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Experimental Study of Using Dielectric Barrier Discharge (DBD) Plasma Actuator as Virtual Winglet

Rouhollah Khoshkhoo[1*], Mahmood Mani[2], Sayyed Mohammadreza Salehi Abri[3], Masoumeh Aghaei Malekabadi[4]

[1] Assist. Prof., Aerospace Engineering-Aerodynamics, Faculty of Aerospace Engineering, Malek Ashtar University of Technology, Iran
[2] Prof., Aerospace Engineering-Aerodynamics, Faculty of Aerospace Engineering, Amirkabir University of Technology, Iran
[3,4] MSc. Student, Aerospace Engineering-Aerodynamics, Faculty of Mechanical Engineering, Malek Ashtar University of Technology, Iran
*Corresponding author: r.khoshkhoo@mut.ac.ir
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Abstract
Flow control to reduce drag and increase drag and finally increase the ratio of Lift to drag (L/D) has always been the focus of aerodynamic scientists. There are many methods to reduce induced drag. The use of DBD plasma operators is one of the newest methods in reducing induced drag. In this research, in order to investigate the performance of DBD plasma actuators, six configurations of plasma actuators have been used as virtual winglets. Experiments have been performed on the wing with the NACA0012 airfoil. These experiments have been carried out in two Reynolds numbers 150,000 and 300,000 and in two voltages, 6 kV and 10 kV and different angles of attack. The results of this research show that the use of this type of plasma actuator at the tip of the wing as a virtual winglet can increase the lift to drag ratio by about 25% in some cases and the use of two small circular and large linear configurations. Respectively, they have the best performance compared to other models for use as a virtual winglet.

Keywords: Virtual winglet, Flow control, DBD plasma actuator, Low Reynolds Number, Artificial jet.

1. Introduction

In recent years, the engineers of the aviation industry have always been improving the efficiency and performance of flying vehicles due to increasing costs and environmental crises. The main reasons in this field include high fuel costs, the requirement for fewer pollutants, and the need for environmentally friendly and compliant aircraft to reduce the impacts of global warming. In the aviation industry, reducing drag is a very big challenge; therefore, there are still many research areas for improvement and creativity in designs. The flow over an airplane wing is three-dimensional, such that a component of the flow is in the direction of the wing span. The difference in pressure distribution causes lift to be generated; also, this pressure difference between the upper and lower surfaces of the wing directs the high-pressure flow under the wing towards the upper part of the wing, causing vortices to be produced at both wingtips [1].

Flow control is one of the important branches of aerodynamics science, capable of actively or passively influencing a fluid field to induce desired changes in it. One of the methods of flow control is the use of Dielectric Barrier Discharge (DBD) plasma actuators. Over the past two decades, research on DBD plasma actuators has been conducted with increasing intensity around the world. The significant progress in the research conducted on these actuators is due to their considerable advantages over other active flow control methods [2].

In 2007, Grundmann and his colleagues conducted experimental and numerical research on the effect of using plasma actuators on boundary layer flow [3]. In the same year, Jolibois and his colleagues investigated the effect of positioning the plasma actuator at three different points on the airfoil, and thoroughly described the phenomenon of separation at each of these points [4].

In 2009, Kengo examined the effect of plasma actuators on flow separation at various Reynolds numbers [5]. In 2010, Xiaofei and his colleagues investigated the effect of the DBD actuator on controlling turbulent boundary layer separation, through experiments and simulations [6]. Gabriele and colleagues in 2012 studied the effect of material, thickness, voltage, and frequency of the plasma actuator on the amount of power consumption [7].

In 2013, Mizunuma and his colleagues turned to examining the flow velocity around the wingtip and the momentum generated by the plasma actuator at different voltages through PIV (Particle Image Velocimetry) imaging. In 2014, they compared numerical simulations with their experimental research findings. It was observed that the simulation results were consistent and well-matched with the experimental data, and the placement of the electrode also affects the uniformity velocity downstream, with the velocity decreasing as the distance between the trailing edge and the installed electrode increases [8, 9].

The aim of past research on plasma actuators as virtual winglets was to study a linear plasma actuator and, in some cases, several linear plasma actuators, determining their positional effects as virtual winglets. However, in this research, various arrangements of Dielectric Barrier Discharge (DBD) plasma actuators on the wing were examined to assess the impact of different arrangements at various Reynolds numbers, angles of attack, and voltages on the aerodynamic performance of the wing.

2. Test Equipments

To conduct this research, various experiments have been carried out in two stages. In the first stage, pressure experiments were performed using static pressure data collection through the pressure holes on the wing. Initially, to validate the results, the static pressure in the middle of the NACA 0012 wing was measured, and then, the static pressure of three rows of holes at the wingtip was measured. The schematic arrangement of the pressure experiments is shown in Figure 1.

