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UNMANNED FLYING DEMOSTRATOR (UAV) WITH PLASMA ACTUATORS FOR SEPARATION CONTROL

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Abstract

Plasma actuators are well known since many years. A large number of publications show the application of plasma actuators for various flow-control applications. The actuators are applied for the tripping of the laminar-to-turbulent transition of boundary layers, for the active cancellation of Tollmien-Schlichting waves, for the delay of the turbulent-to-laminar transition, for the control of jets and most works concentrate on the separation control of airfoils, wings or turbine blades. All experiments have been performed in wind tunnels and labs, since the high voltage generators usually consist of large and heavy equipment.

In the present work the first unmanned aerial vehicle (UAV) equipped with a high voltage generator and plasma actuators for the control of the flow separation on the wings is presented. The small plane demonstrates the applicability of the plasma-actuator technology for real planes of reduced size and paves the way for full-size flight experiments.

1. INTRODUCTION

Surface dielectric barrier discharge actuators, as used in this work, have been published first by Roth et al. in [1] and in [2]. Since then the number of publications dealing with these so called *plasma actuators* increased steadily. A detailed and complete review of the developments on this topic is given by Moreau in [3]. All published experiments have been performed in wind tunnel experiments. The majority of publications deal with separation control at low Reynolds numbers but the feasibility for real flights at these Reynolds numbers has not been shown. The present study demonstrates an unmanned arial vehicle using plasma actuators for separation control, for the first time. In the present investigation an unmanned arial vehicle is developed that is equipped with a high-voltage generator and plasma actuators on the wings to perform in-flight separation control experiments [4]. First preliminary results of in-flight measurements will be presented.

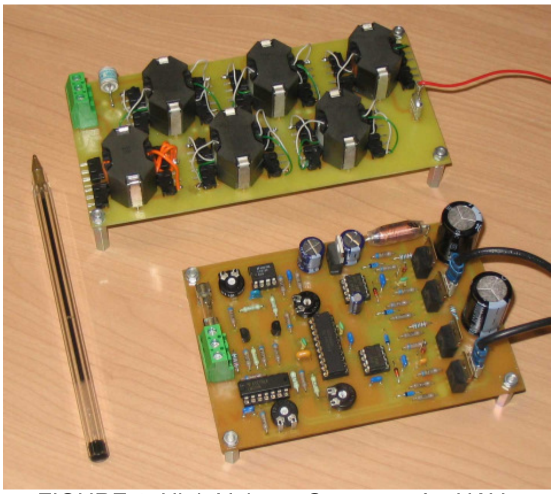

FIGURE 1. High Voltage Generator for UAVs

2. HIGH-VOLTAGE GENERATOR FOR UAVS

The project was made possible by the development of a light and powerful HV-generator. This development was performed by *GBS Elektronik*. The technical specifications of the HV-generator are listed below.

- integrated signal generator
- total weight of 360g
- power supply 15-35 Volt DC
- designed for 900mm maximal actuator length
- configurable for 450mm actuator length
- maximum output voltage 12kV$_{pp}$
- adjustable operating frequency (5 to 20kHz)
- adjustable modulation frequency (50 to 200Hz)
- adjustable duty cycle (0 to 50%)
- remotely switchable
- two printed circuit boards: signal generator and driver (90mm by 120mm) and the transformer cascade (72mm by 153mm)

The generator is highly specialized for the application in UAVs. The low weight could be achieved by a precise tuning of the oscillation circuit to the actuator type and length to minimize the reactive power and by limiting the operation to 50% duty cycle. The HV-generator cannot be operated in continuous mode (100% duty cycle). An image of the generator is shown in Figure 1.

3. AERODYNAMIC DESIGN OF THE UAV

The design of the model plane had to satisfy several contradictory requirements. On the one hand it had to have a very low stall speed since the separation control works best at small Reynolds numbers. On the other hand it had to be designed to carry a payload, such as the HV-generator and its power supply. To achieve a low stall speed it is possible to increase the size of the wing, but a larger chord length increases the Reynolds number and a larger wing span decreases the ratio of the actuator length to the wing span. The aim of the project was to demonstrate an effective separation control. Therefore the design had to be optimized to achieve maximal effects using minimal control. It was decided to realize an almost elliptical planform of the wing, to provide a constant induced angle of attack along the span. Additionally the inner wing is equipped with flaps. The actuators were placed at the outer parts of the wings to provide clean flow conditions for the actuators, away from wing-body interactions. The flaps on the inner part can be inclined upwards to promote stall on the outer wing. This measure shifts the position of the first occurrence of separation to the parts of the wing that are influenced by the actuators.

