Active flow control by means of MHD plasma actuator on a NACA 23012 Airfoil Model

Kazanskiy P., **Moralev I., Bityurin V., Klimov A.**
Joint Institute of High Temperature RAS
Izhorskaya 13 bld.2, Moscow, 125412, Russia

Current paper presents investigation of previous work [1]. It has been revealed that an arc discharge ignition in a magnetic field of plasma actuator leads to change main airfoil aerodynamic coefficients C_x, C_y and longitudinal moment. The research was performed for the NACA23012 airfoil model at flow velocities of up to 60m/s (134 mph). The dynamic flow visualization of an airfoil model after a single discharge ignition was performed. Mean C_y change and the longitudinal moment M change were no more than 5% at pulse repetition frequency 13 Hz. The amplitude of lift change was not more than 10%, the amplitude of longitudinal moment change was not more than 5%. Time resolution of strain scales was more than 30ms. It was not possible to resolve the real change of lift force during the discharge pulse. The amplitude was significantly reduced (approximately by 20-50 times). Mean discharge power was no more than 200 W. The MHD actuator was mounted on the upper side of the wing model. Evolution of the flow after a single MHD actuator pulse was investigated experimentally by PIV. It has been found that the velocity of the arc in a predetermined configuration may be up to 250 m/s. The upstream movement of the arc channel (I= 40-700A) leads to the inhibition and high pressure zones before the arc and local low pressure cavity. Pulse energy input causes a compression wave. Cavities flow past and compression wave leads to momentary (less then few milliseconds) airfoil lift change. The average lift force increased.

Nomenclature

MHD = Magnetohydrodynamics
C_x = drag coefficient
C_y = lift coefficient
M = longitudinal moment
PIV = Particle image velocimetry
I = pulsating current
B = magnetic flux density
HF = high frequency
f = discharge pulse frequency
V = airflow velocity
St= non-dimensional frequency (Strouchal's number)

Introduction

The possibility of generation significant conducting gas acceleration by means of MHD was investigated during engineering of MHD generators, railguns etc. In plasma aerodynamics the employment of MHD effects was limited by supersonic and hypersonic aerodynamics issues. In [2; 3] the discharge was used for acceleration and deceleration hypersonic boundary layer at 28 mmHg and Mach number M = 2.8. In a series of papers [4-13] intensification of mixing was investigated in gas subsonic flow at atmospheric pressure. A great experience was accumulated in investigation of electric arc interaction stiring in a flow by means of Lorentz force f=[jB].

Different configuration of MHD actuators based on principals of momentum transfer from arc to the flow were used in previous works of aircraft exhaust engine jet noise control [14].

Experimental setup

Low-velocity (<80m/s) experiments were cared in the aerodynamic channel with 100x100x300 test section, operating in a continuous regime in wind the tunnel «Дуня-2». Flow velocity can be changed by controlling the blower motor.

The flow was formed by the retractor blower . The air enters the wind the tunnel from the room of the laboratory through the prechamber. Large-scale flow turbulence was quenched by honeycomb and metal mesh . The airfoil was mounted in the test section on the scales (Fig 1).

NACA 23012 airfoil model 8cm x 10cm (chord x span) was manufactured from Nylon-6. Model was positioned in the test section at a desirable attack angle using rotating mechanisms. The electrodes were arranged on the surface of the model so than 4 discharge gaps were 34 mm long and 6 mm wide (Fig. 2). It means that discharge arc covered 24% of the boundary flow. The permanent magnets NdFeB with normal magnetic flux density up to B=0.4 T were mounted under the electrodes. Discharge region was made of ceramics (BK-94) to withstand the temperature in the discharge region. Flow blockage was up to 10% at 5^0 attack angle.

The pulsed discharge was created by generator. It was possible to form current pulses with arbitrary length. The typical parameters of pulses were: pulsating current I < 1 kA, voltage before discharge ignition U < 4 kV, pulse duration t = 75 — 1000μs, pulse frequency f_p<500 Hz, average power < 1500 W (Fig. 3). Initialization of main discharge was implemented by HF DBD.

Discharge voltage was measured with Tektronix P6014A HV probe, discharge current was measured on 50 Ω current shunt. Electrical power input was calculated by digital multiplication of current and voltage signals via TDS 2014B oscilloscope.

