Active Flow Control by Surface Smooth Plasma Actuators

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Summary

Surface smooth plasma actuators were used to control leading-edge flow separation on the flying wing airfoil Eppler E338 for angles of attack of up to 12° past stall at low Reynolds numbers. The plasma actuators were operated over a range of free-stream speeds from 2.2 to 6.6 m/s giving chord Reynolds numbers from 26K to 79K. The plasma actuators produced a 2-D wall jet in the flow direction along the surface of the airfoil and thus added momentum to the boundary layer. Each actuator consisted of two metal electrodes separated by a dielectric layer which was part of the airfoil surface. At all five free-stream speeds from 2.2 to 6.6 m/s, the maximum lift coefficient could be reached and the stall regime relaxed. The power to achieve this was approximately 17 watts per meter or 8.6 watts per actuator over the span width. It was found that the application of low power plasma actuators could simplify the design of mini and micro air vehicles (MAVs) by calculating with the maximum possible lift coefficients obtained from simplified fluiddynamic equations.

1 Introduction

At low Reynolds numbers (less than 200K) the flow phenomena are more complicated than those at high Reynolds numbers because of some peculiar features, namely:

- appearance of leading edge laminar flow separation
- nonlinear lift/drag characteristics caused by laminar separation bubble
- l.ift/drag hysteresis at static conditions.

In this regard, the design of mini and micro air vehicles (MAVs) flying at low speeds below 25 mph is mainly based on empirical and intuitive work. Computational analysis is difficult because many of the simplifications of the fluid-dynamic equations valid for large Reynolds numbers are not valid for MAV flight regimes [4]. Active flow control can help to overcome the basic design problems of MAVs [2], [3]. Because of the weight and space limitations in small fixed wing construction only unconventional, surface-integrated flow control methods like piezo and plasma actuators are considered [1], [3], [5], [6]. The plasma technique used in these experiments is described in the following.

The plasma actuator consists of two metal electrodes separated by a dielectric layer which is part of the airfoil surface. Sufficiently high voltages (at low radio frequencies in the kHz-range) supplied to the actuator causes the air to weakly ionize at the edges of the upper electrodes. These are regions of high electric field potential. In asymmetric configuration, the plasma is only generated at one edge, Figure 1.

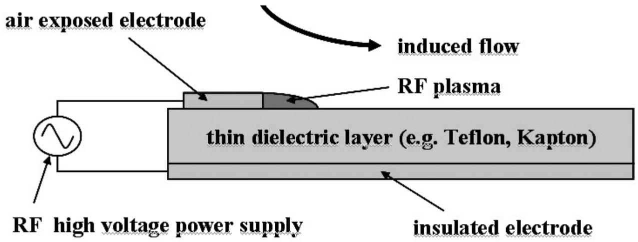

Figure 1 Schematic of asymmetric plasma actuators used in experiments

The plasma moves to regions of increasing electric field gradients and induces a neutral air flow by momentum transfer due to Lorentzian collisions. This causes a plasma induced pressure gradient named "electrostatic body force" by Roth [7] which in one-dimension is formulated as follows:

$$F_E = \frac{d}{dx}\left(\frac{1}{2}\varepsilon_0 E^2\right). \tag{1}$$

In this work, plasma induced downstream orientied wall-jets were used to increase the aerodynamic efficiency of a flying wing airfoil by leading-edge separation control at low Reynolds numbers and large angles of attack.

2 Experimental Setup

The experiments to separation flow control by surface smooth plasma actuators were conducted in the small free-stream wind-tunnel in the Institute of Bionics and Evolutiontechnique at Technical University of Berlin. The tunnel has a free-stream cross-section of 0.60 m diameter and a maximum speed of 7.0 m/s. A sensitive two component balance was used to measure the lift and drag forces at five free-stream speeds of 2.2, 3.3, 4.4, 5.5 and 6.6 m/s.

2.1 Airfoil

The airfoil used in the experiment was an Eppler E338, Figure 2. This airfoil had been previously used in flow control experiments with high voltage (10 – 20 kV) charged corona discharge wires [2], [3] and was originally chosen for a mini flying wing design.

