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Dynamic effects of MHD interaction in high-speed flow under ground-based experiment conditions

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Abstract

The main purpose of the experiment-calculated studies is to determine the scale of the dynamic effect caused by changes in gas-dynamic forces and moments on the surface of an aircraft. The origin of forces is explained by the modification of the flow characteristics as a result of the magneto hydrodynamic (MHD) interaction of a high-velocity flow with a strong magnetic field. The experiments were carried out in TsAGI at the wind tunnel with a magneto hydrodynamic accelerator (SMGDU). The use of MHD accelerator made it possible to create high-velocity flows of partially ionized air at high total enthalpy values. The mobile model installed in the flow reacted to the change in pressure when the pulse electromagnet was turned on. The data obtained were compared with the results of numerical simulation performed with the help of the PlasmAero package developed in JIHT. The code was based on the numerical solution of the Navier-Stokes equations, the equations of electrodynamics in the low-frequency approximation under conditions of chemically non-equilibrium real gas. It was shown that the gas-dynamic component of the MHD effect turned out to be significant. The practical prospect of the research is related to the use of electric and magnetic fields to develop new methods for controlling the flow of a flying body by a gas-plasma stream.

Keywords: *MHD interaction, high-speed flow, MHD accelerator, magnetic field*

Nomenclature

Latin

g – Some symbol

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The task of the flight control of an aircraft flying at high speed is still one of the most important. This problem is especially acute when maneuvers occur while the surface of the rudders undergoes peak thermal loads. The development of alternative non-intrusive ways to control the flight path is of great interest. The natural occurrence of plasma formations around a flying body due to the gas-dynamic heating of air predetermines the direct possibility of active MHD interaction of the ionized gas flow with magnetic and electric fields created by the on-board systems. The application of the methods of magneto plasma aerodynamics has long been regarded as an effective means of influencing the characteristics of high-speed flow around an aircraft, controlling its flight path, reducing thermal loads [1]. The particular attractiveness of this approach is based on the non-intrusive nature of the existing physical mechanisms. In this case, the control is carried out without using aerodynamic control surfaces, but solely due to the forces and moments arising from the interaction of the magnetic field with the ionized flow. MHD effects in the flow around a body with a magnetic system on board are carried out through two main channels. First of all, there are electromagnetic forces and moments applied directly to the on-board magnetic system. They are caused by the direct interaction of currents induced in the flow with the currents of the electromagnet. Secondarily, there are gas-dynamic forces and moments acting on the surface of the body. Their occurrence is associated with the redistribution of pressure and friction stress on the wall in the flow. The origin of forces is explained by the modification of the velocity and temperature fields as a result of the MHD interaction of a high-velocity flow with a strong magnetic field. For the practical development of MHD flow control methods, it is necessary to independently determine both of these components. The main goal of this work was to separate the contributions of direct and dynamic effects under ground-base experimental conditions.

The experiments were carried out in TsAGI at wind tunnel with a magnetogasdynamic accelerator (SMGDU) [2], which simulates the conditions of high-speed (with Mach numbers from 6 to 15) flight at altitudes from 30 to 60 km. Its uniqueness is determined by the use of the MHD accelerator for additional speed-up of the heated gas. This device made it possible to create high-velocity flow of partially ionized air at high specific enthalpy values up to 20 MJ/kg. The task of the modern stage of research was to obtain direct experimental data of dynamic loads on the model surface.

There was a model in the Eiffel chamber. It consisted of two parts mechanically detached. The fixed part stood below the flow and was a magnetic system that was powered by a pulsed current source. The movable part was made in the form of a flat plate swinging around an axis with small friction. This part was located directly in the flow and reacted to a change in pressure above its surface. The plate was held in the flow by a rubber loop. The elasticity coefficient was chosen in such a way that the plate was located approximately at zero angle of attack during the experimental run. In most experiments, additional electrodes were placed on the model. Their position relative to the nozzle, size, shape and number varied in different series of experiments. However, their purpose remained. The electrodes performed a measuring or active function depending on the connection of the external circuit. In the measurement mode, the voltage induced between the electrodes was induced by a magnetic field, and when an external load was connected, the current between them was also measured. In the active mode, a current from an external source could be passed through these electrodes.

