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Plasma actuators for active flow control based on a glow discharge

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Abstract. In this work a glow discharge based active flow control for high flow velocities and low Reynolds numbers is presented. Unlike common plasma actuators such as dielectric barrier discharge (DBD) or spark jets, this actuator uses small impulse bits at frequencies. The actuator is optimized for frequencies up to 40 kHz to counter Tollmien Schlichting wave effects and so reduce overall air foil drag. Several measurements to prove the non-eroding effect of the actuator and the electrical properties were performed. It was found that the actuator is capable of operating at high frequencies without measurable erosion.

1. Introduction

Nowadays strict laws against air pollution require more efficient aircrafts in order to fulfill environment protection regulations. This can be achieved by introducing actuators on the wing surface, which are able to decrease the flow induced drag and thereby to lower the overall energy consumption. Various passive and active mechanical systems have been developed for this purpose. For example fluid oscillation actuators are in use for turbine blades for several years and could demonstrate that they can improve the flow characteristic of modern turbines [1].

Besides mechanical actuators electrically driven plasma actuators can also induce flow perturbations. Their main advantage is that the strength and the frequency of perturbation can be electrically controlled, introducing a flexible system, applicable for a whole variety of problems. Actuators either can be used as a tool for investigation turbulent instabilities or as a system which is able to react to a big range of instabilities. In the last decade, different types of plasma actuators for various flow control applications have been developed and investigated [2, 3, 4]. Low Pressure Turbines (LPT) are one of the applications for which flow control can improve the overall performance by influencing the flow induced drag and flow separation. In an LPT the energy loss is induced by Tollmien-Schlichting Waves (TSW). As illustrated in fig. 4(top) TSW break up the laminar flow and create high frequency turbulences at high aerodynamic loads. Active flow actuators in the TSW evolution zone can keep the flow more stable and reduce the drag (fig. 4 bottom).

First studies at the University of the Federal Armed Forces of Germany in Munich with a cathodic arc discharge showed a too high temperature stress, eroding the cathode surface (arc root points), the carrier plate (heat transfer) and creating a passive actuator. Also the power

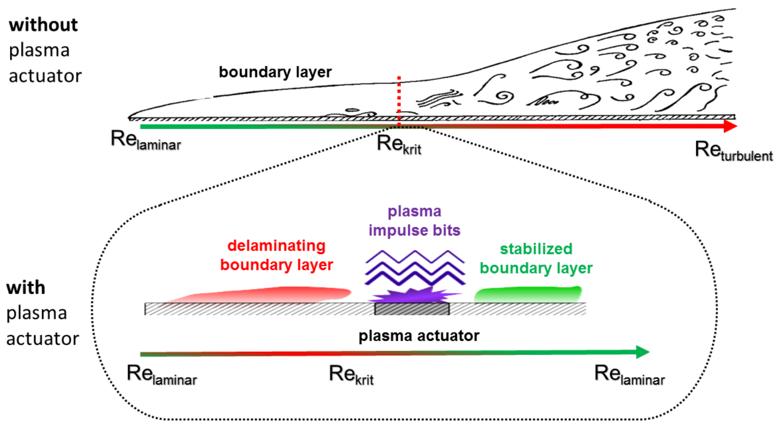


Figure 1: Schematics of the Tollmien Schlichting Wave creation (top) and function principle of plasma actuator for TSW counteraction (bottom).

consumption of this kind of actuator was found to be too high for the desired application. Using higher frequencies than 1 kHz with an inductive energy storage system as a power supply unit lead to a power consumption of more than 100 W per actuator.

Another type of plasma actuators, the so called spark jet-actuators, were also tested for flow control applications. However they are limited in their reachable maximum frequency (up to 5 kHz) and have as well a high power consumption. This frequency limitation results from the recovery times of the actuator after each pulse considering the gas viscosity [3]. The last and maybe best studied plasma actuator is based on a Dielectric Barrier Discharge (DBD). It can reach frequencies in the kHz regime with adjustable power input. However the frequency control and the required high voltages are the main problems for the use of this type of actuator [3].

