Determination of the thrust of an ion thruster by the resonant aerodynamic method (RAM-method)

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Abstract. This paper presents the results of an experimental study of the jet thrust of ionized nitrogen flowing from the working chamber of an experimental sample of an accelerator ion thruster into a vacuum space. The resonant aerodynamic method (RAM-method) was chosen as the main research method. A method for determining low thrust and the design of a stand for implementing the RAM-method are proposed. The object of research is a prototype of an accelerator two-gap ion thruster with a solid-state microwave plasma generator and a toroidal resonator. The study showed that a 2.5 W microwave generator together with a 2.5 W accelerating potential difference voltage source at a nitrogen consumption of 0.1 mg/s creates an ion jet, the speed of which reaches 100 km/s. The current of the ion jet was 5.5-6 μA. The jet thrust was 0.141-0.188 μN.

1. Introduction
An important problem in the design of ion engines with low energy consumption is the problem of determining the true values of the parameters of the ionized gas jet. The most important parameter is the jet thrust. The difficulty of directly determining the thrust of an ion thruster with an energy consumption of less than 10 W is due to the small value of the jet pressure force on the sensitive element of the measuring device. For example, the thrust of the MMIT ion thruster with a power of 8 W, according to the authors [1], is: on argon - 0.217 mN, on xenon -0.392 mN. The MiDGIT xenon thruster produces jet thrust in the range of 0.25-0.48 mN with an energy consumption of 13-18 W [2]. The MRIT argon thruster [3] generates an ion thrust of 1.45-59 μN at an energy consumption of 13-15 W. The Japanese xenon ion thruster μ1 implements a thrust of 0.297 mN at a power consumption of 15.1 W [4, 5]. From the above description of the models of ion propulsion systems, it can be seen that the level of realized thrust is low, with a decrease in energy consumption, the value of the reactive force shifts to the region of micronewtons. The method of determining the thruster thrust is not clear from the above publications. The question also remains open whether the reduced thrust value is the average integral value of the reactive forces created by the neutral gas due to the pressure drop and the ionized gas accelerated by the potential difference of the ion-optical system. Often, in various authors, there is a theoretical calculation of the velocity and force of an accelerated ionized gas. The calculation data cannot fully reflect the real state of affairs.
Therefore, the development of a simple method for directly determining the thrust force of a jet jet of a low-power ion thruster is an urgent task.

There are many ways to register the traction forces implemented. All of them are based on the weight method: the sought unknown force is balanced by a known force. All methods can be divided into two categories: methods for measuring the total thrust of the propulsion system structure (dynamometric platforms) and aerodynamic methods that study the dynamic properties of a jet jet. The methods of the
first category are structurally more complex and involve the use of systems weightlessness imitations that allow compensating for the influence of power supply lines and voltage in flexible pipelines for supplying working gas. Naturally, the lower the level of thrust realized by the propulsion system, the greater the impact on the measurements are the manufacturing errors of weightlessness simulation systems. On the other hand, the presence of electromagnetic fields significantly limits the use of electronic devices in measurements. When testing ion thruster, electrical breakdowns are often formed between the grids of the ion-optical system, which cause electromagnetic interference in the signal lines of measuring instruments that distort the signal. It follows that the methods of measuring thrust should have a minimum number of electronic components.

On the basis of the research laboratory «Micro-traction propulsion systems of small spacecraft» («DUMIT MKA») Omsk State Technical University has developed a prototype of an accelerator two-gap ion thruster with a total energy consumption of 5-10 watts. The prototype implements stepwise acceleration of the microwave plasma in a high-frequency capacitive gap (diffusion of ions from the discharge gap), preliminary acceleration in an ion-optical system with a constant potential difference and acceleration in an alternating electric field of the gap of a toroidal resonator.

As part of the research of the prototype, in terms of determining the reactive thrust of an ionized gas, an aerodynamic method with resonant rocking of the sensor element was developed.

2. Problem statement

The authors developed and manufactured a prototype of an accelerating microwave ion thruster (UMD) with an energy consumption of less than 10 watts. The prototype implements the concept of stepwise acceleration of an ionized gas in the high-frequency gaps of a plasma generator and a toroidal resonator. The intermediate accelerator is a three-grid ion-optical system (IOS) with a potential distribution on the grids: +200 V, 0 V, -1100 V. The external diameter of the toroidal resonator is 140 mm (Fig. 1). The working medium in the tests was nitrogen.

![Figure 1](image-url). The exterior of the prototype of the UMD and a demonstration of its operation in a vacuum chamber (the red diode is lit on the first version of the current sensor, which means that there is a positive charge on the sensor element).

The main objective of the authors’ work is to study the high-frequency low-temperature ionization of gaseous working bodies in reactors based on solid-state RF and microwave elements and to study the gas-dynamic, electrical and thermal parameters of the plasma jet of a prototype ion-plasma micro thruster with the acceleration of ionized gas in a high-frequency gap into a space with low background pressure.

In this part of the work, the authors investigated the power characteristics of the accelerated jet of ionized nitrogen of the prototype of the UMD. The authors proposed the concept of resonant determination of the thrust of an ion thruster.

