

2. Experimental setup

Figure 1 shows the experimental setup and the tested circular cylinder with spanwise plasma actuators. Experiments were conducted in an open type wind tunnel with a working cross-section of 100 × 100 mm². The main flow velocity was in the range of 1.5 m/s to 15 m/s. The test section was supported by both sides of the end plates.
tested circular cylinder was placed 25 mm downstream of the nozzle outlet. The coordinate origin was located at the centre of the tested cylinder. Reynolds number $Re$ based on the main flow velocity $U$ (= 1.5 m/s) and the diameter of the circular cylinder $d$ (= 10 mm) was about $1.0 \times 10^3$.

Figure 2 is a close-up view of the plasma electrode configuration. The thicknesses of the top and bottom electrodes of the actuator were both 25 $\mu$m, and that of the dielectric polyimide film was 50 $\mu$m. The bottom electrodes were embedded at the reverse side of the top electrode (see, the cross sectional view in Fig.1). The length of electrodes along the surface of the cylinder was 6mm. The distance between the adjacent electrodes was $l = 12$ mm. The spanwise width of the electrodes was 2 mm. This distance was decided with reference to the results of Yokoi and Kamemoto (1999). They found that coherent spanwise structures appeared at a distance several times the cylinder diameter. To generate streamwise vortices, the plasma electrodes were installed at an angle of $80^\circ$ from the upstream stagnation point of the cylinder. Both the top and bottom electrodes were connected to a high-voltage and high-frequency power source (KI-tech, PSI-PG1040F). The voltage of 4 kVpp was supplied to the top and bottom electrodes. The discharge operating frequency $f$ was varied from 4 kHz to 10 kHz. The pulse driving frequencies $f_0$ were 30 Hz and 90 Hz. The duty ratio of the plasma duration time to the pulse driving cycle was set to 30 %.

For flow visualization, a laser light sheet (Yueqing North Star Electron, PGL-FS-532-2W) was irradiated from the side of the circular cylinder. The wake region behind the circular cylinder was visualized by tracer particles using high speed video cameras (PHOTORON LTD., FASTCAM SA-3) and a laser as the illumination source. In order to understand the streamwise vortex structure in the wake, the cross-sectional $yz$ plane was photographed. The position of the laser sheet was $x/d = 0$ on the cylinder and $x/d = 3.0$ in the wake region. PIV analysis was performed using software.

![Jet velocity](image)

(a) $f=4$kHz, $f_0=90$Hz  
(b) $f=10$kHz, $f_0=90$Hz

Fig. 3 Counter type plasma jet and rolled up vortex pairs in quiescent air

The wake profile behind the circular cylinder was measured using a hot-wire anemometer with I- and X-type probes. The sampling frequency and the sampling duration were set at 1 kHz and 24 s respectively, with low-pass filtering at 1 kHz. The measurement cross-sectional plane was located at $x/d = 3.0$ in the $yz$ plane.

3. Results

3.1 Flow visualization

Figure 3 shows flow visualizations in still air around the top electrode of the plasma actuator on the surface of circular cylinder. The velocity components obtained from the PIV analysis indicate the collision of the vortex generator jet and entrained surrounding fluids. The injected plasma jets were collided at the centre of the spanwise position between the adjacent electrodes. Then collided jets ejected up to the normal direction of the surface of the cylinder. The jet velocity from the electrode increased as the discharge operating frequency $f$ was increased, as was the vortex scale in the normal direction. In the case of $f=10$ kHz, the vortex scale in the normal direction is much the same as the cylinder diameter. The centre of a rolled-up vortex was also moved upward away from the surface of the cylinder. At the middle position between the adjacent vortex pair, downwash flows collided on the surface of electrode. The downwash velocity was almost same as the collided jet velocity and as a consequence, it was found that the strength of vortex pair does not easily decay. This result suggests that counter type plasma jet succeeded in introducing high momentum fluid into the near-wall region.

Figure 4 shows the relationships of jet velocity and electric power consumption with the discharge operating frequency of the plasma actuator. The jet velocity was average in the adjacent region to the electrode edge. The electric power consumption $P$ was calculated using the following equation.

$$ P = \left\{ \frac{1}{N} \sum_{n=1}^{N} (V(n) \times I(n))^2 \right\}^{1/2} $$(1)

The voltage $V$ and the electric current $I$ were digitized by the sampling number $n$ of the digital oscilloscope (Tektronix, Inc., TDS2024B). $N$ is the maximum number of samples.

