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Control of a turbulent flow separated at mid-chord along an airfoil with DBD plasma actuators

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ABSTRACT

The goal of the present experimental study is to investigate the ability of surface DBD plasma actuators to delay flow separation along the suction side of a NACA0015 airfoil. Three single surface DBD actuators that can operate separately are mounted on the suction side of the profile, at 18%, 27% and 37% of the chord length. The boundary layer is transitioned by a tripper to be sure that the flow control is not due to the laminar-to-turbulent transition. The angle of attack is equal to 11.5° and the free-stream velocity to $U_0 = 40$ m/s, resulting in a chord-based Reynolds number of $Re_c = 1.33 \times 10^6$. The flow is studied with a high-resolution PIV system. In such conditions, the baseline flow separation occurs at 50% of chord. Then, the different single DBD have been switched on separately, in order to investigate the actuator location effect. One highlights that the DBD located at $x_c/c = 18\%$ is more effective than the two others ones, with a separation delay up to 64% of chord. When the three DBDs operate simultaneously, the separation point moves progressively toward the trailing edge when the high voltage is increased, up to 76% of chord at 20 kV. Finally, the effect of the actuation frequency on the control authority has been investigated, by varying the value of the operating frequency and by burst-modulation. For frequencies equal to 50 Hz and 500 Hz (reduced frequency $F^+ = 0.31$ and 3.1), the separation has been delayed at 76 and 80% of chord, respectively.

1. Introduction

Surface dielectric barrier discharges (DBD) based on at least two electrodes mounted on both sides of a dielectric have been widely studied for fifteen years for their application in aerodynamic flow control [1–5]. On one hand, surface DBD based on two linear electrodes supplied by an ac sine high voltage (AC-DBD) produces an electrohydrodynamic force that results in an electric wind based-wall jet. Typically, single DBD can produce mean force and electric wind velocity up to 1 mN/W and 7 m/s, respectively [1], depending mainly on the high voltage magnitude, waveform and frequency, but also on the electrode geometry and dielectric thickness [6–18]. By increasing the number of actuators in series and by taking advantage of a cumulative effect of multi-DBD designs, velocity up to 11 m/s has been measured and force up to 350 mN/m [1,7,19]. Moreover, with specific designs, the produced flow can be strongly 3D, in order to induce vorticity for instance [5,17]. On the other hand, if the high voltage has a nanosecond repetitively pulsed waveform (NS-DBD), the sudden gas heating at the dielectric wall results in a pressure wave with pressure gradient up to 10 kPa [20–23]. In this latter case, the ionic wind produced by the discharge can be neglected and the control mechanism relates to local disturbances caused by the local heat deposition [24].

When the plasma actuator is mounted at the wall of an aerodynamic profile, these two mechanical phenomena (EHD force and wall heat deposition) can interact with the boundary layer and modify the near-wall flow, resulting in the control of the whole convective flow.

Many investigations have shown the ability of plasma actuators to control airflows around different kinds of bodies such as flat plates, cylinders or airfoils. Some of these studies are reported in detailed reviews [2–5]. In the case of airfoils, the main objective is to fully reattach the flow or at least to delay the flow separation. This kind of control results usually in an increase of the mean or dynamic lift-to-drag ratio.

The first publication dealing with flow reattachment along an airfoil by plasma actuators is the one of Roth et al. [25] who investigated the effect of a single AC-DBD and an 8-phase travelling electrostatic wave on the separation by flow visualisations at low

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velocity (2.85 m/s, Re $\approx 10^4$). At the beginning of 2000's, the group of Corke at University of Notre-Dame widely investigated the ability of AC-DBD plasma actuators to manipulate airflow that separates at the leading edge of the airfoil for freestream velocities from 10 to 30 m/s (79,000 < Re < 257,000) [26–31]. The main results showed that the actuators lead to reattachment for angles of attack that were 8° past the stall angle. It was accompanied by an increase of 400% in the lift-to-drag ratio. More, the authors demonstrated that the most effective actuator location to reattach the leading-edge flow separation was at the leading edge and that a burst modulation with a small duty cycle was more effective than a steady actuation. In 2004, Sosa et al. [32,33] conducted experiments with a surface corona-based plasma actuator, for a Reynolds number Re = 375,000 and angle of attack of 19.8°. They highlighted that the actuator effect depends dramatically on the discharge frequency and the input electrical power. Finally, more recently, Benard and Moreau highlighted the physical phenomena that result in the flow reattachment, with the help of time-resolved PIV measurements [34,36] and closed-loop control has been achieved in order to optimize the input parameters like for example the minimization of the electrical power consumption while maintaining the flow continuously attached [37,38].

