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Flow Separation Control on Airfoil With Pulsed Nanosecond Discharge Actuator

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An experimental study of flow separation control with a nanosecond pulse plasma actuator was performed in wind-tunnel experiments. The discharge used had a pulse width of 12 ns and rising time of 3 ns with voltage up to 12 kV. Repetition frequency was adjustable up to 10 kHz. The first series of experiments was to measure integral effects of the actuator on lift and drag. Three different airfoil models were used, NACA-0015 with the chord of 20 cm, NLF-MOD22A with the chord of 60 cm and NACA 63-618 with the chord of 20 cm. Different geometries of the actuator were tested at flow speeds up to 80 m/s. In stall conditions the significant lift increase up to 20% accompanied by drag reduction (up to 3 times) was observed. The critical angle of attack shifted up to 5–7 degrees. The relation of the optimal discharge frequency to the chord length and flow velocity was proven. The dependence of the effect on the position of the actuator on the wing was studied, showing that the most effective position of the actuator is on the leading edge in case of leading edge separation. In order to study the mechanism of the nanosecond plasma actuation experiments using schlieren imaging were carried out. It shown the shock wave propagation and formation of large-scale vortex structure in the separation zone, which led to separation elimination. PIV diagnostics technique was used to investigate velocity field and quantitative properties of vortex formation. In flat-plate still air experiments small-scale actuator effects were investigated. Measured speed of flow generated by actuator was found to be of order of 0.1 m/s and a span-wise non-uniformity was observed. The experimental work is supported by numerical simulations of the phenomena. The formation of vortex similar to that observed in experiments was simulated in the case of laminar leading edge separation. Model simulations of free shear layer shown intensification of shear layer instabilities due to shock wave to shear layer interaction.

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I. Introduction

In this work flow separation control on airfoils with the nanosecond plasma discharge is studied. There are two major kinds of discharge which are used for the separation control — AC discharge and nanosecond plasma discharge. The AC discharge is the most well-known one, and its effect is the result of momentum increase due to ionic wind created by the discharge. But this ionic wind is quite slow (velocities up to several meters per second) and thus the range of flow speeds at which this type of actuators is effective is limited. The mechanism of flow control by nanosecond plasma discharge is different. It is supposed that the vorticity is created by the shock wave, which is produced from the layer of the hot gas. This hot gas in generated during the fast thermalisation process, in which up to 60% of the discharge energy is converted to heat in less than 1 μs. The possibility of such fast thermalisation was shown in paper by Roupassov, Nikipelov et al.[1] and further developed by Aleksandrov et al.[2] This phenomenon give an opportunity for nanosecond discharge actuator to be effective at higher velocities than AC actuators. Previous experiments of Starikovskiy's group[1] have shown the effectiveness of this kind of actuator on different airfoils under different conditions, and the possibility of separation control was proven at the velocities up to Mach number 0.75. Also, flow control with nanosecond plasma actuator was studied by Jesse Little et al.[3] The current work continues studying the performance of nanosecond plasma actuator. A series of wind tunnel experiments was carried out with different actuator layouts under different conditions at flow speed up to 40 m/s. Additionally, a numerical model is developed to prove the shock wave mechanism of actuator operation.

