Flow Control with Multi-DBD Plasma Actuator on a Delta Wing

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Flow Control with Multi-DBD Plasma Actuator on a Delta Wing

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Abstract: In this study, an experiment was carried out to measure the performance of a delta wing with 65° swept angle. The measurement of lift and drag on the delta wing with and without plasma actuator was the main focus of this research. Multi-DBD plasma actuator was implemented on top of the wing. The experiment was conducted in a wind tunnel with a free stream velocity of 5.74 m/s or at Reynolds number of 83000. The performance of the wing was positively affected by the use of plasma actuator, indicated by the increasing lift coefficient and the decreasing drag coefficient, as maximum increase of 0.078 in lift coefficient and 0.053 decrease in drag coefficient were obtained.

Keywords: delta wing, plasma, actuator, lift, drag

1. Introduction

Issues related to energy efficiency and conservation have been heavily investigated in various field. Han et. al. [1)] investigated the energy conservation in building through a smart ventilation system. Byrne et.al. [2)] investigated the possibility to utilize a mixture between fatty acids and an expanded graphite as an energy storage to provide an alternative to batteries. In the field of agriculture, Hanif et.al [3)] studied the possibility of an energy-saving by using a desiccant drying system for the drying of different types of daily products. As in aeronautics and aerospace, one of the main concerns is the fuel consumption of the aircraft. The cruising speed of an aircraft greatly affects its fuel consumption. The faster it reaches its destination, the greater the fuel consumption[4)]. The current problem is that fuel reserves are getting eroded over time. The massive use of fuel will accelerate the depletion of fossil fuels while producing a huge increase of pollution. Because of this, paths to improve efficiency on fuel consumption is very necessary. In this regard, one of the topics that has been discussed over the years is flow control.

Flow control is generally divided into two types, the first one is passive flow control, where the flow control uses a predetermined design that does not need any extra force to be activated [5)]. The second type is active flow control, wherein in this flow control, some energy is used within-the-system to carry out its intended purpose [6)].

Passive flow control has several limitations, one of which is the inflexibility in all conditions because passive flow control has its own design limits. This makes the use of a passive flow control in certain condition might be a liability to the surrounding flow. There is a possibility when a passive control is used in conditions that are not in accordance with its intended purpose, it will cause losses in performance [7)].

There are several types of active flow controls. Generally active controls are divided into 3 types, suction, blowing, or a combination of both (suction and blowing). For example, there are methods to control surrounding flow with synthetic jet and plasma discharge dielectric (DBD) actuator [8)].

Flow control using plasma actuators is very promising [9)] where plasma actuators could delay the separation point of airfoils [8)], delaying the separation of wind turbine blades [10)], attract vortex behind a cylinder, and the most important is its capability to provide momentum to the surrounding flow [11)].

A thorough literature review on active flow control for low Reynolds number by utilizing DBD was well written by Cho and Shyy [12)]. Kelley et.al [13)] investigated the effectiveness of AC-based DBD plasma actuators on high Mach number flow. They reported that the AC DBD plasma actuators provided an increase in lift and stall angle of attack. A comparison of steady and unsteady actuation modes in DBD plasma actuators was performed by Abdollahzadeh et.al. [14)]. A NACA 0012 airfoil was numerically investigated under Reynolds number of 3 x

10^6. Unsteady actuation showed that an imposed frequency equal to the natural frequency increased the resonance actuation effect. An identical NACA 0012 airfoil was experimentally investigated by Feng et.al [15]. A DBD plasma actuator was applied on a Gurney flap in a wind tunnel test. The result showed an increase in the lift with a small drag increase. On the other hand, the effect of DBD plasma actuator surface temperature on its aerodynamics performance was investigated by Erfani et.al. [16]. The induced flow field by the actuator was found to be varied with the surface temperature. Halawa et.al. [17] numerically investigated an active flow control on DU-96-W-180 wind turbine airfoil and experienced a maximum 8% increase on lift. In the hypersonic flow region, the application of plasma actuators was investigated by Shang et.al. The numerical investigation was performed at a hypersonic flow with Mach number of 14.1. [18]

Plasma can be created through the configuration of two sheets of electrodes placed on both sides of the dielectric material with the placement of the two electrode sheets is not parallel to each other [19] as in Fig. 1. It is widely believed that the material of the electrode is far insignificant compared to the material of the dielectric when inducing flow utilizing plasma actuator Dielectric Barrier Discharge [20].

