Multi-Electrode Plasma Actuator to Improve Performance of Flow Separation Control

Norio Asaumi^{1,2}, Shinsuke Matsuno¹
Takashi Matsuno², Masataka Sugahara², and Hiromitsu Kawazoe²

¹ IHI Corporation
1, Shin-Nakahara-Cho, Isogo-ku, Yokohama 235-8501, Japan
E-mail: norio_asaumi@ihi.co.jp

² Department of Mechanical and Aerospace Engineering, Tottori University

ABSTRACT

The advantage of a trielectrode (TED) plasma actuator in the flow separation control on the two-dimensional airfoil model has been investigated experimentally in 30 m/s uniform flow ($Re = 6.0 \times 10^5$). Two exposed electrodes are set on the surface of a NACA0012 airfoil model. For driving SDBD and TED plasma actuators separately, one exposed electrode for applying AC voltages is located at the leading-edge, and DC voltages is applied to another one placed in 41.43 mm downstream from the leading edge. The flow field around the model was analyzed using time-resolved PIV in a wind tunnel. The results indicated superior performance of the TED plasma actuator in separation delay when a high negative voltage ($V_{dc} = -20$ kV) was applied, compared to the SDBD plasma actuator. At the same time, the TED plasma actuator showed higher efficiency in energy consumption, when compared in terms of thrust generated per power supplied.

INTRODUCTION

First investigations with plasma actuators as flow control devices date back to the late 1960's^[1], while research work explosively increased this century^[2-5]. In the field of plasma-utilization, the plasma actuator with single dielectric barrier discharge (SDBD) is a mainstream configuration for recent research. The basic SDBD plasma actuator consists of a pair of electrodes isolated by a dielectric material. One of the electrodes is exposed to air, while the other is buried in dielectric material so as to never get into contact with the air. By applying an AC voltage in the order of 10 kV and 10 kHz, single dielectric barrier discharge occurs at the edge of the exposed electrode and weakly ionized air, called plasma, forms over the buried electrode. Ionized air and electric field of the electrodes create body forces that act on the air flowing over the actuator.

The investigation of plasma actuators is popular in aviation and a large variety of configurations exists^[1]. University of Notre Dame and Boeing have been investigating ways to improve the flow separation on a small-scale model of the wing of an aircraft. Flow reattachment was achieved by using a plasma actuator for Mach numbers up to 0.4 in the wind tunnel at the University of Notre Dame^[6]. Outstanding results have also been obtained numerically and experimentally in the investigation of noise reduction using a plasma actuator from the tandem-cylinder similar to the landing gear configuration of an aircraft^[7]. Tip flow-control in the jet

engine using plasma actuators has been investigated by GE. In a transonic compressor rig, the plasma actuators placed on the casing wall upstream of the rotor's leading edge were tested. The plasma actuators did not affect the steady state performance, but a certain percentage of stall margin improvement was recognized^[8].

The above-mentioned investigations have been successful, although the amount of body force and mass flow generated by the plasma actuators is considered too small. To obtain flow controllability suitable for practical use, more thrust needs to be generated with less electric power. The objective of this research is to develop a high performance plasma actuator that can be utilized in high-speed flow. One of the promising approaches is the discharge and electric field formation by utilizing another exposed electrode to which a high DC voltage is applied. This configuration is called "tリエlectrode discharge (TED)" plasma actuator^[9-11].

Fig. 1 Schematic configurations of SDBD and TED plasma actuators

Figure 1 shows the SDBD and TED plasma actuator configurations employed in this research. The SDBD actuator consists of one electrode on the air side and another one on the other side of the dielectric barrier; an AC voltage in the order of 10kV is applied to the electrodes (Fig. 1a). TED plasma actuators are equipped with a second electrode on the air side; a DC voltage in the order of 10kV is applied between this electrode and the ground (Fig. 1(b), (c)). The electrodes on the air side are called “AC electrode” and “DC electrode”, respectively, in this paper. It is well-known that the flow control performance of a TED plasma actuator is significantly changed by AC, DC voltages and DC polarity^[12]. When a positive DC voltage is applied to the DC electrode, this configuration is denoted as “TED-DBD plasma actuator” here. On the contrary, a plasma is formed between AC and DC electrodes, when a negative DC voltage is applied. This phenomenon is called “sliding discharge (SD)” and, therefore, the configuration is called “TED-SD plasma actuator” in this paper.

