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Separation control by a microfabricated SDBD plasma actuator for small engine turbine applications: Influence of the excitation waveform

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ABSTRACT

Small engines will be finding increasing applications in unmanned aerial vehicles (UAVs), drones and helicopters. However, their turbomachines exhibit lower efficiencies than those of large scale engines. In this context, the aerodynamic losses in the low-pressure turbines (LPTs) are largely accountable to flow separation at low Reynolds numbers operation, i.e. in cruise conditions. Active flow control is a promising technology to suppress separation, thus reducing losses, fuel consumption rates and therefore emissions. The present paper is focused on the experimental investigation of the potentialities of a Single Dielectric Barrier Discharge Plasma Actuator (SDBDPA) to reattach the separated flow at a Reynolds number of $2 \cdot 10^4$. The influence of the high voltage (HV) waveform supplying the SDBDPA on both flow separation control and device power dissipation was studied.

The investigated SDBDPA was manufactured by microfabrication techniques. Photolithography ensured thin metal deposition with high manufacturing reliability control. Due to the possible device degradation during operation, emphasis was put in selecting thin film materials that could withstand the plasma environment. Schott alkali-free borosilicate glass substrate was chosen as dielectric, while a multilayer tungsten (W)/titanium nitride (TiN) as electrode material.

The experimental approach comprised the actuator testing over a curved wall plate, designed with a shape to reproduce the suction surface of a LPT and installed in closed loop wind tunnel test section. The SDBDPA was located at the front side of the adverse pressure gradient area, in order to control flow separation.

Different HV excitation waveforms (sinus, triangle and square) and amplitudes were tested and compared, aiming to identify the input signal that gave the best flow control authority and device energy conversion efficiency. The applied voltage and the discharge current were acquired in order to determine the actuator dissipated power. Two-dimensional (2-D) flow velocity measurements were carried out by laser Doppler velocimetry (LDV) and particle image velocimetry (PIV).

Velocity results showed that the extension of the separation area was reduced by actuation. Moreover, when the actuator was on, the boundary layer thickness and the negative velocity magnitude decreased. Their reduction increased with the applied voltage (i.e. higher power dissipations). At comparable peak-to-peak applied voltages, the sinus waveforms slightly outperformed the other waveforms; however, while the sinus and triangle ones had comparable power dissipation, the square wave always dissipated the most.

1. Introduction

Aeronautical LPT blades might be subjugated to low Reynolds number flow effects due to the change in density from high altitude operation. In this circumstance, the Reynolds number can decrease below 25000. Laminar separation may thus develop on the suction surface together with the appearance of secondary flows [1], with a subsequent drop in the engine performance. The low Reynolds condition becomes even a greater issue when dealing with modern high-lift blades [2] and small/medium-sized gas turbines [3–7]. Because of the reduced size, small LPTs, used or planned to be used in small aircrafts, UAVs and drones, exhibit not only low-Reynolds numbers but also low flow rates, low component pressure ratios and high rotational speed, which lead to a further reduction in efficiency in comparison with larger size

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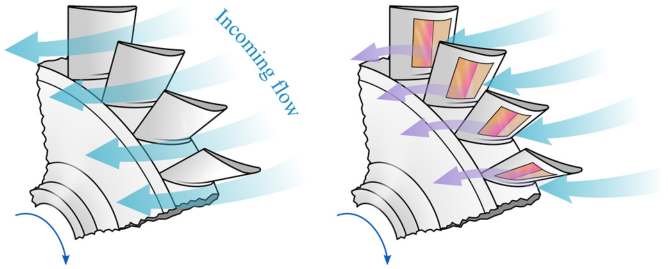

Fig. 1. Conceptual drawing on SDBDPAs applied on the suction surface of LPT rotor blades: absence of control (left); presence of control (right).

machines [5–7]. Counteract flow separation is thus of crucial importance.

Laminar flow separation was experimentally [3] and numerically [8] observed in a single stage axial-flow turbine, operating at a Reynolds number (based on the stator chord length and stator inlet velocity) equal to 20.000 and an inlet turbulence intensity of 0.5%. Moreover, it was also found a strong interaction of the separated flow with the secondary flows. Similar experimental investigations and findings under the same operating conditions are also found in Matsunuma et al. [9]. Secondary flows usually cause almost 30–50% of the overall loss in a blade row with a significant reduction of the LPT efficiency [10]. A nearly 300% increase in the loss coefficient was indicated for an aero-engine LPT at a Reynolds number below $2 \cdot 10^5$, primarily associated with a laminar separation over the trailing half of the blade suction surface [11].

The control of laminar separation bubbles has been subject of many studies in recent years. Several flow control techniques have been investigated with particular interest in active flow control methods [12–16].

