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INVESTIGATION OF FLOW SEPARATION CONTROL BY NANOSECOND PULSED DIELECTRIC BARRIER DISCHARGE ACTUATORS

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1. INTRODUCTION

The ability to manipulate a flow field to improve efficiency or performance of airfoils is of immense technological importance. Efficient flow control devices can be used to modify the laminar to turbulent transition inside the boundary layer, to prevent separation, to reduce drag and enhance airfoil lift. They may also be used to stabilise and mix airflow in order to reduce unsteadiness which generates unwanted vibrations, noise and energy losses [1] [2] [3].

Both active and passive flow control devices can be used to control the flow over an airfoil. In the course of the past decade, the use of plasma actuators as a means of active flow control has been implemented by many researchers and has become one of the most booming realms of aerodynamics [4] [5]. Dielectric barrier discharge (DBD) plasma actuators are composed of at least two electrodes separated by a dielectric material between which a high voltage is applied, creating a plasma sheet [1]. Various electrode geometries are possible, and different signals can be used to excite the actuator. Flow control with plasma is appealing as the actuators used are entirely surface mounted, lack any mechanical parts and possess high bandwidth while requiring relatively low power to be actuated [2]. The response time is very short, enabling real-time flow control. The effectiveness of DBD actuators has been proven for velocities up to 60 m/s, with different geometries or actuation signals showing superiority in different flow regimes [5]. In the experiments presented here short high voltage pulses were applied to the electrodes. Since the duration of these pulses is on the order of nanoseconds these devices are referred to as ns-DBD.

2. EXPERIMENT

The experiments were performed in an open loop wind tunnel with a cross section of 45 cm x 30 cm. The maximum flow velocity in the present experiments was 24 m/s with a turbulence level of Tu = 0.3%. The airfoil used is a NACA 0015 profile, with a chord length of 15 cm and a span of 45 cm. A recess at the leading edge allowed for flush actuator integration. In a first test campaign the profile was tested with a smooth airfoil by filling the recess with a plastic sheet. Oil flow visualization was performed on the smooth airfoil using a mix of oil and fluorescent pigments that were illuminated by black-light, with the aim of finding the optimal location for the plasma actuator based on the separation point. In the ensuing ns-DBD actuator experiments the exposed electrode (height 0.1 mm) created a small surface irregularity.

The ns-DBD actuator was constructed of four layers of Kapton tape, each with a thickness of 70 µm (25 µm Kapton, 45 µm adhesive layer), that separated the air exposed and the encapsulated electrode. The former was 4 mm, the latter 12 mm wide. Both electrodes had an overlap of about 1 mm. The discharge area, that is the length in span wise direction in which both electrodes overlap, was 32 cm wide. It was located at x/c=0.03. Figure 1 illustrates the setup of the actuator.

Seventeen pressure taps were drilled at the centerline of the model between 10% and 80% chord length, seven over the pressure side and eight over the suction side of the profile. Unfortunately, no pressure taps could be included closer to the leading edge because of the actuator. The pressure was measured with Scanivalve DSA3217 pressure sensors at a sampling rate of 20 Hz averaging over 100 samples.

The core of the power supply generating the required high voltage pulses is a Behlke HTS 111-06 GSM push-pull switch. It generates voltage pulses up to 10 kV with rise and fall times down to 20 ns, pulse width 200 ns and frequencies up to about f_p = 10 kHz. In addition, bursts of 3 pulses at a delay of 4 µs can be generated. A detailed description of the power supply can be found in [7]. The actuator was operated at two values of voltage, 3 kV and 6 kV. The frequency was varied up to 10 kHz. The reduced frequency [eqn. 1] based on the model chord length was used in the analysis and discussion of the results.

