Effects of a surface plasma actuation on leading edge flow separation occurring on an aerodynamic airfoil involving a laminar separation bubble


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Abstract: The present study is focused on the enhancement of a NACA0012 aerodynamic airfoil performance by using a thin plasma actuator to suppress flow separation occurring around the leading-edge. The actuator consisted of two copper electrodes flush mounted with an asymmetric disposition on both sides of a dielectric sheet constituted by four layers of Kapton®. It is operated to obtain a discharge following the airfoil leading edge curvature and acting over 90% of the span. The surface dielectric barrier discharge is used to modify velocity close to the leading edge by adding momentum to the boundary layer tangentially to the wall. The goal of the actuation is to control the separation location, by suppressing the laminar separation bubble (LSB) in order to reattach a naturally completely detached airflow at Reynolds numbers within the range of 200,000 – 800,000. Aerodynamic forces measurements, skin friction line visualizations and PIV measurements have been performed to characterize the benefits of the control.

Keywords: plasma actuators, ionic wind, flow separation control

1. Introduction

Active flow control by plasma actuators is currently studied in order to control external flows on aerodynamic geometries. References [1-3] give an overview of various configurations based on the surface Dielectric Barrier Discharge (DBD) and highlight the ability of this type of actuators to manipulate flows. To generate such a discharge, a high voltage is applied to two metal electrodes asymmetrically placed on either side of a dielectric material. The high voltage is generally a sine waveform and the non-thermal plasma produced on the surface of the dielectric induces a flow called ionic wind resulting from the momentum transfer between plasma ions and neutral molecules of the surrounding gas. Since the ionic wind is induced close to the wall, the momentum is added directly inside the lower parts of the boundary layer.

The present study is focused on the enhancement of a NACA 0012 airfoil performance by using a surface DBD actuator to delay the stall regime. The discharge is used to modify velocities close to the leading edge by adding momentum to the boundary layer tangentially to the wall. The goal of the actuation is to control flow separation occurring around the leading-edge, in either suppressing the laminar separation bubble (LSB) or reattaching a naturally completely detached airflow. Aerodynamic force measurements, skin friction line visualizations and particle imaging velocimetry measurements have been performed to characterize the benefits of the control. In this paper, results for controlled flow involving a laminar separation bubble are discussed in comparison with the baseline flow.

2. Experimental setup

The measurements have been conducted at the University of Orléans, in the Lucien Malavard wind tunnel with a turbulence level of the airflow below 0.4%. The testing part of the tunnel is 5m long with a cross-section of 2 x 2m². A plexiglas window is mounted on one side for PIV measurements. The airfoil used in this study is a NACA 0012 profile.
with a chord dimension of $C=0.3\text{m}$ and a span wise length of $1.1\text{m}$. The wing is suspended on both tips to a 6 component platform balance used for time-averaged lift and drag measurements. Experiments have been carried out in a velocity range of $10 \leq U_0 \leq 40\text{m/s}$, resulting in a Reynolds numbers based on the airfoil chord length of $2 \times 10^5 \leq Re \leq 8 \times 10^5$.

The actuator consisted of two copper electrodes flush mounted with an asymmetric disposition on both sides of a dielectric sheet constituted by four layers of Kapton®, representing a total thickness of 0.5mm. The active air-exposed electrode of the plasma actuator is placed at the leading edge of the airfoil (figure 1.).

![Figure 1. Description of the DBD actuator](image)

The grounded electrode was encapsulated in order to create discharges only on the upper side of the dielectric sheet which was exposed to the ambient air. The 6mm width and 1m length electrodes were separated by a gap of 3mm and connected to an AC power supply. The electrodes had a large dimension (90% of the span wise length) in order to maximize the plasma actuation on the airfoil and keep a 2D flow configuration. The plasma discharge was obtained with a steady actuation performed by applying a sinusoidal signal to the air-exposed electrode with a high-voltage peak-to-peak amplitude $U_{pp} = 15\text{kV}$ and a frequency $f_{HV} = 1\text{kHz}$. The ionic wind velocity produced by the actuator was approximately of 1.5–3m/s and acts as a thin wall jet, as shown in our previous paper [4]. The active power dissipated was estimated at 15W/m roughly according to the calculation method exposed by Dong and al. in [5].

