"I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of the degree of Doctor of Philosophy in Engineering."

Signature : *Shigeki Imao*

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Date : May 14, 2015

FLOW CONTROL OF LEADING EDGE SEPARATION ON AIRFOIL USING DBD PLASMA ACTUATOR

（DBD プラズマアクチュエータによる前縁はく離流れの制御）

A thesis submitted in partial

fulfillment of the requirements of the degree of

Doctor of Philosophy

Supervised by

Professor Shigeki Imao

Graduate School of Engineering

(Doctor Course)

GIFU UNIVERSITY

JAPAN

JUNE, 2015

Abstract

In the past, dielectric barrier discharge (DBD) plasma actuators have been shown to be capable of manipulating airflow by producing an electric wind in the boundary layer. Many researchers have investigated the potential of this device. Recently, many researchers have been studying about flow separation control with unsteady actuation. However, the effectiveness of the pulse-modulated drive is still not clearly described when angle of attack is high. Therefore, an investigation on the flow is studied when a plasma surface discharge is driven with pulse modulation both at the stall control condition and at high angle of attack condition.

The purposes of this study are as follows:

1) To study the effect of pulse-modulated drive of plasma actuator on the flow around the airfoil both at the stall control condition and at high angle of attack condition.
2) To study the effect of amplitude modulated pulse modulation on the flow around the airfoil both at the stall control condition and at high angle of attack condition and to compare the improvement of lift coefficient C_l between pulse modulation with amplitude modulation (PM+AM) and only pulse modulation (PM).

In this study, the DBD plasma actuator is located at the leading edge of airfoil because this configuration had been found to be more effective at high angles of attack. The DBD plasma actuator is installed at x/c = 0.025 of a NACA 0015 airfoil with a 100-mm chord and 150-mm width. It is tested at $Re \approx 67{,}000$ in an airflow of 10 m/s for lift force and hot-wire measurement. However, for flow visualization, the airfoil is tested in airflow of 5 m/s for better flow images. A high-voltage AC current is supplied to the exposed electrode while the encapsulated electrode is grounded. The base waveform is an 8-kHz sinusoidal wave, generated by a digital function generator. The signal is amplified by a high-voltage amplifier to give a peak-peak voltage of 6 kV. Unsteady actuation is performed by applying a low modulation frequency to the base wave.

For the next stage of this study, an amplitude modulated pulse modulation is designed to have the same power consumption as pulse-modulated drive. Waveform of pulse modulation in addition to amplitude modulation is set to the same modulation frequency f_M and the same base frequency f_B as that for pulse modulation case. An amplitude modulated pulse modulation is applied to the DBD plasma actuator to investigate the lift coefficient C_l improvement compared to pulse-modulated drive.

The results are summarized as follows:

1. In the case of no actuation, the stall occurs at α = 13.5° and when the actuator is driven at *Duty* = 100% the stall occurs at α = 15°. However, the application of ON-OFF control of the actuator is able to maintain the increment of the C_l value. Furthermore, when *St* = 4.0, the lift coefficient is reduced sharply after reaching a maximum, while when *St* = 0.6, it falls gradually. For a high angle of attack (α = 18°) when the angle of attack exceeds the maximum C_l, there is an optimum pulse length for effectively controlling the flow.
2. Pulse-modulated drive is able to manipulate the behavior of the flow above the airfoil in the high angle of attack. When *St* = 0.6, a large vortex appears and covers almost the entire airfoil surface. When *St* = 4.0, however, a small- scale vortex structure forms near the leading edge and then diverges away from the wing surface.
3. Setting *St* = 4.0 is an effective means of increasing the airfoil performance for the stall control condition (α = 16°). For the high angle of attack case, however, it was found that setting *St* = 0.6 increases the lift coefficient of the airfoil.
4. The lift coefficient C_l showed similar trends for both the PM and PM+AM cases at the same *St* values. When *St* = 4.0, C_l decreased rapidly after reaching a maximum. However, when *St* = 0.6, C_l decreased gradually.
5. The PM+AM case improves the lift coefficient more effectively than the PM case at a high angle of attack (α = 18°), with minimal improvement under the stall control condition (α = 16°).
6. An unsteady amplitude modulated signal stimulates vortex growth more for the PM+AM case than for the PM case, the former forces the flow closer to the wing which improves the lift coefficient.

