Study of Nanosecond Pulsed DBD Actuators in Aerodynamic Flow

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Abstract

The interaction between nanosecond pulsed dielectric barrier discharge (DBD) actuator and air at ambient pressure with and without flow has been investigated numerically (2D) and compared with experimental results. The energy transfer from the plasma into the flow has been simulated by a simplified energy pulse that has been experimentally obtained. Due to the almost instantaneous energy deposition in the discharge region, a weak compression wave is generated. The effects of the pulse repetition rate and of the total amount of deposited energy on the compression wave has been examined for a flat plate DBD actuator. The flow around a typical compressor blade profile with the same type of DBD actuator has been analysed at $Ma = 0,7$ (free stream). This allows comparisons with former experiements using a continuous A/C DBD.

1. Introduction

In aeronautics, plasma actuators, in particular dielectric barrier discharge (DBD) actuators, are on the way to become a new device for active flow control. Up to now there are many open questions regarding the underlying physical principles and parameters that influence the actuator characteristics. Many different actuator configurations have been investigated in the last two decades, differing in electrode geometry, material of the dielectric and power supply. A review of Moreau [1] gives a comprehensive overview about the research conducted in this field. Up to now, most actuators relied on AC voltage, which generates a jet close to the wall. These actuators have proven to be effective at low flow speeds but lack almost any effect in transonic flow [2]. It has been recently reported by the group of Starikovskii et al. [3], that DBD actuators driven by nanosecond lasting high voltage pulses can be used to influence the flow at transonic velocities. The effect is not based on a wall jet, which was reported to be almost negligible, but on the generation of a weak compression wave which emerges from the discharge region into the flow, thus adding momentum to the boundary layer. Unfer and Boeuf [4] numerically investigated the effects of nanosecond pulsed DBD actuators on the flow and confirmed that by the almost instantaneous energy deposition a compression wave is generated. This project aims to investigate numerically the effects of the discharge on air at ambient pressure without flow and at transonic flow speeds ($Ma = 0.7$ free stream). In order to simplify the simulations, the discharge is treated as a pulsed energy source at the wall. First calculations have been conducted for a flat plate geometry with and without flow. Subsequently the flow around a NACA 3506 profile with a surface mounted DBD actuator has been analysed at $Ma = 0.7$ inlet flow speed with local supersonic regions on the profile suction side. The interest in this geometry is the sharp strong shock wave on the leeward side, and the experimental data performed with continuous A/C power supply actuators, [2].

2. Numerical approach

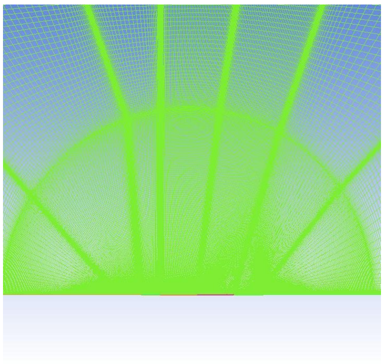
The modelling of plasma and the associated effects is very complex; however, recent results on nano-pulsed plasmas indicate that the main artifact of actuation is due to some form of energy and momentum transfer. The effect of the nanosecond pulsed discharge on the ambient air is hence simulated by an instantaneous energy deposition into a small region at the wall. A commercial CFD solver, CFD++ (version 10.1), which allows for volumetric and geometric source terms, has been used for the simulations.

2.1 Simulation parameters

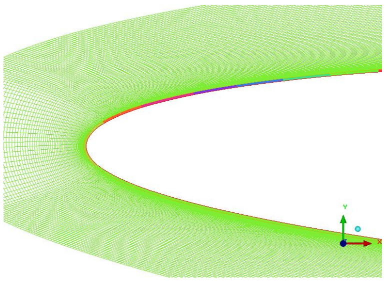
The Navier-Stokes equations are resolved using a Reynolds average model for turbulence effects, (RANS). For the turbulence modelling, the k-ϵ model was selected for the flat plate case, whereas the $k-\omega-SST$ Shear-Stress Transport model has been applied for the profile. A second order spatial discretisation and a centroidal base polynomial type were chosen for the simulations. The equations were solved to the wall and the no slip condition was applied.In order to be able to capture the development of the pressure wave, the Navier-Stokes equations are integrated in time using a time accurate implicit method, and the time step was set to 5 ns. For the simulations, a flow speed of 0.1 m/s was chosen for the flat plate and $Ma = 0.7$ (free stream) for the profile.

