The effect of electrohydrodynamic force on the lift coefficient of a NACA 0015 airfoil

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Abstract. Lift, the force component that is perpendicular to the line of flight, is generated when a small aircraft moves through the air. With the help of the sets of flaps and slats on its wing, the pilot controls his aircraft manoeuvring in the air. In this study, we preferred to cut the drawbacks of the flaps system by introducing the electrohydrodynamic actuator. Widely known as plasma actuator, it is able to improve the induced lift force as well as the efficiency of a small aircraft system. A dielectric-barrier-discharge actuator using a 6 kV AC power supply was developed and tested on a NACA 0015 airfoil using copper as the electrodes and kapton as its dielectric component. The experimental results showed that it was successful in presenting a positive effect of the plasma actuator on the lift coefficient of the airfoil at smaller angle of attack, where enhancements ranged between 0.7% and 1.8%. However, at a higher angle, the results were not as swayed as it was desired since the energy exerted by the plasma actuator on the lift performance of the airfoil was inadequate. Further tests are needed using higher rated voltage supply and other equipment to improve the capability of the actuator in refining the aerodynamic performance of the airfoil.

1. Introduction
This is considered to be an introductory study to understand the improvement an electrohydrodynamic (EHD) actuator or widely known as the plasma actuator brings to the aerodynamic performance of a small aircraft system. Aircraft is lifted by its special design of wing, termed as airfoil [1]. The airfoil’s lift and drag forces are induced by its motion when cutting through the air. Angle of attack (AoA) and aircraft’s speed play important roles as they determine the performance and stalling point of the aircraft [2].

To reduce the effect of turbulence and to help small aircraft maintains its lift at a certain limit, conventional flaps and slats on the wing of the small aircraft are the workable solution for now. Though they are capable, they have some drawbacks, which include putting more weight to the aircraft, complexity of the linkages system, its maintenance cost and also higher fuel consumptions due to the weight needed to be lifted [2] & [3].

As the old system is fully mechanical where the pilot of the small aircraft needs to control the flaps and ailerons using pedal and lever as shown in Figure 1, plasma actuator is totally an electronic system which enables it to be controlled by modern control system. According to [4], plasma actuator can be used to modify the lift and drag forces, just as what the flaps did before.
Plasma actuator can also be used for longitudinal control of the leading edge of an airfoil without employing the conventional hinged flap used on normal airplane. These small size actuators reduce kilograms of weight, depending on the size of the airplane and its conventional flap system. It just needs to be laminated at the designated area at the airfoil and does not require slots or any mechanical change to the wing [5]. In addition, it requires less maintenance routine and cost as compared to the old system [6]. Thus, introducing a plasma actuator will improve these weaknesses, other than giving additional benefits such as increasing and reducing the lift and drag force, respectively, as well as delaying the stalling point [7].

**Figure 1.** The conventional lever and flaps system. The notations of “A”, “C”, and “D” were the flaps of the small aircraft, controlled by the lever at “B”. (image taken from en.wikipedia.org)

Plasma actuator is a type of electrical actuator that is capable of ionizing the flowing air and add localized momentum to the flow through collision process of the migrating charged particles due to the large potential difference with the natural surrounding gasses [2]. This creates the EHD forces that modify the boundary layer of airflow, and also affect the moving parts in that region. The induced flow should be laminar and parallel to the surface to realize flow re-attachment and minimize boundary layer turbulence [7]. Plasma actuator needs high voltage power supply to operate [8] & [9].

In terms of electrical power, a plasma actuator offers an efficient system in transferring the electrical energy to the mechanical form, because with minimum power input, it can generate high energy density and produce great effect on the airfoil or propeller’s blade [5]. It is also fully electronic, which makes it suitable for feedback control [10]. It is a long way to go though, because a lot of studies are required in understanding the effects of the environment, where temperature, humidity and pressure play important roles.

There are different types of plasma actuator, mainly in the research area. Among others include the corona-based discharge, dielectric-barrier-discharge (DBD), sliding discharge actuator, local arc filament and sparkjet [11] & [2] & [10]. The one being used in this study is the DBD type plasma actuator. A DBD places dielectric material in between two electrodes that were connected to a high voltage source. In generating UV emission and low temperature plasma, the discharge performed at the surface of a dielectric layer is usually asymmetric configuration [12].

