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Ground performance tests and evaluation of RF ion microthrusters for Taiji-1 satellite

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The “Taiji-1” satellite is a test satellite for the verification of those key technologies involved in the “Taiji Program in Space”, China’s space gravitational wave detection project; and the spacecraft drag-free control technology is one of its key technologies used to improve the microgravity level of spacecraft. Thus, a demand for a high-precision and continuously adjustable micronewton-level thrust has been proposed on the spacecraft micro-propulsion system. In allusion to such a task, a set of micronewton-level RF ion propulsion system was designed based on the principle of self-sustained discharge of RF plasma so as to conduct studies on the parameter optimization and engineering of RF ion thruster, and an engineering prototype of the micronewton-level continuously adjustable RF ion thruster was successfully developed to meet the design index requirements. The operating parameters have been solidified through further studies on the extreme operating conditions of the engineering prototype, and a series of ground simulation tests of space environment were successfully passed. The ground test and calibration experiment results of the micro-propulsion engineering prototype show that the engineering prototype has fully met the requirements of the Taiji-1 mission, thus having laid a solid foundation for the successful space verification of the key technologies for the “Taiji-1” satellite.

Keywords: RF ion thruster; Taiji-1; Micro-propulsion; gravitational wave; thrust calibration.

1. Introduction

Fundamental space science experiment satellites usually need to be manufactured on a space experiment platform with extremely high microgravity. Any nonconservative forces (atmospheric drag, radiation pressure and cosmic radiation) that the satellite receives need to be continuously compensated by the micro-propulsion system, and the inter-satellite pointing control must be maintained for a long time.[1] Thus, the demands for

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extremely high thrust output performance, thrust control requirements and high specific impulse and long life for the long-term operation of the micro-propulsion system have been raised.

Gravitational-wave detection is a method to reveal the nature of gravity, space–time structure and the evolution of the universe.[2] Therefore, the world's major aerospace powers have been successively formulated; and the gravitational wave detection plans have been carried out.[3] The European Space Agency (ESA) formally proposed the Laser Interferometer Space Antenna (LISA) plan in the 1990s. Several key technologies were also proposed in the plan: long-distance interferometry, drag-free control and ultra-quiet and ultra-stable satellite platforms.[4] In December 2015, ESA successfully launched LISA-Pathfinder and completed the space verification of the key technologies.[5] In 2018, China's space gravitational wave exploration Taiji program was further funded by the Chinese Academy of Science to perform the first step of launching a satellite, Taiji-1, as the Taiji pre-pathfinder for testing some important technologies.[6]

As the drag-free actuator of the "Taiji Program in Space" satellite group, the micro-propulsion system needs to provide a micronewton-level continuously adjustable thrust, the thrust resolution of which should be better than 0.1 μN, while the thrust noise should be better than 0.1 $\mu\mathrm{N}/\sqrt{\mathrm{Hz}}$ within 0.1 mHz–1 Hz, so as to compensate for the nonconservative forces on the satellite.[7] According to the stringent requirements of space gravitational wave detection missions for micro-propulsion systems, the types of micro-propulsion technologies that can meet its requirements are limited, mainly including cold micro- propulsion, field emission electric propulsion (FEEP) and ion micro-propulsion.[8] Among those propulsion patterns, the cold thruster is with the most mature technology and a relatively simple system, but the specific impulse is quite low. It needs to carry a large amount of gas propellant for long-term missions such as space gravitational wave detection, which is a severe waste of the satellite load and internal space. Field emission electric micro-propulsion is featured with a relatively simple principle and system; however, its lifetime is short (a few thousand hours). It's also with a severe problem of plume pollution. RF ion propulsion technology is an electric propulsion technology based on the principle of RF plasma discharge. It has no additional permanent magnets and cathodes and is easy to miniaturize.[9] It is featured with a wide range of thrust, high controllability, high resolution, low noise, fast response and long lifetime. It can realize high-precision thrust control of 1–100 micronewton levels, with a high specific impulse, and meet the lifetime needs of long-term space missions for micro-propulsion systems. It is regarded as one of the feasible schemes for the drag-free control system's implementation mechanism, which is also the main actuator of the Taiji-1 Satellite, in both the European LISA Project and the Chinese Taiji Program.[10,11]

In allusion to the demands of space gravitational wave detection technology test satellites for a micronewton-level propulsion system, the Institute of Mechanics of the Chinese Academy of Sciences has developed a set of micronewton-level continuously adjustable RF ion thruster (μRIT-1). Studies have also been carried out on the engineering of the micro-propulsion system, successfully developed the engineering prototype products, and then delivered such products to the satellite system on time. In this paper, importance has been attached to introducing the composition of the Taiji-1 RF ion micro-propulsion system, the thruster's engineering process and the results of ground calibration.

2. RF Ion Micro-Propulsion

Each microthruster of the RF ion micro-propulsion system of the "Taiji-1" Satellite is designed to be independently operable with a continuously adjustable thrust which can output high-precision and low-noise thrust according to the requirements of drag-free control. The requirement is that the thrust of a single thruster shall cover a range of 5–50 μN, the single thruster thrust resolution should be less than 1.5 μN, the thrust noise of a single thruster should be less than 1.5 $\mu\text{N}/\sqrt{\text{Hz}}$ (10 mHz–1 Hz), the thrust rise and fall time should be less than 50 ms and the system design life should not be less than a year.