This work focuses on the application of plasma actuator control in turbomachinery. In former publications the potential of TED to yield remarkable improvement in performance above SDBD has already been reported. For a TED-DBD plasma actuator made of aluminium oxide (Al_2O_3), the generated thrust was 800% of that obtained with SDBD plasma actuator^[10]. Basic experiments with a TED-SD actuator made of cheaper PTFE revealed an improved thrust of 148% compared to SDBD^[11].

In this paper, TED-DBD and TED-SD plasma actuators with PTFE as dielectric layer material are applied to a NACA0012 airfoil. Control of flow separation is carried out in a low speed wind tunnel and control effect by SDBD and TED plasma actuators are investigated by analyzing velocity distributions using Particle Image Velocimetry (PIV).

EXPERIMENTAL SETUP

Power Supply

Figure 2 shows a schematic of the power supply to the plasma actuator used in this study. A reference waveform of a high-voltage AC input was generated by a function generator and amplified by a solid-state high power amplifier, which increases input power up to 400 W, with the amplitude of $V_{pp} = 70$ V. Using a high voltage transformer, an AC voltage amplitude of up to 30 kV at a frequency of 5-15 kHz was attained. Voltage and current of AC input was monitored by a digital oscilloscope. DC voltage was applied directly from the high voltage power supply (Matsusada Precision, HAR-30), which can generate up to $V_{dc} = 30$ kV with 10 mA of output. Total power consumption of AC and DC power supply were measured by a wattmeter (HIOKI, 3168 clamp on power tester).

Thrust Measurement System

In this research, thrust of the jet induced by the plasma actuator was measured as reaction of the aerodynamic force exerted from the actuator, and was used as indication of the flow control performance. The schematic of the apparatus for the thrust measurement is illustrated in Fig. 3. Thrust from the plasma actuator was sensed by an analytical balance (Shimadzu, AUW320) with a lever. Since the TED-SD plasma actuator generates a directed jet, it is necessary to measure the horizontal and vertical thrust components. Two types of mounting devices for the actuator element were used as shown in Figs. 3(a) and (b).

Wind Tunnel

The low speed wind tunnel of Tottori University is shown in Fig. 4. The wind tunnel comprises a 1800 mm-long test section with a 600 mm square cross-section. The contraction area ratio is 7:1. The uniform flow velocity of the wind tunnel can reach up to 30 m/s at a turbulence level below 0.7% of the free stream velocity.

Fig. 2 Connection diagram of the power supply system for driving TED plasma actuator

(a) Horizontal thrust measurement

(b) Vertical thrust measurement

Fig. 3 Schematics of thrust measurement system

Fig. 4 Schematic of the wind tunnel at Tottori University

Airfoil Model

The model used in the experiments was a two-dimensional wing model with NACA0012 airfoil (shown in Fig. 5). Chord length and span of the model were 300 mm. The airfoil model was made up of two pieces that included a removable edge so that various types of plasma actuators can be mounted. 400 mm diameter splitter plates

were located at the tip of the model. All experiments were carried out in uniform flow of 30 m/s. The Reynolds number was 6.0×10^5 .

Figure 6 shows the configuration of the plasma actuator located on the leading edge of the airfoil (details are listed in Table. 1). In the literature, it is proposed that the exposed electrode of the SDBD plasma actuator should be mounted on the leading edge of the airfoil for efficient control of the flow separation around the airfoil^[6]. Figure 7 shows the SDBD and TED-SD plasma actuators in operation.

Fig. 5 Photographs of the NACA0012 airfoil model

Fig. 6 Schematic of the plasma actuator mounted on the leading edge of the airfoil

Fig. 7 Photographs of the plasma actuators in operation on leading edge of the airfoil

PIV System

A Seika Digital Image corporation PIV system with two single pulsed Nd:YAG lasers, a high speed camera and the analysis software Concerto II were utilized for this experiment. 200 pairs of pictures of the flow field were recorded for 0.1 seconds at each flow condition and averaged to obtain the mean flow vectors.