A pulsed magnetic field which induction was about 1 T was formed above the surface of the plate in a volume encompassing the core of a supersonic flow as a result of passing a pulsed current through a coreless coil. The duration and shape of the pulse depended on the coil inductance. A pulse of a nearly rectangular shape or bell-shaped one was formed in different series of runs. Its base width ranged from 6 to 9 ms. The shape and amplitude of the current pulse were measured at each run using a current sensor specially made for this circuit, known as the Rogowski loop. The plate was deflected down under the influence of the pressure excess arising during the MHD interaction when the magnetic field was turned on for a short time.

The most important measurements made in frames of the research consisted in finding the components of the forces acting on the model the occurrence of which is associated with changes in the parameters of supersonic flow under the influence of electromagnetic fields. The shift of the plate was recorded by two diagnostic techniques. In the first place, a set of images of the flow around the model was shot with a high-speed camera. Registration of images with a high frame rate gave not only a general picture of the flow, but also made it possible to carry out quantitative measurements by which it was possible to determine the law of motion of the model. The film showed well the slow movements of the object over long distances. This was occurring when the pressure in the flow raised or fell, for example, at the beginning and end of the MHD acceleration mode. Sometimes the uneven feed of K-Na additives in individual runs also caused pressure jumps marked. However, rapid and small displacements of the moving part of the model during a short period of the existence of the magnetic field were not always noticeable due to insufficient spatial resolution of the video shooting. In this case, the accelerometer signal followed the movement of the plate. This device was mounted at the edge of the model outside the high-temperature gas flow zone. In essence, this scheme was a beam balance. There was a force created by the pressure in the flow on one balance arm. The swing of the plate was transmitted to the other arm with an accelerometer responding to the movement of the model in two directions. Sensitive element of the accelerometer is a sensor that responds to the acceleration experienced by the body. The acceleration value measured can be recalculated to forces and moments that cause the object to move or rotate, if its mass and sizes are known. ADXL203 2-axis sensors and ADXL335 3-axis sensors manufactured by Analog Devices in iMEMS technology were selected for the experiments. They are notable for low power, bandwidth adjustable, high accuracy and fast response time. In a real experiment the separation of a useful signal is usually hampered by interference caused by switching high-current and high-voltage circuits of the installation, as well as by instability of the characteristics of the gas flow. Two identical sensors were connected in a differential scheme to improve the quality of measurements. Thus the signals of the sensors were summed up and the sensitivity of the accelerometer was doubled.

In order to experimentally determine the dynamic component of the MHD interaction, several series of runs were carried out. In all runs the same mode of operation of the SMGDU was maintained. The generation time of supersonic flow was about 0.7 seconds. In 0.4-0.5 s after the beginning of the MHD acceleration of the conducting gas when the flow parameters can be considered steady a magnetic field was turned on for a few milliseconds.

The changes of supersonic flow gas-dynamic parameters depended on of the magnitude of the magnetic field applied and currents flowing in the direction transverse to the gas flow if its speed was given. The magnetic field induction was easily varied over a wide range by adjusting the current in the coil. In a conducting flow the transverse magnetic field itself induced currents the strength of which was determined by the flow velocity and the conductivity of the medium. To enhance the effects observed these currents could be increased by connecting an external source to the electrodes. In different series of experiments, their value varied from units of amperes to kiloamperes.