For the application of plasma actuators for the drag reduction in LTPs several conditions must be fulfilled. They should be able to operate at pressures from 50 mBar to 100 mBar with an ignition voltage less then 1000 V to keep electrical circuit design complexity as low as possible. The actuator design and size should allow the integration into the LPT guiding blades. Moreover the surface of the actuators must not introduce a passive interaction with the flow. This means that the actuator surface needs to remain unchanged (no surface erosion or change due to heat) throughout its operation. The actuators also have to be controlled in frequency and moreover in energy output. For this reason only planar electrodes can achieve a minimum of flow disturbance.

Earlier studies have shown that glow discharges based actuators can influence flow and fulfill the requirements presented earlier [5]. Unlike DBD actuators the electrodes of the glow discharge actuator can be integrated any disturbance of the profile surface. It does not require such high voltages as needed for DBD actuator operation. This makes it easier to integrate into a given flow profile and electrical system.

In this work, a glow discharge plasma actuator is developed and tested for its applicability for TSW extinction in LPTs. The main aim is to create an actuator which is capable to operate at frequencies of up to 40 kHz without introducing significant thermal damage to the LPT surface.

2. Experimental Setup

In the actuator presented in this work the discharge is ignited between two cylindrical aluminum electrodes (⌀ 2 mm) with a center to center gap of 4.4 mm. The electrodes are embedded in a PEEK carrier plate. Additionally both electrodes are heat insulated with a ceramic tube against the carrier plate. Schematic of the experimental setup is shown in fig. 2. A high voltage, high frequency power supply unit which consists of a simplified high voltage fly-back transformer circuit that is used to ignite a glow discharge between the two electrodes. The discharge is initiated by an external pulse generator of which its amplified signal is applied to a high speed switching MOSFET. The MOSFET is driven by a TC1427 optocoupled driver circuit allowing switching frequencies up the 4 MHz. The high voltage transformer can provide discharge voltages up to 40 kV with a free adjustable frequency up to 40 kHz due to power supply limitations. For the experiments frequencies of 1 kHz, 10 kHz and 20 kHz were used. The charging time of the transformer was set between 3.5 us to 5.5 us in order to keep thermal load on the MOSFET as low as possible.

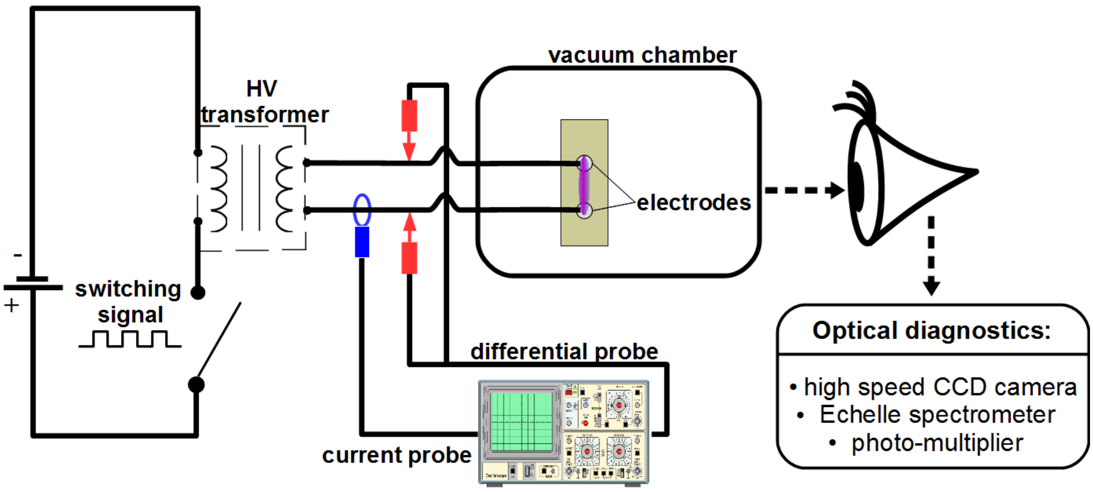


Figure 2: Schematic of the experimental setup.