II. Experiments

A. Setup

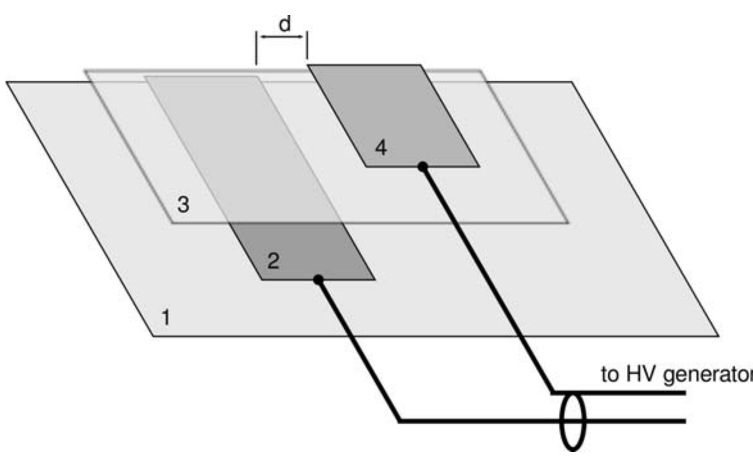

Figure 1. Actuator layout. 1 — base insulation layer, 2 — covered electrode, 3 — inter-electrode insulation layer, 4 — exposed electrode, d — gap width.

In the experiments a linear actuator was used. It was made of layers of kapton and copper foil. Generic actuator layout is presented in figure 1. The actuator consisted of a base layer of insulator (1) attached onto the surface of the airfoil, a covered electrode (2), an inter-electrode layer of insulation (3) and an exposed electrode (4). The thickness of the inter-electrode insulation was about 0.15–0.20 mm. Another adjustable parameter was the inter-electrode gap (d). High voltage electric pulses were fed to the actuator by a coaxial cable. One of the electrodes was connected to the ground, and another was a high-voltage one. In the majority of the cases, exposed electrode was ground, and the high-voltage electrode was covered one.

High voltage nanosecond pulses were provided by a nanosecond pulse solid-state generator, which was capable of producing pulses of up to 12 kV of magnitude with rising time of 3 ns and length of 12 ns at repetition frequencies up to 10 kHz. This pulse generator was controlled by a function generator, and the shape of pulses was observed by an oscilloscope using back current shunt probe.

All the experiments were performed in low speed wind tunnels of Delft University of Technology.

B. Lift and drag measurements

The first series of experiments was carried out in open jet wind tunnel. The model used was the NACA-0015 airfoil with the chord of 20 cm and span about 75 cm. The airfoil was made of metal. The tunnel was equipped with an 1-component balance, which was used to measure the lift force. Tufts attached to the airfoil were used to visualise the separation of the flow. One should note that the tunnel is open-stream, which means that actual angle of attack was not exactly the same as indicated, and should be corrected. The speed range of this tunnel was 0 to 40 m/s.

The length of the actuator was about 65 cm, the voltage used was the maximum available (12 kV) and the pulse frequency was adjustable up to 10 kHz.

Figure 2 shows the dependence of the measured lift coefficient C_L on the angle of attack α with the discharge on and off for one of the actuator geometries at the flow velocity of 30 m/s. It can be seen that with discharge on the critical angle of attack increased by approximately 5 degrees (22 degrees against 17 degrees for discharge off), and at separation angles of attack the lift coefficient increased by up to 20%.