The parameters involved in studying aerodynamic environment are, not restricted to, airstream velocity induced from the thrusters, temperature and the pressure of the surrounding air as well as the air density and the angle of attack. This study focused on only two parameters which were the AoA and airstream velocity. Speed of the aircraft and the AoA are two of the main parameters that determine the action of an aircraft – the lift force induced. Thus, by engaging the open circuit wind tunnel, these two parameters were made the main control factors of the experiment. By varying these two, the effect of the plasma actuator on the lift performance of the NACA 0015 airfoil was studied. Besides providing significant contributions to the lift performance, these two parameters were made easily controllable in the wind tunnel. This experiment dealt only with the lift force to study the plasma actuator’s effectiveness.
The objective of this study involves the development of a plasma actuator system and a study on how effective it is in improving the lift performance of a NACA0015 airfoil. In analyzing this, the performance of the airfoil with and without the plasma actuator was compared and examined.

1.1 Design Parameters for DBD Plasma Actuator
There are several important parameters for the actuator that determine the power requirement of the system, as well as the output drive the plasma actuator is capable of. Firstly, the dielectric. Dielectric is an insulating material with special characteristics. When voltage difference is applied through the dielectric, electric polarization occurs. This makes the electricity passes through the dielectric, and this phenomenon is called dielectric breakdown. In the case of a DBD, it generates the plasma. In terms of the dielectric choices of a plasma actuator, [13] discussed the details of their experimental data, in which they compared the types of dielectric including kapton – our choice for this system because of its availability in terms of the required thickness and size; teflon, plexiglass and plexi-kapton material, using copper as the electrode.

Secondly, the length of the electrode. The length of the electrode is equally important on the plasma generated. According to the experiment by [14], the length of the electrode significantly affected the thrust. They found that when the length of the plate decreased, the thrust generated was increased. The next parameter is the electrode’s gap. The gap between the top and bottom electrode gives some significance too. According to the experiment by [15], it was found that a good gap size was between -2mm to 1mm, where the negative sign indicated that the bottom electrode was overlapped by the top. In this experiment, a 0.9mm-thick dielectric was being used to test the effectiveness of the power generation with gap size ranging from -2mm to 5mm. It was also found that at 3mm gap and above, the supply voltage must be above 6 kV in order for the plasma actuator to discharge power.

Another consideration is the position of the actuator on the wing. The best location of the plasma actuator needs to be determined to have the maximum output out of it. [4] suggested that the best location to put the actuator is chordwise at the leading edge of the airfoil. The last factor is the supplied electrical potential energy. This turn-on-voltage is very important in supplying enough energy for the electrons to cross the gap between the electrodes and the dielectric to create the plasma.

2. Experimental setup and procedure
The experimental setup consisted of three main parts. They were the airfoil as the base of the plasma actuator, wind tunnel as the main testing apparatus, and the plasma actuator itself. The airfoil selected was NACA 0015 of the NACA 4-digit series, where each digit in each series gave geometrical definition of the dimension and shape of the airfoil. This selection was made due to the availability of the model in the laboratory. Besides, NACA 0015 was one of the common airfoils being used in researches; thus, more references and analysis on NACA 0015 were available in the publications for references. The airfoil used had a chord length of 0.125m, and the reference area was 0.0159 m². Reference area is the area of cross section of the airfoil at the chord line. The wind tunnel used in this experiment was an open circuit wind tunnel, as shown in Figure 2.

The dielectric barrier discharge plasma actuator used in this experiment consisted of two copper tapes, each with thickness of 0.1mm. The copper tapes was separated by 0.2mm thick kapton tape as dielectric. The 0.2mm dielectric was built by stacking three layers of kapton tape, which was about 60µm thick each, on top of each other. The width of the top electrode was 2mm, while its length was 65mm. For the bottom electrode, its width was 4mm and its length was 75mm. The power to the PA was supplied by an inverter as shown in Figure 3. The inverter’s rating was 6.0 kilovolt (kV) AC peak-to-peak.

This actuator was attached on the top surface of the NACA 0015. The location of the actuator on NACA 0015 was where the separation was expected to happen, which was slightly off the leading edge of the airfoil. When the plasma actuator was set up on the airfoil, the airfoil was mounted
at the designated place inside the test section, as shown below in Figure 4. To operate the plasma actuator, the switch was turned on and as the voltage supply went into the plasma actuator, it turned on and discharge happened. To stop the action of the plasma actuator, the power button was switched off. The performance of the system’s lift force with actuator turn-on and turn-off was analyzed as well as other observations during the experiment.