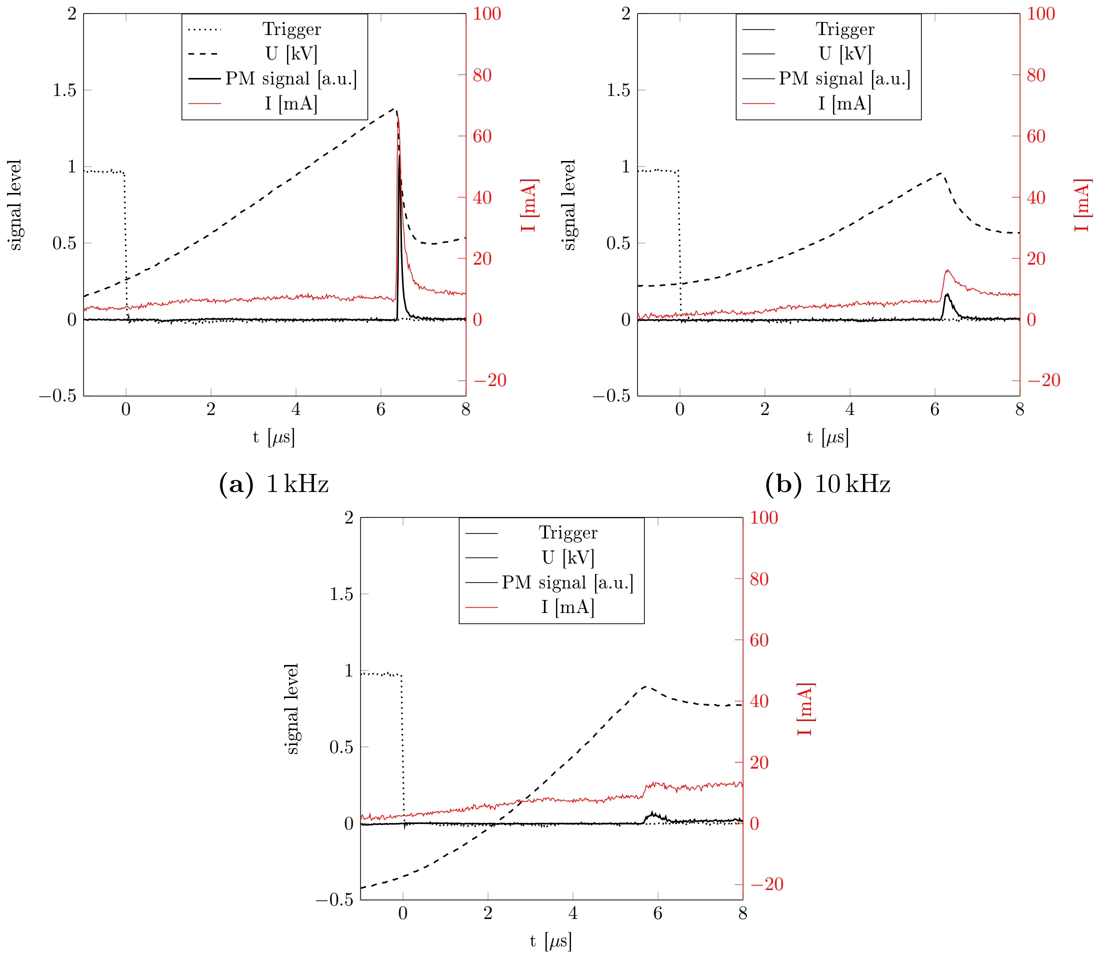
The actuator was operated in a vacuum chamber under pressure values from 50 mbar to 100 mbar, which was previously filled with ambient air, in order to simulate pressure conditions in the LPT. At this pressure the electrodes work around the Paschen minimum for air. Thus, the breakdown voltage is significantly reduced from 3 kV to 350 V in normal air [6] [7].