Plasma actuators working on electrohydrodynamic principle are often incriminated to be restricted to low Reynolds number flows. However, in Patel et al. [39], the time-averaged pressure data and resulting lift coefficient of a NACA 0015 are measured as a function of the angles of attack for different flow speeds reaching a maximal Reynolds number of one million (U_0 = 60 m/s). The airfoil was placed in leading edge separation conditions and a mean gain of about 10–15% in the lift coefficient has been observed for Re = 0.75×10^6. A similar gain was reported by Little et al. in 2010 [40] for a simplified high-lift version of the NASA EET airfoil equipped with a AC-DBD on the leading edge. The absolute gain in pressure coefficient measured in the leading edge region (x/c = 0.05) was equal to unity for an unsteady forcing at $F^+ = 1$. The benefit of plasma discharge for flow separation at high-Reynolds number was further investigated in Ref. [39]. The mean pressure recorded at 0.08c from the leading edge was documented for natural and controlled conditions at $F^+ = 1$ and Re equal to one million. The authors observed a pressure change of about 60% caused by the plasma discharge, but the flow field and resulting lift coefficient were not documented in the publication. The control of flow separation over a NASA EET model has recently received more attention with flow control experiments conducted for Reynolds numbers up to 2.6×10^6 [41]. At Re = 1.4×10^6, lift coefficient measurements shown that the optimal forcing frequency was about $F^+ = 1$ while measuring an increase in lift of about 25% at the optimal unsteady forcing. Static pressure and lift measurements at Re = 2.6×10^6 have shown that the plasma discharge promotes an increase in the suction pressure toward the leading edge and a decrease in the suction pressure toward the trailing edge. The mean lift coefficient was increased by 10% with a stall angle delayed by 1°. Another remarkable result at this flow regime was that the actuator operated in steady and unsteady manners produced a comparable maximum lift enhancement.

The present contribution aims at completing the recent literature with the specific case of flow separation at mid-chord of a NACA 0015 model, this for a high Reynolds number of $Re_c = 1.3 \times 10^6$. As opposed to most of the already reported studies, here the boundary layer is transitioned at the leading edge by a tripper. Then one can be sure that the actuator effects are not due to the laminar-to-turbulent transition but only due to momentum addition close to the wall or to unsteady perturbations that interact with the near-wall flow.

The present paper is divided into four main sections. First, the experimental setup is presented. Secondly, the characteristics of the baseline flow are highlighted by particle image velocimetry (P.I.V.) measurements. In a third part, the ability of three AC-DBD actuators to delay the flow separation is studied. These three single actuators operate separately and are located on the suction side of the airfoil at 18%, 27% and 37% of the chord length, respectively. Finally, a multi-DBD composed of three single DBD acting simultaneously is used in steady and unsteady actuation to reattach the flow, and a particular attention is drawn on the effect of the actuation frequency.

2. Experimental setup

The present experiment has been conducted in a subsonic closed wind tunnel. This facility operates at ambient conditions and has a large test section (2.6 m high, 2.4 m in width and 6 m in length). The maximum freestream velocity can reach 50 m/s with a turbulence level of about 0.5%.

A two-dimensional model with a NACA0015 profile is mounted horizontally in the test section between two profiled end-plates that contribute to a thinning of the boundary layer developing on the side walls. These two end-plates are 5 m in length in the free stream direction and they cross the test section from bottom to top, reducing the section width to 1.2 m. The model has then a span wise length of L = 1.2 m and a chord length equal to c = 0.5 m. It includes a 4-mm thick insert in epoxy resin on the suction side, where the plasma actuators will be mounted (Fig. 1a). Transition of boundary layer is forced on both sides of the airfoil with a 205 μm-high zigzag tripper (Fig. 1b).

The insert in epoxy resin is equipped with three single DBD plasma actuators. As illustrated in Fig. 2a, they are mounted at 18%, 27% and 36% (corresponding to the active electrode edges) of the chord length. These three single DBD can operate separately or simultaneously. Each DBD is composed of a 5 mm-wide air-exposed active electrode and a 20 mm-wide encapsulated electrode placed below the dielectric insert. The electrode gap and the dielectric thickness are equal to 5 mm and 4 mm, respectively. The actuation in spanwise is equal to 57 cm, corresponding to about 50% of the airfoil span. The distance between two successive single DBD is 15 mm. A sine high voltage is applied to every single DBD, with voltage amplitude V_{AC} ranging from 12 kV to 20 kV and frequency f_{AC} between 50 Hz and 1 kHz, with the help of a Trek amplifier (30 kV, 40 mA). When the DBD operates separately, meaning that only one DBD is supplied, the high voltage is applied at the air-exposed electrode when the other one is grounded. When the three DBD operate simultaneously, they are energized as illustrated by Fig. 2b. Here, the interaction between successive DBD is cancelled by alternating the high voltage electrode and the grounded one, from one DBD to the successive one, as in Debien et al. [6]. In both cases (only one DBD or three DBD simultaneously), a streamwise body force is produced, resulting in a co-flow electric wind jet oriented toward the trailing edge. The maximum value of the time-averaged velocity of the produced electric wind is usually obtained between 0.5 and 1 mm above the dielectric wall. A temporal analysis of the electric wind velocity highlights that it is not constant. In fact, it fluctuates with a low amplitude at the frequency of the applied high voltage f_{AC} [1]. This actuation mode is called "standard forcing mode". Moreover, the actuation can be burst-modulated at a specific frequency f_{BM} as explained in Ref. [1]. That means that the discharge is switched on and off at a frequency f_{BM} (smaller than f_{AC}) with a duty cycle fixed here at 50%; that is the "burst-modulated mode", resulting in high amplitude oscillations of the electric wind velocity at f_{BM}.

Time-averaged PIV measurements have been undertaken in order to access the whole velocity field on the suction side of the