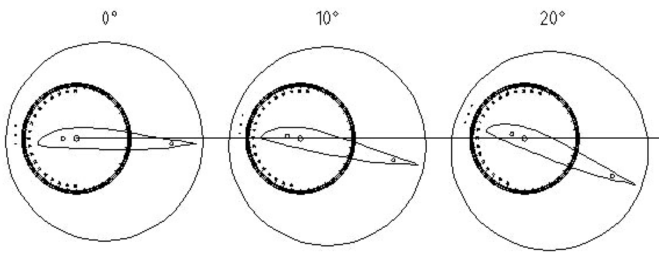

Figure 2 2-D wing with Eppler E338 airfoil and plexiglass end plates

The airfoil has a 17.8 cm chord and a 50.0 cm spanwise length. For the five free-stream speeds this give a range of Reynolds numbers from 26K to 79K. End plates from plexiglass with 22 cm diameter were used to reduce end effects, Figure 3.

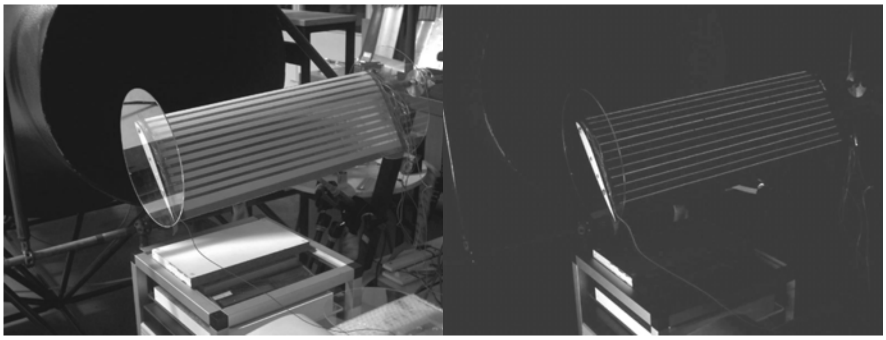

Figure 3 Eppler E338 wing with plasma actuators in the small free-stream wind-tunnel

2.2 Plasma Actuator

The plasma actuator consists of 12 pairs of tinned copper electrodes in asymmetric arrangement separated by a 0.5 mm thick, flexible and self-adhesive Teflon layer which is bonded directly to the surface of the Eppler E338 airfoil and spans its width. The electrodes are made from 0.070 mm thick tinned copper foil tape and have a distance to each other of 9 mm. In these experiments, only two electrodes on the leading edge were supplied with high voltage of 5.8 kV p-p at the operating frequency of 11 kHz, Figure 4. The power consumption was about 17 Watts per meter and one-fourth of the value used in the experiments by Post and Corke with 11 kV p-p [5], [6]. Data acquisition from the polyphase high voltage power supply was done using a self-programmed LabView 8-channel oscilloscope, Figure5.

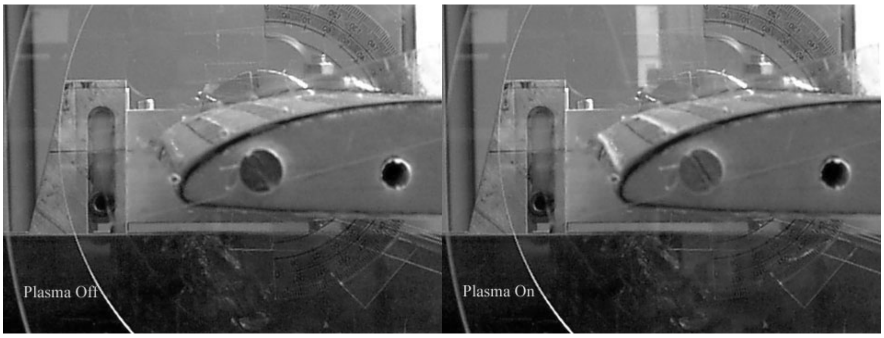

Figure 4 Two activated plasma actuators with 180° phase shift on the leading edge