$$F_c^+ = \frac{f_p \cdot c}{u_\infty} \qquad [1]$$

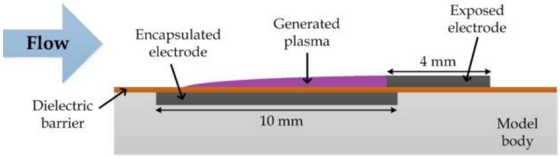

Figure 1: Scheme of the ns-DBD actuator

3. RESULTS AND DISCUSSION

3.1 Flow Visualisation

Images of the oil flow visualisation are shown in Figures 2 and 3. They reveal the formation of a laminar separation bubble at the leading edge that moved upstream with increasing angle of attack to about x/c=0.03 until α = 15° where stall occurred. After the separation bubble reattachment occurs until the flow separates at the trailing edge. The separation point of the latter also moves upstream and is located at about x/c=0.5 at α = 12°. Based on these findings it was decided to install the discharge area of the actuator at x/c=0.03 where laminar separation occurs just before stall.

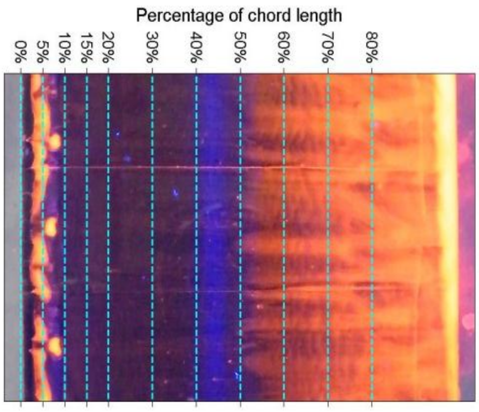

Figure 2: Oil flow visualisation, u = 24 m/s, α = 12°.

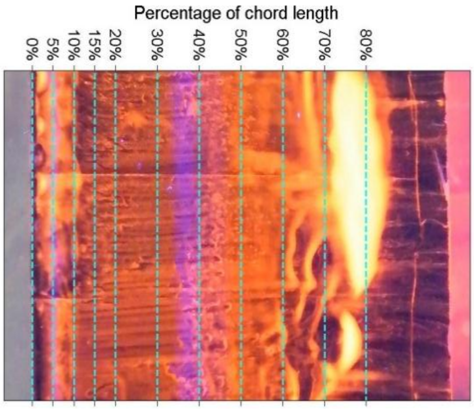

Figure 3: Oil flow visualisation, u = 24 m/s, α = 15°.

3.2 Surface Pressure Distribution

The surface pressure measurements were performed with and without active DBD actuator. Figure 4 shows the result for Re = $2.3 \cdot 10^5$ at α = 18°. The flow without the activated DBD is fully separated on the suction side. If the DBD is operated at f_p = 0.24 kHz, corresponding to a reduced frequency of F_c^+ = 1.5, the flow remains attached until the trailing edge. Both burst and single pulse operation mode yield similar results for these flow conditions, though this is not always the case (discussed in the next section). An increase of frequency, however, decreases the effectiveness. At f_p = 1.76 kHz, corresponding to F_c^+=11, only partial reattachment until x/c = 0.4 can be observed.

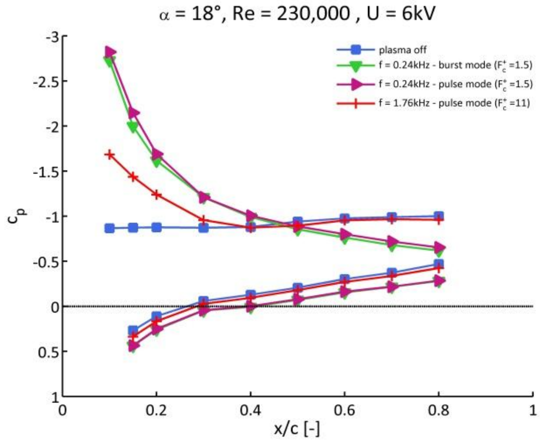

Figure 4: Pressure distribution with and without ns-DBD actuator, u = 24 m/s.

