Jet Control Using the Coaxial Type DBD-PA by Burst Modulation

M. Akimoto, H. Matsumori and M. Kimura

Abstract In this study, a jet control using the coaxial type DBD plasma actuator (=DBD-PA). The coaxial type DBD-PA is an axisymmetric nozzle, and the jet is ejected from this nozzle. DBD-PA is driven by burst modulation control and the induced flow is intermittently generated. The coaxial type DBD-PA controls the jet by controlling vortex generation in the jet. We control the jet at Reynolds number Re = 10,000. As a result, the induced flow of the coaxial type DBD-PA synchronizes vortex generation of the jet in a specific burst modulation control frequency range. This phenomenon is the phenomenon of lock-in. Driving the coaxial type DBD-PA with burst modulation, it is possible to generate an axisymmetric vortex within frequency of burst modulation control in which the phenomenon of lock-in occurs. Consequently, the jet is controlled by the coaxial type DBD-PA within frequency of burst modulation control in which the phenomenon of lock-in occurs.

Keywords Jet · DBD-PA · Phenomenon of lock-in · Visualization

1 Introduction

Jet is one of the typical flow modes occurring in nature and industry [1]. Depending on the state of the jet flow at the nozzle exit, behavior such as vortex generation and coalescence changes greatly [2]. In this study, we control the jet flow ejected from nozzle by an induced flow of the coaxial type DBD-PA (DBD: Dielectric Barrier Discharge, PA: Plasma Actuator). The coaxial type DBD-PA is an axisymmetric nozzle, and the jet is ejected from this nozzle. When AC high voltage is applied to

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DBD-PA, the induced flow from DBD-PA is generated. DBD-PA is driven by burst modulation control and the induced flow is intermittently generated. This intermittently generated induced flow controls the jet. The coaxial type DBD-PA controls the jet by controlling vortex generation in the jet.

2 Experimental Details

Figure 1 is the coaxial type DBD-PA. DBD-PA is configured two copper electrodes and a dielectric. Electrodes place on the front and back of the dielectric. The coaxial type DBD-PA nozzle is made of machinable ceramics of dielectric constant 9 and the two electrodes are made of phosphor bronze of 0.5 mm thickness. The coaxial type DBD-PA nozzle of diameter is $d = 10$ mm. And the converging nozzle with a contraction ratio of 6.25 attaches to the tip the coaxial type DBD-PA nozzle. Applying AC high voltage to the coaxial type DBD-PA occur dielectric barrier discharge. As shown in Fig. 2, the induced flow that is used jet diffusion control and diffusion promotion is generated from the nozzle inner electrode side.

Figure 3 shows an over view of the experimental apparatus. In this study, we conduct experiments in the jet at Reynolds number $Re = 10{,}000$. Compressor supplies Air to experimental apparatus. Then, the mass flow controller adjusts air

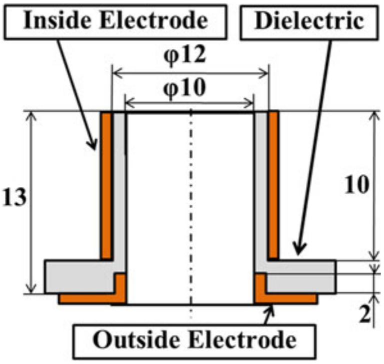


Fig. 1 The coaxial type DBD-PA

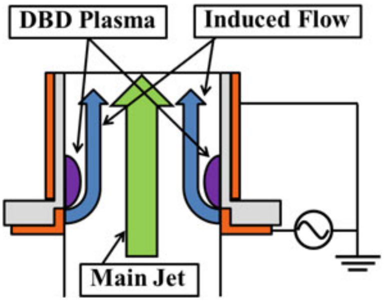
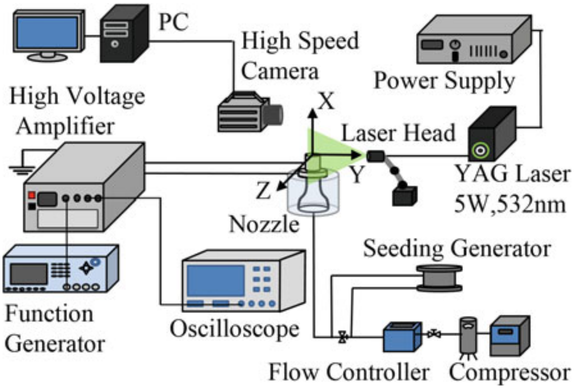