The second stage involves conducting force experiments. Initially, for validation, the lift and drag coefficients of the NACA 0012 wing were measured, and in the second stage, the lift and drag coefficients for various models of plasma actuators, which were installed as winglets, were calculated. The first stage experiments measured static pressure at two different Reynolds numbers and five different angles of attack. Reynolds numbers of 150,000 and 300,000 were considered, and these experiments were conducted at angles of attack of 0, 2, 4, 6, and 8 degrees. In the second stage, the measurement of lift and drag coefficients for the validation of the NACA 0012 wing at Reynolds numbers of 150,000 and 300,000 and even angles of attack between -4 and 20 degrees was performed, and the force experiments for the plasma actuators were carried out in six configurations at the same Reynolds numbers but at three angles of attack of 2, 6, and 10 degrees.

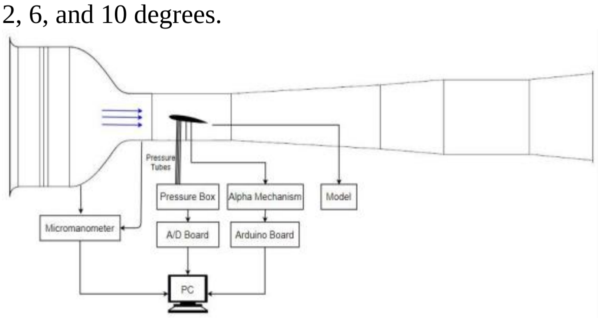

Figure 1. Schematic of Pressure Measurement Equipment

2.1. Plasma Actuators

These actuators have been prepared in six arrangements, the schematics of which can be seen in Figure 2. Sample numbers 1 and 4 are of the type of circular jet synthetic plasma actuators. In sample number 1, the inner diameter and the external credibility of the outer ring are 38 mm and 58 mm, respectively, and the outer diameter of the inner ring is 36 mm. In sample number 4, the inner and outer diameters of the outer ring are 16 mm and 36 mm, respectively, and the outer diameter of the inner ring is 14 mm. In sample number 1, 3 units have been used, and in sample number 4, 5 units have been utilized on the wing, covering it in the direction of the chord length. In samples number 2, 3, and 6, the width of the actuators is 1 centimeter, and in sample number 5, the actuator width is 0.5 centimeters, with a distance of 1 millimeter between two electrodes considered in all samples.

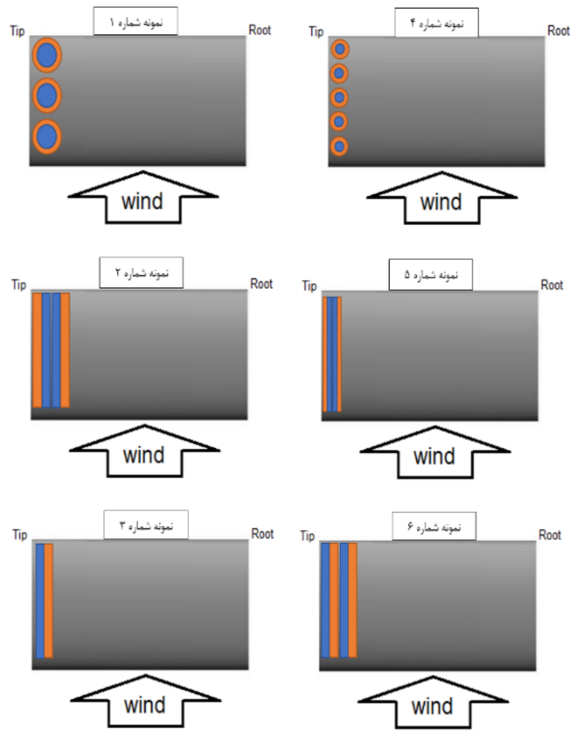

Figure 2. Types of Plasma Actuator Samples Used on the Wing in the Experiment

3. Results and Discussion

In this section, all the results obtained from the experiments are related to the examination of pressure distribution in the absence of a plasma actuator and when using a plasma actuator. Additionally, the force coefficients at different angles of attack for both scenarios, without plasma actuator and with plasma actuator, for all samples and different arrangements of plasma actuators have been presented. All tests were conducted at a temperature of 25 degrees Celsius and atmospheric pressure. As example;

3.1. The Effect of Different Plasma Actuator Arrangements on Wing Performance

In Figure 3, the diagram of the lift-to-drag ratio at different angles of attack in various arrangements of plasma actuators as virtual winglets at a Reynolds number of 150,000 and a voltage of 6 kilovolts is observed. In this situation, at a 2-degree angle of attack, the best aerodynamic performance belongs to the arrangement of a small linear actuator at the wingtip (sample 6) and the small circular model (sample 4), while the rest of the arrangements have shown a similar aerodynamic performance. At 6 and 10 degree angles of attack, the best samples in terms of increasing L/D were, respectively, the small circular arrangement (sample 4) followed by the small linear arrangement (sample 6).