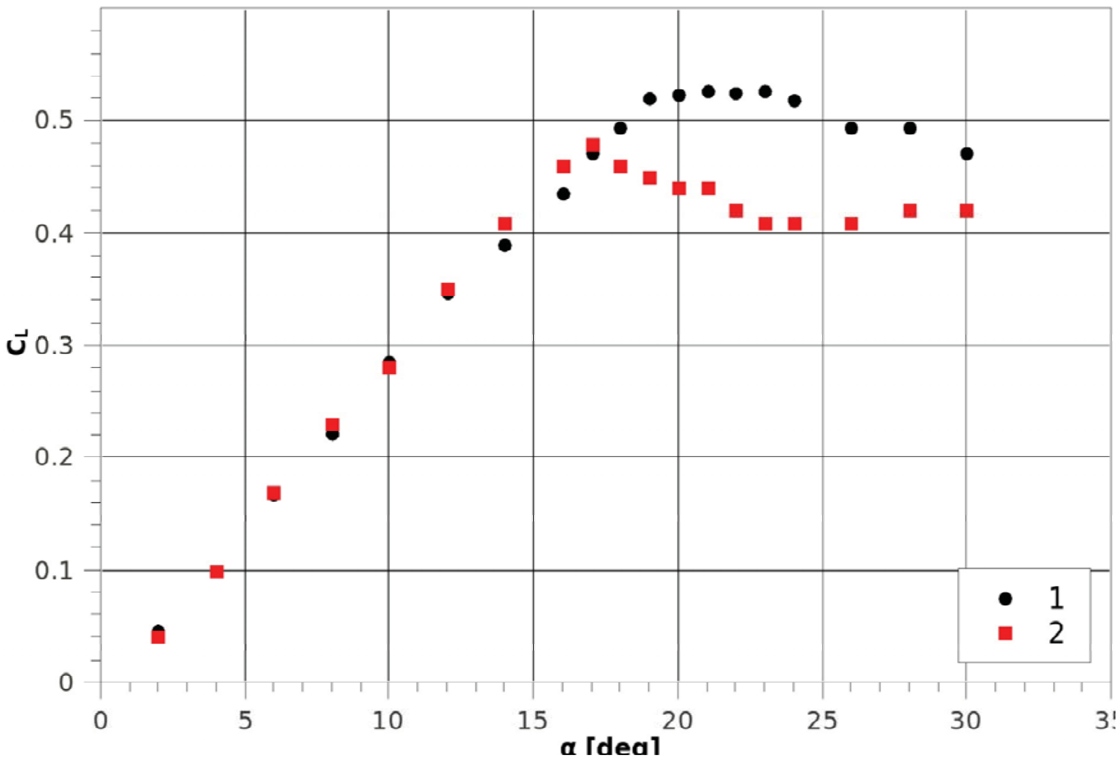

Figure 2. Lift curves of NACA0015 wing at V = 30 m/s. Actuator turned on (1) and off (2). Note that the lift coefficient as well as the angle of attack have not been corrected for open jet wall effects.

Also different geometries of the actuator were tested. The geometries with three or four electrodes were found to perform worse than 2-electrodes geometry, probably because of the lower energy density of the discharge.

The second series of experiments was carried out in the Low Turbulence Tunnel (LTT) which is capable of flow speed up to 120 m/s with low turbulence level. In this case the model was a NLF-MOD22A airfoil made of carbon fiber composite. The chord of the wing was 60 cm, the span was 125 cm. The angle of attack used in these experiments was 15 degrees. The lift and the drag coefficients were measured by surface taps and a wake rake respectively. Additionally tufts attached to the surface of the airfoils were used to visualise the flow. In this case at maximum flow velocity tested of 80 m/s the Reynolds number reached 3×10^6.

With this larger model and the resulting larger Reynolds number it appeared to be more difficult to achieve separation elimination.

At the angle of attack of 15 degrees the increase of lift coefficient of approximately 10% was observed, as indicated in figure 3 on the left.

Additionally the pressure distribution in the wake was measured, which has shown the noticeable shift

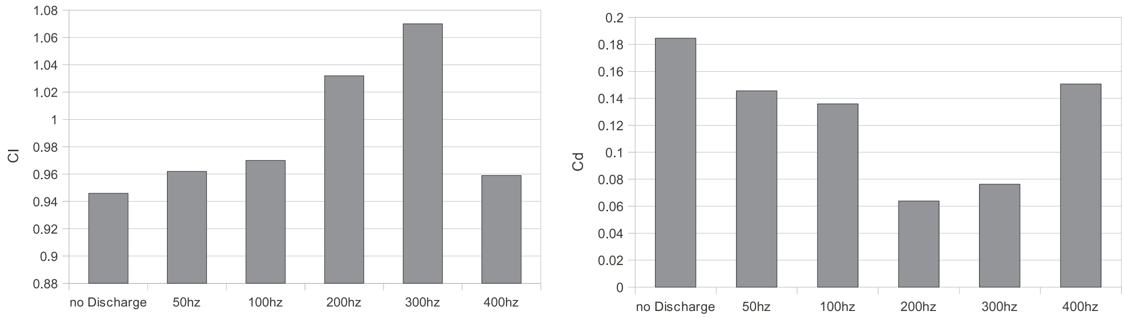

Figure 3. Lift and drag coefficient at different discharge frequencies. $V = 20\,\mathrm{m/s}$, $\alpha = 15°$

of the wake position and decrease in width. The drag coefficient was calculated using wake pressure measurements, and the results are presented in the figure 3 on the right. Unexpectedly, a large decrease of the drag coefficient (to 1/3 of the actuator off value) has been observed.