For characterization of the discharge several diagnostics were used. Discharge voltage and current were monitored using a differential probe (ADP 305, Le Croy, Bandwidth: 20 MHz) and Pearson coil (model 310, 3dB cutoff at 10 MHz). A photo-multiplier (Type: 57X08 PM Section with pre-amplifier operated at 1.2kV) was used to temporally resolve the states of discharge. Furthermore emission plasma spectroscopy was applied to investigate plasma temperature and plasma composition. Here for an Echelle spectrometer (Aryelle 400, LTB Berlin, operation range from 200 nm to 900 nm, exposure time 60 s) with a spectral resolution $\frac{\lambda}{d\lambda} = 150000$ was used. The spatial distribution of the plasma was investigated using a high speed camera (PCO.dimax HD, 1 us exposure time).

3. Results

In fig. 3 current and voltage signals recorded at operation frequencies of 1 kHz, 10 kHz and 20 kHz are presented. The corresponding transformer charging duration was 5.5 µs for 1 kHz and 0.5 µs for 10 kHz and 10 kHz were applied. Furthermore the photo-multiplier signal registering the discharge emission and the discharge trigger signal were recorded.

The photo-multiplier signal confirms that the plasma is ignited for a definite time period. It can be observed that the ignition between both electrodes starts with the highest voltage peak around 6 µs after the MOSFET is switched off. The current through the plasma rises shortly



(a) 1 kHz

(b) 10 kHz

(c) 20 kHz

Figure 3: Electrical and optical characterization of the discharge for different discharge frequencies.

after the maximum voltage peak (ignition point), generating a glow discharge plasma, whose spectral emission is made visible with the photo-multiplier. It can be assumed that the plasma existence directly correlates with the photo-multiplier signal.

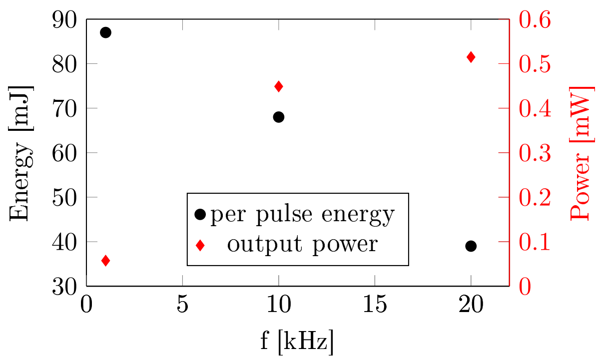
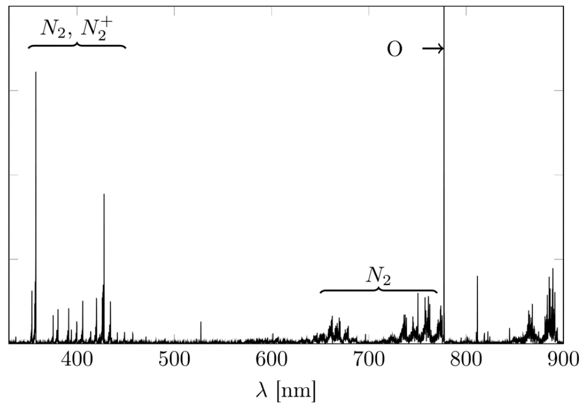
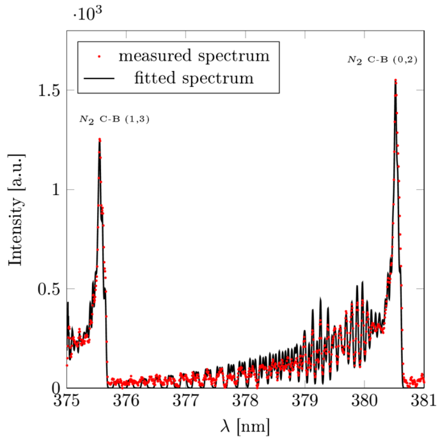


Figure 4: Plasma energy per pulse (black dots) compared to plasma power (red squares).



(a) overview spectrum



(b) second positive N_2 spectrum

Figure 5: Time and space averaged spectra used to obtain the overview of emitting species(a) and vibrational and rotational gas temperature determination using second positive system (b).

