Contents lists available at ScienceDirect
Aerospace Science and Technology
www.elsevier.com/locate/aescte

Lift improvements using duty-cycled plasma actuation at low Reynolds numbers

Xuanshi Meng [a,*], Haiyang Hu [a], Xu Yan [a], Feng Liu [b], Shijun Luo [b]

[a] Northwestern Polytechnical University, Xi'an 710072, China
[b] University of California, Irvine, CA 92697-3975, USA

ARTICLE INFO

Article history:
Received 13 July 2017
Received in revised form 29 October 2017
Accepted 29 October 2017
Available online xxxx

Keywords:
Flow control
Plasma
Low Reynolds number
Elliptic airfoil

ABSTRACT

An experimental study on active flow control over an elliptic airfoil is performed using an alternating-current dielectric-barrier-discharge (AC-DBD) plasma actuator combined with the duty-cycled technique. This study aims to eliminate or decrease the nonlinearities of the lift curves within a range of small angles of attack at low Reynolds numbers. The results of plasma actuator characterization in the quiescent air show that the duty-cycled plasma actuation can generate periodic sustained vortices with strengthened vorticity and streamwise momentum in comparison of steady-on mode. The wind tunnel test results show that the baseline airfoil exhibits the clearer nonlinear behavior at small AOA for lower Reynolds numbers. With duty-cycled plasma actuation, a rigidly linear proportional control of the lift that varies with the AOA is achieved with the reduced frequency $f^+ = 1$. The surface oil-flow measurement shows the plasma actuator can delay the separation and result in an enhanced lift when the laminar boundary layer separation occurs without reattachment. When the long laminar separation bubble appears in the trailing edge region, the plasma actuator can eliminate the bubble. In this case, the extra lift supplied by the bubble is eliminated, leading to a reduced airfoil lift. The linear proportional control of the lift can be achieved by the appropriate enhanced and reduced lift changes which can be supplied by the duty-cycled plasma actuation.

1. Introduction

In response to a requirement for the Vertical Take-off and Landing (VTOL) Unmanned Aerial Vehicles (UAVs), a concept called Canard-Rotor–Wing (CRW) has been developed [1–3]. The CRW is a stoppable-rotor design which can hover and fly at low-speeds like a conventional helicopter, whereas in its stopped-rotor mode it can fly at high speeds comparable to those of fixed-wing aircraft. Because the CRW's rotor is stopped to allow high-speed forward flight, the rotor's airfoil cross section must be elliptical. This is a compromise between the optimum airfoil shape for conventional rotor flight and that for high-speed stopped-rotor flight [1,4].

The CRW UAVs will experience the low Reynolds numbers (Re) range, especially during the conversion from rotary to fixed-wing flight and vice versa, which tends to make the aircraft unstable and hard to control due to the complex aerodynamics [3]. One important reason is that significant aerodynamic problems, nonlinearities in lift-curve characteristics, occurs of the symmetric airfoil when the chord Re is below 200,000 [5–7]. Moreover, the elliptic airfoil possesses a unique characteristic, in that, the blunt trailing edge causes flow separation and vortex shedding in the flow field aft of the airfoil at low angles of attack (AOA). This characteristic may lead to a more unusual lift curve performance and has received much interest in recent studies [8,9].

Unusual lift characteristics are not desirable. Therefore, the aerodynamic analysis and lift performance improvements of the elliptic airfoil at low Re is a very important point but still lacking in the practical application of CRW UAVs. Many types of research show that such unusual aerodynamic phenomena at low Re have a close relation with the existence of a laminar separation bubble (LSB) [10,5–7]. Additionally, LSBs are characteristically sensitive to small fluctuations in upstream flow characteristics and are consequently prone to instability. Consequently, methods of controlling or eliminating LSBs are a priority of many aerodynamicists [11,8,12–14].

Plasma actuators have received growing research attention for flow control in recent years because of their advantages of non-mechanical parts, zero reaction time, broad frequency bandwidths and relatively low energy consumption. Most importantly, the plasma actuators can be conveniently arranged on the surface of the vehicle parts [15–17]. One such development is the use of

* Corresponding author.
E-mail address: mxsbear@nwpu.edu.cn (X. Meng).

https://doi.org/10.1016/j.ast.2017.10.038
1270-9638/© 2017 Elsevier Masson SAS. All rights reserved.

dielectric barrier discharge (DBD) plasma actuators driven by an alternating current (AC) source. The AC-DBD plasma actuator is composed of two electrodes separated by one dielectric material arranged in an asymmetric fashion. Application of a sufficiently high-voltage AC signal between the electrodes weakly ionizes the air over the dielectric covering the encapsulated electrode. The dielectric barrier allows the generation of a large volume of plasma by preventing the discharge from collapsing into an arc. The induced flow is predominantly directed away from the exposed electrode toward the covered electrode. The AC-DBD actuator imparts momentum to the flow, much like flow suction or blowing but without mass injection and has a clear effect on the boundary layer [18,19].

Experimental and numerical investigations on airfoils at low Re using AC-DBD plasma flow control have been performed [20–24]. Such investigations focused on the studies of lift enhancement [21,20], dynamic stall characteristics [22], and separated flow control at poststall angles [24]. Aholt et al. [23] examined the plausibility of an external body force generated by plasma actuator on an elliptic airfoil with 16% thickness at 10° AOA in CFD way. The effects of altering the strength and location of the actuator on the size and location of the LSB and on the aerodynamic performance of the airfoil were observed. When properly located and with sufficient magnitude, the body force could effectively eliminate the LSB.