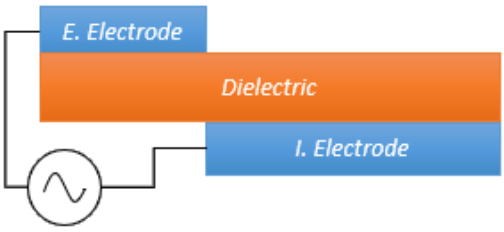

Fig. 1: Plasma actuator general configuration.

To generate plasma from these configurations, AC current provided needs to be relatively high [6] the frequency of alternating current voltage also uses radio frequencies of 10^3 Hz to 10^{11} with some of these components the plasma layer will be created [6]. After a layer of plasma on the actuator has been created, the air will be driven due to the electric field, then there will be suction phenomenon that happens above the exposed electrode [21].

One of the flow-manipulation carried out by plasma is forming tangential jets on top of the wing [21]. This occurs because of the ionization of the surrounding air that happens after applying an alternating electric current that has a relatively high voltage [6]. After ionization, particles from the air will move because the air is affected by the electric field of the electrode and produces a tangential force from the wing's surface and this is called "ionic wind" [9]. Ionic wind is used in controlling the flow in this method [6]. This can also be seen from the research conducted by Boesch, G. [22]. This study focused on reducing the influence of downwash by placing a-number-of DHF on the tip of the wing to adjust the formed tip vortex.

Research on this subject is not only carried out on low aspect ratio wing. Plasma actuators also began to be applied on the delta wing type which has a high aspect ratio. This is due to the increasing demand for this type of wing especially for supersonic and hypersonic flight. Plasma actuators have a role to control the vortexes that are formed on top of the wing so that the stability of the aircraft is maintained and its performance increases [23].

To reveal the full capability of plasma actuator, many experiments are needed, especially the effect on the delta type wing because there are still many things that have not been revealed regarding the capabilities and limitations of plasma actuators on the delta wing.

This study aims to reveal the effects of flow control on the delta wing by using a plasma actuator on the back of the wing, allowing the aerodynamics analysis in form of drag and lift.

2. Experimental Setup

The aerodynamic forces of a delta wing with a swept angle of 65° was experimentally investigated. The delta wing was stationed inside a wind tunnel under a steady air velocity of 5.74 m/s or equal to Reynolds number of 83000. The wind tunnel was operated in a suction mode where the air flow was generated by a 1.5 kW DC motor. Moreover, the delta wing was set at 6 different angle of attack (AoA) namely 0, 16, 32, 34, 36 and 42°. For every AoA, the delta wing was tested with and without the plasma actuator. The schematic of the experimental setup is pictured in Fig. 2.

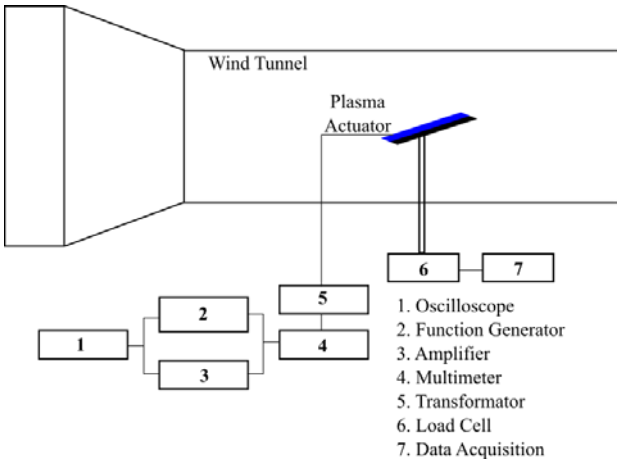

Fig. 2: Schematic of the experiment setup.

Two load cells were connected to a data acquisition system (Arduino Uno) to measure the lift and drag force acting on the delta wing. Both load cells were calibrated and have an accuracy of +/- 0.05 g. The data acquisition system was able to record up to 12 data per second. The measurement result of the lift and drag force was used to calculate the lift and drag coefficient, which can be calculated as follow:

$$CD = \frac{D}{\frac{1}{2}\rho V^2 A} \qquad (1)$$

$$CL = \frac{L}{\frac{1}{2}\rho V^2 A} \qquad (2)$$

Where *CD*, *CL*, *D*, *L*, ρ, *V*, *A* are drag coefficient, lift coefficient, drag force (N), lift forece (N), density (kg/m^3), velocity (m/s) and characteristic area of the delta wing (m^2), respectively.