In either of these figures non-monotonic dependence on the discharge frequency is found, with the largest effect obtained at frequency approximately given by the formula

$$f = \frac{V}{d}$$

where V is the flow velocity and d is the characteristic length, assumed to be equal to the chord of the wing. In other words, optimal reduced frequency was $F^+ \approx 1$.

C. Schlieren imaging

In order to investigate the shock wave interaction with the flow, a series of experiments using Schlieren imaging technique was performed. The experiments were carried out in the W-tunnel of Delft University of Technology. A model of NACA 63-618 airfoil with the chord of 20 cm and span of 40 cm with the actuator applied was used for experiments.

Several different actuators were used, including single, double and triple ones. The flow speed was 30 m/s.

The results are shown in figure 4. The wave created by actuator can be clearly seen, as well as large scale vortex structure as it developed 40μs microseconds after the discharge.

Under some conditions after several discharges the flow pattern changed completely, the with no more separation zone present or separation shifted further downstream. Also it can be seen that subsequent vortices propagate along the airfoil surface rather than along the separation zone as the first ones. In other cases the separation was not eliminated, but shifted downstream. It was found, however, that placing second actuator into the point to where separation was shifted by the first one, shifts the separation even further. In the case E, however, there is a separation still present after the fourth burst. But in this case the achievement of separation elimination is still possible by increasing of number of pulses in burst from 2 to 5, as shown by the case F in the figure. This shows the scaling abilities of the actuation: increase of number of actuators and number of pulses in a burst allows to broaden the range of effectiveness.

As far as Schlieren technique shows the density gradient integrated along the light path (in these experiment it means along the span), and the vortex structure is clearly seen, it leads to the conclusion that this vortex structure is coherent along the span. It might be uniform along the span or consist of several distinct vortices, it needs further investigation.

D. PIV flow diagnostics

The next series of experiments was carried out using PIV technique. The goal of this was to measure parameters of the vortex structure observed using Schlieren imaging, and try to investigate the way haw this vortex is born using zoomed in measurements in the area close to actuator itself.

Figure ??? shows the velocity field in the separation zone before actuation and during vortex propagation after actuation.

Also experiments on the plat plate in the still air were done to find out the mechanism of the vortex formation in the near-actuator area. The air motion normal to the surface was observed. The velocity of