Figure 2. Open circuit wind tunnel used in this experiment.

Figure 3. The inverter setup used as the power supply for the plasma actuator in this experiment.

Figure 4. The plasma actuator attached on top of the NACA 0015 airfoil. The airfoil is mounted at the adjustable hook inside the test section of the wind tunnel.
During the experiment, the speeds of the air and the AoA of the airfoil were varied. The lift force induced was recorded. For each airstream velocity and its pair of AoA, two sets of lift force data were recorded. One set was the value of the lift forces where the plasma actuator was turned off, while another set of data was when the plasma actuator was turned on.

The data of the lift forces collected were then converted to the correspondent lift coefficient, $C_L$, using equation 1 below,

$$C_L = \frac{L}{\frac{1}{2} \rho v^2 S} \quad (1)$$

where $L$ is the lift force in N, $\rho$ is the air density in kg/m$^3$, $v$ is the stream velocity in m/s and $S$ is the reference area in m$^2$. The $C_L$ data was plotted into a $C_L$ vs. AoA plot and analyzed. The data of the plasma-off and plasma-on were compared and analyzed to perceive what contribution a plasma actuator brought to the aerodynamic characteristics of an airfoil.

One thing that is important in studying fluid flow is the characteristics of the flow. In order to compare or analyze different situations or specimens, there must be characteristics of the air that need to be set in a controlled situation. Reynold’s Number (Re) can be used as the reference tool. The speeds of airflow inside the wind tunnel used in this testing were 40 m/s and 45 m/s. These speeds were selected in order to see the difference of flow for different Re. The Re is defined based on the chord length shown below;

$$Re = \frac{\rho v c}{\mu} \quad (2)$$

where $\rho$ is the air density in kg/m$^3$(taken as 1.1839), $v$ is the stream velocity in m/s, $c$ is the chord length in m, and $\mu$ is the dynamic viscosity of the air in kg/(m)(s) ($1.84 \times 10^{-5}$).

3. Experimental outcome
To study the effectiveness of the plasma actuator in enhancing the lift performance, the results from the experiment were compared between the plasma OFF and plasma ON. Plasma OFF is when no plasma actuator is initiated in the system, whereas plasma ON is when the plasma actuator is activated. Theoretically, to see the positive effects of the plasma actuator on the NACA 0015 airfoil’s aerodynamic performance, the values of $C_L$ for plasma ON must be of higher values compared to the values of $C_L$ during plasma OFF [16]. Higher values of $C_L$ for plasma ON as compared to plasma OFF indicated that there were improvements in the airfoil’s lift performance induced by the plasma actuator itself.

The Reynolds number selected for the analysis were $3.2 \times 10^5$ and $3.6 \times 10^5$ in accordance to the respective airstream velocity, while the AoAs were 12°, 14°, 16° and 18°. Table 1 presents the values of $C_L$ for plasma OFF and plasma ON at each Reynolds numbers and AoA. From the tabulated data, we can see whether the $C_L$ for plasma OFF is higher than the $C_L$ for plasma OFF. Negative values in the “Diff” column of Table 1 indicated that $C_L$ of plasma ON was lower than the $C_L$ of plasma OFF, while positive values indicated otherwise. The differences shown at the extreme right column of the tables are based on the plasma OFF since it is the reference value. From Table 1 (a) and (b), we can see that the percentage differences were sometimes negative and sometimes positive.

At lower to medium AoA of 12 to 14 degrees, we can undoubtedly tell that the percentage differences were of positive values, ranging from 1.0% to about 1.8% of improvements from the OFF conditions for Reynold’s number $3.2 \times 10^5$, and from 0.7% to 1.6% for Reynold’s number $3.6 \times 10^5$. This might indicate the positive effect of the EHD forces that we are expecting it to provide to the lift performance of the airfoil. However, at higher AoA of 16 and 18 degrees, the value became inconsistent and more negative. This means that the values of $C_L$ for plasma ON were not always
consistently higher than the plasma OFF, which showed that the actuators were hardly making its account. This might be because, at higher degrees, the flow is reaching turbulence, thus making the power produced by the actuator hardly seen affecting the flow characteristics. Figure 5 (a) and (b) illustrate the results graphically.

**Table 1.** Differences of $C_L$ values between plasma OFF and plasma ON for Reynolds number (a) $3.2 \times 10^5$ and (b) $3.6 \times 10^5$.