To determine the thrust force of the prototype jet jet, it was necessary to solve the following tasks:

1. To develop the concept of a resonant aerodynamic method for measuring the thrust of an ion thruster and to make a pendulum stand. Determine the attenuation coefficient of the pendulum;
2. To develop a system that provides pulsed voltage supply to the grids of an ion-optical system with an adjustable frequency;
3. Conduct vacuum experimental studies to determine the amplitude of the forced oscillations of the pendulum. Determine the magnitude of the driving force;
4. To conduct vacuum experimental studies in order to obtain the full ion current of the prototype by means of a Faraday cylinder and the ion flow velocity by the ion-label method. Define the value of the prototype thrust from the obtained speed and mass flow data;
5. Compare the thrust values obtained by the two methods.

3. Theory

Resonance (fr. resonance, from Lat. resono) is a frequency-selective response of an oscillatory system to a periodic external influence, which manifests itself in a sharp increase in the amplitude of stationary vibrations when the frequency of the external influence coincides with certain values characteristic of this system [6].

It is known that when the frequency of the driving force coincides with the natural frequency of the oscillatory system, the amplitude of the oscillations increases noticeably. Knowing the amplitude of the oscillations, the resonant frequency and the attenuation coefficient of the pendulum, it is possible to determine the driving force by the ratio:

$$P = 2 \cdot A_{RES} \cdot \beta \cdot m \cdot \sqrt{(2 \cdot \pi \cdot f_{RES})^2 + \beta^2 \cdot \frac{L}{H}}$$

where $A_{RES}$ - the amplitude of the pendulum at resonance; $\beta$ – the attenuation coefficient; $m$ – the mass of the pendulum; $f_{RES}$ - the resonant frequency (in Hz); $L$ – the distance from the pendulum suspension to its center of gravity; $H$ – the distance from the pendulum suspension to the center of pressure.

Figure 2 shows a stand for the implementation of the RAM-method.

![Figure 2](image)

**Figure 2.** The scheme of the sensitive element and the stand for the implementation of the RAM-method.

I Figure 2 shows the positions: 1 - a copper disk-screen; 2 – a suspension made of organic glass; 3 – a scale with a degree measure; 4 – a mirror (early amplitude measurements were carried out using a laser); 5 – a suspension support.

During the tests, the mass of the moving part of the stand was 10 grams, the distance to the center of gravity $L=172$ mm, the distance to the center of pressure $H=198$ mm. Accordingly, the amplitude was determined by the ratio:
The readings of the arrow installed on the copper screen were recorded by a webcam. The time code of the video recording was used to determine the attenuation coefficient of the pendulum (Fig. 6) and the preliminary resonant frequency.

For the operation of the RAM-method, the IOS voltage source was additionally equipped with a pulse voltage supply system. The pulse frequency was set by the pulse generator. In the prototype of the UMD, it is not possible to pulse a discharge in the microwave gap, which is a disadvantage of the method: the sensor element captures the fluctuations of the driving force. At the same time, there is an additional continuous flow of neutral gas and plasma accelerated by the first microwave gap in the UMD.

The scheme of the experimental setup is shown in Fig. 3.

![Figure 3](image)

**Figure 3.** Test scheme for determining the thrust of an ion thruster by the RAM-method: 1—a gas cylinder with a working substance; 2—a gearbox; 3—an electropneumoclap; 4—a throttle; 5—a flow meter; 6—a transition coupling; 7—a pressure gauge; 8—a vacuum chamber; 9—an ion engine; 10—a traction measurement stand.

The measurements are made according to the sequence:
1. Assemble the circuit (Fig. 3).
2. Install a traction measurement stand in the vacuum chamber. The disk screen is located 20 mm from the external grid of the toroidal resonator of the ion thruster;
3. Install a webcam in the vacuum chamber, so that the scale of the traction scale stand is visualized on the personal computer monitor;
4. Connect the electrical contacts of the microwave generator and the IOS to the power sources and check them;
5. Vacuum the system until a pressure of less than 18 Pa is reached;
6. Feed the working fluid (nitrogen) into the working cavity of the prototype ion thruster;
7. Turn on the microwave generator. Reach the occurrence of a high-frequency discharge;
8. Achieving a steady flow rate of the working fluid according to the flow meter readings [7];
9. Apply a pulse voltage to the grids of the IOS;
10. Using a webcam, register the deviation of the indicator arrow on the scale of the traction measurement stand (Fig. 4, 5);
11. Record the readings of the arrow indicator and the flow rate of the working fluid;
12. Perform a theoretical analysis of the obtained data according to formulas (1) and (2).
Figure 4. The image of the prototype of the UMD in experimental studies to determine the thrust by the RAM-method: 1—the prototype of the UMD; 2—the ion beam; 3—the pendulum; 4—the graduated scale; 5—the webcam

Figure 6 shows the damping curve of the pendulum oscillations in vacuum conditions. For the selected design of the sensor element, the attenuation coefficient was $\beta=0.002$ – for vacuum, $\beta=0.033$ - for air.
The resonant frequency was previously determined by the time code of the video recording and refined by the selection method on the pulse generator. The frequency was 1.25232 Hz.
The power supply voltage of the microwave generator is -6 V, the current consumption is -0.39 A.

