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Application of Plasma Actuator with Two Mesh Electrodes to Active Control of Boundary Layer at 50 Hz Power Supply

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ABSTRACT

Numerous studies are conducted to improve the flow in the boundary layer to ensure laminar flow and in particular to increase flight safety. A new solution used to improve the laminar flow is the plasma actuator. The classic configuration of DBD plasma actuators is commonly used with the asymmetric electrode system. The manuscript describes the results of tests with a plasma actuator. Experimental tests were carried out on the built model of the wing with the SD 7003 profile, a plasma actuator was mounted on the upper surface. In contrast to the commonly used solution with solid tape copper electrodes, the novelty in the described research in the manuscript is the use of a large GND electrode (covering 70% of the upper surface of the wing) and a HV mesh electrode. The use of a plasma actuator on the upper surface of the wing affects the air flow in the boundary layer as a result of air ionization. The tests were carried out for a supply voltage from $V = 7.0$ kV to 12 kV and Reynolds number, $R_e = 87500$ to 240000, flow velocity during the tests in the tunnel was in the range of $U = 5–15$ m/s and the angle of attack $\alpha = 5–15$ degrees. On the basis of the results experimental tests, the percentage change in the lift coefficient was calculated for the switched on and off DBD system. The obtained results indicate a maximum 17% increase in the lift coefficient for the plasma actuator activated for air flow $U = 5$ m/s and angle of attack $\alpha = 5$ degrees. In the remaining configurations, changes in the lift coefficient amounted to 4%.

Keywords: plasma actuator, DBD, lift coefficient, mesh electrodes.

INTRODUCTION

In aviation, many different design solutions are used to increase laminar flow, the most important of which can be divided into wing mechanics and which are non-mechanical aerodynamic elements affecting the change of flow in the boundary layer. Currently, the most frequently used solutions include construction in aviation to change the flow in the boundary layer, among others; flaps, slots or wing construction elements in the form of wing fence, vortex generator, dogtooths, vortilons or other elements influencing air circulation in the boundary layer. Manufacturers introduce new solutions in the construction of aircraft to improve aerodynamics. Despite the introduced design changes, there are cases of stall, which often turns into a corkscrew. The stall is the effect of the loss of lift force associated with the wing operation at large angles of attack and the disturbance of the laminar air flow. The DBD actuator is a new non-mechanical solution that allows to change the air circulation in the boundary layer of the wing.

The use of a new technology using DBD (Dielectric Barrier Discharge) to change the flow in the boundary layer is a relatively new solution [1, 2]. The construction of the DBD plasma actuator is not very complicated. In the standard solution, the plasma actuator consists of two flat strips of copper electrodes separated by a dielectric. One of the copper HV electrodes is directly exposed to the airflow on the wing surface. The second GND electrode is completely covered by a dielectric. Both GND and HV electrodes are connected to the power supply system (several kV) [3–5]. The use of a dielectric on the GND electrode prevents the formation of sparking or arcing (arc discharge have a high temperature) [6]. The most popular in the literature is the asymmetric configuration of the electrodes in the DBD system, which consists of two flat solid copper electrodes that are separated by a dielectric layer, as shown in Figure 1. The asymmetric configuration aims to exert a force on the ionized gas generated by the discharge and induction of a directional flow of inert gas by collisions with free ions. The gas ionizes under the influence of the applied high voltage to the electrode system.

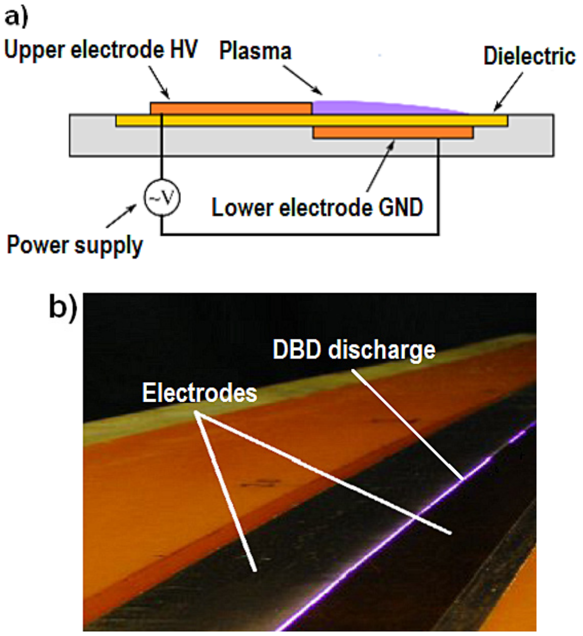

Fig. 1. Schematic diagram of a plasma actuator with an asymmetric arrangement of electrodes with DBD discharges; (a) a diagram, (b) a real model in operation [15]