3. Results

For $2 \times 10^5 \leq Re \leq 4 \times 10^5$, while increasing the incidence up to the stall regime, a laminar separation bubble (LSB) can occur and the boundary layer can be partially or fully separated. Laminar separation bubbles play an important part in determining the behavior of the boundary layer on the surface and consequently, the stall characteristics of airfoils. Due to a positive pressure gradient, a laminar boundary layer separates from the surface and becomes transitional then turbulent, reattaching downstream on the body surface. This fact creates a stagnant fluid zone characterized by a stationary re-circulating vortex, called laminar separation bubble. Such phenomenon occurs close to thin airfoil leading edge and causes the decrease of energy efficiency.

From skin friction line visualizations in Figure 2, we can notice that the 2D flow configuration with a LSB is not disturbed when the actuator is mounted on the leading edge. Nevertheless, with the actuator mounted on the leading edge, the stall incidence is decreased of 0.5 degree, as shown further in Figure 6. It induces a slight disturbance on the natural boundary layer due to its thickness. Skin friction line visualizations also underline that the LSB is suppressed with the actuation.

![Figure 2. Skin friction line visualizations ; Re = 200 000.](image)

Time-averaged PIV measurements were performed around the leading edge to focus on the LSB in order to investigate the effects of the plasma discharge on the LSB and on the fully separated flow. To get the average flow fields, 300 image couples were used per case. The dimensions of captured images were
77 x 77mm² with a resolution of 2048 x 2048 pixels².

In Figure 3, a LSB can be observed close to the leading edge (X=40,Y=32) with a maximum thickness of 2mm. With the plasma actuation, the LSB is totally suppressed as shown in Figure 4.

PIV measurements were also performed around the trailing edge to investigate the effects of the plasma discharge on the separation location in the stall regime. Whereas the natural flow is fully separated at an incidence of 12° for Re=400,000; with the plasma actuation, the reattachment of the airflow takes place and the separation line is shifted to the trailing edge at X≈80mm as shown in Figure 5.

Finally, evolution of lift and drag coefficients (CL and CD) according to the incidence are investigated for different cases: baseline, plasma actuator on the leading edge without actuation, plasma actuator on the leading edge with actuation and turbulator on the leading edge (carborundum, usually used in wind tunnel tests to promote laminar-to-turbulent transition, avoiding here a LSB occurrence and inducing a turbulent boundary layer separation). These aerodynamic coefficients are commonly defined as:

\[
CL = \frac{L}{\frac{1}{2} \rho U_0^2 S} \quad \text{and} \quad CD = \frac{D}{\frac{1}{2} \rho U_0^2 S}
\]

where L and D refer to the lift and drag forces and are determined from time-averaged force measurements; \( \rho \) : air density, \( U_0 \) : free stream velocity; \( S \) : lifting area (chord*span).

As illustrated in Figure 6, for Re=200,000 the baseline lift coefficient increases with the airfoil incidence up to a limit of 11° beyond which an abrupt loss in lift is observed. Close to the leading edge, the laminar boundary layer is unable to reattach downstream inducing the burst of the LSB. A massive flow separation occurs resulting in an increase in the drag coefficient (Figure 7).
4. Conclusion

This experimental study was focused on the enhancement of a NACA 0012 airfoil performance by a surface plasma actuation. For $Re \leq 4 \times 10^5$, experimental results showed that the actuation enabled to avoid the occurrence of a LSB close to the leading edge by promoting the laminar-to-turbulent transition, to increase the lift-to-drag ratio and to delay the stall regime. Although the actuation was performed with a high voltage peak-to-peak amplitude of only 15kV, a naturally detached airflow was reattached. For $Re > 4 \times 10^5$ and up to $8 \times 10^5$, experimental results showed that the lift was slightly enhanced and the drag was reduced, although the stall regime was not delayed. A more efficient mechanism of flow control should be used to add enough momentum to the boundary layer for these higher Reynolds numbers.

Future works will continue to investigate leading edge separation control by operating others DBD plasma actuators and to estimate aerodynamic benefit versus the power consumption which is a fundamental issue considering plasma actuator design for aircraft companies.

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References