Acknowledgements

First and foremost, I would like to express the deepest appreciation to Professor Shigeki Imao for his valuable advice and guidance in all aspects during my study in Gifu University. Without his supervision and continuous help this research would not be able to success. I would also like to express my special thanks to Assoc. Prof. Yasuaki Kozato for his contribution in stimulating suggestions and idea to coordinate my research. In addition, I would like to express my sincerest appreciation to Assoc. Prof. Satoshi Kikuchi for his invaluable advice and guidance and also to the honorable members of my dissertation examining committee, Prof. Tomonao Kobayashi and Prof. Shuhei Takahashi.

I wish to express my appreciation to all master and undergraduate students in Imao laboratory for their constant cooperation and guidance in all aspects during the entire period of my study. Besides, I would like to express my deep gratitude to Ministry of Education Malaysia and Universiti Teknikal Malaysia Melaka (UTeM) for sponsoring my study in Gifu University, Japan.

Lastly, I wish to express my deep gratitude and special thanks to my dear wife and daughters, who encouraged and support me in all aspects during my study in Japan.

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Nomenclature

The following conventional symbols are used in this thesis

C_l	lift coefficient = $L/(0.5\rho U_0^2 A)$
C_d	drag coefficient = $D/(0.5\rho U_0^2 A)$
c	chord length
D	drag force
Duty	ratio of ON time to the period of modulation actuation (duty ratio)
E	output voltage of the hot-wire anemometer
E_0	output voltage when $U_r = 0$
f_B	base frequency
f_M	modulation frequency
$I(t)$	actuator current
L	lift force
Re	Reynolds number = $U_0\, c/\nu$
P	power spectrum of fluctuating velocity
$\overline{P}_a$	actuator average power
$\overline{P}$	average power evolution for actuator
$P(t)$	instantaneous power
S	wing area = (span) x (chord length)
St	non-dimensional pulse modulation frequency = $f_M\, c/U_0$

St_u	non-dimensional frequency of fluctuating velocity
T	period of ON-OFF cycle
T_{on}	period that DBD plasma actuator is ON
U	time-mean velocity
U_0	uniform flow velocity
u'	rms value of fluctuating velocity
u_b'	rms value of the dominant frequency components
$V_{\text{peak-peak}}$	base voltage
$V(t)$	voltage of the actuator
x,y	horizontal and vertical distance measured from the leading edge
α	angle of attack
ρ	air density
ν	kinematic viscosity of air

1. Introduction

1.1 Background

In the past, dielectric barrier discharge (DBD) plasma actuator has become the popular device in the aerodynamic flow control application. An excellent review of plasma actuators history, basic physics, flow control application and its type is provided by Moreau (2007) and Corke et al. (2010). The interest in research is growing due to their special features such as no moving parts, quick response and a very low mass device. For example, plasma actuators have been applied for flow separation control on airfoils (Post and Corke, 2004a; Corke et al., 2004; Hasebe et al., 2011), flow control around a circular cylinder (Jukes and Choi, 2009; Asghar and Jumper, 2003; McLaughlin et al., 2004; McLaughlin et al., 2006), delaying separation on turbine blades (Greenblat et al., 2012; Corke and Post, 2005) and manipulating boundary layer (Porter et al., 2007; Opaits et al., 2005; Boxx et al., 2006; Jacob et al., 2004; Font, 2006).

Sosa and Artana (2006) have divided plasma actuators into three large groups: corona-based devices (Colver and El-Khabiry, 1999; Noger et al., 1997; Moreau et al., 2006), dielectric barrier discharge (Roth and Sherman, 2000; Wilkinson, 2003) and plasma sheet devices (D'Adamo et al., 2002; Artana et al., 2003; Sosa et al., 2004; Moreau et al., 2008a). In this study, a dielectric barrier discharge plasma actuator will be focused.