3.1. The Airfoil

It was chosen to realize an almost elliptical planform of

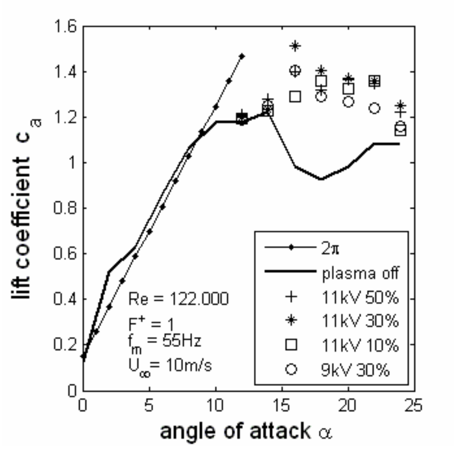

FIGURE 3. Wind tunnel measurements as proof of concept at 10m/s.

the wing, to provide a constant induced angle of attack along the span. Additionally the inner wing is equipped with flaps. The actuators were placed at the outer parts of the wings to provide clean flow conditions for the actuators, away from wing-body interactions. The flaps on the inner part can be inclined upwards to promote stall on the outer wing and therefore achieve more clear results. The airfoil geometry was chosen to be a thick airfoil with a docile stall behavior. The idea is to have a separation propagating forward from the trailing edge and not a sudden leading edge stall. This behavior should allow a circulation control using plasma actuators at cruise conditions far away from the stall speed. A so-called *Clark Y* profile was chosen to satisfy these requirements. The size of the wing was then determined using

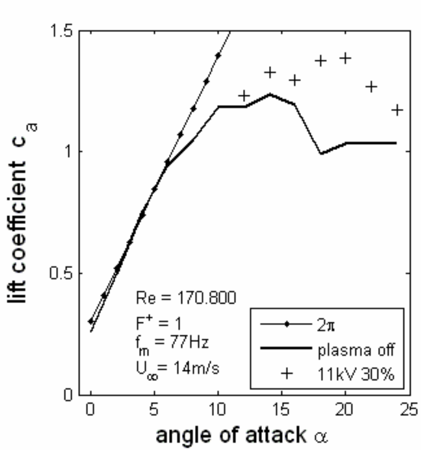

FIGURE 2. Wind tunnel measurements at 14m/s.

estimations for the weight of the components of the plane. With the size of the wing and the chosen profile first wind tunnel experiments could be performed to prove the effectiveness of plasma actuators for separation control on this type of wing. A two-dimensional model with the mean chord length of the part of the wing that will be influenced by the actuator on the plane was built. Different positions of the plasma actuator were tested and finally a position at 3% chord length was found to be effective. Measurements were performed with different operating voltages and different duty cycles at two different air speeds to make sure that a detectable effect would be achieved in the flight experiments. The results are shown in Figures 2 and 3.

3.2. Fuselage Design

The fuselage is another component that had to be

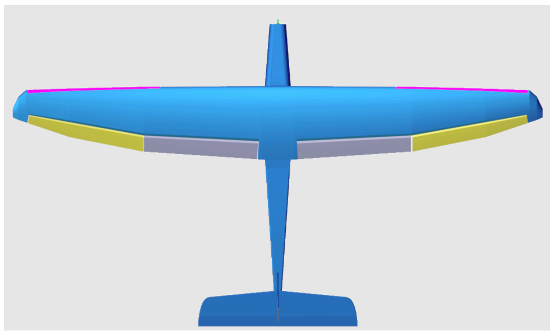

FIGURE 4. Top view of the CAD-model.

designed for the requirements of very low weight and a volume large enough to carry the payload. A specially designed fuselage of an other research UAV was chosen and slight changes were made to adapt it for the designated motor and for the expected high angles of attack during take off and landing. Figure 4 shows a top view of a CAD model of the UAV.

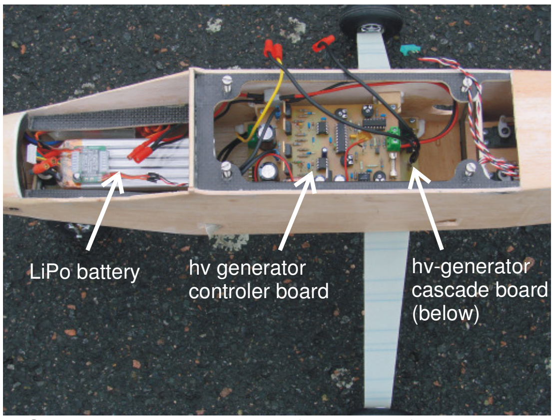

FIGURE 5. View inside the fuselage of the plane

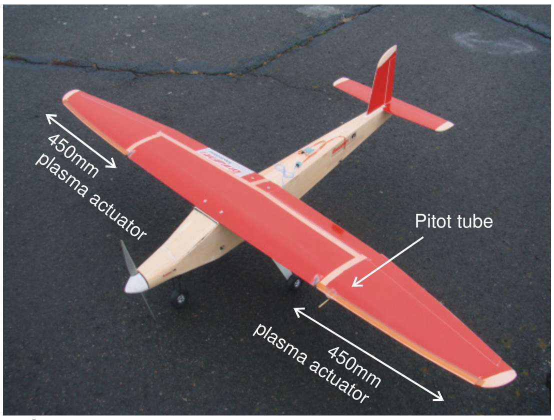

FIGURE 6. The real UAV.