Wake structure was studied by a LaVision PIV system, based on 200mJ NdYAG laser and a 2048x2048 pix camera. Frames were acquired at frame rate ~7Hz, with further averaging of 50-140 images. Accuracy of a single measurement was about 3% (for 40 m/s), while averaging error was several times higher, velocity field resolution was about 1.5mm. Diagnostic equipment was synchronized with the discharge pulses through the frequency divider and delay generator, allowing phase-locked acquisition of data. Flow was seeded with TiO2 particles with the typical size 150 nm.

The scales consisted of 4 tensoresistive sensors (T24A-0,01-C3), dynamic converter (ПД-004), and power supply (АИП-012). The digital signal was processed whit Lab View soft. The limit of force measurement was 10 kg. Accuracy of measurement was δ<0.7%. Time resolution was 0.03 s (30 Hz).

Results

The impact of the arc on the flow was held within the conductive channel of discharge. Several operating characteristics depends on a flow dynamic, such as electrode service period, surface overheat (can lead to magnet damage) etc.

The dynamic of the discharge arc in the flow with the magnetic field was studied with high speed camera MotionStudio N. The video was held at 30 kHz with 1 μs exposure along the span of the model. It has been found that the arc runs up to 150 m/s towards the 60 m/s flow at discharge current I up to 700A.

The main parameter results for the airfoil are shown on (Fig.4). One can see the increase of discharge frequency leads to increase of MHD actuator influence on the flow.

Main change of C_x, C_y, M parameters were held at maximum f_{mod}=150Hz. It was impossible to get higher f_{mod} because of the generator capacity limit at the current pulse energy. The largest effect for momentum change was observed when discharge was passing up to the leading edge against the flow. The largest effect for drag and lift force was observed when discharge was spreading down the flow. The maximum increase of C_x was 1.8% (V=60m/s) and 5% (V=40m/s), for Cy 3.1% (V=60m/s) and 2.3% (V=30m/s)

It should be noted, that the averaging data was held by integration in several seconds after switching off the discharge. Thus, the substantial contribution to measurement results could be done because of thermal deformation of the electrodes and the model. Besides, such algorithm couldn't determine the flow reaction of every single discharge impulse.

The PIV visualization of the flow near the airfoil at angle of attack 5^0 is presented at Fig.5. It is possible to trace the evolution of perturbation created by the moving plasma channel in the magnetic field. For all pulse currents major impact of the arc channel on the flow is the formation of separation zones. The separation point of the flow is following the discharge arc. The main steps of the flow evolution can be divided on following processes:

Electrical breakdown. Weak shock waves are formed at the moment of breakdown. The amplitude of the shock wave decays relatively quickly. The shock wave leads to vortex formation on the sharp trailing edge of the model. It is necessary to mention, that the zone of high pressure is located on the up side of the wing for more than 0.2 ms and provides significant force effect on the model only this period of time.

Major energy supply. Major energy supply was carried out during 100 –1000 μs in studied regimes. The arc channel moves up the flow leaving heated cavern behind. The size of the cavern depends on pulse parameters and arc dynamics while moving in the magnetic field. The formation of the cavern leads to the flow change as it would be in case of increasing the effective thickness of the profile in this area.

The stage of the flow relaxation. The braking apart arc channel, the upper high boarder of the cavern, moves back under the force of the streaming flow. At the same time the thickness of the cavern is getting larger. Relaxation time is 1.5-2 ms that corresponds to the approximate time passage for the giving model.

Mainly impulse characteristics influence to the size of the cavern. Obviously there exist three important values: arc moving speed, gas heating and the arc rise under the surface of the model. Short cavern of 15mm thickness is formed under the high current. The length of the perturbing is determined by the distance, that discharge makes over the surface of the model, and the time of its existence at the front edges of electrodes.

Size and shape of the cavern are connected to the arc dynamics in the magnetic field at the different values of peak to peak current. At current <100A, the field of permanent magnets completely determines arc traffic. Under the discharge current increase, the magnetic field of the arc is swelling and breaking away from the surface of the model. Wherein form a "horseshoe" with the ends situated on the electrodes with the top streaming up the flow. The rise of the discharge under the surface of the model leads to the reduction of the acting Lorenz force, that theoretically may lead to the reduction of the effectiveness of the actuator. At the same time the forming cavern leads to the separation of the flow from the profile and to the high speed perturbation.