A dielectric barrier discharge (DBD) plasma actuator is a device that consists of exposed electrode and encapsulated electrode which separated by a dielectric material. A plasma is created when sufficient voltage is applied between exposed and encapsulated electrodes. The DBD plasma actuator is usually excited with AC voltage in order to allow continuous plasma generation. Momentum is transferred from the plasma discharge to the ambient air through a collision of ions which creates an induced air or a body force. The electrochemical interaction between air and plasma causes to plasma kinetic phenomena because of existing low density of electrons, positive and negative ions and neutral particles (Wang et al., 2007; Singh and Gaitonde, 2006). In the classic definition, ionized air is referred as plasma. This is the reason why the term plasma is used for DBD plasma actuator (Cavalieri, 1995; Corke and Matlis, 2000; Corke et al., 2001). The ionized air appears blue color due to the air recombine and de-excite to ionized components (Davidson and O'Neil, 1964).

The first model of DBD plasma actuator was developed by Massines et al. (1998). It was a 1D model based on a simultaneous solution of the continuity and Poisson equations. After that Paulus et al. (1999) developed 2D simulation to study the time-dependent evolution and the electrical field of particles during a high-voltage pulse. The simulation revealed that the charged particles transferred to the high electric potential region and created a high-electric field strength near the electrode's edges. It also showed that the plasma built up on a very short period in microsecond timescale.

Roth et al. (2000) and Roth and Dai (2006) presented a model of the body force produced by the plasma on the neutral air. The body force is proportional to the gradient of the squared electric field based on the derivation of the forces in gaseous dielectric (Landau and Lifshitz, 1984). However, Boeuf and Pitchford (2005) did not agree with the model equation. Enloe et al. (2004b) claimed that the model was relevant to the 1D condition only.

Shyy et al. (2002) presented a body force based on the assumption that the electric–field strength decreased linearly from the edge of the bare electrode to the dielectric-covered electrode. However, the assumption was not consistent with the findings from Enloe et al. (2004b); Orlov (2006); Orlov et al. (2006). While, Singh and Roy (2008) developed the 2D body-force components by using the results from a first-principle simulation and empirical observations of actuator behavior. Both Shyy et al. (2002) and Singh and Roy (2008) models did not scale properly with the voltage.

Suzen et al. (2005) and Suzen and Huang (2006) proposed the electrostatic equations into two parts which were due to the external field for the first part and the second part due to the electric field created by the charge particles. However, the scaling of AC voltage was not proportional to $V_{\mathrm{AC}}^{3.5}$. Boeuf and Pitchford (2005) presented a body force model in 2D asymmetric DBD by considering nitrogen at atmospheric pressure. As a result, they found that the asymmetry in the electrode configuration induced an asymmetry in the flow. Boeuf et al. (2007) extended the findings to investigate multiple microdischarge process. They also concluded that the charge particles left on actuator caused the force production due to the electric-field effects.

Some of the DBD models have been developed with complicated chemistry reaction equations. These equations referred to electron, ion-neutral and neutral reaction in different gases

(Gibalov and Pietsch, 2000; Golubovskii et al., 2002; Kozlov et al., 2001; Madani et al., 2003; Pai et al., 1996). Most of these models were developed for simple 1D geometries. Font (2004) and Font and Morgan (2005) considered the plasma discharge in a 2D asymmetric plasma actuator that consisted only oxygen and nitrogen reactions. They developed the simple chemistry reaction and simulated the propagation of a single streamer from the bare electrode to the dielectric surface and back. Likhanskii et al. (2006) proposed a DBD model where they considered the weakly ionized-air plasma as a mixture of neutral molecules, electrons and positive and negative ions.