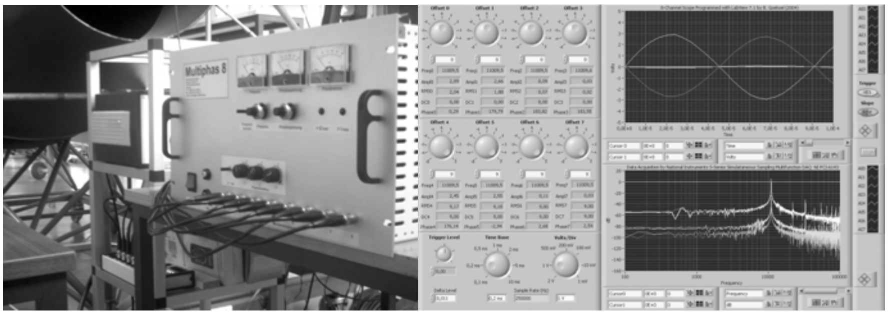

Figure 5 Polyphase high voltage power supply with LabView 8-channel PC oscilloscope

3 Results

The results presented here relate to laminar leading-edge separation flow control experiments at low Reynolds numbers from 26K to 79K and large angles of attack up to 25 degrees using the Eppler E338 flying wing airfoil.

At Reynolds numbers lower than 60K the flow already separates at small angles of attack below 10 degrees. So the maximum lift coefficient is between 0.6 to 0.8. With plasma actuation the flow separation can be delayed to higher angles of attack up to 16 degrees giving maximum lift coefficients between 1.1 and 1.2. Furthermore, the stall regime is more relaxed up to 24 degrees, Figures 6 and 7.

At Reynolds numbers lower than 30K the lift coefficient drops dramatically even at zero angle of attack but can be recovered after activating the plasma actuators. The lift characteristics is more nonlinear, Figures 8 and 9.

At Reynolds numbers higher than 60K the flow separates at an angle of attack of 20 degrees. Plasma actuation gives a more relaxed stall regime, Figures 8 and 9.

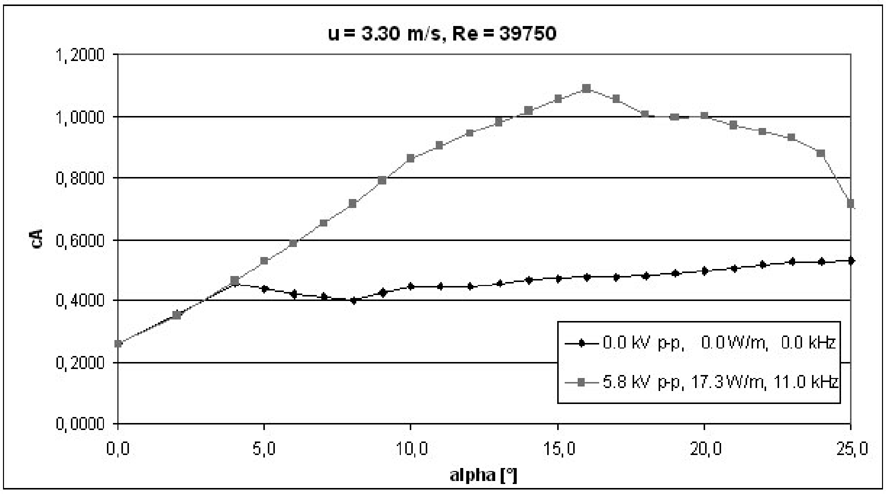

Figure 6 Comparison of lift coefficient versus angle of attack at Re = 39750 without and with RF plasma actuation

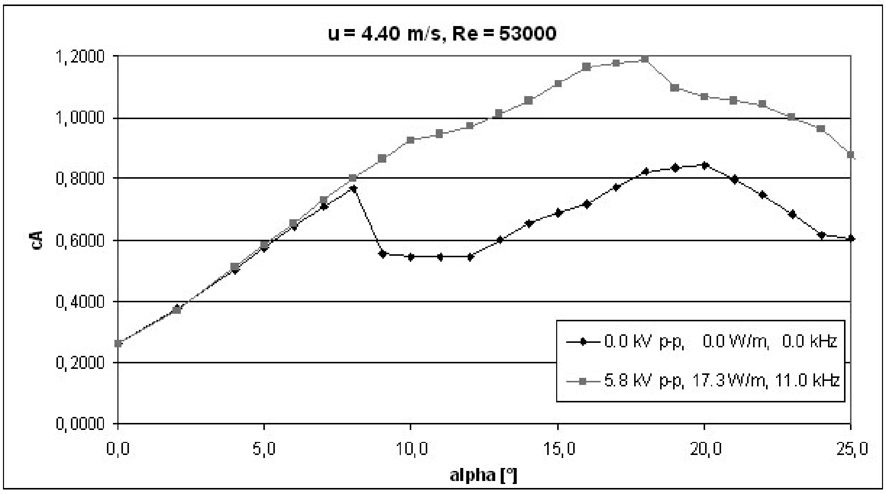

Figure 7 Comparison of lift coefficient versus angle of attack at Re = 53000 without and with RF plasma actuation