The principle of operation classic DBD plasma actuator is as follows, the ionized air moves from the surface of the exposed high-voltage HV electrode towards the grounded GND electrode covered with a dielectric. During the movement of plasma (ionized air), the plasma collides with neutral air particles. As a result of elastic collisions between the migrating molecules of charged and inert gas molecules, their speed increases, this phenomenon causes the formation of an „ion wind" in close proximity to the wing surface [7–9]. The air moving over the HV electrode is ionized and attracted to the charged dielectric surface (under which the GND electrode is located), thus creating a wall flux. This phenomenon is shown in Figure 2. An operating DBD system in the air generates ozone from the oxygen in the air. Ozone is an oxidant and causes oxidation and corrosion of metal electrodes. Classical copper electrodes easily form oxides even in air, so in a plasma environment this oxidation is much stronger. Copper oxides formed on the upper surface of the HV electrode constitute a barrier to the conductivity of the electrode.

A very big advantage of the DBD system is that it does not have moving parts like; rods, membranes, gears that would activate it. The solution of the DBD system does not pose any problems related to the wing structure. DBD plasma actuators can be used for active flow control, easily adapting to operating conditions. DBD flow control systems are much faster than currently available, DBD systems have very short response times of fractions of a second. Currently, there are numerous studies around the world on the use of plasma actuators to increase laminar flow in the boundary layer. Most often, in order to increase the efficiency of the DBD system, engineers introduce numerous modifications, e.g.

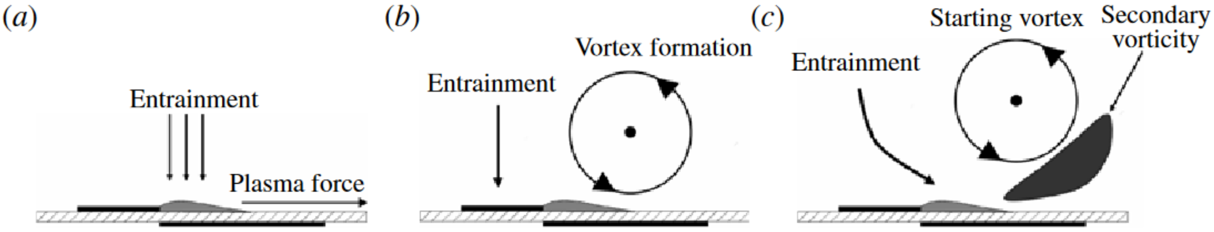

Fig. 2. Vortex formation at the starting point (a) plasma initiation, (b) vortex formation, (c) secondary vortex generation [8]

changes in the geometry of the electrodes, modification of the power supply system by changing the frequency and voltage, as well as the number and position of the electrodes. Most of the experimental studies and modifications carried out are carried out for systems with an asymmetric arrangement of electrodes, as shown in Fig. 1a. The experimental tests presented in the manuscript were carried out on a wing model with profile SD 7003 and dimensions of 250×250 mm. On the upper surface of the wing model there is a GND mesh electrode covered with Kapton dielectric. The wing model used in experimental research was made of modeling materials, including glass fiber and balsa, plywood. The DBD plasma actuator is powered by two strip-shaped connectors that are positioned along the wing profile, as shown in Figure 3. This solution allows the installation of a ground electrode on 70% („large ground electrode”) of the upper surface of the wing model, and also allows moving the upper high voltage electrode along the HV convector. The mesh electrode is made of stainless steel. This solution prevents oxidation of the electrode during the generation of plasma in the plasma actuator. The mesh size is 0.05×0.05 mm.