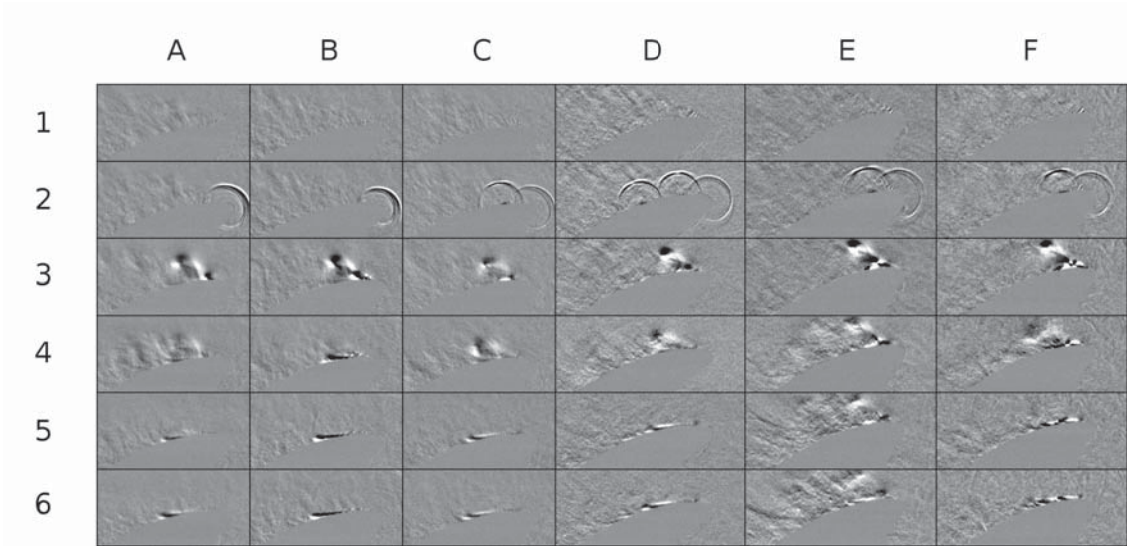

Figure 4. Schlieren imaging of the actuator effects in different cases: A — $\alpha = 26\,\mathrm{deg}$, single actuator, no burst; B — $\alpha = 26\,\mathrm{deg}$, single, burst 10 pulses, $\Delta t = 100\,\mu\mathrm{s}$; C — $\alpha = 26\,\mathrm{deg}$, double, no burst; D — $\alpha = 26\,\mathrm{deg}$, triple, no burst; E — $\alpha = 29\,\mathrm{deg}$, double, burst 2 pulses, $\Delta t = 300\,\mu\mathrm{s}$; F — $\alpha = 29\,\mathrm{deg}$, double, burst 5 pulses, $\Delta t = 300\,\mu\mathrm{s}$; Images taken at moments in time: 1 — $0\,\mu\mathrm{s}$ (before the first pulse); 2 — $40\,\mu\mathrm{s}$ (shock wave propagation); 3 — $1\,\mu\mathrm{s}$ (vortex formation after 1st burst); 4 — $6\,\mu\mathrm{s}$ (after 2nd burst); 5 — $11\,\mu\mathrm{s}$ (after 3rd burst); 6 — $16\,\mu\mathrm{s}$ (after 4th burst); In all cases burst-to-burst frequency was 200 Hz, pulse voltage 10 kV.

the flow produced by actuator was measured to 0.1 m/s, which is clearly insufficient for changing flow of 30 m/s. There were no jets along the surface present such as in case of AC actuators. So we can conclude that the ionic wind mechanism is not relevant in case of nanosecond pulsed actuators.

III. Numerical simulation

In order to understand the mechanism of the actuator effects, the numerical simulation was developed.

The key assumption behind the numerical simulation is the representation of the actuator as a instantaneous gas heating by the discharge. It is assumed that during first microsecond after the discharge most of the energy (more than 50%) is released into heat and there are no more plasma effects present. Taking this into account allows to represent discharge just as an initial condition in gasdynamics simulation.

The second assumption is an assumption of 2D nature of the phenomena. This assumption arises from schlieren imaging results, as it seems that the vortex structure formed by actuator is quasi-2D. The correctness of this assumption still needs to be proven.

First simulation made was the simulation of the separation on the airfoil. First, the separating flow around the airfoil was simulated. Then, the heating produced by the discharge was put into the flow. The value of preheating was chosen based on measured electrical energy input into discharge. Assuming that the area of preheating is uniform in span-wise direction and has a cross section of $0.5 \times 0.5\,\mathrm{mm}^2$, and usind measured value of dischage energy of $10\,\mathrm{mJ}$, we have a temperature increase $\Delta T = 22\,\mathrm{deg}$.

After that, the affects of the actuator were simulated.

It was found that in the case where the separating flow was laminar, actuation led to formation of the vortex structure, which is similar to that observed by schlieren imaging. The structure formed is shown in figure 5.