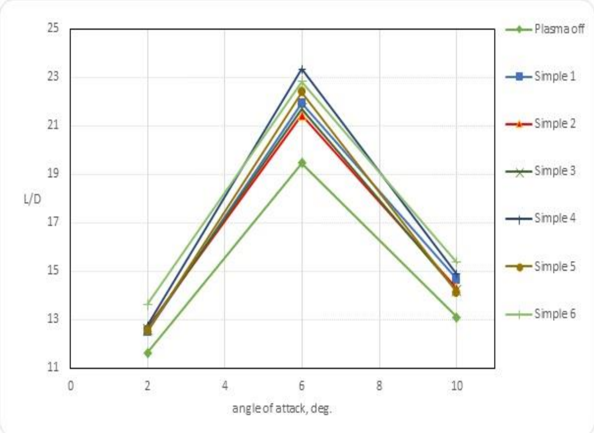

Figure 3. Diagram of lift-to-drag ratio at different angles of attack in various arrangements at a Reynolds number of 150,000 and a voltage of 6 kilovolts

In Figure 4, the diagram of the lift-to-drag ratio at different angles of attack in various arrangements of plasma actuators as virtual winglets at a Reynolds number of 300,000 and a voltage of 6 kilovolts is observed. In this condition, at a 2 degree angle of attack, no significant difference in aerodynamic performance is seen among all samples. At a 6 degree angle of attack, the arrangement of a large linear actuator (sample 3) has created a greater aerodynamic performance advantage compared to the rest of the arrangements, and at a 10-degree angle of attack, although all arrangements have produced a roughly similar increase in L/D, the superiority of the small circular (sample 4) is relatively seen.

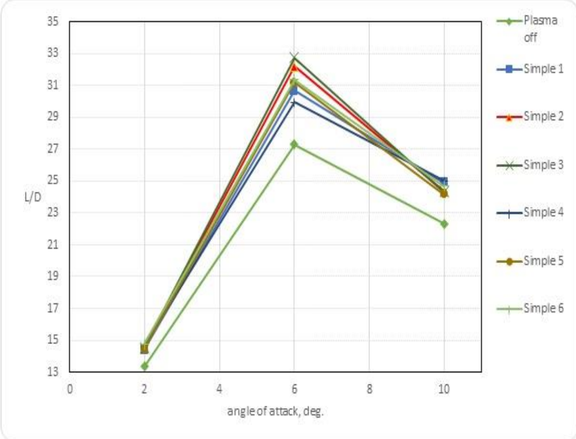

Figure 4. Diagram of lift-to-drag ratio at different angles of attack in various arrangements at a Reynolds number of 300,000 and a voltage of 6 kilovolts.

In this section, all the results obtained from the experiments presented are related to the examination of pressure distribution in the absence of a plasma actuator and in the case of using a plasma actuator. Additionally, the force coefficients at different angles of attack for both conditions, without the use of a plasma actuator and with the use of a plasma actuator, for all samples and different arrangements of plasma actuators are provided. All tests were conducted at a temperature of 25 degrees Celsius and atmospheric pressure.

4. Conclusions

In this study, the experimental investigation of using different arrangements of plasma actuators as virtual winglets has been conducted to evaluate the effect of plasma actuators as virtual winglets. For this purpose, the aerodynamic performance at the wingtip, including pressure distribution and the lift-to-drag ratio (L/D), for six different configurations of plasma actuators was examined. Additionally, the effects of voltage levels and Reynolds numbers at various angles of attack were also investigated. The results of this research show:

-With an increase in the angle of attack, the pressure coefficient also increases, and as one moves towards the wingtip, significant fluctuations in the pressure coefficient are observed, indicating turbulence in the pressure at the wingtip. These fluctuations seem to be due to the pressure difference with the free stream and the flow returning from under the wing to the top at the wingtip section. Also, the pressure coefficient decreases towards the wingtip.

-In both Reynolds numbers, the lift-to-drag ratio (L/D) in the plasma-on state increased compared to the plasma-off state. The highest lift-to-drag ratio is observed at a 6-degree angle of attack, and due to a further increase in drag at a 10-degree angle of attack, it leads to a reduction in the lift-to-drag ratio at both Reynolds numbers.

-Using DBD plasma actuators at the wingtip as virtual winglets can increase the lift-to-drag ratio by up to about 25% in some cases.

-Small circular and small linear configurations are considered the best among the six configurations for using the plasma actuator as a virtual winglet. Also, almost in all cases, at low angles of attack, the effects of different configurations of plasma actuators are similarly impactful.

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