A schematic of the PIV setup is shown in Fig. 8. The laser sheet

was introduced through a window in the test section on the suction side of the model. Its focal plane was orthogonal to the laser sheet and perpendicular to the suction surface of the model. The flow field at the mid span location around the suction side of the airfoil covered a $400 \times 400 \text{ mm}^2$ square region (Fig. 9). Figure 10 shows a sample of the flow field as obtained by PIV. Note that the flow field near the airfoil surface is not clearly seen in this picture due to perspective view. It is shown in a later section, that the flow field close to the surface is resolved properly.

Fig. 8 Schematic configuration of the PIV system used in the wind tunnel tests

Fig. 9 Visualization area investigated with PIV

Fig. 10 Typical PIV result with overlaid photograph of airfoil

Experimental Conditions of TED

In the present work, AC voltage and frequency were kept constant and the DC voltage was chosen as parameter to be examined. Experimental conditions, physical dimensions and properties of the TED plasma actuator used in the experiment are summarized in Table 1.

Table 1 Specification of the TED plasma actuator

Dielectric material	PTFE
AC frequency: f_{ac} [kHz]	13
AC voltage: V_{pp} [kV]	15.6
DC voltage: V_{dc} [kV]	-23~21
Electrode material	Copper
Dielectric layer thickness [mm]	1.08
Streamwise length of buried electrode [mm]	40
Streamwise length of exposed electrode [mm]	5
Overlap of electrodes [mm]	0
Spanwise length of exposed electrode [mm]	255

RESULTS

Thrust Measurement

Before the experiments in the wind tunnel were carried out, the performance of TED-DBD ($V_{dc} > 0$) and TED-SD ($V_{dc} < 0$) plasma actuator were studied in order to determine the DC voltage (V_{dc}) to be used in the following tests in the wind tunnel.

Figure 11 shows the change of thrust induced by the TED plasma actuator with applied DC voltage. Note that for $V_{dc} = 0$ kV, the TED plasma actuator operates exactly as SDBD plasma actuator (absolute thrust of 11.3 mN/m). This plot demonstrates that the thrust generated by the TED plasma actuator varies with applied DC voltage. Vertical thrust is low, namely 3 to 5 mN/m, while horizontal thrust is almost constant for low voltage ($|V_{dc}| < 10$ kV), showing a slight increase from 11.1 mN/m at -10 kV to 13.1 mN/m at 10 kV.

When positive DC voltage is applied (TED-DBD), the horizontal thrust first increases from 10 kV to 15 kV, then monotonically decreases. On the other hand, vertical thrust is almost constant from 10 kV to 20 kV, then rapidly increases. The absolute thrust, which is defined as square root of the sum of squared horizontal and vertical thrusts, is 17.5 mN/m for $V_{dc} = 21$ kV, which means a 40% improvement upon the SDBD plasma actuator for the same AC voltage.

When negative DC voltage is applied (TED-SD), the thrust shows a different behaviour for voltages below -10 kV. While the vertical thrust is similar to TED-DBD plasma actuator, horizontal thrust continuously decreases from 10.6 mN/m at -10 kV to -16.2 mN/m at -20 kV. The negative thrust, which means thrust in the opposite direction, is due to the onset of sliding discharge, as already reported in [11]. It occurred when applying $V_{dc} \leq -20$ kV to the TED-SD plasma actuator. The overall thrust of 23.7 mN/m for $V_{dc} = -20$ kV is two times stronger than that of the SDBD plasma actuator. The TED-SD plasma actuator tends to generate higher thrust than the TED-DBD plasma actuator in this experiment.

In this paper, we focus on the comparison of TED-SD with SDBD. The two conditions of the DC voltage, $V_{dc} = 0$ kV and -20 kV, have been selected for the following reasons. For $V_{dc} = 0$ kV, TED-SD plasma actuator works as simple SDBD plasma actuator. Hence, this condition was selected for comparison. $V_{dc} = -20$ kV was chosen as the typical condition for the TED-SD plasma actuator, because the sliding discharge occurs only for $V_{dc} \leq -20$ kV. There were not any significant changes in magnitude and direction of the generated thrust during the existence of sliding discharge for the range investigated in this research. Figure 12 shows the total power consumption of the plasma actuator. Compared to the power consumption of 114 W for

the SDBD plasma actuator, the TED-SD plasma actuator consumed 135 W at -20 kV. Considering generated thrust divided by total power consumption, the TED-SD plasma actuator generates thrust 1.6 times more efficient than the SDBD plasma actuator.

