Particle image velocimetry analysis of the flow around circular cylinder induced by arc discharge rotating in magnetic field

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Abstract. An experimental study of the flow around a circular cylinder model with magneto-hydrodynamic (MHD) actuator was carried out in subsonic wind tunnels (\(M < 0.2\)). Combined (high frequency and pulsed-periodic) electrical discharge was used in this MHD actuator. This intense pulsed-periodic discharge had the following characteristics: voltage amplitude up to 15 kV, current amplitude up to 16 A and frequency up to 1 kHz. Permanent magnets with an induction of \(B = 0.1 \text{T}\) on the model surface were placed inside the cylindrical model. Annular electrodes were situated on the surface of the cylindrical model. The Lorentz force causes the rotation of the electric arc on the model surface. In turn, the movement of the arc discharge induces the rotation of the gas near the surface of the model. In this experiment were carried out the measurement of the flow velocity profile near the surface of the model on the following operational modes: with plasma and without plasma. A parametric study of the aerodynamic performance of the model was fulfilled with respect to the discharge parameters and the flow velocity. To measure the velocity profile was used particle image velocimetry method.

1. Introduction

Intensive research is currently being conducted in the field of plasma aerodynamics on the possible use of various plasma formations to control the flow around streamlined bodies [1–4]. The main advantage of plasma actuators (active devices to control the flow using local plasma formations) is their performance, which is based on the electronic control of the parameters of electric discharges. This property, in turn, allows realizing feedback control of various disturbances in the gas-dynamic flow near streamlined bodies (for example, to control the laminar-turbulent transition of the boundary layer, flow separation, etc). An important task in plasma aerodynamics is the control of the flow circulation around streamlined bodies, such as cylinders and wings. However, there is few experimental work on the subject [5–19]. This work fills a gap in the area and is dedicated to the study of the flow around a cylinder with magneto-hydrodynamic (MHD) actuator. Rotating electric arc in external magnetic field provides a concomitant increase in the gas flow near the surface of the cylindrical model and causes the flow circulation around it. Therefore, the objective of this paper is to measure the magnitude of the induced airflow circulation \(\Gamma\), the lift force \(L\) on the cylinder (Magnus–Zhukovsky force) and the study of the velocity profile around the cylinder with the help of shadowgraph and particle image velocimetry (PIV) methods.
Figure 1. General view of the model and drawing of the MHD actuator on the circular cylinder model with one discharge plasma belt: 1—quartz tube, 2—copper ring, 3—spark gap electrodes, 4—nuts and screws of polyamide, 5—Nd-Fe-B magnet (a). Spark gap electrode possible positions: $\alpha = 5^\circ$ or $90^\circ$ (b).

2. MHD actuator and aerodynamic model
General view of the model is shown in figure 1. The aerodynamic model used in this study is a cylinder made of a quartz tube 1 with an external diameter of 20 mm, length of 95 mm and a wall thickness of 2 mm. On the model surface were placed copper ring electrodes 2 to create an arc discharge on the surface of the quartz tube. The ring electrodes are located at a distance of about 10 mm from each other. In order to start the arc discharge at a specific location of the electrode par, spark gap electrodes 3 were added to the design. Ring magnets of Nd-Fe-B 5 are located inside a quartz tube, in order to create a zone of the radial magnetic field near the surface of the cylinder. Within the model, there are screws and nuts 4 made of a dielectric material of polyamide 6. The purpose of these details is to hold and mount the ring magnets at a certain distance between each other. Note that there is a considerable repulsion force between equal poles of the ring magnets which produce a radial magnetic field on the surface of the cylinder (between the electrodes). The magnetic field measured on the surface of the model on this position reaches $B = 0.1$ T.

3. High voltage power supply
A high voltage power supply was developed and tested in order to create the arc discharge. This MHD actuator used two types of power source: DC-generator (direct current) and high-power pulse repetitive discharge generator. In order to initiate these discharges, a high-voltage pulse generator HF (high frequency) Tesla was used. The specifications of the power supply for the generation of pulse repetitive discharge were as follows: $F_i < 3$ kHz (pulse discharge repetition frequency), $U_m < 15$ kV (maximum voltage), $I_m \leq 16$ A (maximum current), $P_m < 8$ kW (maximum total power), $P_a \approx 200$ W (average total power). Specifications of the DC-generator
Figure 2. Pulse discharge current $I_d$ (blue) and the voltage $U_d$ (green) of the MHD actuator.

No. 1 were the following: $U_m < 8 \, \text{kV}$, $I_m \leq 2 \, \text{A}$ and $P_a \leq 2 \, \text{kW}$. Specifications of the DC-generator No. 2 were the following: $U_m < 15 \, \text{kV}$, $I_m \leq 0.6 \, \text{A}$ and $P_a \leq 0.6 \, \text{kW}$.

The measurement of the electric current and voltage was accomplished with the sensors: Tektronix P6021 and Tektronix P6015A.