Throughout this paper, by affecting the size and location of the LSB using plasma actuation, we attempt to eliminate or decrease the nonlinearities lift-curve characteristics of an elliptic airfoil at small AOA. To the best knowledge of the authors, very little research in the literature can be found to focus on such study. An elliptic airfoil with 16% thickness is selected to test the effect of plasma actuation in this paper. We report wind-tunnel experiments that demonstrate the linearly proportional control of the lift over the elliptic airfoil at small AOA using an AC-DBD plasma actuator near the leading edge combined with the duty-cycled technique. This study proves the feasibility of using low-power plasma actuators to avoid nonlinearity onset and provide the highly needed lift improvements for the elliptic airfoil under small AOA for low Re.

2. Experimental setup

2.1. Wind-tunnel and airfoil model

The tests are conducted in an open-circuit closed-test-section low-speed low-turbulence wind tunnel at Northwestern Polytechnical University, as shown in Fig. 1. The test section for the airfoil has a 0.4×1.0 m cross section and a maximum wind speed of 70 m/s. The turbulence intensity is adjustable in a range of 0.02–0.3% by changing the screen numbers. For the case of empty test section in the streamwise direction with 12 layers of screens and the contraction ratio of 22.6, the turbulence intensity is 0.03%, 0.025% and 0.02% at 12, 15 and 30 m/s free-stream velocities, respectively. In this study, the free-stream velocity is from $U_\infty = 8.5$ to 18 m/s with the Re based on the chord from 1.0 to 2.2×10^5.

The airfoil section shape used in the experiments is a 16% thick elliptic airfoil. The model is designed to be made up of one piece that included the steel structure and pine wood surface painted with white color paint. The chord of the airfoil is 0.2 m and the span is 0.4 m, which is the same as the width of the cross section. The AOA is set at $-2.5° \le \alpha \le 13.5°$.

2.2. AC-DBD plasma actuator

One 0.4 m long strip of DBD plasma actuator is installed on the upper surface of the airfoil, while 0.36 m long actuator is activating when the plasma is on due to the electric wire connection

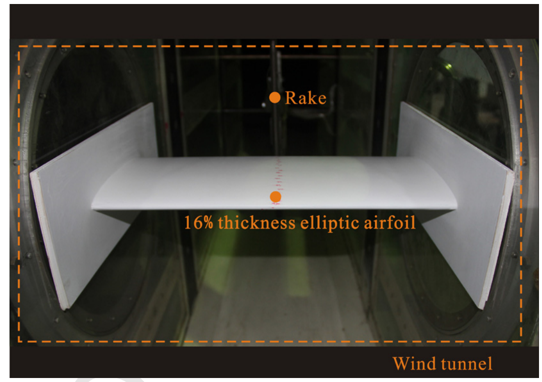

Fig. 1. Photograph of the airfoil model in a low-speed low-turbulence wind-tunnel test section.

(see Figs. 2a and 2b). The actuators are composed of two 0.03-mm-thick copper tape electrodes separated by Kapton tape dielectric arranged in an asymmetric fashion (Fig. 3a). The dielectric barrier is composed of 3 layers of 0.055-mm-thick Kapton tape. The total thickness of the device as a whole, including those of the copper tape, the Kapton film, and the glue, is 0.24 mm. The actuator is hand-made and directly attached to the upper surface of the airfoil with no allowance. This manual actuator will affect the boundary layer like a thin trip [11]. Thus, the contribution to the flow field changes using plasma actuator consists of two effects in comparison with the baseline airfoil: the plasma jet and the geometry of plasma actuator. They will be analyzed and discussed separately later.

There is no gap or overlap between the exposed and covered electrodes to encourage uniform plasma generation. The covered ground electrode is 5 mm wide and the exposed high-voltage electrode is 2 mm wide. The upstream edge of the exposed electrode is covered with 0.18-mm-thick Kapton film, thus, no electromagnetic discharge was observed except the plasma jet over the dielectric layer between the two electrodes.

The experiments for the baseline and plasma control cases are performed in two time periods due to plasma actuator design and wind-tunnel scheduling. In the first period, the location and size of the LSBs are found over the baseline airfoil (the smooth airfoil without actuator). In the second period, the geometry and location of the actuator are designed based on measured location and size of the LSBs in first-period test. The actuator is located at $x = 20$ mm (defined as the junction of the two electrodes), i.e., 10% c from the leading edge of the airfoil, where there locates a short LSB at about 0.03–0.1 c when $\alpha = 7.5°$ for $Re = 1.4 \times 10^5$, which has been founded in the performance study of the baseline airfoil (Fig. 3b). The design intends to affect the reattachment of the leading-edge short LSB through a plasma-induced Coanda effect (Fig. 3c), in the meantime, we hope the induced flow here can also affect the laminar separation or long LSB occurring at the trailing edge of the airfoil.

The actuator is connected to a high-voltage AC source (model CTP-2000K by Nanjing Suman Co.) that can provide a peak-to-peak amplitude varying from 0 to 30 kV and center frequency from 1 to 100 kHz. The voltage applied to the actuator is measured by a Tektronix P6015A high-voltage probe. The current through the actuator is measured by a GMW Associates model PEM CWT3N Rogowski AC current probe. The signals from these devices are processed in real time by a Tektronix DPO3054 oscilloscope. The voltage and frequency sinusoidal excitation to the electrodes in the present study is kept constant at 9 kV and 9 kHz, respectively. Fig. 4a shows the voltage and current traces of time, whereas Fig. 4b shows the DBD electrical instantaneous power consumption and coupled energy waveforms.

Please cite this article in press as: X. Meng et al., Lift improvements using duty-cycled plasma actuation at low Reynolds numbers, Aerosp. Sci. Technol. (2017), https://doi.org/10.1016/j.ast.2017.10.038