The flow of kilo ampere currents through the interaction area was provided as follows. Two copper electrodes with a 6 mm diameter were mounted at the edges of the plate. They had a curved shape, so that a 12 mm gap remained between them. The discharge gap was connected to the circuit of the current source in series with the magnetic field coil. Thus, the pulses of electric current and magnetic field were precisely synchronized in time. The accelerometer signal recorded in one of these starts is shown in Fig.1.

In the left figure (a), the record covers the entire stage of the MHD acceleration in the interval from 0.8 s to 1.5 s. A noise recorded at the beginning of the oscillogram (up to 0.8 s) was corresponded to the outflow from the gas nozzle when the electric heater was turned on and K-Na feed was delivered through the dispenser. The velocity and temperature of the flow increased sharply when the voltage applied to the MHD accelerator electrodes. The pressure surge in the oncoming gas hit the moving plate deflecting it down. The plate made several damped oscillations under the action of the elastic force of the rubber loop partially compensating for the pressure force on the model. Three periods of such oscillations were clearly recorded in this launch. Then the plate was stopped in the position when the pressure on its surface was compensated by the elastic force of the rubber. The noise increased of about two times was visible only on this recording interval until the moment of turning on the magnetic field. The lifetime of the field coincided with the position of the Rogowski loop signal on the lower oscillogram. The pressure dropped sharply, the plate rapidly moved upwards and hit the nozzle under the action of the restoring force of the rubber loop at the end of the acceleration stage.The impact caused higher frequency oscillations of large amplitude.

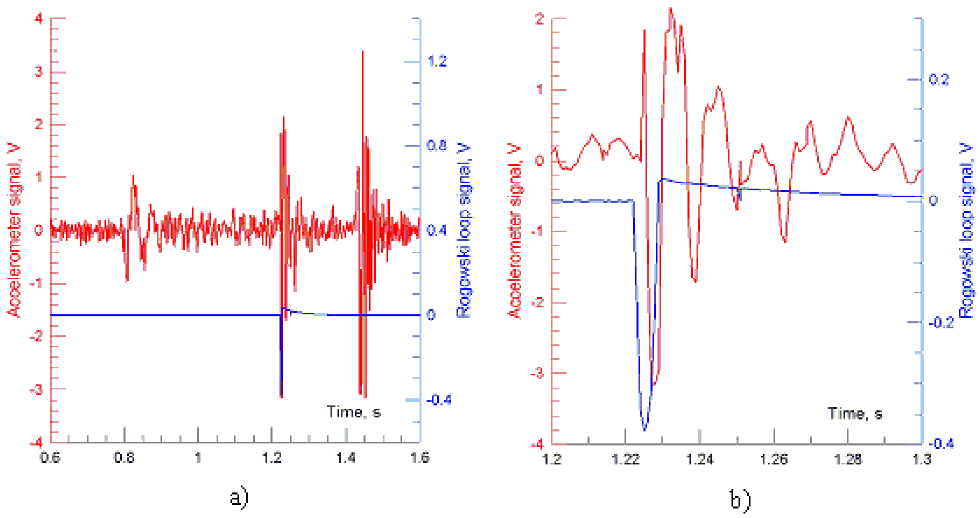

Fig 1. Accelerometer signals under current flowing between the electrodes about 3 kA

Figure (b) on the right shows a fragment of a full record, stretched in time, in which the accelerometer signal is presented in more detail before, during and after the magnetic field pulse. This signal increased in the process of applying an external magnetic field to the flow. At first the curve sharply went down that indicated an increase in pressure over the plate, similar to the initial phase of switching on MHD acceleration. Further, the signal was changed in accordance with the swing of the plate observed in the frames of high-speed shooting, also. The amplitude of the accelerometer signal in the presence of a magnetic field in this run was very large, the signal went off-scale as it was clear that it was limited at the level of the supply voltage of the accelerometer circuit. For the ADXL335 accelerometer this means that the acceleration experienced by the plate exceeded 3g where g is the free fall acceleration.However, it should be emphasized that in this run the current between the electrodes measured by the signal of the Rogowski loop reached an enormous value of 3 kA.