In all the measured current signals a nonzero current was observed before the actual plasma ignition point. It is most likely caused by a parasitic capacitance in the secondary transformer circuit. All voltage and current values are typical for a glow discharge. However the discharges vary in their maximum peak currents and voltages depending on the operation frequency. It can be stated, that both ignition voltage and discharge current decrease with increasing frequency. This can be explained by the limited power of the DC power supply used for the charging of the transformer. The overall discharge length of 0.6 µs was determined from the photo-multiplier signal as reference for all operation frequencies.

A plasma energy input calculation for each pulse was performed as shown in fig. 4. It is clearly visible, that an increase of the frequency leads to a decrease in the pulse energy but also to a significant increase of the power consumed by the plasma. This data shows that an optimization of the current actuator design is necessary to reduce the power consumption. This can be achieved by decreasing theinter-electrode distance; therefore lowering the breakdown voltage. Furthermore the actual PSU setup requires optimization. The oscillating effects show the frequency limitation of the actual setup, which are caused by higher losses in the electrical system.

In order to confirm that no metal vapor was present inside the plasma hence no electrode erosion was taking place during the discharge, emission spectroscopy measurements were performed. The resulting spectrum is shown in fig. 5. Only nitrogen and oxygen emission lines could be detected here. This leads to the assumption that the electrodes are not measurably eroded. The spectrum could also be used for the plasma temperature estimation using N_2 emission lines at 375.4 nm and 380.5 nm. Using the model described by Herzberg rotation temperatures 600 K to 700 K and vibration temperatures 1600 K to 5000 K were calculated [8].

The spatial distribution of the discharge were evaluated using high speed images. As shown in fig. 6 the cathode spot is clearly visible as the brightest part of the discharge. The light intensity changes to lower intensities when working at higher frequencies which correlates with the already mentioned less energetic pulses at higher frequencies. The side view clearly visualizes, that the glow discharge forms a bow line between the both electrodes. This shape remains constant with varying frequencies.

After testing the electrode setup for 30 minutes at 10 kHz no visible erosion of the electrodes or the carrier PEEK plate could be observed using a microscope.

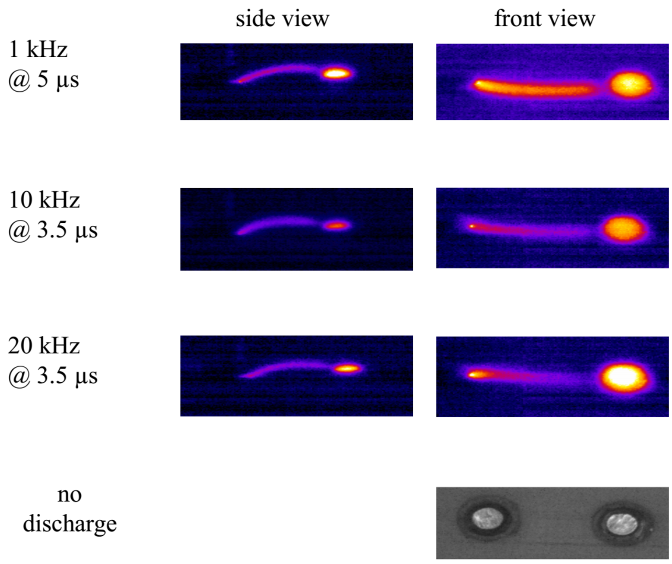


Figure 6: Images of the discharges taken at different discharge frequencies and corresponding charging times of the transformer.

4. Conclusion

In this work a concept for active flow control has been presented. It is based on a glow discharge with a self-made transformer circuit. Under operating conditions which were kept close to application in LPTs (pressure and frequencies) the actuator has shown a reliable and reproducible performance. It confirms, that the actual setup is suitable to be used for further investigations in the wind tunnel.

The next step will be a test with multiple actuators inside a wind tunnel with flow dynamics measurements to see if the actuator is capable of influencing Tollmien Schlichting waves. Furthermore the actuator power supply needs to be optimized for higher frequency range and for multiple actuators operation in order to deliver better power efficiency. For this optimized cooling of the MOSFETs and special designed on-board circuits could improve the switching characteristics. Moreover, an other high voltage transformer could improve the system.

5. Acknowledges

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