Elongated-DBD Actuators Inducing Curved Wall Jets for Circulation Control Around Turbine Airfoils

A. Leroy¹, J. Podlinski², S. Baleriola³, P. Devinant¹, and S. Aubrun¹
¹University of Orléans, France
²The Szewalski Institute of Fluid Flow Machinery, Polish Academy of Sciences, Poland

Abstract—A feasibility study for implementing circulation control method to improve aerodynamic load alleviation on wind turbine blade airfoils was performed. The experiments investigated the ability of surface elongated-DBD actuators attempting to control the streamline separation point at a rounded trailing edge, leading to the modification of the velocity vector circulation, and so, the lift. Depending on the implementation at the trailing edge, the actuator induces a wall jet directed to the lower or the upper surface of the airfoil, increasing or decreasing the lift respectively, keeping constant the angle of attack. First the flow induced by the elongated-DBD implemented on a curved surface is investigated in quiescent air conditions. Then, results of the preliminary testing of circulation control are presented showing ±8% variation in lift obtained with this actuator configuration implemented on an airfoil with a chord of 300 mm at a freestream velocity of 10 m/s.

Keywords—DBD actuator, curved surface plasma actuator, circulation control

I. INTRODUCTION

Wind energy is one of the most dynamic industries worldwide with an annual increase rate of activity of 20%, and it is still necessary to improve the robustness and the life duration of the wind turbines to ensure operation availability and an optimal energy production during periods longer than 15 to 20 years. Due to inhomogeneous and unsteady wind conditions in the atmospheric boundary layer, wind turbines are subjected to load fluctuations which are necessary to properly manage to diminish material fatigue for example. In order to mitigate these aerodynamic load fluctuations and to improve the efficiency of the wind energy production by innovative flow control solutions, a strategy of circulation control, acting at the blade airfoil trailing edge, allowing lift increase and decrease is studied. On the aerodynamic point of view, the baseline configuration is a fully attached flow on the blade airfoils, and the objective is to maintain the lift at a fixed value, whatever the incoming flow disturbances. Such a strategy can be investigated by using fluid wall jet along a rounded airfoil trailing edge in order to manipulate the streamline separation point at the trailing edge, leading to the modification of the velocity vector circulation, and so, the lift. A large amount of circulation control simulation experiments were performed taking advantages of Coanda effects over curved surfaces in addition. Initially, applications were focused on fixed wind aircraft and were progressively applied to any control surface (flap, aileron, engine, propeller...), then submarine/hydrodynamics and rotary wings. The main objective was to increase the circulation by acting at the trailing edge when large lifting forces and/or slow speeds are required, such as at take-off and landing of aircraft.

Indeed, circulation control is able to significantly improve lift at low angle of attack. One can find a survey of circulation control applications in [1], [2]. Recent applications are turned nowadays towards wind turbines [3], [4] and water turbines.

Interest in plasma actuators for flow control has been largely reported in the literature over the last decade. Recent papers [5]–[7] give an overview of various configurations based on the surface Dielectric Barrier Discharge (DBD) and highlight the ability of this type of actuator to manipulate flows. Most of previous research works reported in [8]–[11] for example focused on separation control and separated flow control around different airfoils by performing plasma actuation located at the leading edge or along the chord. These separation control applications for aeronautics lead to improve airfoil aerodynamic performances as the angle of attack increases, as stall delay for example. The airfoil sections used in the wind energy community are thicker than those for aeronautics in order to make the blades withstand extreme loads and to smooth out the potential stall effects. Regarding plasma actuators, a few works reported their ability to control circulation on airfoils, showing the feasibility of this strategy [12]–[14]. In this work, surface plasma actuators are used to assess the possibility to increase or decrease the lift by inducing either a downward or an upward wall jet respectively for a wind turbine blade airfoil specifically designed with a rounded trailing edge [15]. The wall jet is supposed to alter the overall circulation around the airfoil keeping constant the angle of attack. This is achieved by the use of an elongated-DBD actuator with floating electrodes, allowing actuation distributed along the chord, leading to a cumulative effect on the ionic wind. Such a DBD actuator and its operation has been described in [16] and tested for flow separation control [17].