To clarify the mechanism of the actuator effects different series of simulations were carried out. The geometry used in these simulations was a backward step, which is the ultimate case of separation. The actuator was placed on the upper surface of the step. In this case the intensification of the shear layer instability was observed after actuation, and the the point at which instability developed into vortices shifted upstream.

To simplify the phenomena even more, the simulation of free shear layer was used. In this simulation, a shear layer is formed between two flows with different velocities. The actuator created preheating has been put into the shear layer, and then the variations of the velocity were observed in several points inside the shear layer. Time plots of these values shows the intensification of component of the velocity, normal to the

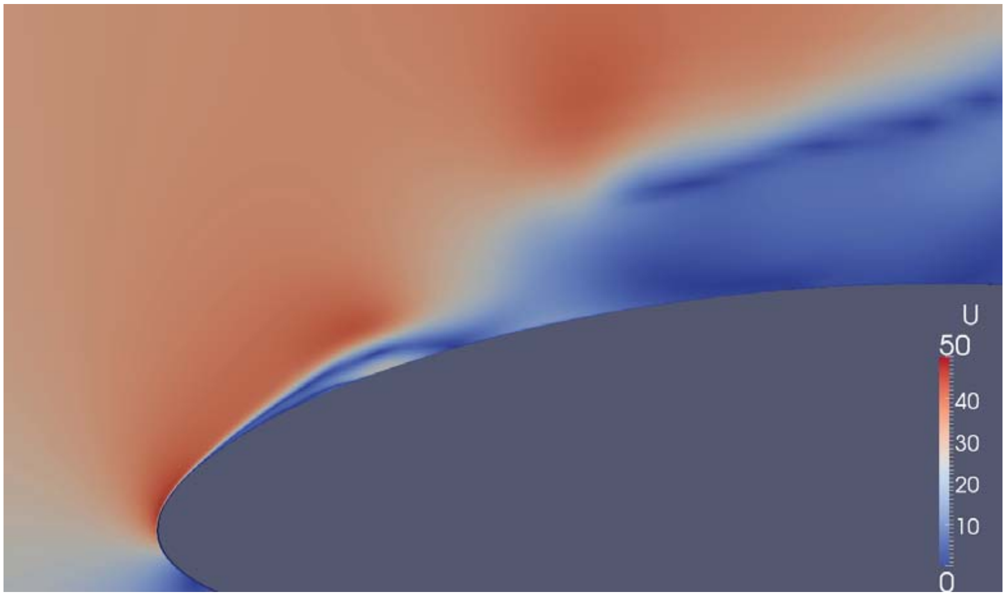

Figure 5. Simulation of the laminar separation with actuation: velocity field after the discharge. Magnitude of the velocity is shown by color.

shear layer. In order to separate the effects of changing density (which leads to change in viscosity, and in turn to change in local Reynolds number) and effects of the wave, several simulations were performed using only pressure or only temperature change as an initial condition. The results with pressure only coincide with the results of the combined effects, although the simulation with temperature effect only shows no effect at all. The examples of flow fields with and without separation are shown in figure 6.