(a)

| No | AoA (˚) | Lift coefficient, $C_L$ |
|----|---------|------------------------|
|    |         | Plasma OFF | Plasma ON | Diff. (%) |
| 1  | 12      | 1.256      | 1.278     | 1.787     |
| 2  | 14      | 1.385      | 1.399     | 1.015     |
| 3  | 16      | 1.568      | 1.571     | 0.172     |
| 4  | 18      | 1.682      | 1.673     | -0.509    |

(b)

| No | AoA (˚) | Lift coefficient, $C_L$ |
|----|---------|------------------------|
|    |         | Plasma OFF | Plasma ON | Diff. (%) |
| 1  | 12      | 1.290      | 1.300     | 0.747     |
| 2  | 14      | 1.354      | 1.376     | 1.620     |
| 3  | 16      | 1.526      | 1.512     | -0.906    |
| 4  | 18      | 1.624      | 1.619     | -0.304    |

![Figure 5(a): $C_L$ for Re=3.2x10^5](image)
The results of this experiment also informed us on the importance of a suitable power generator for plasma generation. Referring to the literatures, this experiment realized a few reasons based on the inconsistency of the data recorded. The main differences between this study and other literatures showed that power supply might not be sufficient enough in producing adequate plasma thrust to affect the airflow, especially at above medium AoA. [17] explained that a voltage source of 20 kV was needed to effectively reattached the separated flow, while [18] used a power supply of 13 kV to increase the lift performance of more than 30% of its original value. Furthermore, [3] supplied their plasma actuator with 16kV and achieved 50% improvement in its lift performance. Although these experiments setup were different with ours, they gave indications on the suitability of power needed to supply the plasma actuator in order for it to give good results in improving the aerodynamic performances of the airfoil. In addition, although we can see that the plasma was generated due to the existence of the bluish discharge, this showed that the plasma generated did not sufficiently affect the airflow characteristics that surrounded the airfoil.

Although the results of the experiment did not give us convincing conclusions, there were also other observations to note from the experiment. Firstly was the effect of the gap between the top and bottom electrodes, as briefly explained in its design parameters. By using a relatively low 6 kV-rated voltage source, gap of the electrodes can give significant remarks. The plasma generated was not uniform and continuous when there was a gap of 1mm between the two electrodes, whereas when the gap was 0mm, the discharge was much better in its form as shown in Figure 6. This showed that when the gap was increased, the plasma generated was less and as a result less effect can be produced by the plasma.

Another observation was that after long hours of experiment, a clear white line was formed at the top of the covered electrode as shown in Figure 7 below. This might due to the degradation effect [12]. This degradation effect was caused by the ion bombardment from the top to the bottom electrode. The degradation of the dielectric material was related to the high voltage applied, and it could be lessened by increasing the electrode gap.
4. Conclusion

It is known from various findings that a plasma actuator is able to affect the aerodynamic performance of airfoils. Among others, it can increase lift performance, reduce the drag force and delay the separation of flow. The intent of this work was to study the effect of plasma actuator on the lift performance of NACA 0015 airfoil.

Throughout this report, the procedures of the experiment as well as the complete results were detailed out. The experiments were successful in showing the effect of the plasma actuator on the lift performance of a NACA 0015, even though the results were not as swayed as it was expected. The improvement on the lift performance of the airfoil was found to be positive at lower to medium AoA, with improvements ranging between 0.7% and 1.8%, as compared to the original plasma OFF value. However, at higher degrees, the thrust generated was not adequate. This, as we can summarize, might be mainly due to the insufficient power supplied to the actuator. In addition to that, we studied the traits of the plasma actuator, especially on the effects of other parameter such as electrode gap, on the plasma generated.

There are many things that can be done in order to improve the research of plasma actuator effect in the future. Firstly is by using a higher and adjustable power supply. Our fixed 6 kV-rated inverter was proven insufficient to generate enough thrust for the whole experiment. Increasing the voltage to the actuator is the easiest way to increase actuator thrust; thus, increasing the actuator effectiveness [19] in influencing the aerodynamic performance. Improvement in the aspect of the equipment and apparatus used in the experiment can also benefit this study. Besides power supply,
employing a high speed and resolution camera could examine more aspect and traits of the plasma, such as the uniformity of the plasma discharge, the form of the surrounding air flow, and the fluid flow characteristics ambiances the airfoil. This will aid in further developing a mathematical model for the DBD plasma actuator and its computational fluid study.

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