The effects of voltage and AC frequency on the ionic velocity of the DBD plasma actuator also have been discussed by many reseachers previously. Orlov et al. (2006), found that the velocity is increased linearly with increasing AC voltage amplitude. Furthermore, Enloe et al. (2004b), investigated the reaction of thrust generated by the induced flow. Thomas et al. (2009) also performed a similar experiment in order to investigate parameters for designing the actuator. A shematic of experimental setup and the results are shown in Fig. 1.1(a). Enloe et al. (2004b), claimed that at the lower voltages, the induced thrust was proportional to $V_{\mathrm{AC}}^{3.5}$. While, Thomas et al. (2009) found the consistency between the force and fluid momentum by integrating the velocity profiles. Post and Corke (2004b) and Enloe et al. (2004b) showed that the maximum velocity produced by plasma actuator was limited by some distances from the exposed electrode. This effect is proven in Fig. 1.1(b), where the highest voltages for the Teflon dielectric is no longer increases after about 18 kV of V_{AC}.

Sato et al. (2013) and Nonomura et al. (2013) have conducted numerical analysis on the separated flow over airfloil. Both of them applied large-eddy simulation (LES) on the separated flow which controlled by a DBD plasma actuator. Sato et al. (2013) found that the most effective burst frequency of burst wave was 500 Hz. From the simple analysis of turbulent kinetic energy distribution, they justified that the cases with quick turbulent transition over airfoil had better aerodynamic performance. Nonomura et al. (2013) focused on the flow control mechanism to control the separation bubble. They obtained that the case with nondimensional burst wave of 600 Hz had earlier and smooth transition. This is because the actuation with nondimensional burst wave of 600 Hz effectively excites the Kelvin-Helmholz instability. Fujii (1995) applied zonal method from the extension of fortified solution alghorithm which was an effective computational fluid dynamics tool for complex flow physics and complex body configurations.

The dissipated power of plasma actuator is also proportional to $V_{\mathrm{AC}}^{3.5}$. This is proven by Enloe et al. (2004a). They computed the power dissipation by sampling the current and voltage waveforms. The product of waveform is integrated numerically over one period of discharge to obtain the power dissipated of the plasma.

The dielectric barrier configuration also supports a uniform discharge particles process which is proven by Kanazawa et al. (1988). The mechanisms are explained by Decomps et al. (1994); Roth (1995); Massines et al. (1996); Massines et al. (1998); Trunec et al. (1998). The stability of the diffuse mode depends on the gas type, AC frequency, and excitation power. The discharge is most stable in helium (Decomps et al., 1994; Kanzawa et al., 1990; Massines et al., 1996; Massines et al., 1998; Roth, 1995; Trunec et al., 1998).

Generally, the important features regarding the DBD plasma actuator are the base frequency, voltage, power consumption, geometry of the actuator, and the velocity produced by the generated plasma. Understanding these features are very important for the next stage of further research.

1.2 Outline of previous studies

Understanding the physics behind DBD plasma actuator is very important in order to develop and optimize its performance. The features can divided into AC waveform, geometry of actuator, dielectric, voltage and AC frequency as mentioned in Chapter 1.1. For example, Enloe et al. (2004b) performed PIV methods, Roth and Dai (2006) used pitot tubes and Forte et al. (2007) applied pitot tubes and LDV for better explanation of parametric studies of DBD plasma actuator. Some researchers have investigated these features in term of vortex development, ionic wind velocity enhancement, flow separation control and unsteady actuation of DBD plasma actuator.

1.2.1 Vortex development

When DBD plasma actuator is actuated in quiescent air, it will create a shear layer that rolls up to form a vortical structure. At the beginning of the excitation, the interaction between the discharge and the surrounding gas results in the formation of a counter clockwise rotating vortex situated near above the active electrode (Moreau et al., 2008a; Corke et al., 2007). Post (2004c) investigated the starting vortex induced by DBD plasma actuator by using phase-locked particle image velocimetry (PIV) in order to observe the transient flow field. The vortex moved away from the wall under the continuous actuation of DBD plasma actuator. This study also has been conducted by Whalley and Choi (2012), which proposed the mechanism of starting vortex formation as shown in Fig. 1.2. They suggested that the laterally ejected jet flow was supplied by entrainment of fluid above plasma actuator. As a result, a starting vortex is formed. The secondary vorticity was also generated along the wall and it wrapped around the starting vortex. Meanwhile, Sattari et al. (2012) investigated the temporal development of the starting vortex at the trailing edge of a flat plate by using time-resolved PIV. Both location of the vortex core and the strength of the vortex were measured without the influence of the wall. Okita et al. (2008) demonstrated a spanwise DBD plasma actuator to generate streamwise vortices for flow separation control. While, Jukes et al. (2006); Choi et al. (2010); Roy and Wang (2009) used a streamwise DBD actuators to produce a spanwise vortices.