According to the above results, a large difference of the induced flow fields between SDBD and TED-SD could be expected for a DC voltage of -20 kV. Hence, this condition was chosen for the PIV measurements in the wind tunnel experiments.

Fig. 11 Horizontal, vertical and absolute thrust of the TED plasma actuator versus applied DC voltage ($V_{pp} = 15.6$ kV, $f_{ac} = 13$ kHz)

Fig. 12 Absolute thrust versus total power consumption ($V_{pp} = 15.6$ kV, $f_{ac} = 13$ kHz, $V_{dc} < 0$)

Flow Control Performance of TED Compared with SDBD

The performance of plasma actuators in flow separation control on an NACA0012 airfoil at poststall angles of attack (AoA) was investigated. These tests have been conducted with the PIV system introduced in Fig. 8.

Streamlines around the airfoil for various angles of attack are shown in Fig. 13. It is readily seen that the flow around the airfoil is attached to the surface up to AoA = 16 degrees (Fig.13(d)). In Figs. 13(e) and (f), the flow is detached from the surface. Hence, the stall angle of attack for this airfoil is determined to be between 16 and 17 degrees.

The flow around the airfoil is compared for SDBD and TED-SD plasma actuators. Primary focus of the current experiment was on the improvement of AoA at onset of stall by the two actuators.

At first, PIV results for the flow field generated at $V_{dc} = -20.0$ kV in quiescent air are shown in Fig. 14. In Fig. 14(a), the wall jet induced by the SDBD plasma actuator is observed. On the contrary, a wall normal jet is generated by the TED-SD plasma actuator (Fig. 14(b)). From this result and direct observation it is inferred that for TED-SD plasma actuator, sliding discharge occurred on the airfoil at the same voltage conditions as in the thrust measurements.

Figs. 15 and 16 show the velocity profiles in x- and y-directions of the flow induced by SDBD and TED-SD plasma actuators near the leading edge of the airfoil. Three findings can be stated. Firstly,

the flow induced by the TED-SD plasma actuator is approximately twice as fast as that induced by the SDBD plasma actuator. Secondly, the TED-SD plasma actuator induces a flow in opposite direction. Thirdly, the TED-SD plasma actuator influences the flow field in a larger extent, i.e. to a further distance from the airfoil surface.

The wind-tunnel experiments were performed at a flow velocity of 30 m/s. Figure 17 shows the PIV results with the SDBD plasma actuator at AoA = 22, 22.5 and 23 degrees. The flow is attached to the surface at AoA = 22 degrees (Fig. 17(a)). However, the shear layers are separated from the airfoil surface at the higher angles (Figs. 17(b), (c)). Hence, it is found that the SDBD plasma actuator delayed flow separation from 17 degrees without actuator to 22 degrees. Figure 18 shows the PIV results as obtained with the TED-SD plasma actuator at the same AoAs. When comparing the flow fields obtained with SDBD and TED-SD plasma actuators, it is seen that flow separation is further delayed in amount of 0.5 degree by the TED-SD plasma actuator.

When the thrust generation was measured, it has been found that the TED-SD plasma actuator caused a higher thrust than the SDBD plasma actuator, leading to velocities about two times faster (Figs. 15, 16). It is interesting to note that the u-velocities differ by about 2 or 3 m/s in Fig. 19, which must be compared with a difference of about 0.5 m/s in quiescent air and opposite directions of the induced flow. Although the flow induced by the plasma actuators is in the order of 1 m/s, this induced flow appears to influence the flow as fast as 40 to 50 m/s. Therefore, it must be concluded that the result of delay in flow separation to a higher AoA is not simply the result of superposition of the flow field around the airfoil without plasma actuator and the flow induced by the actuator in quiescent air.