Flow velocity measurements were performed to characterize, in quiescent air conditions, the flow jet induced by the actuator mounted along a curved surface in comparison with the actuator mounted along a plane surface. Then aerodynamic load and flow velocity measurements were performed to study

Corresponding author: Annie Leroy
e-mail address: annie.leroy@univ-orleans.fr

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the efficiency of elongated-DBD actuators implemented on a wind turbine airfoil installed in a large wind tunnel to modify circulation. Results for the preliminary testing at a flow velocity of 10 m/s, corresponding to a chord Reynolds number of $2 \times 10^5$, are presented showing the lift range that can be controlled with this actuator configuration.

II. ELONGATED-DBD ACTUATOR DESIGN

The elongated-DBD actuator with floating electrode used in this experiment is schematically shown in Fig. 1 and was previously described in [16]. It consisted of either a main dielectric in PMMA of 3 mm in thickness or a flexible main dielectric barrier made of a 4 layers of Kapton tape (45 μm-thick Kapton tape), for the experiments conducted in quiescent air (section III) or on airfoil in wind tunnel (section IV) respectively.

As shown in Fig. 2, a smooth grounded (a) electrode and a saw-like high voltage (b) and floating (c) electrodes were used. All electrodes were made of a 50 μm-thick copper tape. The floating electrode, a series of separated copper teeth was used. The high voltage and floating electrodes were partially insulated (only tips of the saw teeth were exposed to ambient air) and were mounted on the upper side of the main dielectric, while the insulated ground electrodes were on the opposite side. The first grounded electrode was 9 mm wide and the second was 6 mm wide, the high voltage electrodes were 2 mm wide and the floating electrode was 3 mm wide. The distances from the high voltage electrodes to the grounded electrodes were 2 mm (e.g. from $x = 2$ mm to $x = 4$ mm and from $x = 18$ mm to $x = 20$ mm). The distance from the floating electrode to the high voltage electrode was almost 3 mm. The floating electrode saw teeth were slightly shifted (less than 0.5 mm) with respect to the first grounded electrode edge.

The actuator was supplied by a home-made power supply and was operated with sinusoidal signals of variable amplitude and frequency ($V_{HV} = 9$–$18$ kV, $f_{HV} = 1$–$2$ kHz) in continuous actuation mode.

III. FLOW INDUCED ALONG A ROUNDED WALL IN QUIESCENT AIR

In order to take advantages of Coanda effects along the rounded trailing edge of the airfoil (see Fig. 3), it is usually necessary for conventional fluidic jets to be characterized by high momentum coefficient as exposed in [1]. Although the flow mass rate of the induced wall jet by DBD actuators remains low compared to fluidic jets, the induced wall jet is supposed to adhere to curved surfaces because the ionic wind is generated by momentum transfer occurring very close to the wall. Investigations were conducted to characterize the flow jet induced by the elongated-DBD actuator mounted on a curved surface in comparison with a similar actuator on a plane surface to see curvature effects on its topology.

A. Elongated-DBD actuator setup

The actuator was implemented by using 3 mm thick PMMA for the dielectric material as a plane surface and as a rounded surface obtained by thermoforming and represented in Fig. 4.

In Fig. 4, $X^*$-axis and $Y^*$-axis refer to the curvilinear frame related to the surface with its origin located at the end of the second high voltage electrode.

The measurement of the active power $P$ was achieved as a function of the high voltage amplitude according to the method presented in [18] and using a capacitor between the grounded electrode and earth. For both actuator configurations, Fig. 5 indicates similar typical values and curves for the power consumption consumed by DBD with the thick dielectric, which can be estimated by the empirical law:

$$P = K \cdot f_{HV} \cdot (V_{HV} - V_0)^2$$  \hspace{1cm} (1)
where $K$ and $V_0$ are two coefficients depending on the actuator setup [18].