2.2 Meshing

Extensive studies were made on grid convergence, due to the extremely small time variables, and the wave propagation phenomena, it is necessary to compare the influence of the grid density on the results. Figures 1 show examples of typical grids that have been selected for the simulations; typical sizes of these 2D grids are 250'000 cells for the Flat Plate, and 1.3 million cells for the airfoil grid.



(a) Zoom of mesh: Flat Plate



(b) Zoom of mesh: NACA

Figure 1: Zoom of the meshes close to the DBD's for the Flat Plate geometry (a) and the NACA3506 (b). The DBD's are indicated by the coloured boundaries.

2.3 Pulses

A simplified model of the experimentally measured input power was used to simulate the discharge. This pulse was modified to investigate the influence on the different parameters; see Figure 2. Typically the input power of the pulses runs from 0 to $60'000$ J/s.

3. Experimental setup

Experiments were conducted with and without flow to investigate the characteristics of the DBD actuators and their influence on the air in the vicinity of the discharge. The output current and voltage of the power supply that provided the nanosecond voltage pulses for the DBD actuators were recorded on a digital LeCroy Waverunner 64XI oscilloscope. Schlieren visualisation was applied to acquire phase averaged images of the interaction between the discharge and the air. In the following, a short description of the power supply system will be given. Afterwards, some details of the DBD actuators and the wind tunnel test facility will be presented.

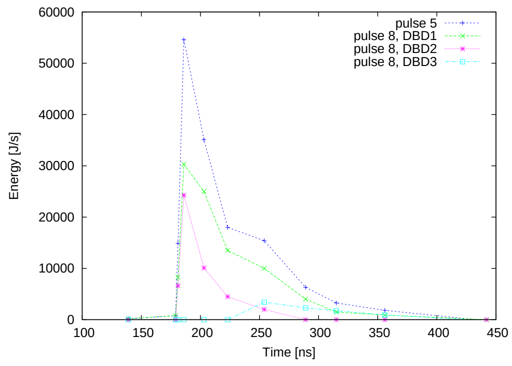
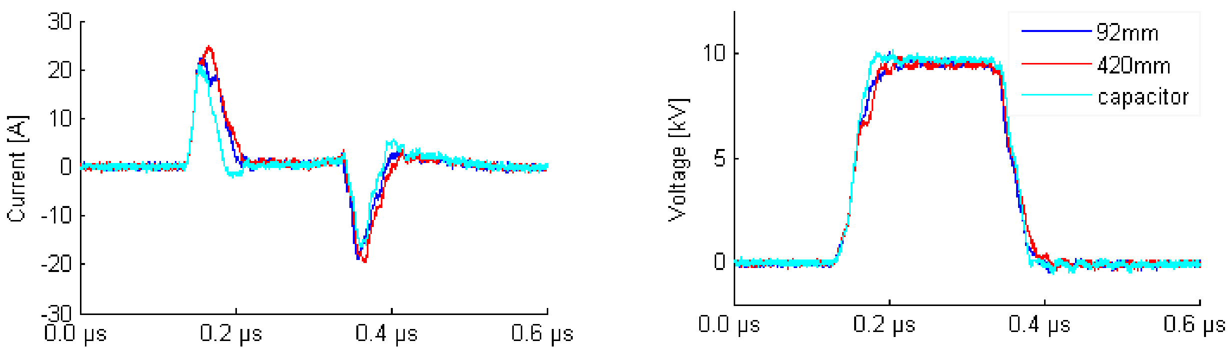


Figure 2: Different forms of input pulses given for the different DBD

3.1 Power supply

The fast rising high voltage pulses were provided by a power supply system which has been developed at EPFL. It can provide pulses with a voltage of up to $U_p = 10\ kV$, with voltage rise and decay times down to $t_r = 20\ ns$ and with a minimum pulse width of $t_w = 200\ ns$. For the experiments presented here, pulse repetition rates between 100 Hz and 1000 Hz were chosen, although higher frequencies can also be generated. The output current and voltage waveforms of a typical pulse are illustrated in figure 3. It compares the waveforms of a 27 pF capacitor with two generic DBD actuators with two electrodes in an asymmetric configuration, one with an electrode length of 92 mm (fig. 4), the other one with 420 mm electrode length. It can be seen that the waveforms are quite similar, which suggests that the capacitance of the actuators and the capacitor are of the same order of magnitude.