In reference [13], it is reported that the mechanism of separation control for the standard SDBD plasma actuator is classified as (1) direct momentum addition (steady phenomenon) and (2) freestream momentum entrainment (unsteady phenomenon). The main mechanism of the TED-SD plasma actuator should be the freestream momentum entrainment, because the induced flow velocity of the TED-SD plasma actuator is still slow compared to the freestream, although the jet is significantly faster than that of the SDBD plasma actuator. Particularly, when the freestream and the jet induced from the plasma actuator are interacted, strong Reynolds stresses are generated, which cause the freestream momentum entrainment, as reported in [13, 14]. It is suggested that the higher thrust from the TED-SD plasma actuator successfully entrains the momentum from the freestream above the boundary layer due to the Reynolds stress augmentation.

Concerning the effect of actuator position on the performance of separation control, it is well-known that the location of the actuator plays an important role to determine flow control performance (as shown in [14]). In the present paper, both actuators were installed at the same location for the sake of comparison. The flow control performance will increase by optimization of the location. Also, a periodic pulse actuation is known to enhance the flow control capability of plasma actuator compared to steady actuation^[6,13]. Further studies on these two factors will be carried out in order to evaluate the effectiveness of the TED plasma actuator.

CONCLUSIONS

Wind-tunnel experiments aimed at the evaluation of flow separation control of the flow around an airfoil by trielectrode discharge (TED) plasma actuators have been performed. The TED plasma actuator has been used in both, single dielectric barrier discharge (SDBD) operation and sliding discharge (TED-SD) operation modes on a NACA 0012 airfoil at a Reynolds number of 6.0×10^5 . The conclusions are summarized as follows.

1. As already confirmed for other configurations and materials, the TED-SD plasma actuator used in this work generated higher thrust than the SDBD plasma actuator. As a result, the TED-SD plasma actuator induced a faster flow in quiescent

air.

2. In this work, DC voltage has been changed in the range from -23 kV to +21 kV for AC voltage of 15.6 kV and frequency of 13 kHz. High thrust is obtained by applying a DC voltage ≤ -20 kV, due to the onset of sliding discharge. When DC voltage of -20 kV is applied, the thrust yields an improvement of more than two times higher induced velocities than SDBD. When evaluating thrust per supplied power, TED-SD plasma actuator is 1.6 times more efficient than the SDBD plasma actuator.
3. Steady operation of both SDBD plasma actuator and TED-SD plasma actuator mounted on the leading-edge of the airfoil were examined to study the effect on the onset of stall. The experiments revealed that the SDBD actuator delayed the stall from 17 degree to 22 degree, while the TED-SD actuator further delayed stall to 22.5 degree.