The obtained speed fields correlates to the results of the weight measurements. The increase of the lift force, resistance and longitudinal moment observed at the moment of this impulse obviously are connected to the around flow of the cavern. The forming high speed zones under the surface of the cavern after the impulse leads to the pressure drop of the back side of the profile. The pressure increase in the arc area at the moment of impulse appearance is non-essential.

Discussion

There were made a research of potential use of plasma actuators for flow modulation under the profile NACA 23012 with unseparated initial flow-around, angle of attack 5° and speed of flow up to 60m/s.

Flow evolution after a single impulse of MHD actuator, mounded on the downwind side of the profile, has been investigated through experimental method PIV. The experimental results are compared with theoretically ones done by the method of the numerical simulation [15]. It is shown that the arc speed in the configuration given may come up to 250 m/s. The upward movement of the arc channel with current 40-700A leads to the zone of the deceleration and high pressure in front of the arc and local cavern with hypotension behind. Flow-around of cavern and compression wave, spreading under pulse energy input, lead to the short-duration (several milliseconds) lifting force of the model. Herewith on average per impulse the lifting force is growing.

The average change of the lifting force and longitudinal moment of the wing that was obtained in the experiment (investigation) is 5% under pulse repetition impulse 13 Hz, oscillation amplitude lift up to 10%, moment – up to 5%. It should be noted, that the balance reaction time did not allow to make real lifting force measuring during impulse, as well as reduce the amplitude (app in 20-50 times). Average capacity delivered to the discharge was not higher than 200W.

Conclusion

With the use of MHD actuators, established in the field 0.8-0.35% chord, there was received the force modulation and moments acting to the profile. Within flow speed 60m/s with the values $dCx<2,8\%$, $dCy<6\%$, $dM<7,2\%$, vibration amplitude of lifting force and moment rich 10%. Flow visualization shows that arc movement at the surface of the model towards the flow is accompanied with the flow deceleration before the arc and cavern formation behind the channel of discharge. Cavern forming behind the channel of discharge leads to the pushing off the streamlines from the wall and pressure reduction in the cavern area.