1.2.2 Ionic wind velocity

Some researchers also studied the DBD plasma actuator in term of producing higher ionic wind velocity (Pons et al., 2005), while some of them investigated the effect of DBD plasma actuator with unsteady actuation to improve flow control performance (Likhanskii et al., 2007). The first measurement of ionic wind produced by actuator in quiescent air was conducted by Roth et al. (2000). They came out with a jet velocity up to 3.4 m/s at a few mm apart from the wall. This is supported by Johnson and Scott (2001) which obtained a similar jet velocity profiles at several distances downstream by using hot-wire anemometry. Forte et al. (2007) have conducted some experiments and they obtained an ionic wind velocity up to 7 m/s at 0.5 mm from the wall for a single actuator and 8 m/s for multiple actuators. Meanwhile, Craig et al. (2010) came out with a new configuration of plasma actuators. They studied the potential of multiple encapsulated electrodes (MEE) to increase the induced velocity. As a result, MEE actuators were able to produce the induced velocity 36.5% higher than the baseline case. Moreau et al. (2008b) conducted experiments with DBD three electrodes configuration. One electrode was supplied by an AC high voltage while two other electrodes were excited by a DC high voltage. Based on their results, the highest electric wind velocity was about 4 m/s at x = 10 mm. Jean-Charles Laurentie et al. (2009) investigated the effect of encapsulation of the grounded electrode of the plasma actuator. Velocity measurements showed that the electric wind velocity for a DBD with encapsulated grounded electrode was higher than DBD with encapsulated high voltage electrode. However, higher ionic velocity was not strictly related to improve flow control performance (Bernard et al., 2009).

1.2.3 Flow separation control and unsteady actuation method

It was proven that DBD plasma actuator was suitable to be applied on circular cylinder or airfoil especially for the flow separation control. Flow separation is generally described as detachment of fluid from a solid surface (Telionis, 1979; Gad-el-Hak and Bushnell, 1991). Separation is always associated with losses of lift and, increase of drag and losses of pressure recovery. Therefore, many researchers have been studying the control of flow separation on circular cylinder and airfoil by using DBD plasma actuator (Gronskis et al., 2008; Tabatabaeian et al., 2012; Benard et al., 2009; Segawa et al., 2009). In this study, the application of DBD plasma actuator on airfoil will be discussed. Some researchers claimed that the success of the separation control for airfoil in the high angle of attack depended on the vortex interaction due to the actuation effect. This is because pulse modulation drive may cause the separated shear layer near the leading edge to roll up and to develop. Asada et al. (2009) also reported that the smaller duty ratio caused stronger separation control capability in spite of less input energy. Rethmel et al. (2011) investigated flow control for an airfoil with nanosecond-pulse dielectric barrier discharge (DBD) plasma actuators. Asada et al. (2009) also conducted experiments using burst wave plasma actuators in a low-speed wind tunnel. Balcon et al. (2009) studied the effect of the ionic wind produced by DBD plasma actuator with positive and negative sawtooth signals. Amitay and Glezer (2002) focused on the effect of the actuation frequency for manipulating the flow reattachment over a stalled airfoil. Jukes et al. (2012) have demonstrated the DBD vortex generator to develop streamwise vortices in their experiments. They found that the method was successful in reducing the separation region.