The AeroLab wind tunnel was used to measure the forces acting on the wing model during the tests. Experimental tests were carried out in a wind tunnel on a wing model for the Reynolds number in the range Re = 87500–240000.

The main aim of the experimental research is to check the correct operation of the new plasma actuator with mesh electrodes. Another aim of the research is to determine the effectiveness of the new design of the DBD system at low frequency f = 50 Hz power supply and its impact on the system performance when changing the angle of attack and air flow velocity.

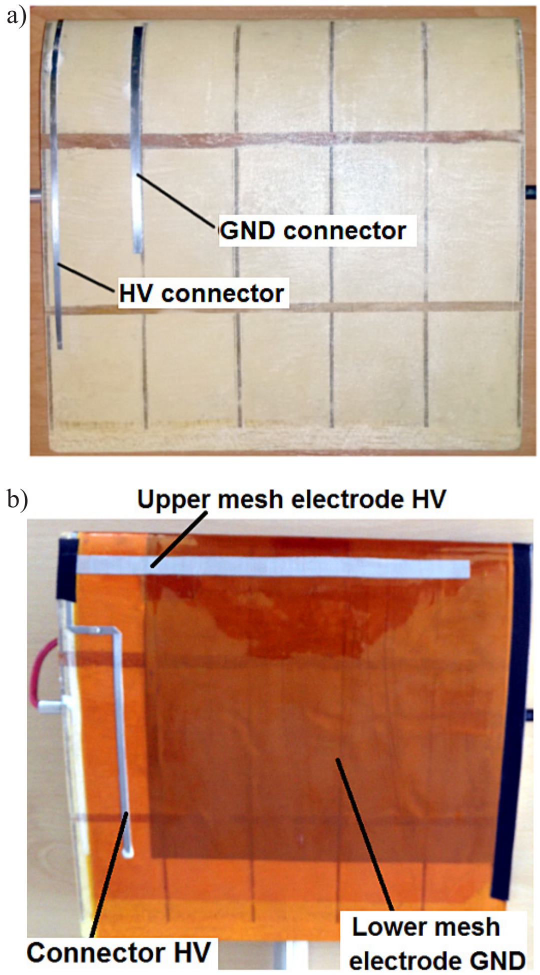

Fig. 3. Design of the wing model SD7003 profile; (a) without mesh electrode and dielectric, (b) with dielectric and mesh electrodes HV, GND

MATERIALS AND METHODS

The experimental research were carried out for various angle of attack in the range of α = 5–15 degrees with a change of every 5 degrees and the air flow velocity U = 5–15 m/s in the wind tunnel. The high voltage power supply system used to power the DBD plasma actuator consisted of an autotransformer which allows for smooth regulation of the voltage on the HV transformer by 230/100000V 50 Hz. Voltage and current waveforms were measured and registered by Keysight DSO-X 2012A oscilloscope. The oscilloscope was equipped with high voltage Tektronix P6015A probes and P2220 current probe (Tektronix). The Figure 4 shows a diagram of the measurement and Figure 5 shows the operating principle of a plasma actuator with a „large grounded” electrode and a high voltage mesh electrode. During the tunnel tests, photos were registered by Phantom V2511 high speed camera.

Another element of the system is the wind tunnel, which is the main measuring element for controlling and modifying the conditions of the experiment, such as; air flow velocity, measurement of forces acting on the wing model and the angle of attack.

The tests were carried out for angles of attack α = 5, 10 and 15 degrees. For each of the angles of attack, the forces acting on the wing model were measured for air flow velocities U = 5, 10 and 15 m/s.