Square-form waves were generated by the function generator at a frequency of 9 kHz. The signal was transmitted with an amplifier and increased by a step-up transformer and then used to power the Multi-DBD plasma actuator. Moreover, a multimeter was utilized in the setup to avoid electric current disturbance. The photograph of the delta wing equipped with the plasma actuator is shown in Fig. 3.3. Results and Discussion

The discussion will cover the forces that affect the characteristics of the wing itself, namely aerodynamic forces i.e. lift and drag forces of the delta wing model.

3.1 Lift Coefficient

To confirm the reliability of the current experimental setup, the characteristics of lift coefficients at different AoA are compared with a result from Nelson and Pelletier [24] as can be seen in Fig.4. Generally, both studies show a good agreement of the trend of lift coefficients.

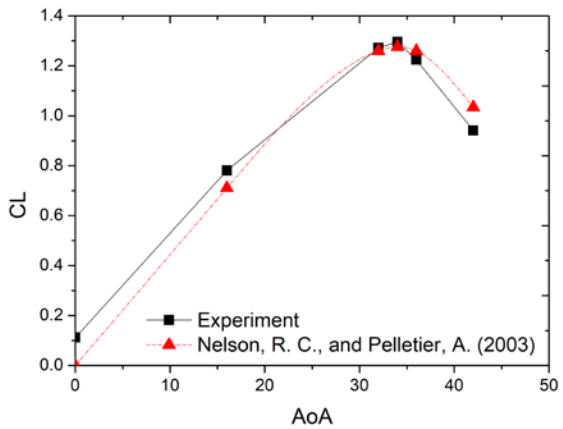

Fig 4. Comparison of lift coefficient with literature data

Table 1 shows the comparison of lift forces produced on the wing at Reynolds number of 83000 with an air velocity of 5.74 m/s. with and without the use of plasma actuator, under the variation of AoA. Meanwhile Table 2 shows the corresponding lift coefficient.

Table 1. Lift Force.

AoA	Plasma (OFF) [N]	Plasma (ON) [N]
0	4.80	4.81
16	33.59	36.53
32	54.71	57.15
34	55.74	58.79
36	52.64	54.59
42	40.48	42.00

Table 2. Lift Coefficient

AoA	Plasma (OFF)	Plasma (ON)
0	0.11	0.11
16	0.78	0.85
32	1.27	1.33
34	1.3	1.37
36	1.22	1.27
42	0.94	0.98

In the plasma-free wing experiment, the lowest lift coefficient was obtained at the AoA of 0° which has the lift coefficient value of 0.11. On the other hand, the highest lift coefficient of 1.30 was achieved at AoA of 34°.

Fig. 5. shows the comparison of the *CL* as a function of AoA. The result shows that *CL* increases as the plasma actuator activated. The highest *CL* of 1.37 was achieved at AoA 34°.

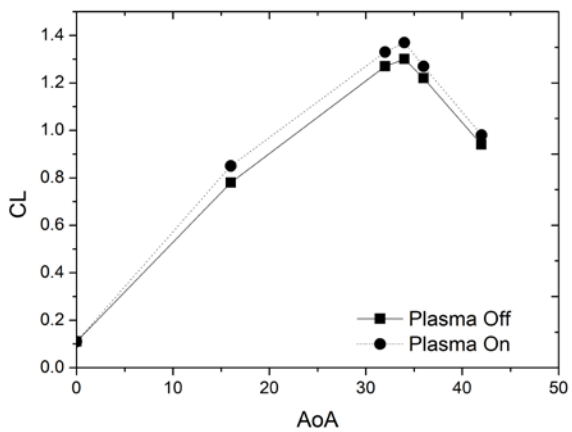

Fig 5. Effect of plasma activation on lift coefficient

Table 3 shows the difference in the magnitude of the lift coefficient in the experiment. The differences obtained are satisfactory because the differences obtained are positive which can be interpreted that the lift force produced by the wing model becomes larger. The increase in the change in the lift coefficient at the beginning increases where the

Table 3. Lift coefficient differences before and after the use of plasma actuators.

AoA	ΔC_L
0	0.0002
16	0.0683
32	0.0568
34	0.0780
36	0.0452
42	0.0353

increase starts from AoA = 0° to AoA = 42°. At AoA = 16°, the increase of the lift coefficient is maximal.

As indicated in Fig.6, the data from the difference in the lift coefficient is not constant with respect to the AoA. Where the difference from the lift coefficient is close to linear until a particular angle-of-attack then decreases from the performance of the plasma actuator so that the difference is not too large. Changes to the lift coefficient can be seen using plasma actuators, for low angles to angles ranging from 36°. After that, the ability of the plasma actuator flow control is reduced due to many flow disturbances that occur at the approaching stall angle.

