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Wind tunnel testing of multi-tip corona actuators on a symmetric airfoil

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ABSTRACT

A set of 15 different corona actuators with triangular tips on their anodes is studied by installing them on the leading edge of a NACA 0015 airfoil. Each actuator is identified by its tip sharpness and tips number/unit length. The aerodynamic forces on the airfoil are measured in the wind tunnel over a wide range of angles of attack, for different airstream velocities. The performance of the actuators is evaluated by means of several parameters, including critical and mean lift increase, drag reduction and power saving effectiveness. The best configurations are identified in terms of the above parameters.

1. Introduction

Corona discharge actuators are useful devices for flow control applications [1]. When a sufficiently high DC voltage is applied between two electrodes mounted on a dielectric surface, the air between the electrodes weakly ionizes. The accelerated ions, by means of collisions, transfer momentum to neutral air molecules, giving rise to an electric or ionic wind of some meters per second, that may be exploited for energizing the boundary layer. This electric wind is defined as “the movement of gas induced by the repulsion of ions from the neighbourhood of a high voltage discharge electrode” in the fundamental work of Robinson [2]. This particular kind of plasma discharge is defined as a *cold* plasma, since the energy is mainly spent to accelerate the ions, rather than to increase their temperature.

Historically, the first attempts to control a flow with an electrical discharge were performed with corona actuators during the last two decades of the last century, even though the use of a wire-to-wire corona actuator to control boundary layer transition was already reported in a paper in 1968 [3]. In more recent years, corona actuators have been studied both from a numerical [4–7] and an experimental point of view [8–11]. In particular, the ability of these devices in reattaching a separated flow on a flat plate has been investigated [12,13], up to freestream velocities of 25 m/s [11]. Other applications of DC coronas include separation control on bluff bodies such as cylinders [14], modification of mixing layer properties [15], separation control of a free turbulent jet exiting from a nozzle [16] and stall control over aerodynamic airfoils [17,18]. Different discharge regimes have been identified for increasing current values in a surface corona: following Moreau classification [1], they are called *spot*, *streamer*, *glow*, *filamentary* and *arc* regimes. In what follows we will refer to this classification, but we notice that it is not universally adopted, and other authors introduce a different terminology to indicate these phenomena, even in different geometries, as for example [19,20]. With the surface corona configuration investigated in the present paper, the streamer and glow regimes are the most interesting for flow control, while electric arcs should be avoided, since they may excessively heat the electrodes and the dielectric surface, leading to local melting and permanent damaging of the actuator. As reported in literature, properly designed *localized arc filament plasma actuators* (LAFPA) may exploit the electric arc for high speed flow control problems [21,22], however their geometry and operating principle are very different from the surface corona considered in this work.

In a typical surface corona, the different discharge regimes, and consequently the magnitude of the induced ionic wind, are influenced by electrical and geometrical parameters [10], mainly the applied voltage and the size and shape of the electrodes. Also the polarity of the high voltage has an effect on the actuator performance: in particular a positive corona seems more performing than a negative one, both in terms of induced velocity and electromechanical efficiency [23,24]. Furthermore, corona discharge is very

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sensitive to external factors, such as the cleanliness of the dielectric surface and the relative humidity of the air [9]: a high level of humidity or a non-optimal dielectric cleaning, for instance, may greatly affect the production of ionic wind and eventually worsen the stability of the discharge, with transitions to the arc regime. For this reason, in the last years the interest of most of the scientific community shifted towards Dielectric Barrier Discharge (DBD) plasma actuators, more stable thanks to the presence of a dielectric between the electrodes [25,26]. Thus, the literature on corona actuators applications to flow control problems is quite limited today.

The present work is focused on corona actuators with multi-tip geometry [27], where the anode is characterized by periodic triangular tips, not necessarily adjacent. This geometry is an extension of the *serrated edge* configuration, already investigated for DBDs in previous literature works [28–30]. To the authors knowledge, the multi-tip coronas have never been tested on a surface for flow control purposes, whereas an application of the serrated geometry in a volumetric discharge for a multistage ionic wind generator may be found in Ref. [31]. In Ref. [27], the authors measured at the bench the ionic wind induced on a flat plate by 12 different multi-tip coronas and compared their performances with the traditional *wire-to-plate* actuator, whose anode is made by a thin wire. The new geometry induced higher velocities and mass flows with an electro-mechanical efficiency larger than for the traditional configuration. Furthermore, the ease of ignition and the stability of the discharge are remarkably improved with the multi-tip geometry, in particular for tips of high sharpness [32]. Moreover, a comparison with traditional and multi-tip DBDs showed that multi-tip coronas are able to induce velocities similar to DBDs, although with a maximum located at a larger distance from the wall, but with a much lower power consumption, implying a higher electro-mechanical efficiency.