Figure 2 shows a typical voltage and current signals measured at the discharge gap of the MHD actuator. It can be seen that the amplitude of the electric current reaches a value of about $I_d = 16 \, \text{A}$ (discharge current), the duration of the power pulse is $T_i = 12 \, \text{ms}$ (pulse discharge duration) and the pulse repetition frequency is equal to $F_i = 7 \, \text{Hz}$. The amplitude of the voltage is $U_d = 1.5 \, \text{kV}$ (discharge voltage). The value of total pulse power can reach the order of $N_i = 16 \, \text{kW}$ (pulse discharge power).

4. Experimental setup

In the experiments, two wind tunnels (WT) were used. Technical characteristics of the first wind tunnel WT-1 was as follows: working section of the wind tunnel is made of a dielectric material (polyamide 6) and its external dimensions are $500 \times 200 \times 250 \, \text{mm}$. The internal cross section of WT-1 was $100 \times 100 \, \text{mm}$. This working section is equipped with quartz windows $200 \, \text{mm}$ diameter and $10 \, \text{mm}$ thick. The cylindrical model with aerodynamic actuator is fixed on the quartz window with its length positioned perpendicular to the airflow.

WT-1 has a freestream air velocity of $20 \, \text{m/s}$. Measurements of airflow velocity was performed using thermo-anemometer.

The flow around the surface of the cylindrical model, induced by the rotating arc discharge in an external magnetic field, was studied using PIV method.

The second wind tunnel WT-2 consists of the following components and modules: aerodynamic model, power supply and multi-axis force sensor MC15-3B. Wind tunnel WT-2 allows to obtain air flow rates up to $70 \, \text{m/s}$ (much higher than on WT-1). The turbulence
Figure 3. Average velocity field $V(X,Y)$ around the cylindrical model, induced by rotating arc discharge. Configuration without external freestream flow.

level on this wind tunnel in the working section was very small and did not exceed 0.02%. The relative error in determining the flow rate of this method is 3%. All parts of WT-2 were metal parts except the working section of the wind tunnel, which was made of a dielectric material Plexiglas (PMMA). This section has hermetic electric connectors that allowed the connection between the power supply and aerodynamic model.

5. Experimental results

On the experiments, particular attention to the structure and dynamics of the arc discharge on the model on the presence of freestream airflow and without it.

5.1. Arc discharge rotation in magnetic field without external freestream airflow

Particular characteristics of the arc discharge and its rotation around the cylindrical model are shown in figure 4. It is evident the formation of an arc discharge “head” and “tail”, apparently due to different arc discharge glide speed on anodic and cathodic electrode. The middle part of the arc discharge rises above the surface of the cylindrical model. The reason for this phenomenon is not clear, and requires further study.

Using PIV method were measured gas velocity field near the surface of the model and its flow circulation, induced by rotating DC arc discharge and without external freestream airflow, figure 3. DC discharge parameters used in this experiment are as follows: direct current $I_d = 0.64$ A and discharge voltage $U_d = 1$ kV. It was verified that, under these parameters, the average speed of induced flow near the surface of the cylindrical model is $V_i \approx 2.0$ m/s and the value of the induced flow circulation reaches $\Gamma \approx 0.0124$ m$^2$/s. The typical thickness of the disturbed layer of gas flow is $h \leq 2.5$ mm. The value of flow circulation $\Gamma$ was determined using the following
The expression [6]:

\[ \Gamma = \int \int_S (\nabla \times V) \, ds = \int_0^{2\pi} \int_{R_0}^{(R_0+h)} (\nabla \times V) R_0 \, d\theta \, dr \approx 0.0124 \, \text{m}^2/\text{s}, \]  

where \( R_0 = 10 \, \text{mm} \) and \( h = 4 \, \text{mm} \).

The term inside the brackets in the integral sign is the swirl flow value \( \Omega = \nabla \times V = \text{rot} \, V \).

The velocity field around the model \( V(X, Y) \), induced by the rotating arc discharge working on the pulse repetitive discharge mode, is shown in Figure 4. The discharge parameters used in this experiment are the following: pulse duration of 12 ms, pulse repetition frequency \( F_i = 7 \, \text{Hz} \), output voltage of the power supply \( U_m < 15 \, \text{kV} \), maximum arc discharge current \( I_m \approx 16 \, \text{A} \), maximum pulse total power \( P_m < 8 \, \text{kW} \) and average power consumption \( P_a \approx 200 \, \text{W} \). Spark gap electrodes are set at the position \( \alpha = 5^\circ \), Figure 1b. From Figure 4 it follows that the plasma
arc discharge rotates stable around the cylinder in this mode. The average speed of the induced flow reaches $V_i \approx 8$ m/s. Typical thickness of the flow circulation is about 10 mm.

From figure 4 it follows that:

- the arc discharge has a complex three-dimensional shape. The head of the arc discharge lies ahead of its tail. The middle part of the arc discharge rises above the surface of the model. The typical height of arc discharge can reach 10–15 mm.
- The head of the arc discharge pushes gas radially. As consequence, the concentration of PIV dust particles sharply decreases in the discharge zone. Therefore, processing PIV results in this area presents difficulty.
- Behind the arc discharge appears suction of the surrounding gas and also giant vortex.
- It follows from figure 4 that the flow circulation occurs at the arc discharge itself and the gas suction zone appears at its tail.
- It was observed that the ratio of the radial to circumferential (tangential) gas velocity near the model surface varies with respect to the arc discharge electric current.