Therefore, vortex interaction due to the actuation effect or actuator position is important to improve flow control performance. The effect of unsteady actuation is normally evaluated by the

Strouhal number or optimum dimensionless burst-wave frequency. However, the effectiveness of the pulse-modulated drive has still not been clearly described in the case of high angle of attack conditions. Different authors have stated different effective Strouhal numbers due to their methodologies and case studies. For example, Sidorenko et al. (2007) reported optimum dimensionless burst wave frequencies of 2.6 to 14. Rethmel et al. (2011) obtained a value of 2.0. Meanwhile, Asada et al. (2009) and Goksel et al. (2006) obtained 9.1 and 1.0, respectively. Asada et al. (2009) claimed that smaller burst ratio caused stronger separation control capability in spite of less energy consumption. The effect of DBD plasma actuator can be seen by the smoke wire method where the smoke flowed in the vicinity of the wing surface. Rethmel et al. (2011) found that at higher flow speed and angle of attack, DBD plasma actuator with nanosecond pulse signal excites natural flow instabilities that developed into large coherent structures. As a result, this device generates coherent spanwise vortices that transfers momentum from the freestream to separated region, so that the flow will reattach to the wing surface. Sidorenko et al. (2007) demonstrated the influence of the microsecond and nanosecond pulses on the flow control. A lift force improvement and a strong decrease of the drag force have been obtained from their experiments. In addition, modulating the DBD actuators at optimum dimensionless burst wave frequency of 1.0 resulted in improvement of C_l (Goksel et al., 2006).

Generally, the ratio of C_l/C_d increases with the angle of attack until the airfoil stalls. Lift is generated because the flow velocity at the top surface is higher and thus the pressure on that surface is lower due to the Bernoulli effect. Stall is accompanied by a loss of lift and a marked increase of drag. One obvious way to increase lift of an airfoil is by using flap and generator. However, these mechanical systems are too complex, producing noise and add weight. Therefore, an investigation on the flow is studied when a plasma surface is driven with pulse-modulation both at the stall control condition and at high angle of attack. The DBD plasma actuator is located at the leading edge because this configuration had been found to be more effective at high angles of attack (Jolibois, et al. 2008). In this study, airfoil model NACA 0015 is tested at the $Re \approx 67{,}000$ in an airflow of 10 m/s for lift force and hot-wire measurement. However, for flow visualization works, the airfoil is tested in airflow of 5 m/s for better flow images. For the next stage, amplitude modulated pulse modulation will be designed to have the same power consumption as pulse-modulated drive. An amplitude modulated pulse modulation will be applied to the DBD plasma actuator to investigate the lift coefficient C_l improvement compared to pulse-modulated drive.

1.3 Purpose of this study

The purposes of this study are stated as follows:

1) To study the effect of pulse-modulated drive of plasma actuator on the flow around the airfoil both at the stall control condition and at high angle of attack condition.
2) To study the effect of amplitude modulated pulse modulation on the flow around the airfoil both at the stall control condition and at high angle of attack condition and to compare the improvement of lift coefficient C_l between pulse modulation with amplitude modulation (PM+AM) and only pulse modulation (PM).

1.4 Outline of this study

This study is conducted in order to investigate experimentally flow control of the leading edge separation on airfoil using DBD plasma actuator. It consists of five chapters, which the first chapter is an introduction of the DBD plasma actuator including the background of the research, the previous studies from other researchers, and the explanation on the purpose of this study.

Chapter 2 explains the experimental apparatus, measuring instruments and preliminary experiments that have been conducted in this study. It will also discuss about the measurement methods and conditions of the experiment. In addition, this chapter also consists of the result of preliminary experiments such as ionic wind velocity of DBD plasma actuator on flat plate by using pitot tube and particle image velocimetry (PIV) and also the measurement of power consumption of DBD plasma actuator.

Chapter 3 describes the effect of DBD plasma actuator driven by pulse modulation signal to the airfoil performance characteristic by using flow visualization, lift force, and velocity measurement. The flow around the airfoil in the stall control condition and high angle of attack also will be explained in this chapter.

Chapter 4 explains about the effect of DBD plasma actuator driven by pulse modulation with amplitude modulation signal to the lift coefficient, C_l. The comparison between the effect of pulse modulation with amplitude modulation and pulse modulation case is discussed in this chapter.

Finally, chapter 5 concludes the overall results in this study.

2. Experimental Setup, Method and Preliminary Experiments

2.1 Experimental Setup

This section discusses about the experimental apparatus and measuring instruments that have been used in this study. The explanation about experimental methods, experimental conditions and the results of the preliminary experiments are also included in this section.