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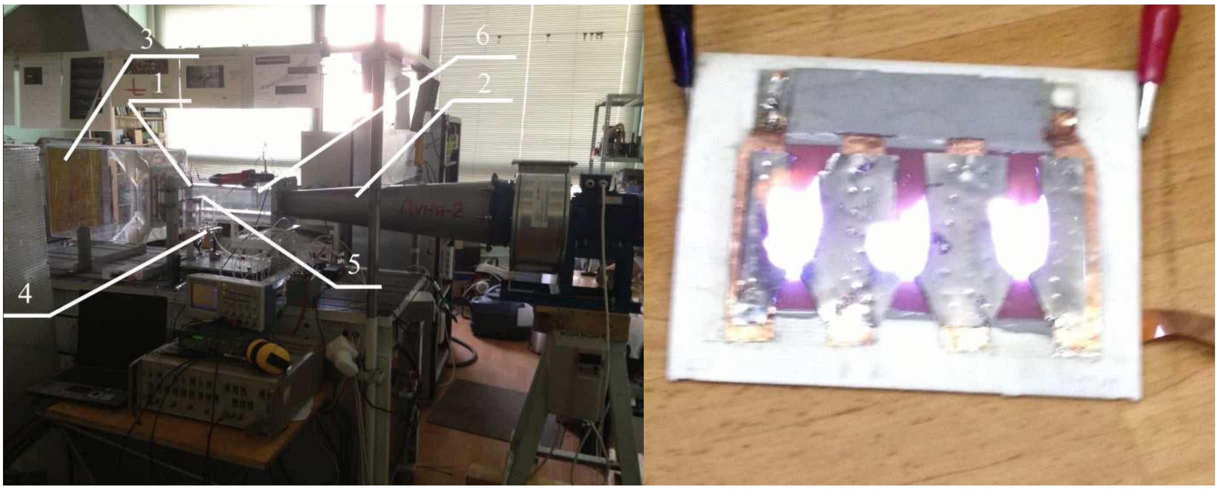
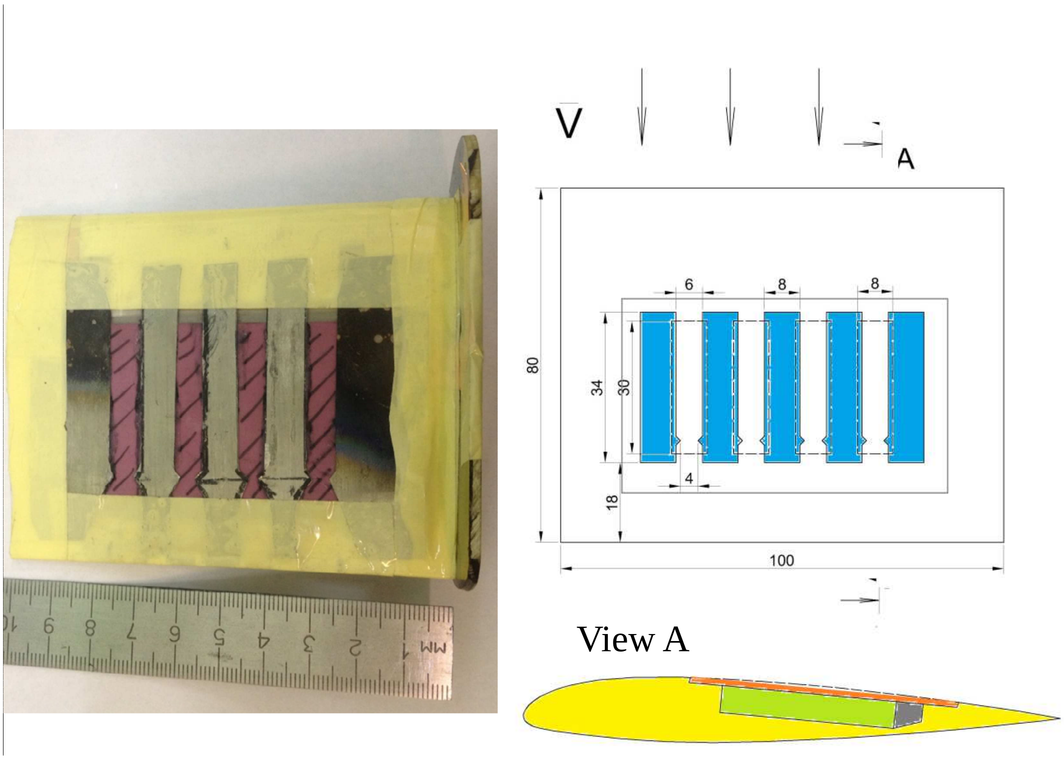
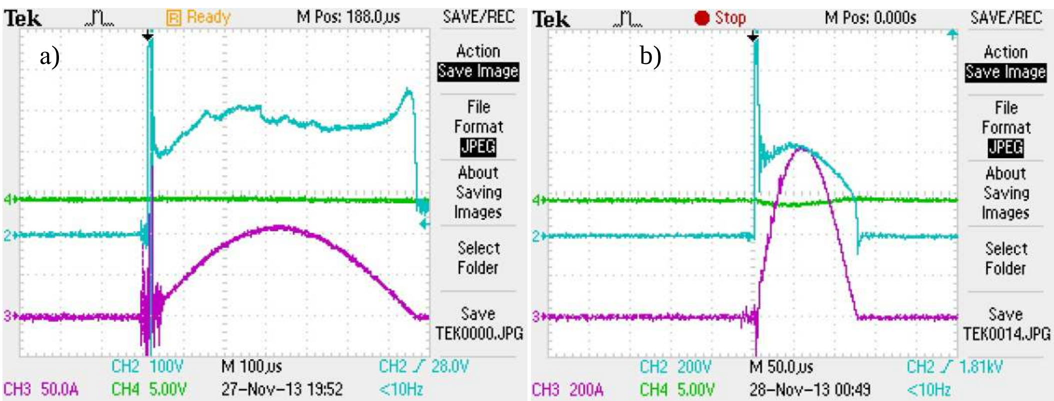