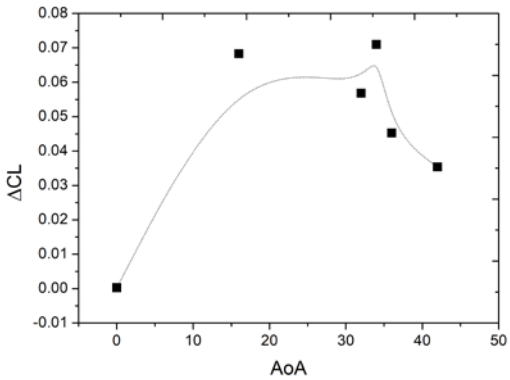

Fig 6. Lift coefficient difference

When viewed from the distribution of raw data, there is a unique trend in each AoA. As shown in Fig. 7, the distribution of data for each AoA has similarities to the trends obtained using either plasma or not. This can be reviewed on measurements for AoA of 0°, 16°, 34°, 36°, and 42°. There is an anomaly at AoA of 32°, the measurement when plasma is turned off has a trend

towards the left while when the plasma is activated the trend from the data obtained tends to the right.

By analyzing the lift coefficient, it can be said that the use of plasma actuators was able to improve the performance of the wing in increasing the lift force. The increase in lift force is effective at a certain angle, but if angle of attack has led to the stall condition of the plasma actuator flow control will have difficulty in controlling the flow.

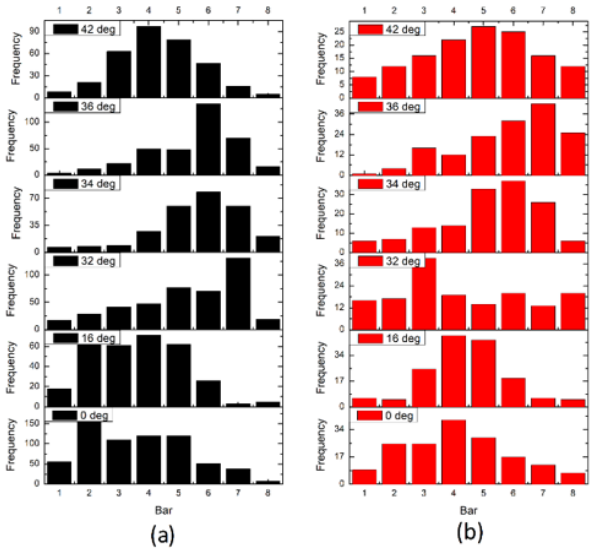

Fig 7. Histogram of the raw data for lift force (a) plasma off and (b) plasma on.

3.2 Drag coefficient

Figure 8 indicates the trend of the experimental results which resembles the results in previous published works.

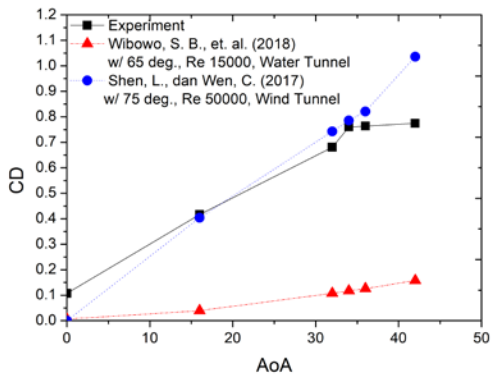

Fig 8. Comparison of drag coefficient with literature data

However, there are differences in the results of experiments with literature. This is caused by differences in test conditions between the literature and experimental results. Wibowo et. al [25] conducted an experiment on a a delta wing with swept angle of 65° in a water tunnel with the value of the Reynolds number of 50400. While Shen and Wen [23] tested on a model with a delta wing swept angle of 75° using wind tunnel with a Reynolds number of 50000.

Table 4 shows the comparison of drag forces produced on the wing at Reynolds number of 83000 with an air velocity of 5.74 m/s. with and without the use of plasma actuator. Meanwhile Table 5 shows the corresponding drag coefficient.

Table 4. Drag Force

AoA	Plasma (OFF) [N]	Plasma (ON) [N]
0	4.61	2.98
16	17.92	15.73
32	29.26	26.99
34	32.70	31.98
36	32.84	32.14
42	33.29	33.18

Table 5. Drag Coefficient

AoA	Plasma (OFF)	Plasma (ON)
0	0.11	0.07
16	0.42	0.37
32	0.68	0.63
34	0.76	0.74
36	0.76	0.75
42	0.77	0.77

Without plasma control, the lowest drag obtained was at AoA of 0° with the drag force produced at 4.61 N and the value of the highest drag force produced is located at AoA of 42° with the resulting force equaling 33.30 N. The increase in AoA affects the force acting on the wing. Meanwhile, when the plasma actuator was activated, the lowest drag force of 2.98 N was obtained at AoA of 0°. Comparison of the two data is shown in Fig. 9. Overall, the drag coefficient is lower when plasma actuator flow control is carried out compared to experiments without plasma actuators.