2.1.1 Wind tunnel

The schematic diagram of wind tunnel is shown in Fig. 2.1. A low-speed semi-closed wind tunnel has been used in this study. Air is sucked by the turbo blower through air filter and it passes diffuser and enters into the settling chamber and convergent nozzle. A uniform airflow with a low turbulence flows through a measuring section with a square section of 500 × 500 mm and a length of 2300 mm. A pitot tube is placed at the downstream of the measuring section to detect the velocity of the airflow. The flow velocity can be varied from 0 m/s to 40 m/s. Moreover, a hot-wire probe is installed on the traverse device on the top of the measuring section.

2.1.2 Wing model

An airfoil model NACA 0015 is tested in this study. The dimension of the airfoil is shown in Fig. 2.2. The airfoil has the span length of 150 mm and chord length of 100 mm. Therefore the aspect ratio *AR* of this airfoil is 1.5. While, large enough end plates of the airfoil are made to ensure the two-dimensional flow around the wing. The end plates are made of the transparent acrylic with 1 mm thickness. The transparent acrylic is used to enable the visualization of the flow. This is shown in Fig. 2.3. A rod support is attached at 25% from the leading edge of the airfoil. The fixed rod support is used to install airfoil on the load cell in order to set the angle of attack α.

2.1.3 DBD plasma actuator

The DBD plasma actuator is installed at x/c = 0.025 of the chord length as shown in Fig. 2.4. The DBD plasma actuator consists of two copper-tape electrodes, each 50 μm thick and 5 mm wide. The two electrodes (exposed and encapsulated electrodes) are arranged in parallel with a 1 mm overlap. The electrodes are separated by a 100 μm thick Kapton film, which acts as a dielectric. In order to avoid discharge at the wing tip, both exposed electrode and encapsulated electrode are placed 5 mm from the end edge.

Figure 2.5 shows the schematic diagram of DBD plasma actuator. A voltage at high enough level (≥ 5 kV) and AC (1 - 10 kHz) causes the air over the exposed electrode to weakly ionize as shown in Fig. 2.6(a). When the terminal at exposed electrode is positive, the positive ions accelerate and collide with neutral particles (Fig. 2.6(b)). As the polarity change, the positive ions will move to the exposed electrode and collide again with the positive ions (Fig. 2.6(c)). The movement of these charged particles will produce momentum to the flow in one direction in a certain time (Fig. 2.6(d)). This momentum can be effective in altering the airflow over the actuator surface (Wilkinson, 2003; Post and Corke, 2003; Ashpis and Hultgren, 2003; List et al., 2003; Huang et al., 2003; Corke et al., 2002; Roth et al., 1998).

Some researchers have studied about the fundamental feature of light-emmision time series of DBD plasma actuator (Enloe et al., 2004a; Massines et al., 1998; Eliasson and Kogelschats, 1991; Kogelschatz et al., 1997). They came out with the conclusion that at first, the air was ionized only over part of the AC cycle. Secondly, the character of the light emmision was different between the first and second halves of the AC cycle. Lastly, the light emission was made up of narrow spikes due to the numerous microdischarges.

Figure 2.7(a) shows the time series of photomultiplier-tube (PMT) output and Fig. 2.7(b) indicates a sample of voltage time series for two and a half cycles of plasma actuator (Orlov et al., 2006). During the forward stroke where the negative charges are deposited on the dielectric surface, it can be seen that the light emmision is low due to the uniform low density of microdischarges (Fig. 2.7(a)). While the back stroke causes the less uniform and higher light emmision compared to forward stroke.

The detail of the features of microdischarges are shown with high speed photography in Fig. 2.8. Figure 2.8(a) shows the behaviour of individual microdischarges during forward stroke while Fig. 2.8(b) illustrates the bahaviour of individual microdischarges during back stroke (Enloe et al., 2008). Figure 2.8 supports the result in Fig. 2.7 where the back stroke causes the less uniform of microdischarges compared to forward stroke.