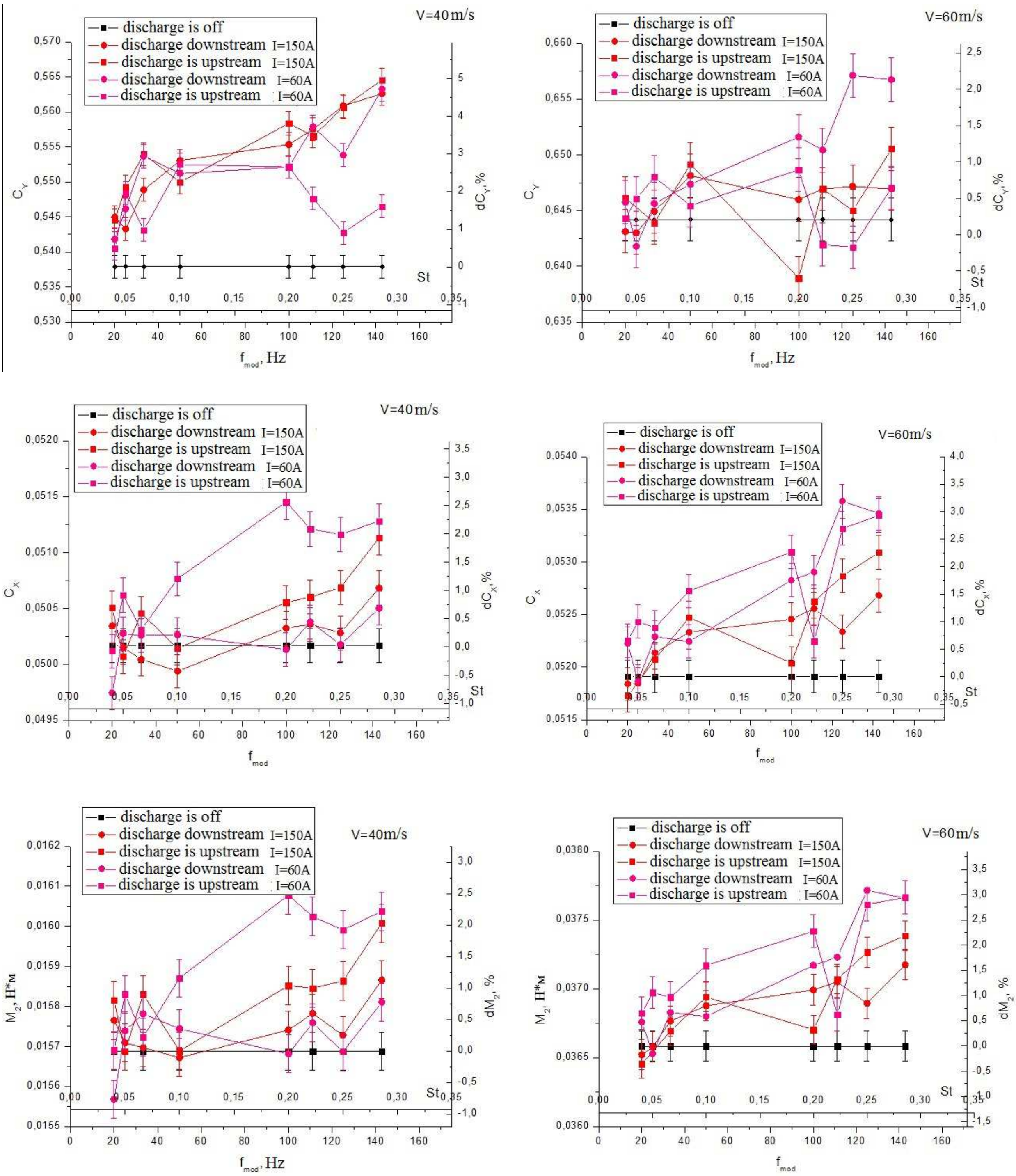
Pic. 1. Photo of wind tunnel with of NACA 23012 Airfoil Model inside. The plasma MHD actuator is switched on. 1 – test section, 2 – diffuser, 3 – Honeycomb, 4 – strain gauge scales, 5 – airfoil model, 6 - Pitot tube.