In the next series of experiments electric current between the electrodes of the model was still flowing from an external source; however, the current was significantly reduced and amounted to tens of amperes. The current was set from a standard power source of a pair of MHD channel electrodes. The source provided current flow at a level of 30-50 A under normal conditions. Fig. 2 shows the accelerometer signal in one of the runs (the upper curve). It should be mentioned that the signal of the accelerometer is proportional to the acceleration of the object, and not to its movement. This means that the sensor response amplitude can be significant even with small plate shifts. This circumstance was observed on the oscillogram in the form of high-frequency noise, caused, basically, by vibrations of the model in the flow. The reaction of the accelerometer is clearly visible in Fig. 2 also when the external magnetic field turned on. The general view of the signal has not changed, and its amplitude has decreased to values recorded in the linear range of the accelerometer. The polarity of the signal indicated a deviation of the plate downward that specified on an increase in pressure above its surface. In accordance with the calibration of the accelerometer its amplitude corresponded to an acceleration of about 1.5*g*.

Apparently, the most interesting are the runs in which the external current source was completely absent. Under these conditions the intensity of the MHD interaction will be determined by the strength of the current induced by the applied magnetic field in the gas flow. It is expected that its strength will be even smaller since the current was forced to close to the periphery of the flow where the electrical conductivity of the medium is small, and the effect under investigation will weaken with a decrease in the induction currents. The current can be increased by placing the electrodes on the sides of the model. Then the induced current could be closed through the external circuit, and the electrodes would turn from active ones into measuring ones. The voltage between the electrodes was measured with a load in the circuit of 15 Ohms in one of the runs. It was obtained that its value at the maximum exceeded 70 V. Consequently, the strength of the current flowing between the electrodes reached 5 A. It is clear that the strength of the induced current will increase with decreasing load resistance. The model electrodes in this circuit were shorted in order to achieve the maximum level of MHD interaction in the next run. In this case, it was possible to single out a useful signal in the recording of the accelerometer signal, which coincides in time with the turning on of a magnetic field. Its amplitude was about 1 V that was recalculated to an acceleration of 0.5*g* according to the calibration.

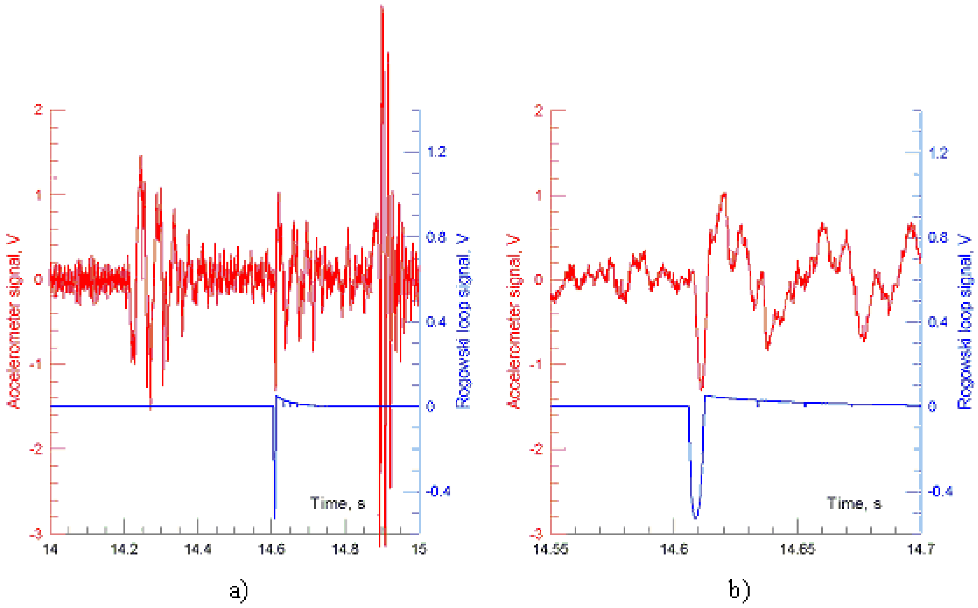

Fig 2. Accelerometer signals under current flowing between the electrodes about 30-50 A