The jet velocity and power consumption increased as the frequency was increased. This tendency is reported by other researches related with plasma control. The jet velocity increased linearly up to the discharge frequency of 7 kHz. This suggests that the efficient driving of this actuator to generate streamwise vortices was achieved with a frequency of under 7 kHz. It should be note that, however, this tendency may depend on the characteristic and the electric

![Figure 4 Changes of jet velocity and electric power consumption with discharged operating frequency of plasma actuator](image-url)
Figure 5 are instantaneous pictures of the streamwise vortices in the wake of the cylinder. The measuring plane was located at $x/d = 3.0$. The Reynolds number of the flow is $1.0 \times 10^3$. The white broken line represents the size and the position of the controlled circular cylinder. In the case without a plasma jet as seen in Fig. 5(a), a coherent vortex structure was not clearly observed in the wake. With plasma control, the cross-section of the streamwise vortex pair was clearly observed in the case of $f = 7$ kHz (Fig. 5(b)). The size of the vortex pair appears to be same as that in quiescent air. The growth of streamwise vortex was promoted even in separated shear layer. When the discharge frequency was increased $f = 9$ kHz in Fig. 5(c), several vortex pairs in the spanwise direction were observable. It was found that the momentum mixing by the counter type plasma array was effectively enhanced in spanwise direction.

### 3.2 Spanwise structure

Figure 6 shows the time mean velocity $u$ profiles behind the cylinder with and without the counter type plasma jet control (Yamada, et. al., 2011). Figure 6(a) is the spanwise position between adjacent electrodes $z/l = 0$. Figure 6(b) is the spanwise position on the electrode $z/l = 0.5$. The X-type hot-wire probe was used at $x/d = 3.0$. The Reynolds number of the flow is increased to $3.0 \times 10^3$. Because when the flow velocity is low, hot-wire measurement has difficulty to
maintain in linearity in our experimental setup. There is no significant difference in shear layer region between with and without plasma control. However the counter type plasma jet enhanced the velocity recovery on the wake centre region of $y/d=0\sim0.5$. The velocity defects in each spanwise position were estimated about 30% improvement by the counter type plasma jet of $f=9$kHz. This suggested that the streamwise vortex generated by the counter-type plasma jet enhanced the introduction of the mixing between inner and outer region.

Spanwise structures generated by streamwise vortex pairs were shown in Fig. 7, the contours of the streamwise velocity in the cross-sectional measurement plane at $x/d=3.0$. These are time-averaged structures by X-type probe measurement. Inherent spanwise structures, which are large velocity components above the electrode, were observed at a distance several times the cylinder diameter. It is necessary to give a consideration to the end wall condition of the cylinder and the accuracy of hot-wire measurement. With plasma actuator jets, the streamwise velocity in the separated shear layer at $y/d = 0.8\sim1.0$ was slightly decreased by the mixing of the streamwise vortex pairs. These results indicate that the streamwise vortices generated by the counter-type plasma actuator would further evolve in downstream positions past $x/d = 3.0$. The effect of the solid vortex generators installed on the surface of a circular cylinder has been discussed by Igarashi (Igarashi, 1985), Ünal and Atlar (Ünal and Atlar, 2010). They mainly focused on flow characteristics in near-wake region before $x/d=2.5$. The streamwise vortices generated by the solid vortex generators are first grown by downwash flow from the tip of the generator. Hence, this tip flow is easily decayed in the wake behind cylinder with pressure gradient by the interaction with high momentum outer flow. However, the plasma actuator jets are ejected from the points closer to the surface of the wall. The streamwise vortices generated by the counter-type plasma actuator possibly have stiffness on the durability of vortex characteristics. Figure 8 shows the turbulent intensity $u'$ distributions. The colliding plasma jets increased the turbulent intensity. It was found that the mixing of high momentum fluid was actively enhanced in the separated shear layer by the counter-type plasma jet actuator.

4. Conclusions

A spanwise array of counter-type plasma actuator jets introduced streamwise vortex pairs into the separated shear layer over a circular cylinder. Plasma jets from adjacent actuator's electrodes on the surface of the cylinder collided and exhibited roll-up motion. Then streamwise vortex pairs were introduced into the separated region affecting the wake structure of the separated flow around the cylinder. It was confirmed that the streamwise vortex pair generated by counter type plasma actuator well interacted with separated shear layer enhancing the turbulent mixing. The streamwise vortex pairs were clearly observed in the wake region by flow visualization. It was observed that interactions of the vortex pair occurred widely in spanwise direction. In hot-wire measurements, time mean velocity profiles showed that the velocity defect in the wake centre region yielded about 30% improvement by the plasma actuator. This suggests that
drag on the circular cylinder may be decreased by flow control by this plasma actuator. We can conclude that the counter-type plasma actuator is an effective flow control device for generating streamwise vortices.
References