In the present work, a traditional wire-to-plate corona and the same 12 multi-tip geometries previously tested at the bench, with the addition of two more shapes, have been positioned at the leading edge of a NACA 0015 airfoil and tested in the wind tunnel. The effectiveness of the different shapes is evaluated in terms of lift increment and drag reduction at high angles of attack, with respect to the non-actuated case. Voltage and current measurements are also performed, in order to calculate the consumed power and the mechanical power saving due to the actuators. We wish to remark that the objective of this work is the comparison of electrodes with different shapes and not the research of the best ever performance, so that other parameters as for instance the electric field have not been set to extreme values.

2. Experimental setup

2.1. Wind tunnel and airfoil

In this experiment, a symmetric NACA 0015 airfoil (chord $c = 250$ mm, span $b = 470$ mm) is located in an open-return wind tunnel with a test section of 500×700 mm^2 in cross section and 2 m in length. The flow velocity in the test chamber can be varied from 0 to 25 m/s, with a turbulence level not larger than 0.5%.

The airfoil is made of a special kind of polyurethane, with excellent mechanical performance and insulating characteristics, and it was purposely designed for this experiment with a cavity around the leading edge. Plasma actuators are mounted on interchangeable C-shape inserts that accurately fit the cavity on the airfoil, so that the overall profile of the NACA 0015 is not modified (see §2.3). Two end plates limit the 3D effects at the lateral sides of the airfoil and help to recover an ideal two-dimensional behaviour. A rotative positioning system with optical precision (positioning accuracy $\pm 0.005°$) allows to set the angle of attack α.

In the experiment, the flow velocity is set in the range $5 \le U \le 20$ m/s, corresponding to Reynolds numbers based on the chord length in the interval $0.83 \times 10^5 \le Re \le 3.33 \times 10^5$. A particular attention has been given to $U = 10$ and 15 m/s, corresponding to Reynolds of 1.66×10^5 and 2.50×10^5 respectively. The wind tunnel is located in a large room where the temperature is controlled and kept in the range 22 ± 2 °C. The relative humidity has been maintained in the range 25–40% for the entire experimental campaign. In order to account for the effects of the flow confinement between the airfoil and the tunnel walls, both solid and wake blockage corrections have been applied, following the procedure described in Refs. [33,34]. All the results, and in particular the force coefficients c_l and c_d, are directly presented in corrected form.

2.2. Balance and measuring system

Lift and drag of the airfoil are measured by means of an external aerodynamic balance, purposely built for this research project. The balance has been realized from 4 load cells, symmetrically located on the two lateral sides of the test chamber. Two cells are sensitive to horizontal forces (drag) and the other two measure vertical loads (lift). The airfoil is connected to the balance by means of two lateral insulating stings. Because the output signals from the cells are in the order of millivolts, an appropriate conditioning and amplification system has been implemented to increase rejection to electromagnetic disturbances, that can constitute an important issue in the presence of a corona discharge. The accuracy on the measured forces is ±0.2 N in the horizontal direction and ±0.4 N in the vertical one. A representation of the balance, the airfoil and the test section is presented in Fig. 1. The flow velocity in the test chamber is measured by means of the pressure jump in the contraction section located upstream: the pressure jump is acquired through suitable wall taps connected to a differential transducer, and is correlated with the velocity in the test section thanks to a previous calibration procedure carried out by means of a precision pitot probe.

The output analog signals are acquired by means of an A/D converter and digitally stored in a personal computer. Each force value is obtained as an average on a time window at least 7 s long, with a sampling rate of 4 kHz. It has been verified that this time interval is enough to reach a stationary average value, also in the

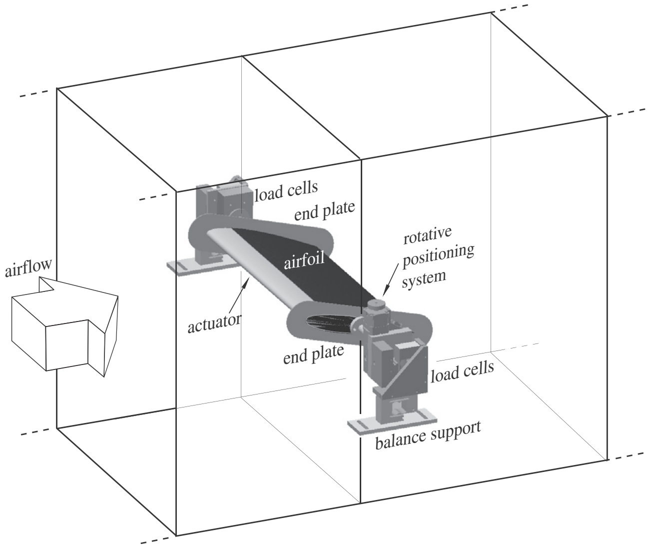

Fig. 1. Experimental setup: airfoil, external balance and outline of the test section in the wind tunnel.