3.2 Airfoil performance enhancement

The increase of lift is approximated by the increase in peak negative suction side pressure at the tap closest to the leading edge (x/c = 0.1) [2]. Figures shows this parameter plotted against the reduced frequency. The dependence of the lift on F_c^+ can be clearly seen; the values of 1-2 being the most effective in reattaching the flow, provided that the energy supplied to the flow is large enough to excite coherent structures over the profile, causing entrainment of the flow which leads to a

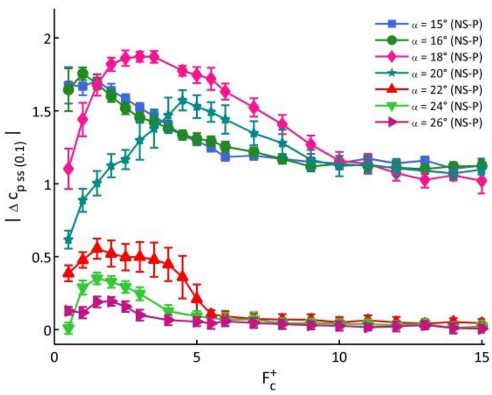

Figure 5: Comparison of increase in lift due to different α at U = 6 kV and Re = 166,000

more effective attachment. Additional discussion of the effect of actuation frequency on the flow attachment will be included in the final paper.

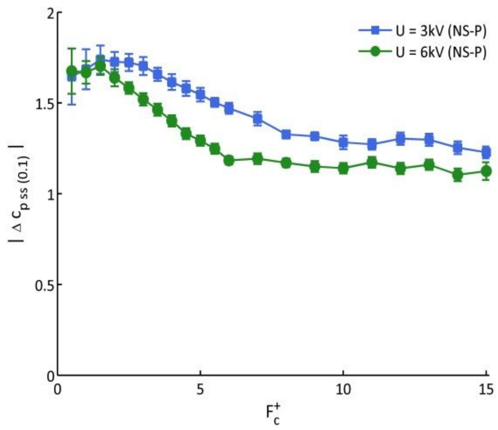

Figure 6: Comparison of increase in lift due to different applied voltages at α = 15° and Re = 166,000.

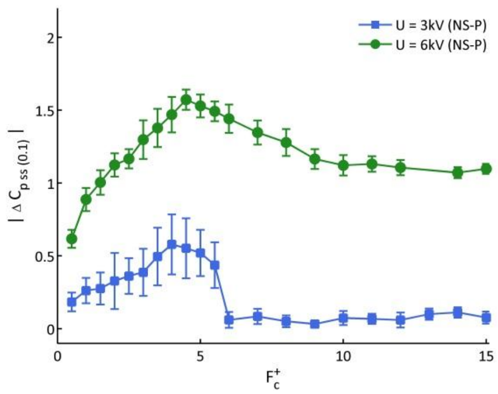

Figure 7: Comparison of increase in lift due to different applied voltages at α = 20° and Re = 166,000.

Figures 6 and 7 show that at some flow conditions (α = 15°), the 3 kV plasma is more effective than the 6 kV, however its effectiveness is reduced as α increases (Figure 7). The results showed that once the minimum plasma energy required for flow attachment was reached, any increase in energy input (whether by increasing the voltage or operating in burst mode) had a detrimental effect on the flow attachment. However, if the minimum energy was not reached (Figure 7), the flow attachment is unsteady (as evidenced by the large error bars showing the standard deviation) and the peak effectiveness shifts towards higher frequency values. This effect was consistent throughout the experimental campaign and will be discussed in further detail in the final paper.

4. CONCLUSIONS

Experiments have been performed with ns-DBD actuators at the leading edge of a NACA 0015 profile up to 24 m/s. The results confirm that stall can be delayed significantly by these actuators. The scope of the present study has been expanded to investigate the importance of different voltage pulse parameters, namely voltage amplitude, actuation frequency and burst operation mode. It has been shown that the frequency plays an important role as lower frequencies have proven more effective than those much above $F_c^+ = 5$, provided the plasma is sufficiently energized. Furthermore, the results suggest that a change of the voltage amplitude can have a significant effect, one that is at times non-intuitive since the results consistently show that at certain flow conditions a weaker plasma can have an improved effect on the flow attachment – provided that a minimum energy threshold is reached. The final paper will include a detailed description of the results in terms of the parameters varied in this study.

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