The whole set of the experimental results obtained made it possible to assert that the evidences of the influence of an external magnetic field on the parameters of supersonic flow were obtained at SMGDU set-up. As was to be expected the intensity of the MHD interaction depended on the induction of the magnetic field and the strength of the current flowing across the gas flow. For different cases the values of the accelerations measured were close to 1g. A rough estimate of the forces acting on the plate yielded values of 1-2 N if the mass and design of the model used was took into account. An excess pressure of 200-400 Pa should have been created above a rectangular surface with sides of 0.1 m (along stream) and 0.05 m for the formation of such forces.

The data obtained were compared with the results of numerical simulation. For this purpose, a preliminary calculation of possible dynamic effects was carried out using the PlasmAero software package developed in JIHT [3].

The code was based on the numerical solution of the Navier-Stokes equations, the equations of electrodynamics in the low-frequency approximation in conditions of a thermo chemically non-equilibrium real gas. The main parameters of the simulation that were specified were close to the characteristics of the supersonic flow in the wind tunnel SMGDU. The MHD interaction was determined by magnetic induction under these gas dynamic conditions. The case of impulse action caused by a short current pulse in the magnetic system was considered. It was assumed that the current pulse is close to the sinusoidal half-period in shape. Its amplitude provided maximum induction of the magnetic field of about 1 T. The half-period duration was 6.28 ms according to the typical experimental mode. The shape of the magnetic field pulse corresponds to the blue curve in Figure 3. The red curve in the same figure shows the time dependence of the pressure on the surface of the model integrated over the plate length. To determine the force acting on the swinging plate it is necessary to multiply the value of the integral pressure by the width of the MHD interaction region. The maximum change in the integral pressure of about 800 N/m could cause a force of up to 40 N. Thus both numerical calculation and experimental measurements demonstrated that the dynamic effects caused by the magnetic field on the high-speed flow lead to the appearance of forces that additionally act on the model the magnitude of which lies in the range from units to tens of newtons. The difference between the numerical evaluation and the measured value is explained by the incomplete agreement of the parameters incorporated in the calculation with the experimental conditions of the SMGDU installation.

For the first time the experimental study was performed which showed that the expected effect lies in a range of measurable values in principle, even taking into account the small scale of the installation and the model used. Moreover, the gas-dynamic component of the MHD effect turned out to be significant. MHD interaction of an ionized airflow with a magnetic field leads to a change of the gas-dynamical forces taking action on the streamlined surface. The results of the research can be applied to the development of new methods of the flow control around a body by helps of external electromagnetic field.

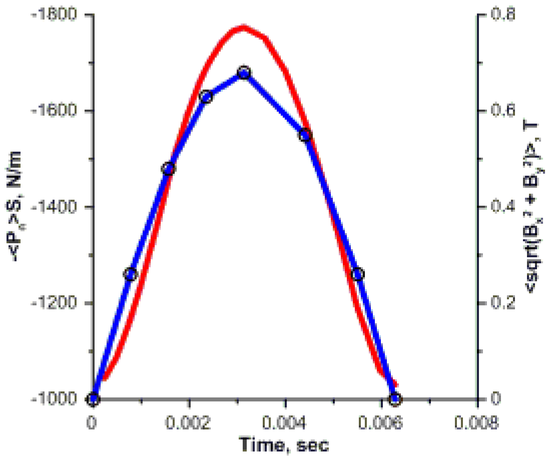

Fig 3. Calculation of the pressure on the model surface that integrated over the length of the plate (red curve) for different values of the magnetic field induction (blue curve)

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