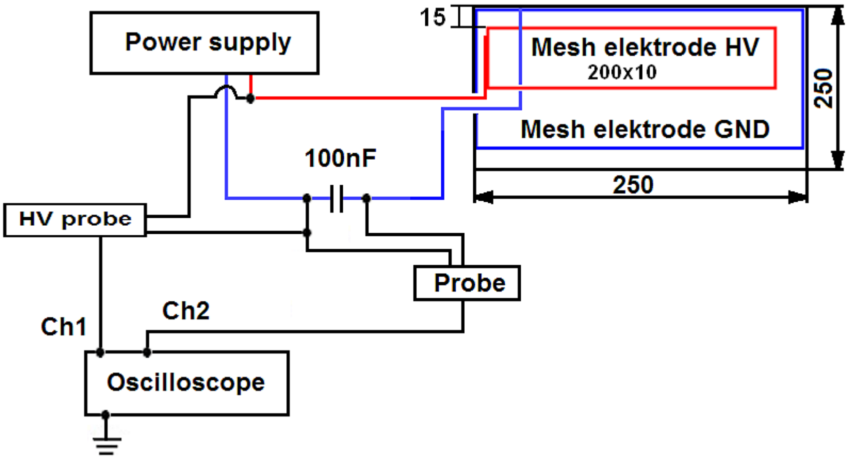

Fig. 4. Diagrams of the construction and configuration of the plasma actuator and the measurement system

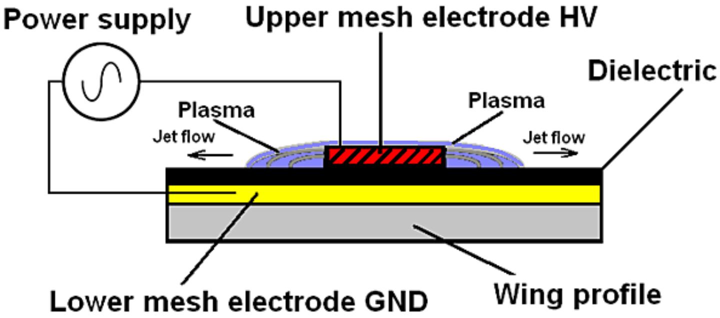

Fig. 5. Schematic diagram a plasma actuator with a large mesh electrode and a high-voltage mesh electrode

RESULTS

Experimental tests in the tunnel were carried out on the built model of the wing with the SD 7003 profile. The results of the experimental tests allowed to determine, among others, power applied to the DBD plasma actuator during experimental tests and register the forces on the wing model for various system configurations. During experimental tests, the discharge power ranged from $P = 1.10$ W up to 2.0 W, with a supply voltage from $V = 7.0$ kV to 12 kV. In DBD systems, the power of lightning is influenced by several factors, the most important of which are; frequency of the supply system, supply voltage, dielectric type [10, 14], distance between HV and GND electrodes, geometry of electrodes [11–13]. In experimental studies, the frequency $f = 50$Hz was used to power the plasma actuator.

The performance comparison of the plasma actuator with the large mesh and high voltage mesh electrode was expressed by the percentage increase in lift by comparing the system operation with the plasma actuator off and on under the same experimental conditions.

During the experimental tests, the highest increase in the lifting force with the plasma actuator turned on was recorded for $\alpha = 5$ degrees and the air flow $U = 5$ m/s, for the other configurations of the system, the values of the lower increase in the lifting force were recorded. For the configuration $\alpha = 5$ degrees and the air flow $U = 5$ m/s, the percentage increase in lift is 17% in relation to the system with the plasma actuator switched off. With an increase in the angle of attack in the range of $\alpha = 5$–15 degrees (every 5 degrees), the percentage increase in the lift force is smaller and amounts to 17% to 4% for the speed $U = 5$ m/s.

During the experimental tests, tunnel photo were recorded, selected for $\alpha = 5$ degrees and the air flow $U = 5$ m/s, as shown in Figure 6.

The tunnel photos shown in Figure 6 show the change in airflow with the plasma actuator turn on. Figure 6b shows a laminar flow, especially in the area of the wing trailing edge. The turbulence at the surface of the wing profile was also flattened compared to Figure 6a, which is also confirmed by the results of experimental tests. The analysis of the lift coefficient diagram for the air flow rate of $U = 5$ m/s and the angles of attack in