REFERENCES

- [1] Touchard, G., 2008, "Plasma Actuators for Aeronautics Applications – State of Art Review –," *Journal of Plasma Environmental Science & Technology*, Vol. 2, No. 1, pp. 1-25.
- [2] Corke, T. C., Post, M. L., and Orlov, D. M., 2007, "SDBD Plasma Enhanced Aerodynamics: Concepts, Optimization and Applications," *Progress in Aerospace Sciences*, Vol. 43, No. 7-8, pp. 193-217.
- [3] Font, G. I., and Morgan, W. L., 2007, "Recent Progress in Dielectric Barrier Discharges for Aerodynamic Flow Control," *Contributions to Plasma Physics*, Vol. 47, No. 1-2, pp. 103-110.
- [4] Matsuno, T., Maeda, K., Yamada, G., Kawazoe, H. and Kanazaki, M., 2013, "Improvement of Flow Control Performance of Plasma Actuator Using Wind-Tunnel Test Based Efficient Global Optimization," *31st AIAA Applied Aerodynamics Conference*, AIAA 2013-2512.
- [5] Forte, M., Jolibois, J., Pons, J., Moreau, E., Touchard, G., and Cazalens, M., 2007, "Optimization of a Dielectric Barrier Discharge Actuator by Stationary and Non-Stationary Measurements of the Induced Flow Velocity: Application to airflow control," *Experiments in Fluids*, Vol. 43, pp. 917-928.
- [6] Kelley, C. L., Bowles, P. O., Cooney, J., He, C., Corke, T. C., Osborne, B. A., Silkey, J. S., and Zehnle, J., 2014, "Leading-Edge Separation Control Using Alternating-Current and Nanosecond-Pulse Plasma Actuators," *AIAA Journal*, Vol. 52, No. 9, pp. 1871-1884.
- [7] Eltaweel, A., Wang, M., Kim, D., Thomas, F. O., and Kozlov, A. V., 2014, "Numerical Investigation of Tandem-cylinder noise Reduction using Plasma-based flow Control," *Journal of Fluid Mechanics*, Vol. 756, pp. 422-451.
- [8] Saddoughi, S., Bennett, G., Boespflug, M., Puterbaugh, S. L., Wadia, A. R., 2014, "Experimental Investigation of Tip Clearance Flow in a Transonic Compressor with and without plasma actuators," *ASME Turbomachinery Technical Conference & Exposition*, GT 2014-25294.
- [9] Sosa, R., Arnaud, E., Memin, E., and Artana, G., 2009, "Study of the Flow Induced by a Sliding Discharge," *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 16, No. 2, pp. 305-311.
- [10] Matsuno, T., Fujita, N., Yamada, G., Kawazoe, H., Matsuno, S., Asaumi, N., and Kouwa, J., 2014, "Vectored Jet Control by Trielectrode Plasma Actuator for Turbomachinery," *Asian Joint Conference on Propulsion and Power*, AJCPP 2014-155.
- [11] Matsuno, T., Kawaguchi, M., Fujita, N., Yamada, G. and Kawazoe, H., 2012, "Jet Vectoring and Enhancement of Flow Control of Trielectrode Plasma Actuator Utilizing Sliding Discharge," *6th AIAA Flow Control Conference*, AIAA 2012-3238.
- [12] Luo, X., 2012, "Plasma Based Jet Actuators for Flow

Control,” *Ph.D. Thesis*, University of Southampton, Faculty of Engineering and the Environment, <http://eprints.soton.ac.uk>

- [13] Sato, M., Nonomura, T., Okada, K., Asada, K., Aono, H., Yakeno, A., Abe, Y., and Fuji, K., 2015, “Mechanisms for Laminar Separated Flow Control Using Dielectric-Barrier-Discharge Plasma Actuator at Low Reynolds Number,” *Physics of Fluids*, Vol. 27, 117101.
- [14] Sato, M., Okada, K., Nonomura, T., Aono, H., Yakeno, A., Asada, L., Abe, Y., and Fuji, K., 2013, “Massive Parametric Study by LES on Separated-flow Control around Airfoil using DBD Plasma Actuator at Reynolds Number 63,000,” *43rd AIAA Fluid Dynamics Conference and Exhibit*, AIAA 2013-2750.

Fig. 13 Mean velocity fields without plasma actuator in 30 m/s flow (velocity magnitude [m/s])

(a) SDBD ($V_{pp} = 15.6$ kV, $V_{dc} = 0$ kV) (b) TED-SD ($V_{pp} = 15.6$ kV, $V_{dc} = -20$ kV)

Fig. 14 Mean velocity fields as obtained with plasma actuator in quiescent air (velocity magnitude [m/s])

(a) U-velocity (x-direction)

(b) V-velocity (y-direction)

Fig. 15 Mean velocity fields with SDBD plasma actuator in quiescent air

(a) U-velocity (x-direction)

(b) V-velocity (y-direction)

Fig. 16 Mean velocity fields with TED-SD plasma actuator in quiescent air

(a) AoA = 22 degrees

(b) AoA = 22.5 degrees

(c) AoA = 23 degrees

Fig. 17 Mean velocity fields with the SDBD in 30 m/s flow (velocity magnitude [m/s])

(a) AoA = 22 degrees

(b) AoA = 22.5 degrees

(c) AoA = 23 degrees

Fig. 18 Mean velocity fields with the TED-SD in 30 m/s flow (velocity magnitude [m/s])

(a) U-velocity (x-direction)

(b) V-velocity (y-direction)

Fig. 19 Mean velocity fields with plasma actuators in 30m/s flow (AoA = 22 degrees)