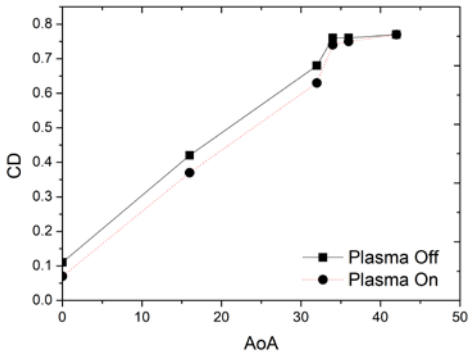

Fig 9. Effect of plasma activation on the drag coefficient

Table 6 and Fig. 10 show the difference of *CD* between the flow with plasma actuators and without plasma actuators as a function of AoA. At low AoA, the effectiveness of plasma actuators is large enough. The negative sign on *ΔCD* indicates a decrease in *CD* when the plasma actuators was activated. However, the result also shows that the higher the AoA, the lower effectiveness. A decrease in the effectiveness of plasma actuators can be attributed to the flow at high AoA experiencing more interference and stall might lead to poor flow control.

Table 6. Drag coefficient difference before and after the use of plasma actuators.

AoA	ΔC_D
0	0.038
16	0.051
32	0.053
34	0.017
36	0.016
42	0.003

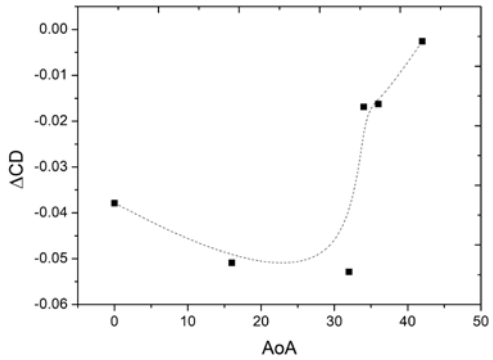

Fig 10. Drag coefficient difference

The distribution of raw drag data is demonstrated in Fig. 11 for the angles-of-attack of 0°, 16°, 34°, 36°, and 42°. Like lift data, generally the distribution that occurs in drag raw data also has similarities when plasma is activated or not.

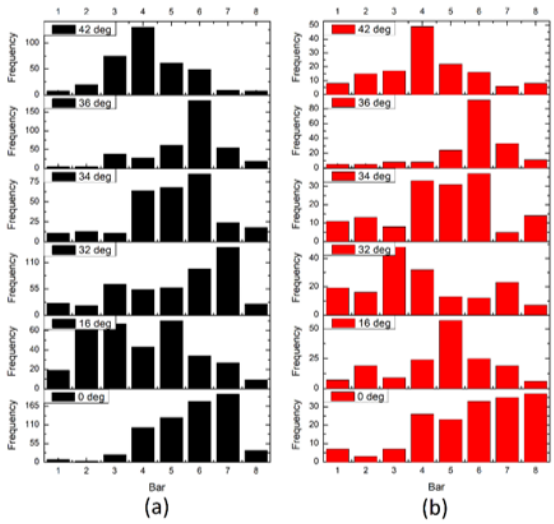

Fig 11. Histogram of the raw data for drag force (a) plasma off and (b) plasma on.

Overall, analysis of the draft coefficient suggests that flow control of plasma actuators can improve the

performance of the wing in reducing coefficient drag it produced. Reduction of coefficients drag is quite effective at certain angles, but when the stall condition has been reached or the stall condition will occur the influence of the plasma actuator will decrease and tend to be detrimental.

4. Conclusions

The performance of plasma flow control has been investigated experimentally on a delta wing with a swept angle of 65°. The measurement of lift and drag on the delta wing without and with a multi-DBD plasma actuator was investigated. Some findings can be summarized as follows:

(a) Under the multi-DBD plasma actuator's influence, a maximum of 0.078 increase in lift coefficient was experienced.
(b) A decrease of 0.053 in the drag coefficient was experienced when the multi-DBD plasma actuator was activated.
(c) When the wing's positions are getting closer to the stall condition, the influence of the plasma actuator decreases to both lift and drag. This is because the flow on the back of the wing has begun to become irregular and the plasma control cannot be efective any longer.

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