The propulsion system consists of a brushless electro motor with a propeller, a LiPo battery and the necessary controlling devices. The LiPo battery is also used as power supply for the HV-generator. Figure 5 shows a view into the fuselage to illustrate the positioning of the battery and the two circuit boards of the HV-generator. The fuselage is large enough to carry all parts and there is still space left over for more equipment. Nevertheless additional equipment is difficult to store since a displacement of the center of gravity would be occur. The HV-generator is adjusted to produce a rectangularly modulated sine wave of E_{pl}=10.5kV$_{PP}$ with a modulation frequency of f_m=80Hz and a duty cycle of DC=30%.

4. IN-FLIGHT EXPERIMENTS

The HV-generator is adjusted to produce a rectangularly modulated sine wave of E_{pl}=10.5kV$_{PP}$ with a modulation frequency of f_m=80Hz and a duty cycle of DC=30%.

The airspeed is measured with a pitot tube on the left wing (Figure 6) and results are documented using a micro-controller based data-logging system. The test flights were performed at absolutely quiet weather conditions. Always the same flight procedure was conducted for each single measurement. First a horizontal flight was established and the throttle was drawn back to 10% of the maximum power. During the following deceleration due to the lack of thrust the elevator was pulled to maintain a horizontal flight until the stall occurred. The pilot had to ensure that the flight remains horizontal during the whole procedure. The airspeed decreases and will come to a minimum right before a complete flow separation on the wing occurs. A diagram of one of these in-flight measurements is shown in Figure 8. The noise of the raw data is filtered by local averaging. The filtered curve and the original data is plotted. The Pitot tube, used for the measurement of the flight velocity, cannot produce reliable results when the probe is under an angle of attack larger than 10 degrees. After stall

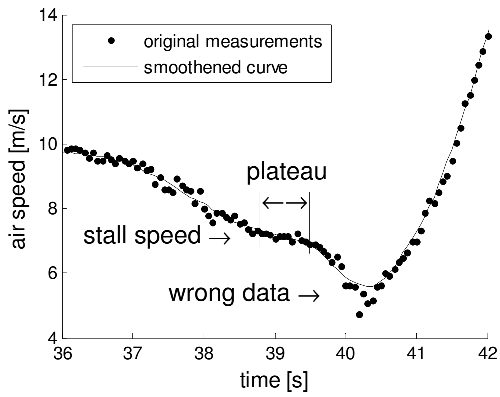

FIGURE 7. Example of a single measurement of the stall speed.

occurred the plane begins to fall and a vertical velocity component is added to the horizontal component. This additional velocity increases the angle of attack of the probe and leads to erroneous measurements. The small velocities that occur during this phase, must not be misinterpreted as stall speeds. In each time trace of the flight velocity during a stall-speed measurement a short plateau occurs right before a minimum stall speed is reached, see Figure 8. The plateau is the moment when the flow separates. After that the plane starts to fall and the pitot tube is under large angles of attack. The velocity increases quickly after the minimum because the the pilot pushes the elevator and the plane looses height. During the post processing of the recorded flight velocities the velocity values of the plateaus before the minima are interpreted as stall speeds.

5. RESULTS

The stall speeds of the case without control and the case with the plasma actuators working were to be determined in the first measurement campaign. To achieve these results a total of 68 flights were performed, 34 flights with control and 34 without. Since the whole procedure has several error sources a statistical analysis hat to be performed to find a reliable result. Figure 9 shows the stall speeds of the 68 single stall speed measurements in two histograms. The lowering of the stall speed by an effective separation control, from $u_{min,off}$=10.2m/s to $u_{min,on}$=6.6m/s is obvious. Even though the separation-control actuators cover only 50% of the wing span, the control is very effective and the project can be evaluated as a full success.

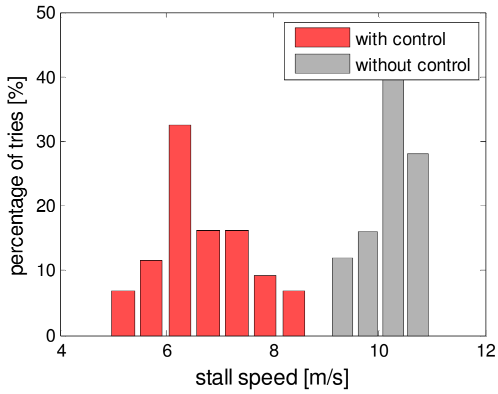

FIGURE 8. Results of 68 in-flight stall-speed measurements.

6. OUTLOOK

Currently the preparations for further in-flight experiments are running. It is planned to gain more flight-data by using a sensor that measures the angle of the plane with respect to the gravity vector in two axes. The aim of the next test flights is to use the plasma actuators as circulation-control devices that can replace the application of ailerons.

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[2] Roth, J., “Electrohydrodynamically induced airflow in a one atmosphere uniform glow discharge surface plasma,” 25th IEEE Int. Conf. Plasma Science (Raleigh, USA), 1998.

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[4] Frey, M., “Auslegung, Konstruktion, Bau und Erprobung eines unbemannten Kleinflugzeuges (MAV) mit Plasma Aktuatoren zur Zirkulationskontrolle am Tragflügel,” Bachelor’s Thesis, Technische Universität Darmstadt, 2008.