(a)

(b)

Figure 3: Comparison of current (a) and voltage (b) waveforms acquired with a 27 pF capacitor and single DBD actuators with 92 mm (actuator 1) and 420 mm (actuator 3) electrode length ($U_p = 10\ kV$).

3.2 DBD actuators

A first set of experiments has been conducted without flow. For these experiments a simple flat plate DBD actuator was manufactured (fig. 4). The electrodes were made from copper tape (0.05 mm thickness) and arranged in a typical asymmetric configuration without a gap between the electrode edges. The electrodes had a length of 92 mm and were separated by a Al_2O_3 dielectric (0.63 mm thickness). In the next step, experiments with DBD actuators will be conducted in the transonic wind tunnel and compared with numerical results.

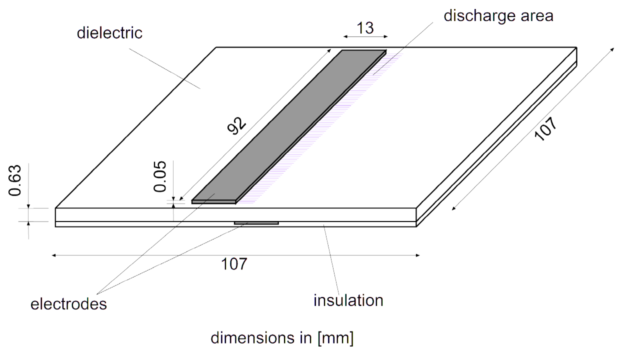


Figure 4: Configuration of the DBD actuator with Al_2O_3 dielectric.

4. Results

4.1 Frequency analysis

Many simulations at different pulse repetition rate from 50 kHz to 1000 kHz have been conducted in order to examine the influence of the pulses per second on the generation of the compression wave. Figure 6(a) illustrates the pressure distribution 710 ns after the fourth pulse while figure 6(b) shows the pressure distribution 850 ns after the second pulse. The values represent the pressure distribution along a line normal to the wall in the center of the discharge area (figure 5) for the different repetition rates. Several observations can be made: in particular, there is no influence of the frequency on the compression wave propagation velocity.

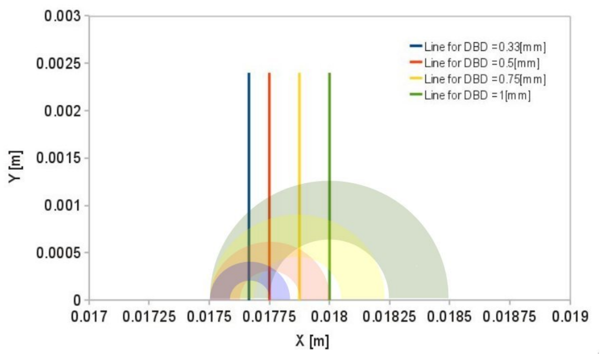
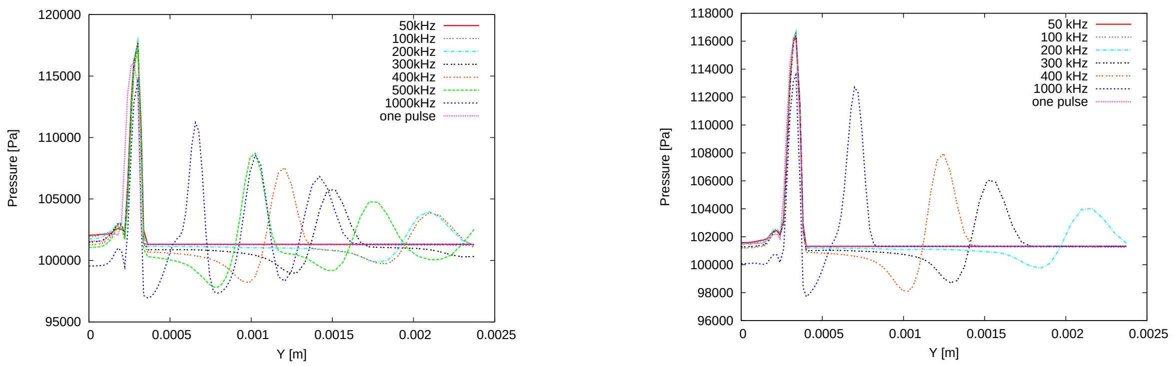


Figure 5: Lines where the pressure values are extracted for each wave.