**B. Time-averaged wall jet topology**

A two-component Laser Doppler Velocimetry system (Dantec Dynamics®, BSA Series 51N) was chosen to carry out the velocity measurements of the induced flow by the actuator in quiescent air. The LDV system used a four-beam optical arrangement of a 15-W ionized Argon laser (Spectra-Physics® Series 2000) providing two 532 nm-wavelength beams in addition with two 488 nm-wavelength ones. A fiber optic probe with a 500 mm focal length lens generated an ellipsoid-shaped measurement volume with dimensions of 80 $\mu$m $\times$ 80 $\mu$m $\times$ 1000 $\mu$m. An angle of 8° was settled between the lasers beams and the dielectric surface, thus, measurements could be performed above the plasma region for heights not less than 0.2 mm from the dielectric panel. The whole system could be displaced precisely along two axis by means of two linear units (Isel®) driving by a computer (resolution of 0.1 mm). The test section was seeded with olive oil particles by means of an aerosol generator (Pivtec® Series PivPart30). Droplets of olive oil with mean diameter of approximately 1 $\mu$m could be generated as it was expected from the particle size distribution mentioned by the constructor. Measurements were performed in a 1 m long, 0.5 m high and 0.5 m wide closed box in order to ensure that no recirculation would be present during the actuator working. The sample records were ranging from 0.5 to 5 kHz and were dependent on the velocity of the induced flow and on the measurement volume height from the dielectric panel. The acquisition time for each measurement point was 20 seconds.

In Fig. 6, longitudinal $u$-velocity mean contours and velocity vector fields are represented along the actuator in plane configuration. When the actuator is operated, the classic wall jet evolving along the actuator is observed focusing on the three main phases: suction effect, acceleration close to the wall and diffusion.

In Fig. 7 are plotted velocity vector profiles measured at different longitudinal $X^*$-positions indicated on the scheme along the actuator in plane or rounded configuration. For both configurations, the $X^*$-position corresponds to the curvilinear abscissa. When the actuators are operated, the classic wall jet evolving along the actuator is still observed. For both configurations, the ambient air is deflected towards the plasma region with a strong acceleration close to the wall, highlighting the higher velocity at the plasma-gas interface along the whole actuator, even for the rounded configuration. Downstream of the main actuation zone, one can observe diffusion of the induced jet on the normal direction. Nevertheless, this diffusion zone is quite more intense for the rounded configuration than for the plane configuration. The profiles suggest that the wall jet expands away from the wall because of the curvature resulting in a widened jet in this zone with
slight lower $u$-velocities. This can be confirmed by computing the mass flow rate $Q$ produced by the DBD from velocity profiles by:

$$Q = \rho \int_{y=0}^{\infty} u(y) \, dy$$

(2)

where $u(y)$ is the velocity longitudinal component according to the curvilinear abscissa $X^*$-direction. For $X^* = 10$ mm, the mass flow rates are 2.17 g/s and 2.05 g/s for the plane and the rounded configurations respectively. Due this quite low mass flow rate in comparison with classic fluidic jets, it is unlikely to take advantage of Coanda effects along the rounded trailing edge of the airfoil. Nevertheless, as the wall jet still adheres to the curved surface, an interaction with the natural flow can be expected as discussed in the next section.

IV. CIRCULATION CONTROL INVESTIGATION

A. Experimental setup

The generic wind turbine airfoil used for these experiments was a NACA651-421 profile. The trailing edge of the model was replaced by a rounded trailing edge with a radius of curvature of 2% of the chord length $c$ (i.e. 6 mm in this case) while keeping the same chord length. The shape adjustment between the modified trailing edge and the pressure side was designed in order to increase the airfoil camber, as a counterpart of the expected degradation of the aerodynamic performance due to the rounded trailing edge. Fig. 8 shows the comparison between the generic NACA651-421 airfoil profile and the CC-oriented airfoil profile NACA651-421-CC. The chord length $c$ is 0.3 m and the spanwise length is 1.1 m, $\alpha_0$ defines the zero angle of attack for this airfoil designed with a round trailing edge.