At a free-stream speed of 3.3 m/s, giving Re = 39750, the flow reattached produced by the actuator increases lift by up to 129% for $\alpha = 16°$, Figure 6.

At a free-stream speed of 4.4 m/s, giving Re = 53000, the flow reattached produced by the actuator increases lift by up to 78% for $\alpha = 12°$, Figure 7.

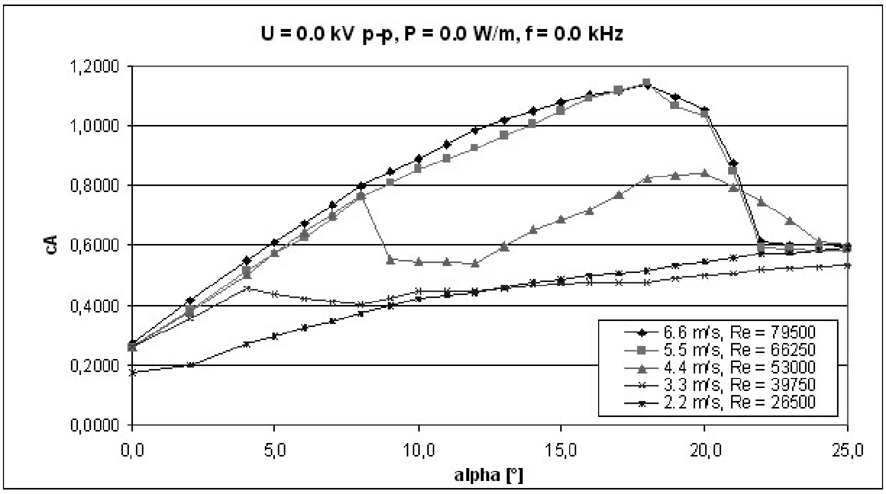

Figure 8 Comparison of lift coefficient versus angle of attack at different Re numbers without RF plasma actuation

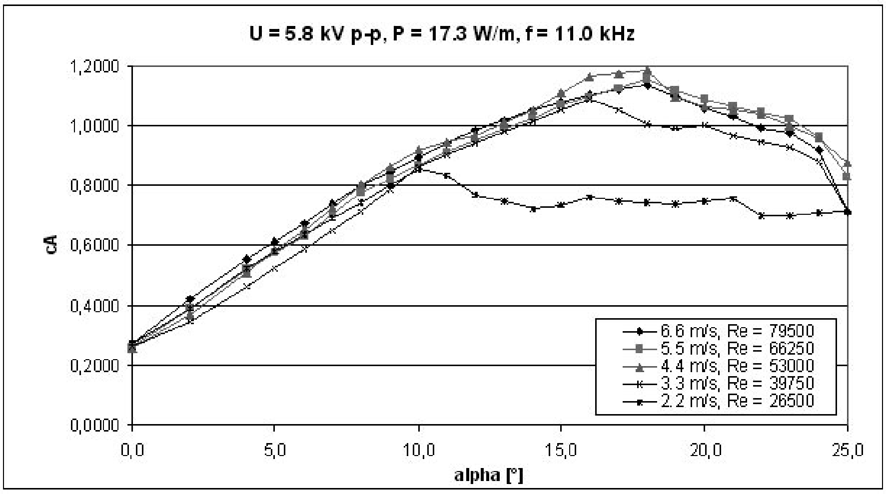

Figure 9 Comparison of lift coefficient versus angle of attack at different Re numbers with RF plasma actuation at the leading edge

At a free-stream speed of 2.2 m/s, giving Re = 26500, plasma actuation increases lift by 57% for $\alpha = 0°$ and at maximum by 103% for $\alpha = 10°$, Figures 8 and 9.