4.2 Interaction with flow

4.2.1 Flat plate low speed

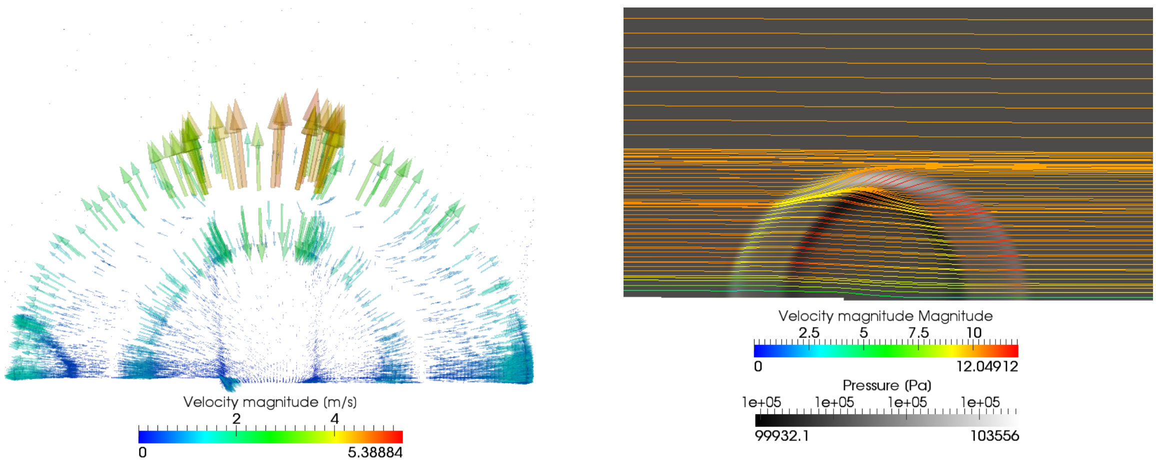
The behavior of the flow in the presence of the compression wave has been analysed at $v = 0.1\ m/s$ and $v = 10\ m/s$. Figure 7 illustrates the field of the velocity vectors inside of the compression wave and the behavior of the streamlines. Evidently, there is an interaction of the incoming streamlines with the expanding compression wave. Especially in the center of the wave, where the pressure gradient is the strongest, the streamlines are significantly deviated. It is important to consider that this is only an instantaneous snap shot, since the shock wave continues to expand. Hence, the spatial location of the disturbance depends on the time and repetition rate of the pulse. In an ideal case, this would enhance the mixing within the boundary layer, thus preventing separation. This issue will be subject of future research and thoroughly presented in the final paper.



(a) Pressure comparison 710 ns after the 4Nd pulse

(b) Pressure comparison 850 ns after the 2Nd pulse

Figure 6: Frequency analysis



(a) vector fields without flow

(b) Streamline and pressure wave for v=10 m/s at 6μs

Figure 7: Behaviour of the compression wave

4.2.2 Profile in transonic flow

To see the influence of a profile mounted DBD, an energy deposition at the location of the profile shock has been implemented. When the DBD is activated, a compression wave that propagates into the shock is observed as shown in figure 8.

4.3 Comparison with experiments

The experimental visualisation gives a wave not circular but slightly different. To obtained the same shape, a different pulse has been tested (pulse 8, fig. 2). Figure 9 shows the result calculated with this pulse and a phase averaged schlieren images obtained in the experiments.

4.4 Interaction with ambient air

In order to verify that the developed DBD actuator yields a compression wave, optical measurements using the schlieren technique were performed. Figure 9(b) shows the phase averaged schlieren image of the compression wave at 35 μs after the onset of the voltage pulse.

