Experimental Study on the Performance of One Micro Pulsed Plasma Thruster

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Abstract. In the vacuum environment, the experimental platforms of discharge waveform measurement, impulse bit measurement and electromagnetic interference testing were set up for one designed micro pulsed plasma thruster (μPPT) to study the effect of the capacitance capacity, discharge voltage and electrode pads’ spacing on the discharge waveforms and impulse bit of it, as well as the electromagnetic interference. The experimental results show that the oscillation of discharge waveforms can be reduced by increasing the capacitance capacity and the distance between the two electrodes or decreasing the discharge voltage. With the increasing of the capacitance capacity, the discharge voltage and the distance between two electrodes, the impulse bit of μPPT rises. In the frequency range of 0.8~2.6 GHz, the work of μPPT will not cause electromagnetic interference to spaceborne equipment and its signal transmission.

1. Introduction

Pulse plasma thruster (PPT) is an electromagnetic thruster which produces electromagnetic field by pulse discharge of the capacitor, produces plasma by ablation and ionization of the working medium, and then accelerates plasma by electromagnetic force. Usually, PPT, the mass of which is less than 1 kg and the discharge energy of which is less than 5 J is called μPPT, whose volume, mass and power consumption are at least one order of magnitude lower than that of PPT [1]. Because μPPT is light in mass, small in volume, simple in structure, long in life and high in specific impulse and control precision, it has a broad application prospect in orbit maneuver, attitude control, resistance compensation and formation flying of modern NanoSats. Although the structure of μPPT is simple, the pulse working time is short, the working process is complex, and the coupling of electric, magnetic, optical and thermal fields is involved [2]. Therefore, it is extremely necessary to study the real working conditions of μPPT through experiments.

In the experiment, the effect of the capacitance capacity, discharge voltage and electrode pads’ spacing on the discharge waveforms and impulse bit of μPPT was studied [3-7]. At the same time, the electromagnetic interference of μPPT to the spaceborne equipment and its signal transmission were also tested.

2. Experimental devices

2.1. The μPPT prototype

The main parameters of the μPPT experimental prototype (as shown in figure 1) are shown in table 1.
Table 1. Parameters of the μPPT prototype

| parameters                                      | values                                      |
|------------------------------------------------|---------------------------------------------|
| Sparkplug size (screw thread diameter)          | M10                                         |
| Sparkplug mass (g)                              | 8/15                                        |
| Electrode pads size (length*width*thickness/mm) | 12*10*3.5                                   |
| Electrode pads spacing (mm)                     | 0-33 (adjustable)                           |
| Circuitry system size (mm)                      | 100*100*30                                 |
| Circuitry system mass (g)                       | <200                                        |
| Prototype body mass (g)                         | <150                                        |
| Single capacitance capacity (μF)                | 0.1                                         |
| Charging voltage (V)                            | <1700                                       |
| Main discharge energy (J)                       | <5 (adjustable)                             |
| Ignition frequency (Hz)                         | <2 (adjustable)                             |
| Total size (length*width*thickness /mm)         | 35*50*40                                    |
| Total mass (g)                                  | <350                                        |

Figure 1. The μPPT experimental prototype

2.2. Vacuum environment
The vacuum chamber used in the experiment, the final atmospheric pressure of which is 5×10⁻⁴ Pa, is 3 m in length, 2.4 m in diameter. In the vacuum system, the pre-pumping subsystem is mainly composed of one ZJP-600 pump with Roots relief valve and two 2X-70A oil-seal rotary vane pumps. The working subsystem is mainly composed of one 2X-30A oil-seal rotary vane pump, one Z-300 oil diffusion booster pump and two K-900C oil diffusion pumps of high vacuum and wide area. When the vacuum system was working, the vacuum degree of the vacuum chamber was pumped below 5 Pa by the pre-pumping subsystem, then it was pumped below 3×10⁻³ Pa by the working subsystem to meet the requirements of the working environment of μPPT.

2.3. Discharge waveform measuring equipment
The voltage of the capacitor was measured by the P5100 high voltage probe produced by Tektronix Company. Before using the high voltage probe for data acquisition, the DPO4034 four-channel oscilloscope produced by Tektronix Company was used to compensate and correct it. The attenuation coefficient of the probe is 100, the bandwidth is 250 MHz, and the allowable peak voltage is 2500 V. The current of the discharge loop was measured by the CWT150 rogowski coil produced by PEM Company and its corresponding integrator. The conversion coefficient of the CWT150 rogowski coil is 5000 A/V, the sensitivity is 0.2 mV/A, and the allowable peak current is up to 30 kA.

2.4. Impulse bit measuring system
Impulse bit is one of the most important performance parameters of μPPT. In this paper, the C-type
torsion pendulum designed for micro thrust measurement in our laboratory was used to measure the impulse bit of μPPT. The specific structural composition is shown in figure 2.

![Image of torsion pendulum]

1-thruster, 2-torsion arm, 3-C-type torsion rod, 4-reflecting lens, 5-He-Ne laser, 6-calibration system, 7-counterweight, 8-Position Sensitive Detector (PSD), 9-optical path magnifying glass group, 10-wiring device

Figure 2. The C-type torsion pendulum

The impulse bit of the thruster can be calculated by processing calibration data and measuring data. The distance between the calibration device and the torsion rod, namely the torque of the calibrated impulse, is L. The distance between the thruster and the torsion rod, that is the torque of the impulse to be measured, is R. The relationship between the calibrated impulse and the impulse to be measured leading to the same swing amplitude is as follows:

\[ I_{bit} = L \frac{I}{R} \]

In the experiment, a non-contact electromagnetic damping method was used. It is that basing on the real-time motion state of the torsion pendulum, the adjustable current is input into the calibration coil, thus the corresponding ampere force is produced to hinder the motion of the torsion pendulum. In this way, the attenuation can be accelerated and the measurement efficiency can be improved.