Figure 5. Photo of the deviation of the indicator arrow during testing: 1—graduated scale; 2—indicator arrow

Figure 6. The attenuation curve of the vibrations of the sensor element in a vacuum
The ion thrust of the thruster is determined by the speed and mass flow rate of ions that have gone beyond the nozzle cutoff. According to the data from the Faraday cylinder, the beam current of the UMD prototype depends on three parameters:
– The voltage on the grid and the cathode of the ion-optical system;
– Voltage at the anode and grid of the ion-optical system;
– The power supplied to the microwave generator.
In the operating modes of the microwave generator specified above, and the rated voltage between the cathode and the grid 1100 V and the voltage between the anode and the grid 200 V, the beam current is 5.5-6 µA.
The mass flow rate of the ions involved in the creation of ion thrust can be determined by the formula:
\[ \dot{m}_l = \frac{m_I \cdot I_n}{q_e}, \]  
where \( m_I \) – is the mass of the ion (can be taken as the mass of a nitrogen molecule); \( I_n \) – is the beam current along the Faraday cylinder; \( q_e \) – is the electron charge.
Accordingly, the ion velocity can be determined by the formula:
\[ u_I = \frac{P}{\dot{m}_l}. \]  

As part of the study of the prototype of the UMD, an ion-label method was used to construct a diagram of the velocities of charged particles depending on the voltage at the cathode and the grid of the ion-optical system (Fig. 7). An enlarged fragment is shown in Fig. 7b (purple rectangle, Fig. 7a).
When testing the prototype of the UMD by the RAM-method, the grid-cathode voltage was constant and amounted to 1100 V. The grid-anode voltage was 200 V. The diagram shows that at these voltages, the ion velocity is at the level of 100 km/s (the average value according to the results of three measurements).
According to the classical theory, the velocity of a charged particle in a full vacuum in the absence of a voltage drop can be determined by the formula:
\[ u_{vac} = \sqrt{\frac{2 \cdot q_e \cdot U_{nom}}{m_I}}. \]  
According to the formula (5), the velocity of the nitrogen ion should be 86.8 km/s.
Figure 7. The speed diagram of the UMD prototype: a) – a general view; b) – an enlarged fragment for voltages of 350-650 V

4. Results experiments
As a result of the conducted studies, the angle of deviation of the forced oscillations of the pendulum ($\alpha_{RES} = 0.15 - 0.2^\circ$) and the amplitude of the oscillations ($A_{RES} = 0.45 \text{ mm}$) were obtained. The mass flow rate of neutral gas was 0.107 mg/s. The steady-state voltage between the grid and the cathode was 904 V at a current of 124 $\mu$A.
According to the formula (1), the value of the jet thrust was obtained. It was 0.141-0.188 $\mu$N.
According to the formula (4), the speed of the ionized working fluid was 76.312-101.749 km/s.
For comparison, the nitrogen ion speed of the UMD prototype, determined by the ion-tag method, was 100 km/s.

5. Discussion of results
As part of the study of the prototype of an accelerating two-gap microwave ion thruster, a simple method for determining the reactive thrust of an ionized component of the thruster working fluid was proposed. The method is implemented in the case of an impact that can be given an impulse character.
In the case of the UMD prototype, this is the voltage at the electrodes of the ion-optical system.
An experiment was conducted to determine the thrust of the prototype on the selected unchanged input parameters: the constancy of the neutral gas flow rate; the constancy of the voltages on the electrodes of the ion-optical system and the constancy of the supply voltage of the microwave generator. The velocity of the ionized gas was determined from the obtained values of the jet thrust and the readings of the Faraday cylinder. These values are correlated with the values of the flow rates obtained by the ion-label method.
The authors conducted many experiments with the prototype of the UMD in terms of the RAM-method. Changes in the mass flow rate of neutral gas showed that there was no connection between the gas flow rate and the oscillation amplitude. Measurements by the Faraday cylinder also showed no influence of the flow rate of the working fluid on the beam current.
Thus, the RAM-method shows only the thrust of the ionic component of the jet.
The disadvantages of the manufactured stand for the RAM-method include the large mass of the pendulum. The weight of the pendulum was 10 grams. By reducing the mass, you can achieve a greater sensitivity of the stand to the driving force. At the same time, the rigidity of the structure should not be affected.
6. Conclusion

The article presents the results of the authors’ work in the field of measuring the power characteristics of low-thruster ion engines for small spacecraft. The authors developed a stand and presented a resonant aerodynamic method for determining the reactive thrust of a prototype UMD with microwave plasma generation in a capacitive emitter followed by ion acceleration by a constant potential difference [8]. According to the results of the measurements, the thrust and velocity of the ionized gas were obtained.

The total power consumption of the UMD prototype was 5 W for all systems, a thrust of 0.141-0.188 μN was realized, the ion velocity was 76.312-101.749 km/s.

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