Fig. 2 Flow and DBD plasma

Fig. 3 Experimental apparatus

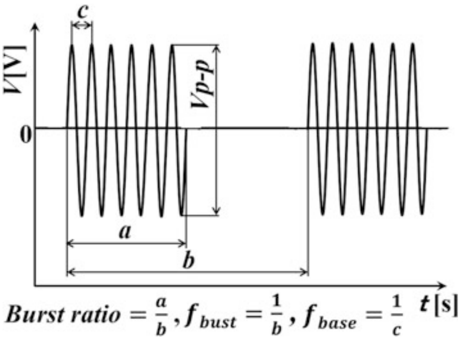


flow rate. Passing through the seeding generator, adjusted air is mixed tracer particles for visualization. Here, tracer particles are corn oil with a particle size of about 1 μm. To rectify the flow of adjusted air, pass through an air filter with a filtration degree of 5 μm and a pipe for run-up. This pipe for run-up of an inner diameter is 25 mm and of a length is about 1.2 m. After that, air jet out vertically upward from the coaxial type DBD-PA nozzle attached the converging nozzle.

Visualization of the jet is conducted by laser sheet scattered light technique with YAG laser. And the jet is photographed by the high speed camera. Here, frame rate of the high speed camera is 12,000 fps. The function generator generates AC waveform. Here, AC waveform is sine wave. The high voltage amplifier boosts this AC waveform. The high voltage amplifier boosts AC high voltage $V_{p\text{-}p}$ (peak to peak) = 16 kV. The AC high voltage waveform is applied to the coaxial type DBD-PA.

Figure 4 shows burst modulation control parameter of AC high voltage applied to the coaxial type DBD-PA. Here, f_{burst}: the frequency of the on-off cycle of AC high voltage waveform of burst modulation control. Burst ratio of burst modulation control in all experimental conditions is 50%. The f_{burst} is determined on basis of the natural vortex frequency f_n. Here, f_n: the frequency of naturally generated vortices of a free jet at plasma off. The f_n at $Re = 10{,}000$ is searched by measured frequency of flow velocity fluctuation of the free jet with laser doppler velocimeter. As a

Fig. 4 Burst modulation control parameter



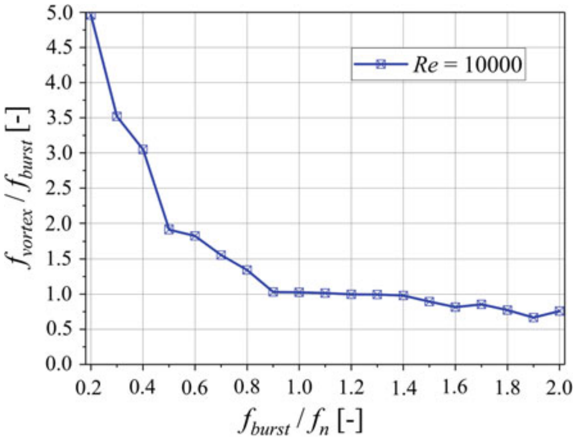
result, the f_n of $Re = 10{,}000$ is 1984 Hz. In addition, this f_n is confirmed by counted the naturally generated vortices. The high-speed camera photographs the free jet at $Re = 10{,}000$ of XY plane. The naturally generated vortices of the free jet are counted at a height x/d = 0.5 from nozzle exit using this moving image for 1.0 s. f_{base}: AC high voltage driving frequency is about 7 kHz. This study is investigated effect on the jet from change in the f_{burst}. The influence of change in the f_{burst} is evaluated by searched the f_{vortex}. Here, f_{vortex}: frequency of generated vortices of plasma excited jet. The f_{vortex} is searched by counted the generated vortices of plasma excited jet at a height x/d = 0.5 from nozzle exit using moving image for 0.1 s.

3 Results and Discussion

Figure 5 shows the searched result of f_{vortex} at $Re = 10{,}000$. The vertical axis of graph is the ratio of f_{burst} and f_{vortex}, the horizontal axis of graph is the ratio of f_n and f_{burst}. This graph can be divided into three sections of $f_{burst} < f_{vortex}$, $f_{burst} = f_{vortex}$, $f_{burst} > f_{vortex}$. Within $f_{burst} = f_{vortex}$ ($f_{vortex}/f_{burst} = 1$), the induced flow of the coaxial type DBD-PA synchronizes f_{burst} and f_{vortex} [3]. This phenomenon is the phenomenon of lock-in [2]. Driving the coaxial type DBD-PA with burst modulation, it is possible to generate an axisymmetric vortex within frequency of burst modulation control in which the phenomenon of lock-in occurs. Consequently, the jet is controlled by the coaxial type DBD-PA within frequency of burst modulation control in which the phenomenon of lock-in occurs.