2.5. Electromagnetic interference testing facility
The μPPT with 3 µF ultrahigh-voltage pulsed film capacitor was selected for the electromagnetic interference testing. The testing facilities include a AV4051F spectrum analyzer, a HPE4421B signal generator and a number of transmitting and receiving antennas. The AV4051F spectrum analyzer can display 300 MHz frequency spectrum at both sides of the setted center frequency. The signal generator and the spectrum analyzer are connected to antennas respectively. The μPPT, the distance from which to the spectrum analyzer antenna is 0.5 m and to the signal generator is 1 m, is placed between them. And its distance from the ground is 1.2 m.

3. Experimental measurement

3.1. Experimental results and analysis of μPPT performance testing

3.1.1. Discharge characteristics. Figure 3(a) and figure 3(b) are the discharge voltage curve and the current curve respectively with different capacitance capacities. From figure 3, we can see that when the capacitance capacity increases, the discharge period of the capacitor increases, the peak discharge current increases, the reverse voltage and reverse current decrease, so the impact of the discharge process on the capacitor is reduced.

Figure 4(a) and figure 4(b) are the discharge voltage curve and the current curve respectively with different discharge voltages. From figure 4, it can be seen that when the initial discharge voltage of the capacitor increases, the discharge period of it is basically unchanged and the peak discharge current
increases. The reverse voltage and reverse current increase, and the oscillation of discharge waveforms intensifies.

Figure 5(a) and figure 5(b) show the discharge voltage curve and the current curve with different plate spacing. From figure 5, we know that when the plate spacing increases, the electric resistance increases while the oscillation intensity of discharge waveforms weakens.

To sum up, the oscillation of discharge waveforms can be slowed down by increasing capacitance capacity and plate spacing or decreasing discharge voltage, which is very beneficial to the performance improvement of μPPT.
3.1.2. **Impulse bit measurement.** Figure 6 shows the impulse bit curve with different capacitance capacities. From figure 6, it can be seen that when the capacitor capacity increases, the impulse bit of μPPT increases and the increasing rate is almost unchanged.

Figure 7 shows the impulse bit curve with different discharge voltages. From figure 7, we know that when the initial discharge voltage of the capacitor increases, the impulse bit of μPPT increases, and the increasing rate rises slightly with the increase of initial discharge voltage.

Figure 8 shows the impulse bit curve with different plate spacing. From figure 8, we can see that when the capacitor capacity increases, the aspect ratio of the electrode plate of μPPT increases, the corresponding impulse bit also increases with the increasing rate almost unchanged.

In conclusion, the increase of discharge voltage, capacitance capacity and plate spacing is beneficial to increasing the impulse bit of μPPT when the discharge energy is low (< 5J).

3.2. **Electromagnetic interference testing**

With the operation of μPPT ignited at a frequency of 2 Hz, four frequency bands (0.5~1.1 GHz, 1.1~1.7 GHz, 1.7~2.3 GHz, 2.3~2.9 GHz) were selected for electromagnetic interference testing. The spectrum analyzer was adjusted to send out signals with the center frequency of 0.8 GHz, 1.4 GHz, 2.0 GHz and 2.6 GHz respectively. Observing the electromagnetic wave spectrums received by the spectrum analyzer during the operation of μPPT, it was found that the received spectrums when μPPT was in operation are basically the same as those when μPPT was not working. It illustrates that there is no interference in the transmission and reception of signals in the neighboring frequency ranges of 0.8 GHz, 1.4 GHz, 2.0 GHz and 2.6 GHz during the discharge of μPPT. The testing results of signals whose center frequency is 2.0 GHz are shown in figure 9 and figure 10.

To conclude, in the frequency range of 0.8~2.6 GHz, the work of μPPT will not cause electromagnetic interference to the related instruments and their signal transmission.

4. **Conclusions**

In this paper, the performance of a specific μPPT prototype, mainly the discharge characteristics and impulse bit variation with different capacitance capacities, discharge voltages and electrode pads’
spacing, has been studied. In addition, the electromagnetic interference experiment of μPPT has been completed, either. The main conclusions are as follows:

- When the capacitance capacity is increased, the single pulse discharge energy of μPPT increases and the oscillation degree of discharge waveforms weakens, making the impulse bit of μPPT increase. Therefore, when the quality and volume requirements of μPPT are satisfied, its system performance can be optimized by increasing the capacitance capacity.
- When the discharge voltage increases, the peak value of discharge waveforms and the impulse bit of μPPT increase. However, the high discharge voltage will cause the intense oscillation of discharge waveforms, shortening the life of the capacitor and possibly leading to the "secondary ablation" of the working medium which is very harmful to the performance of μPPT. Therefore, we can't blindly increase the discharge voltage.
- With the increase of plate spacing, the oscillation degree of discharge waveforms weakens, the releasing time of capacitor energy decreases, and the impulse bit of μPPT increases. However, in the design of μPPT, we still need to consider the space size of thruster when selecting the distance between two electrodes.
- The electromagnetic interference testing of different frequency bands has been carried out. The results indicate that the working medium of μPPT will not cause electromagnetic interference to the spaceborne equipment and its signal transmission in the frequency range of 0.8–2.6 GHz.

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