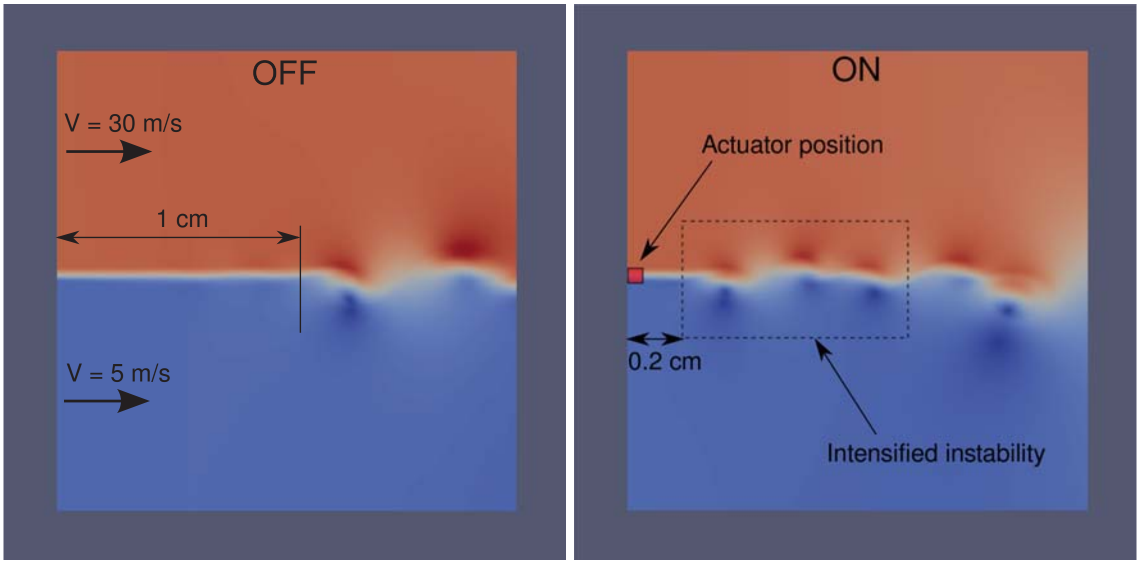

Figure 6. Velocity field without and with actuation in shear layer simulation. Thickness of shear layer at the inlet is 0.5 mm.

This phenomena may be explained if we note that the shock wave propagation speed differs on different sides of the shear layer because shock wave propagation speed is equal to shock speed in still air plus flow speed. This leads to misalignment of waves, which creates pressure gradient normal to the shear layer, and the opposite gradient on the back front of the wave. This could lead to creation of the vorticity in the shear layer.

As a conclusion, simulations show the elimination of separation in laminar case and amplification of Kelvin-Helmholtz instability of shear layer. The key component of the interaction was found to be a shock wave in the shear layer simulations. It should be kept in mind, however, that the connection of the shear layer instability and separation elimination is not clear.

IV. Discussion and conclusions

The performance of the nanosecond pulse plasma actuator for separation control on two low speed airfoils was studied. Different types of geometries were used under a range of conditions on two different airfoils with different dimensions (chord of 20 and 60 cm) at the flow velocities up to 40 m/s. On the smaller airfoil under these conditions a complete elimination of flow separation was shown, leading to up to 20% of lift increase.

On the larger wing 10% of lift increase was shown with drag decrease to 1/3 of its original value. The discharge power accounted to 12 W per meter of wingspan. The dependence of the effectiveness of the actuator on the geometry of actuator (number of electrodes, gap size and thickness of dielectric) was studied. The optimal frequency was proven to follow predictions related to expected reduced frequency.

Schlieren imaging was used to visualize the shock wave propagation. Formation of large-scale vortex structure was observed. This vortex structure was measured using PIV technique, as well as flow produced by actuator in still air. The velocity of flow produced was found to be 0.1 m/s which is very low value compared to flow speeds at which actuator was shown to be effective. This leads to the conclusion that flow generated by actuator does not play the primary role in phenomena.

The results are in agreement with theoretical assumptions of the mechanisms of this phenomenon, the most important role there plays the fast thermalisation of plasma of nanosecond discharge, which creates a shock wave which in turn creates vorticity.

Numerical simulations carried out using the model of the actuator as an instantaneous preheating of the flow shown the formation of the vortex structure similar to that observed in experiments in case of laminar separation. Also, instabilities of the shear layer were simulated, and it was found that actuation leads to intensification of instabilities, and the key role is played by shock wave.

The nanosecond pulsed actuator proved to be effective for separation control at relatively high flow speeds up to 40 m/s with low energy consumption, which is promising for applications. The results obtained may be used for further optimization of the actuator design for practical applications and to improve understanding of the underlying mechanisms of flow control with nanosecond plasma.

V. Acknowledgments

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