At a free-stream speed of 6.6 m/s, giving Re = 79500, plasma actuation relaxes the stall regime and increases lift by 62% for $\alpha = 23°$, Figures 8 and 9.

4 Conclusion

Weakly ionized plasma actuators were used for leading-edge flow separation over the flying wing airfoil Eppler E338 for angles of attack of up to 12° past stall at low Reynolds numbers. The effectiveness of the plasma actuator was demonstrated for a range of velocities from 2.2 to 6.6 m/s, corresponding with chord Reynolds numbers from 26K to 79K.

The plasma actuator was arranged in an asymmetric configuration to produce a quasi-steady 2-D wall jet in the flow direction and thus add momentum to the boundary layer. Each of the 12 actuators over the chord length consists of two metal electrodes separated by a dielectric layer which is part of the airfoil surface. In the experiments, only two actuators with 180° phase shift were activated at the leading edge.

At all five free-stream speeds from 2.2 to 6.6 m/s, giving a Reynolds number range from 26K to 79K, the maximum lift coefficient could be reached and the stall regime relaxed. The power to achieve this was approximately 17 watts per meter or 8.5 watts per actuator over the span width.

The application of low power plasma actuators can simplify the design of mini and micro air vehicles by calculating with the maximum possible lift coefficients obtained from simplified fluiddynamic equations. This is of specific interest for the design of bionic flying wing models, currently under development at the Institute of Bionics and Evolutiontechnique, Figure 10. The Reynolds numbers in the outer wing are in the range from 26K to 97K at speeds up to 11 m/s (25 mph).

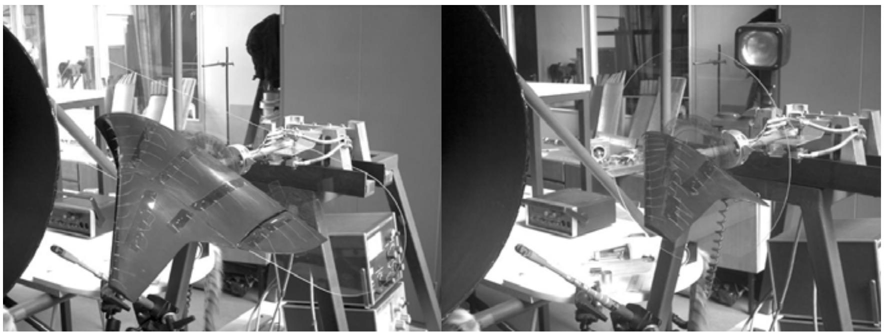

Figure 10 Bionic flying wing model with Eppler E338 airfoil

Acknowledgement

This work was supported by the Bundesministerium für Bildung und Forschung (bmb+f), Germany, under contract No. 0311984.

References

[1] B. Göksel. "Applications of Electric Fields in Aerodynamics". Thesis in Aerospace Engineering, Technical University of Berlin, 1997, p. 120 (in German).

[2] B. Göksel. "Improvement of Aerodynamic Efficiency and Safety of Micro Aerial Vehicles by Separation Flow Control in Weakly Ionized Air". In Proceedings of the German Aeronautics Congress, DGLR-JT2000-203, 2000, pp. 1317-1331 (in German).

[3] B. Göksel, I. Rechenberg. "Wind-Tunnel Experiments to Active Flow Control at Low Re Numbers". In Proceedings of the First European Micro Air Vehicle Conference and Flight Competition, EMAV 2004.

[4] T. J. Mueller (ed.). "Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications". In Progress in Aeronautics and Astronautics, Volume 195, 2001, pp. 115-142.

[5] M. L. Post and T. C. Corke. "Separation Control on High Angle of Attack Airfoil Using Plasma Actuators". AIAA 2003-1024, 2003.

[6] M. L. Post and T. C. Corke. "Separation Control Using Plasma Actuators – Dynamic Stall Control on an Oscillating Airfoil". AIAA 2004-2517, 2004.

[7] J. R. Roth, D. Sherman and S. Wilkinson. "Boundary Layer Flow Control with One Atmosphere Uniform Glow Discharge Surface Plasma". AIAA 1998-0328, 1998.