These experiments were conducted at the laboratory PRISME of University of Lorraine, in the “Lucien Malavard” closed return wind tunnel. 2D testing was performed into the main test section of 5 m long with a cross-section of 2 m $\times$ 2 m. In the present study, the operating speed of the wind tunnel varied from 7 m/s to 20 m/s with an airflow turbulence level below 0.4%. The airfoil was mounted horizontally between two vertical flat planes in order to achieve a 2D flow configuration. It was mounted on both tips onto a 6-component platform balance used for time-averaged lift and drag measurements and located under the test section. The balance was carefully calibrated, lift and drag coefficient uncertainties were estimated at 10 m/s to be less than 5% for the lift force and 10% for the drag force. Mean velocity fields around the airfoil trailing edge were studied from 2D-PIV measurements in order to analyze flow topology in the longitudinal plane of symmetry. The PIV system consisted of a double pulsed Nd:Yag laser emitting light pulses ($\lambda = 532$ nm) of 200 mJ with a 4 Hz double-pulse repetition rate. The seeding consisted of submicron-sized olive oil droplets sprayed by a PIVTEC seeding system. The light sheet was placed parallel to the streamwise direction in the median plane and emitted from the top of the test section. Consequently a shadow zone was present below the airfoil. Images were acquired with two TSI Power View Plus 2048 $\times$ 2048 pixel cameras fitted with a 105 mm lens. Data acquisition and processing were performed using the TSI PIV Insight 4GTM data acquisition and analysis software. The two successive images were recorded with a time interval equal to 50 $\mu$s at a freestream velocity of 10 m/s. The image size was 194 mm $\times$ 194 mm with a spatial resolution of 94 $\mu$m per pixel and the spatial resolution resulting from 16 $\times$ 16 pixels interrogation windows was approximately 1.5 mm. For this configuration 300 image pairs were recorded to evaluate mean flow velocities. Flow field details were not available very close to the airfoil surface mainly due to high levels of laser light reflection and light emitted by plasma. It can be considered that first velocity values are only valid beyond 2 mm from the surface.

Design of the elongated-DBD actuator with flexible dielectric materials (Kapton) enabled us to flush mount it on the airfoil model. For the model, the high voltage electrodes and the grounded electrodes were 950 mm long, while the length of the floating electrode was 900 mm. Placement of the actuator electrodes on the circular trailing edge of the airfoil is presented in Fig. 9 when inducing a downward velocity. When inducing an upward velocity, the electrodes are symmetrically disposed with respect to the configuration in which the actuator produces a downward velocity. Depending on the electrode arrangement, the actuator induces either a downward or an upward velocity in order to increase or decrease the lift respectively, keeping constant the angle of attack. Due to the relatively small radius of the trailing edge and the large span of the airfoil used in this experimental setup, the implementation was relatively hard, and then, was a limitation to test the effects of different locations for actuators.

Characterization of the curved wall jet induced by this actuator was performed by PIV measurement in quiescent
Fig. 10. Time-averaged velocity vector field in quiescent air for (a) downward and (b) upward arrangement for 9 kV, 1 kHz.

air. Fig. 10 shows the mean velocity field at the vicinity of the rounded trailing edge of the airfoil represented by flow vectors inducing a wall jet in downward and upward directions. The shadow of the laser sheet prevents from visualizing the complete flow induced by the upward arrangement. Both blowing induce a similar flow topology along the rounded trailing edge. For the same PIV setup and parameters and despite the shadow zone below the airfoil, induced velocity values close to the rounded leading edge appeared to be slightly higher in the upward arrangement for this spanwise location. It was not possible to verify the homogeneity of the actuation by measuring the induced flow along the spanwise direction. It suggests that the upward configuration actuator could have produced a more intense jet than the downward configuration. Nevertheless, aerodynamic load modifications were observed as shown in the next section.

B. Aerodynamic forces

Fig. 11 shows the lift coefficient at different angles of attack (AOA) without, and with upward and downward actuation at $U_\infty = 10$ m/s. For example at AOA = 4°, the lift coefficient of the airfoil increases from 0.891 to 0.964 with downward actuation and at AOA = 4.3° decreases from 0.891 to 0.85 with upward actuation. Time-averaged lift coefficient gain was defined by the ratio, $(C_{L(on)} - C_{L(off)})/C_{L(off)}$ to quantify the effects of the plasma actuation, $C_{L(on)}$ and $C_{L(off)}$ corresponding respectively to the lift coefficients for the controlled and the uncontrolled flow. The lift gains are positive or negative with the downward and upward actuation respectively and are summarized in Table I.