Among active flow control devices, an interesting one is the SDBDPA, which is cheap, easy to be implemented on a surface, light in weight and high response frequency. Moreover, it is powered with an electrical input energy that allows easy control and high-bandwidth modulation of the actuation. The SDBDPAs are composed of two metallic electrodes separated by a dielectric layer: one electrode is supplied with a HV waveform and exposed to the surrounding flow; the other one is grounded and covered by insulating material. The application a voltage waveform in the kV and kHz ranges (with or without modulation or pulsing) causes the air near the plasma actuator to weakly ionize. The electric field interaction with the charged particles results in a net body force that acts on the neutrally charged air. When operating in a separated flow, the body force effect leads to the energization of the boundary layer, which can result in its reattachment.

Plasma actuators have been already investigated as an effective active control strategy in eliminating the LPT separation at low Reynolds numbers [1], [11], [15–19]. Fig. 1 shows a conceptual drawing on SDBDPAs applied on the suction surface of LPT rotor blades. The actuators, placed approximately at the separation location, bring to flow reattachment. However, it is important to mention that these devices possess low electrical-to-fluidic energy conversion efficiency and the effect that the external flow has on the performance of the actuator itself must also be considered [15], [20–22]. For this reason, they have primarily been limited to relatively low speed (freestream velocities lower than 30 m/s) and low Reynolds number (of maximum a few 10^5) [23], [24]. Nevertheless, claims of control authority for freestream velocities as high as 60 m/s with Reynolds number of 10^6 have been presented in the literature [25], [26]. Among the parameters improving the effectiveness of the SDBDPAs, it is established that changes in the geometry of the actuator (dielectric layer material [27], [28], thickness of the both the dielectric layer [27], [28] and exposed electrode [29], electrode gap [28], grounded electrode width and number [30], [31]), in the dielectric layer surface temperature [32] and in the electrical settings [26–28], [33–41] can be effective to significantly enhance electric wind velocity and, consequently, the resulting force production. Moreover, multiple actuator arrays could be adopted [27], [28]. However, the cost implications in terms of dissipated power should be always evaluated.

In Bernard and Moreau [37], the influence of the HV waveform was experimentally investigated for four different signals (sine, square, positive and negative ramps) supplying a SDBDPA placed in initially quiescent flow conditions. Results showed that, if one wants to optimally use the SDBDPAs in terms of mean force by electrical power consumption, the sine waveform is recommended as input voltage. Indeed, at a constant consumed electrical power, a sine waveform gave the best performance. Nevertheless, at constant applied voltage or frequency, the square signal caused higher thrust, but at a price of a large consumed power. A second metric that determines the effectiveness of such actuator for control is the mean velocity of the electric wind produced by the plasma, as well as the amplitude of the velocity fluctuations that can be achieved. Always in Bernard and Moreau [37], the largest mean flow velocity, at constant applied voltage and frequency, was observed for a square input waveform; this agrees with the force measurements. The sine waveform led to a slightly smaller mean flow velocity when performances were further degraded by using the ramp shapes (especially the positive one). However, the largest fluctuations in the velocity component in the horizontal direction (i.e., direction of the plasma layer) are observed for a sine waveform when they are minimized by using a positive ramp. This suggested that sine waveform could be probably more effective in flow separation control. Again, the amplitude of vertical velocity fluctuations was increased by using a sine waveform.

In Jolibois and Moreau [38], the waveform of the applied voltage (sine, triangle, square, trapezium, positive and negative ramps) has also been investigated experimentally as input parameter able to influence the actuator electromechanical performance. Experimental tests were always performed in absence of external airflow. Results showed that at same electrical power consumption, the discharge induced the same maximum velocity whatever the waveform, excepted with the square and the positive ramp ones that resulted in a smaller electric wind velocity. Comparing the sinus and square waveforms, it was found that, at similar power consumption, the sine voltage induced a faster electric wind with a discharge closer to the wall than the square waveform. This might be explained by the fact that, for example, a voltage of 18 kV was needed to consume 0.75 W/cm with the sine HV whereas only 16 kV were necessary in the case of the square high voltage.

The aim of this paper was to investigate the influence of the HV waveform supplying a SDBDPA on flow separation control in a LPT at low Reynolds number. Therefore, differently from the available literature studying the role of the electric waveform (where the actuator was always placed in a quiescent flow [27], [37–39]), in the present work experiments were conducted in presence of external flow. Three different excitation signals (sine, square and triangle) were experimentally tested at fixed frequency and different amplitudes. The LPT rotor blade investigated in the works of Matsunuma et al. [1], [9], [42], [43] was considered. 2-D flow velocity measurements in presence of actuation were carried out by PIV. Simultaneously, the SDBDPA applied voltage and the discharge current flowing in the circuit were acquired in order to determine the device dissipated power. Velocity measurements in absence of actuation were also performed by PIV and LDV.

The SDBDPA materials and manufacturing procedure were carefully chosen, both influencing the actuator durability [44], [45].

Dielectric materials to be used in SDBD plasma actuator applications must possess a high dielectric strength and must not chemically degrade in the presence of the plasma [27]. In many

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