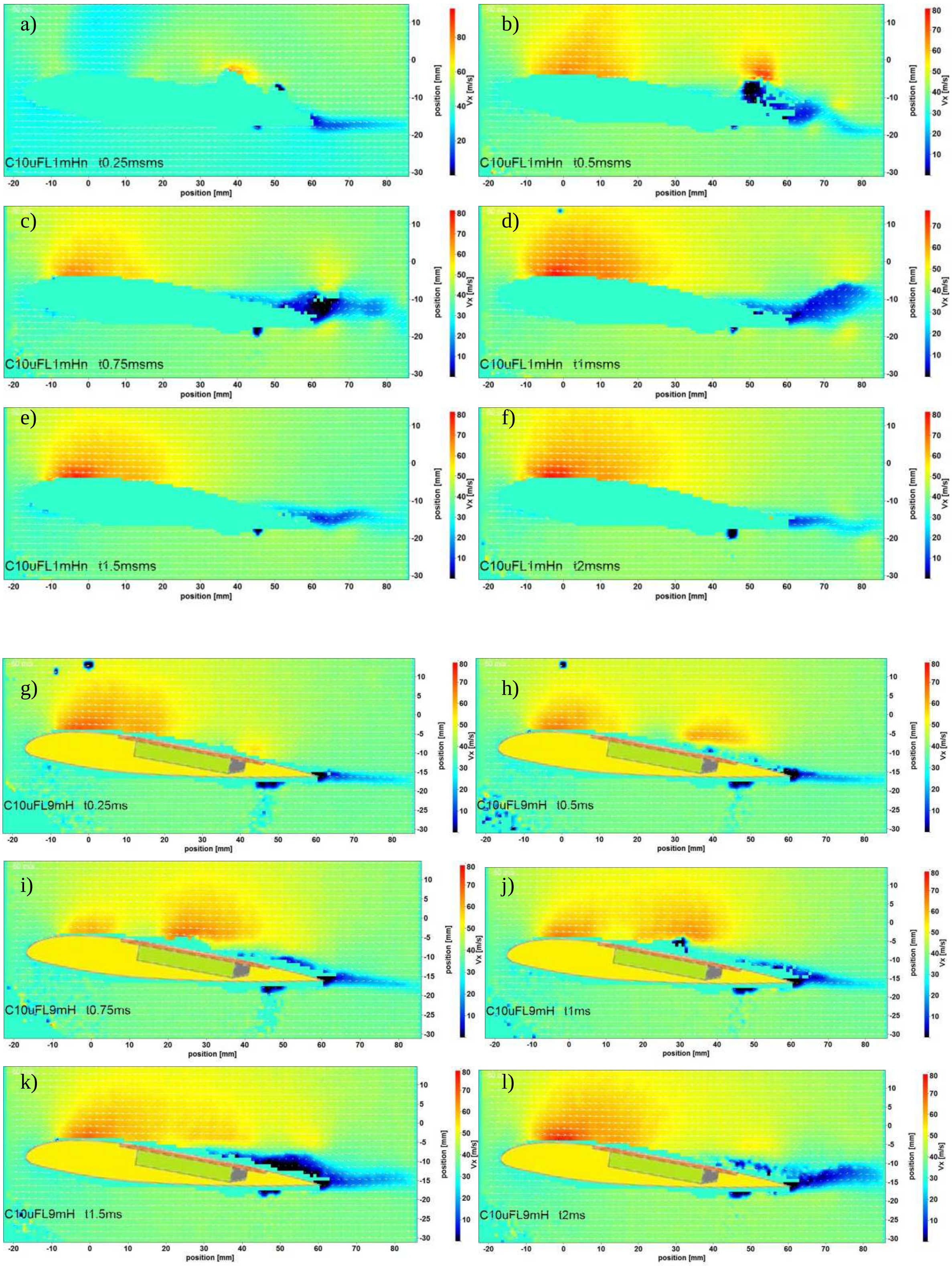
Pic. 2. Airfoil model.



Pic. 3 The current and voltage oscillograms of MHD discharge actuator. a) Capacitance of the capacitor discharge C=10 µF, inductance of the coil L=9mH, I=70A; b) C=10 µF, L=1 mH н, I=700A.



Pic. 4. Comparison C_y, C_x и M of the airfoil at different modulation frequencies (Strouhal numbers). left - V = 40 m/s, right - V=60 m/s.



Pic. 5. The PIV visualization of the flow near the airfoil at angle of attack 5^0. a-f) I = 700A, g-l) I=70A.

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