Figure 5. Average velocity field around the cylindrical model measured by PIV method at $V_\infty \approx 6$ m/s. DC power supply: discharge current $I_d \approx 0.64$ A.
Figure 6. Averaged PIV image of the velocity field around the cylinder model with a rotating plasma arc discharge. External airflow velocity of $V_\infty \approx 6.5$ m/s. Time delay after turning on the electric discharge: $T_1 = 2$ ms (a) and $T_2 = 4$ ms (b). Red circle indicates the “head” position of the arc discharge.

5.2. Arc discharge rotating in magnetic field with external freestream airflow

PIV measurements of the flow field around cylindrical model with operating MHD actuator were fulfilled. Average velocity field around a cylindrical model, with operating MHD actuator and external freestream airflow velocity of $V_\infty \approx 6$ m/s, is shown in figure 5. These experiments used a DC power supply with discharge current $I_d \approx 0.64$ A. The figure 5 shows that in this experiment occurs a significant change in the position of the flow separation point on the model. The shift in the flow separation can reach an angle of $\Delta \theta \approx 40^\circ$.

External synchronization mode of video camera and PIV system was used in order to study the flow separation and the arc discharge rotation on the model, under the condition of external freestream airflow. The average angular velocity of the arc discharge in this experiment was about 290 Hz. Changes in the dynamic of the velocity field near the streamlined cylinder model,
with operating MHD actuator and external freestream airflow, is shown in figure 6. In this experiment was used pulse repetitive discharge with the following characteristics: \( F_i = 7 \) Hz, \( U_m < 15 \text{ kV}, I_m < 16 \text{ A}, P_m < 8 \text{ kW} \) and \( I_a \approx 200 \text{ W} \).

The airflow rate was \( 6.5 \text{ m/s} \). Spark gap electrodes are placed in the position \( \alpha = 5^\circ \).

Number of measurements made in order to build the average PIV picture: 70 measurements.

Under these conditions, was revealed a significant effect of the rotating arc discharge on the flow around the model (both in averaged and instant measurement). It is evident the formation of large-scale vortices 1 and 2 (figure 6a) on the marked area of the model. Figure 6b shows the flow field around the cylindrical model with operating MHD actuator at the middle of the second rotation cycle of the arc discharge around the model. In this configuration mode, the entire velocity field is perturbed around the model, including the front half of the cylinder model. Figures 6a, 6b, 6c show also the synchronized image of the rotating arc discharge correspondent to each PIV image. Induced flow circulation is visible both in the “head” and “tail” portion of the arc discharge. It is important to notice that, in figure 7, the area with stimulated flow circulation occurs exactly on this portion of the model. For this reason, there is practically no flow separation around the cylinder on an area correspondent to 270 degrees.

This result allows to determine the average induced vorticity field and flow circulation around the model, figure 7. On these conditions, the value of the average stimulated vorticity equals: \( \Omega = 2000 \text{ s}^{-1} \). Such a high value of vorticity was obtained by the use of a high electric current value of the pulse repetitive discharge present in this experiment (in comparison with the vorticity value obtained using a low direct current discharge, figure 3).

The value of the flow circulation \( \Gamma \) in figure 6 was determined by the expression (1):

\[
\Gamma \approx 0.095 \text{ m}^2/\text{s}.
\]  

wherein \( R_0 = 10 \text{ mm} \) and \( h = 4 \text{ mm} \).
6. Estimation of the aerodynamic characteristic of the cylindrical model

It is clearly seen in figure 6b that there is an asymmetrical flow around the cylindrical model caused by induced flow circulation around the model. This asymmetrical flow of the exterior gas around the model may lead to the appearance of lift force. At the same time, virtually no flow separation allows the estimation of the lift coefficient value $C_L$, generated by the stimulated flow circulation $\Gamma$ [6]:

$$C_L = \frac{w \rho \infty V^2 \infty \Gamma}{\frac{1}{2} \rho \infty V^2 \infty w d} = \frac{2 \Gamma}{V^2 \infty d} \approx 0.2,$$

wherein $\Gamma = 0.095 \text{ m}^2/\text{s}$ and $V^\infty = 42 \text{ m/s}$.

We see that the magnitude of the estimated value of $C_L$ is quite a high value. Thus, we can assume that the physical appearance of the lift force $L$ can be caused by stimulated flow circulation $\Gamma$, created by the rotating arc discharge.

7. Conclusion

In conclusion, the plasma created by the MHD actuator is able to create a flow circulation around the surface of the cylindrical model. This statement is confirmed by direct measurements using PIV method. It is assumed that a lift force $L$ can be caused by stimulated flow circulation $\Gamma$, created by the rotating arc discharge. The value of the estimated lift coefficient $C_L$, due to stimulated flow circulation, reached a maximum value of the order of $C_L \approx 0.2$. Further experiments are planned in order to confirm this hypothesis, by measuring the aerodynamic forces of the model in the wind tunnel. It is planned to use the developed MHD actuator on the model of a wing in our future experiments.

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