In the present study, it can be observed that the increment in the lift is nearly the same for the three angles of attack investigated with actuation (-4.8°, 1°, 4°) for which the flow is fully attached. In the principle of circulation control, the induced wall jet re-energizes the boundary layer and delays its separation. The increase in lift depends on the operating angle of attack and on the configuration (location and strength) of the wall jet. Indeed, according to the investigation conducted by using numerical simulation or experiments of circulation control by plasma actuation and reported in [13], [14], the angular location of the actuator on the rounded trailing edge influences the lift enhancement. In these experiments, one single angular location for the downward and the upward jet configuration was implemented but different angles of attack were investigated. It was observed that the lift increment value was slightly different depending on the angle of attack. The effectiveness of the actuation decreases with the freestream velocity and the angle of attack. Beyond 8°, effects of plasma actuation are negligible. Indeed, the boundary layer separates too far upstream of the rounded trailing edge and the actuation cannot any more be effective.

The variation of the drag force value due to the actuation measured in both actuation modes was comprised in the

<table>
<thead>
<tr>
<th>ANGLE OF ATTACK (°)</th>
<th>DOWNWARD</th>
<th>UPWARD</th>
</tr>
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<tbody>
<tr>
<td>Lift coefficient gain (%)</td>
<td>+7.3</td>
<td>+8.2</td>
</tr>
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uncertainty interval related to the drag force measurement in all cases at 10 m/s and 15 m/s. Nevertheless, it suggests that the actuation effect did not engender penalty in drag.

C. Near wake modifications
The actuation effects on the flow field were characterized using PIV around the rounded trailing edge of the airfoil in order to observe modification of the near wake features and to highlight the mechanism for lift decrease or increase. Fig. 12 shows the flow around the airfoil trailing edge without actuation at AOA = 4° for a freestream velocity of $U_\infty = 10$ m/s by plotting mean velocity contours, and streamlines. It can be observed that the near wake, characterized by a recirculation zone due to the thick rounded trailing edge, develops on a length of 10% of the chord around. Streamlines enable to highlight the two counter-rotating structures that can be observed similar to the ones that can be observed at the base of bluff bodies.

In order to observe the slight deflection of the wake towards the pressure side or the suction side depending on the wall jet direction, derived from the mean velocity field obtained by PIV, Fig. 13 zooms in on velocity profiles in the near wake at the streamwise location $x/c = 1.06$ in the recirculation area for upward and downward actuation modes, respectively.

It can be observed a change of the recirculation area due to the actuation, more particularly, the maximum streamwise velocity deficit slightly moves downward or upward with the downward actuation and upward actuation respectively, establishing the wake deflection due to the plasma actuation. This leads to flow circulation modification around the airfoil.

V. CONCLUSION
In order to improve aerodynamic load alleviation on wind turbine blades, a strategy of active circulation control allowing lift increase or decrease keeping constant the angle of attack was investigated by using an elongated-DBD flush mounted around the rounded trailing edge of an airfoil, inducing a wall jet directed to the lower or the upper surface of the airfoil.

In quiescent air conditions, the flow jet induced by the elongated-DBD mounted on a curved surface in comparison to the actuation, more particularly, the maximum streamwise velocity deficit slightly moves downward or upward with the actuation, establishing the wake deflection due to the plasma actuation. This leads to flow circulation modification around the airfoil.
with a similar actuator on a plane surface appears to be widened because of the curvature. Results of the preliminary testing of circulation control show ±8% of variation in lift obtained with the elongated-DBD actuator configuration implemented on an airfoil with a chord of 300 mm at a freestream velocity of 10 m/s. It is expected that wind turbine airfoils under real operating conditions may encounter wind direction variations of ±5° around in AOA inducing load variations to mitigate. From the results presented above, it can be deduced that the effects of both actuation modes result in an absolute variation of 0.1 in lift coefficient. It corresponds to a variation of ±1° around in AOA.

The flow interaction mechanism is likely due to a modification of the boundary layer separation in the vicinity of the rounded trailing edge, and then, the wake just at the base of the rounded trailing edge. Consequently, the overall circulation around the airfoil is altered.

Future works will focus on finding an optimum solution for a given angle of attack in more details to be able to take into account both the location of the boundary layer separation point and the modification of the recirculation area in view of increasing the effects of the actuation. Moreover the thickness of the boundary layer developing along the pressure (lower) side is thinner close to the trailing edge than the one developing along the suction (upper) side. The wall jet induced by the same actuator could interact differently with both boundary layers. Finally, as the absolute increase in lift coefficient obtained was still low, it will be also necessary to investigate the upscaling of the actuator carefully.

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