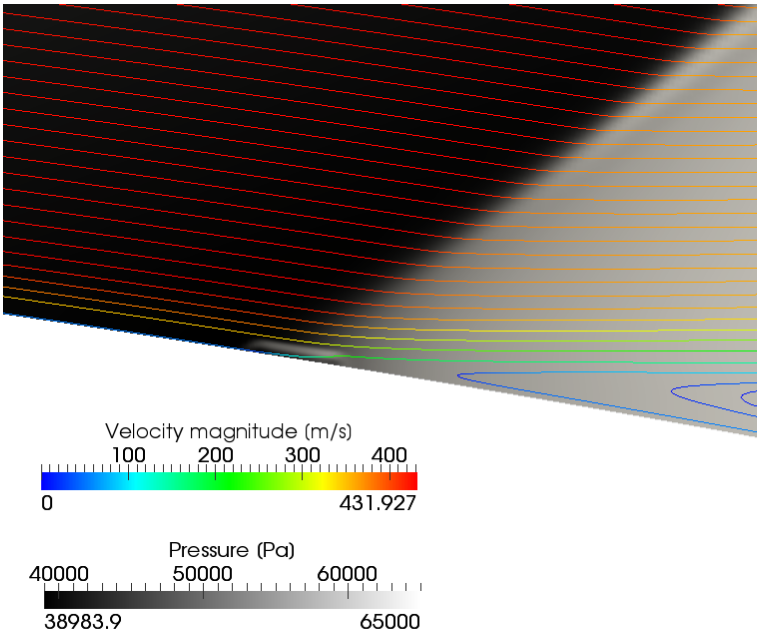
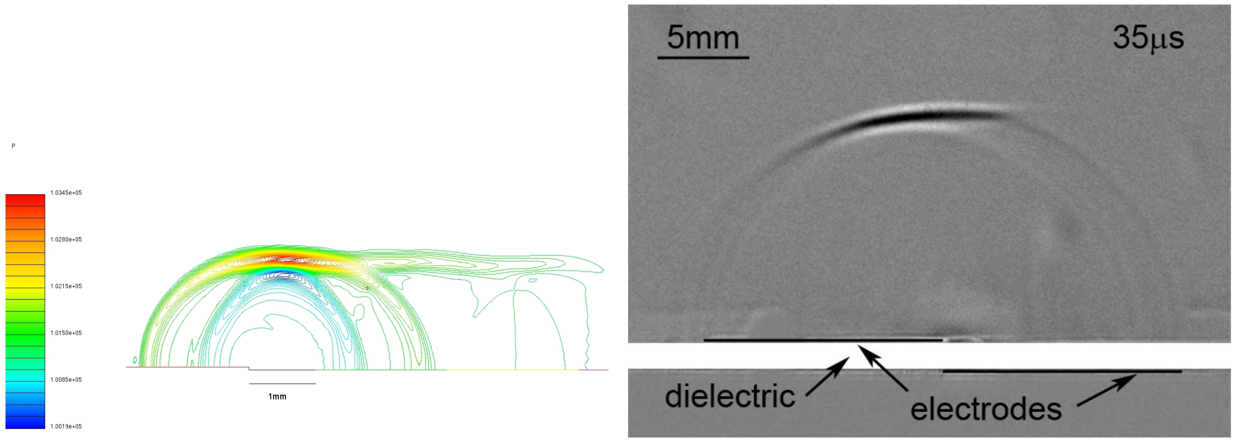


Figure 8: Streamline and pressure fiels for the profile Naca3505 at Mach=0.7 in the shock region



(a) (b)

Figure 9: Simulation at t=5μs (a) and phase averaged schlieren images of the compression wave emerging from the surface of actuator 1 without flow (U = 10 kV, t_w = 200 ns, R_s = 33 Ω)(b).

4.5 Interaction with transonic flow

The experiments in the transonic nozzle are currently conducted. The results will be presented in the final paper.

5. Conclusion

A power supply system to generate fast rising nanosecond pulses has been developed and tested. It relies on a cheap, simple but robust circuit that enables long term operation without requiring significant maintenance. Although the voltage is limited to 10 kV, it has been shown that these systems are powerful enough to generate a compression wave with generic DBD actuators as it was observed in other studies at higher voltages. Whether the effect on the flow is sufficient to beneficially modify the flow structure has to be investigated in the upcoming experiments.

Acknowledgments

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