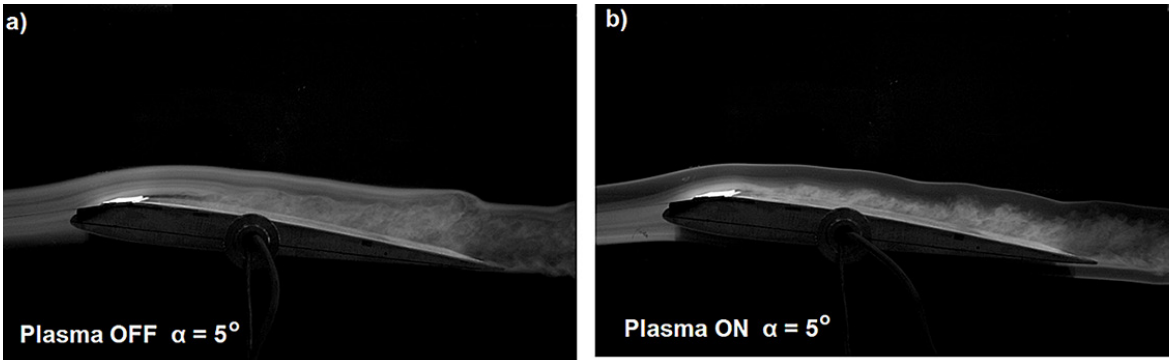

Fig. 6. Tunnel photos recorded during experimental tests for α = 5 degrees and air flow $U = 5$ m/s

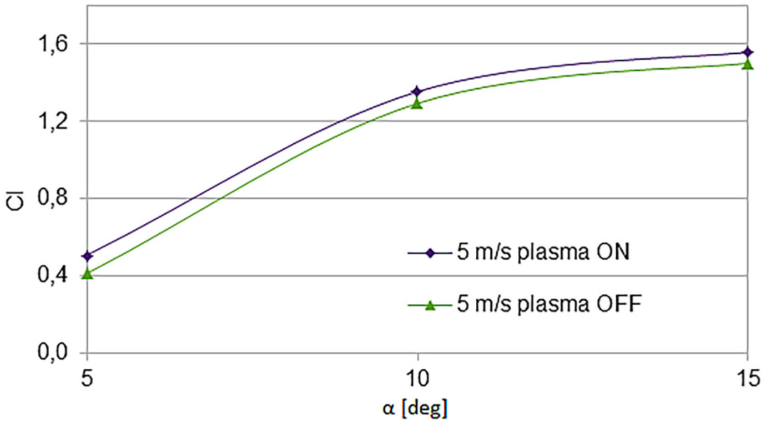

Fig. 7. Graph of change of the lift coefficient for the wing model with the SD 7003 profile for air flow velocity $U = 5$ m/s and angles of attack in the range α = 5–15 degrees

the range α = 5–15 degrees presented in Figure 7 shows a decrease in the lift coefficient with an increase in the angle of attack.

The analysis of Figure 7 shows a decrease in the lift coefficient with an increase in the angle of attack in the range of α = 5–15 degrees, this phenomenon results from the low $f = 50$ Hz operating frequency of the power supply system.

CONCLUSIONS

The obtained results of experimental tests indicate the performance of the new solution of the DBD plasma actuator with mesh electrodes. The calculated percentage changes in the lift coefficient amounted to 17% in the plasma actuator activated for the air flow $U = 5$ m/s and the angle of attack α = 5 degrees. In other cases, the changes in the lift coefficient were much smaller and amounted to 4%. The use of two mesh electrodes, one large GND and a high voltage mesh electrode, allows to obtain a “double effect”, the first effect in which the two edges of the upper HV mesh of the electrode take part in the formation of ion wind. The second effect of using mesh electrodes is to increase the surface area of the discharges, because discharges also occur on the upper surface of the electrode through the perforated surface of the mesh electrode. In the construction of plasma actuators with an asymmetric electrode arrangement using solid copper tapes, it is not possible to obtain such discharges (discharges on two edges and directly through the HV electrode surface). In an asymmetric electrode arrangement, discharges are generated at only one. The two mesh electrode arrangement has high operational efficiency due to the larger discharge area of the HV electrode directly affecting ionization and the create of ion wind. The analysis of lift coefficient data shows a decrease in lift coefficient with increasing angle of attack in the range of α = 5–15 degrees, and with increasing air flow velocity, this phenomenon results from the low frequency of the power supply system. The low number of discharges generated by the DBD system due to the low operating frequency of the power supply system $f = 50$ Hz per unit volume of air flow at high angles of attack and air velocity significantly reduces the ion wind effect. Additional tunneling tests are required to optimize the plasma actuator with mesh electrodes in terms of power and frequency.

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