Figure 6 shows XY plane of jet visualization image at $Re = 10{,}000$. Figure 6a is the free jet of plasma off. The free jet is not controlled. The free jet generates vortices in an unsteady cycle. In Fig. 6b is $f_{burst} = 0.3f_n = 595$ Hz. This condition generates a large vortex and a small vortex near the nozzle of the jet in an unsteady

Fig. 5 Relationship between f_{vortex}/f_{burst} and f_{burst}/f_n



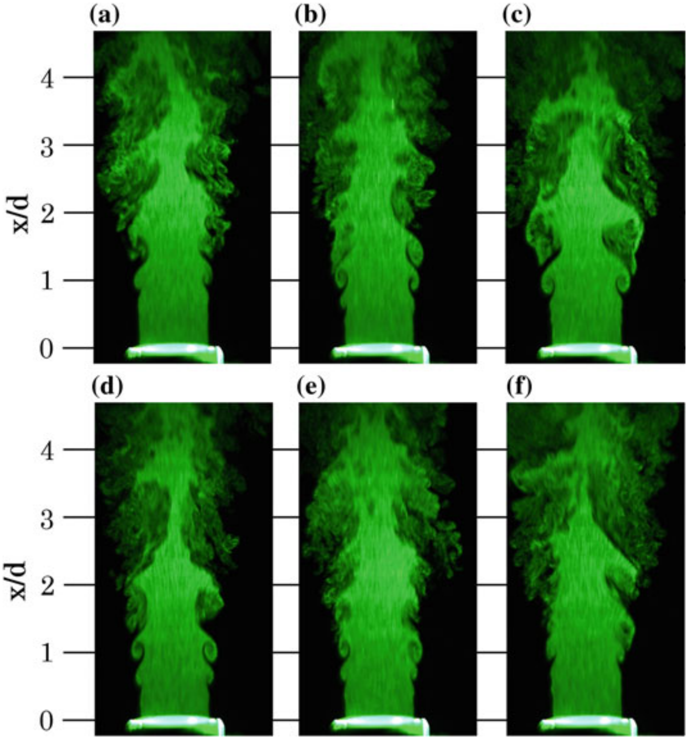


Fig. 6 XY plane of jet visualization image at $Re = 10{,}000$. **a** Plasma off. **b** $f_{burst} = 0.3f_n = 595$ Hz. **c** $f_{burs} = 0.9f_n = 1786$ Hz **d** $f_{burst} = 1.0f_n = 1984$ Hz. **e** $f_{burst} = 1.4f_n = 2778$ Hz. **f** $f_{burst} = 2.0f_n = 3968$ Hz

cycle. We consider that the induced flow of the coaxial type DBD-PA generates a large vortex and Shear layer instability of jet generates a small vortex. In Fig. 6c–e, the jet is controlled by driving the coaxial type DBD-PA frequency of burst modulation control in which the phenomenon of lock-in occurs. Figure 6c is $f_{burst} = 0.9f_n = 1786$ Hz, the phenomenon of lock-in begins with this f_{burst}. Figure 6d is $f_{burst} = 1.0f_n = 1984$ Hz, this f_{burst} is the natural vortex frequency. When the coaxial type DBD-PA driving condition is $f_{burst} = 0.9f_n$ or $1.0f_n$, these conditions generate large vortices near the nozzle of the jet in a steady cycle and these vortices coalescence develop large-scale vortex ring compared to other experimental conditions (Fig. 6a, b, e, f). Figure 6e is $f_{burst} = 1.4f_n = 2778$ Hz, the phenomenon of lock-in ends with this f_{burst}. This condition generates a small vortex near the nozzle of the jet in a steady cycle. Figure 6f is $f_{burst} = 2.0f_n = 3968$ Hz. This condition generates a small vortex near the nozzle of the jet in an unsteady cycle. We consider that frequency of the induced flow of the coaxial type DBD-PA is higher than other conditions and the generation of vortex can not follow.

4 Conclusions

The coaxial type DBD-PA is driven by burst modulation control and the intermittently generated induced flow control the jet. As a result, following knowledge is obtained.

1. By the phenomenon of lock-in, the induced flow of the coaxial type DBD-PA synchronizes vortex generation in the jet in a specific burst modulation control frequency range. Consequently, the jet is controlled by the coaxial type DBD-PA within frequency of burst modulation control in which the phenomenon of lock-in occurs.
2. Driving the coaxial type DBD-PA with burst modulation control generates a large vortex near the nozzle of the jet in a steady cycle and these vortices coalescence develop large-scale vortex ring.

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