As required for the purpose of those tasks mentioned above, four units of μRIT-1 RF ion microthrusters (numbered A1, A2, B1 and B2, respectively) were put into use. Each microthruster can work independently, the thrust adjustment of which can be achieved by merely adjusting the voltage of the positive high voltage module. The propellant mass flow and RF power are both fixed. At the same time, eight field emission carbon nanotube neutralizers classified into two groups in a 4+4 parallel connection pattern were put into use. Each group can meet the need of on-orbit neutralization while working separately. Since the field emission neutralizer does not require a gas proppellant and the thruster works in a fixed gas mass flow mode, the mass control unit only needs to get provided with four identical and stable gas mass flows, which can greatly reduce the complexity and improve the reliability of the mass control unit.

The working principle of RF ion microthruster is shown in Fig. 1.[12] The gas propellant flows through the mass flow controller and the gas distributor and enters the discharge chamber. After that, it collides with the high-energy electrons in the plasma, forming a self-sustained RF plasma discharge. The ions in the plasma are accelerated and ejected by the ion optical system to form an ion beam, generating a reverse thrust. The carbon nanotube neutralizer emits electrons to neutralize the ion plume, making the propulsion system electrically neutral to guarantee its effectiveness. In this self-sustained discharge mode, a built-in electron source is not required, and the fast and accurate thrust adjustment can be achieved by merely adjusting the acceleration voltage.

The RF ion micro-propulsion system is mainly composed of two microthruster clusters, one electric control unit and one mass flow control unit. The mass flow control unit controls and monitors the propellant's flow entering the thrusters by realizing the 4-channel high-precision mass flow control. The microthruster ejects the ion beam to generate a designated amount of thrust. The neutralizer ejects the electron beam to neutralize the ion beam, thereby ensuring the propulsion system's electrical neutrality and the spacecraft's effective operation. The electric control unit mainly provides power for the microthruster and the neutralizer.

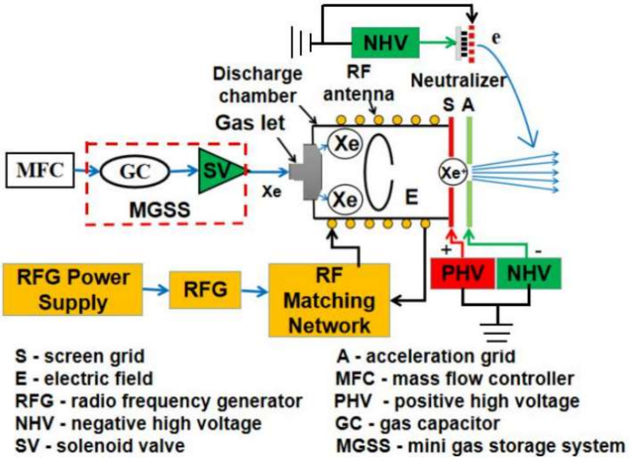

Fig. 1. μRIT-1 Structure and principle.[12]

The electric control unit establishes its communication with the satellite platform while monitoring and controlling the thrust.

The RF ion microthruster can use various gases as the propellant, and Xe is used in this mission, for it is commonly used as the propellant. Since this satellite platform is equipped with a variety of micro-propulsion devices, where Xe is used as the propellant, the Xe storage and supply system can be shared by the devices. The satellite system generally provides the Xe storage and supply system; therefore, it is not separately included in the RF ion micro-propulsion subsystem.

3. Performance Tests and Evaluation

Targeting at the requirement of the “Taiji-1” satellite mission for the micronewton-level propulsion system, a set of micronewton-level RF ion thruster (μRIT-1) is designed and developed, and its key components are optimized. The thruster’s stability and performance are to be directly affected by the choices of materials and parameters of the RF antenna, discharge chamber and ion-optical system. According to the theoretical analysis and experience summary of Prof. Leob from Giessen University and given the demand of micronewton-level thrust, it is more appropriate to design the discharge chamber’s internal diameter as 1 cm, and other structures need to be explicitly optimized.[13] After conducting studies on the effects of ion optical system, the material of discharge chamber, propellant mass flow, RF coil, RF frequency, RF power, and grid voltage on the thrust output performance, the operating limit parameters of the thruster have been obtained and the operating parameters that meet the task requirements are cured in these studies. The engineering prototype also needs to pass the space environment ground simulation test while the curing parameters of the engineering

Table 1. Working limit parameters of RF ion thrust cluster.

No.	Gas flow rate (μg/s)	Min RF power (W)	Min thrust (μN)	Max thrust (μN)
1	3	8.15	4.0	55.6
2	4	7.63	4.0	61.2
3	5	6.68	4.2	53.1
4	6	6.17	4.2	53.5
5	7	6.2	4.4	61
6	8	5.97	4.5	61.3
7	9	5.93	4.6	62.6
8	10	5.8	4.7	55.5

prototype and the results of various environment simulation tests are to be introduced in the following session.

3.1. *Curing working parameters of the microthruster cluster*

The working limit parameters of μRIT-1 microthruster are shown in Table 1. The RF power needs to be adjusted to meet the thrust range requirements under different propellant mass flow. When the propellant mass flow is selected as 8 μg/s, the RF power is about 6 W, and the positive high voltage adjustment range is 300–2000 V, which meets the requirements of the design indicators in the previous stage. In the later stage, RF power can be saved by 1 W, that is, lowered to 5 W while generating the same thrust range to meet the mission requirements by further optimizing the material and design parameters of the RF antenna.

The carbon nanotube field emission neutralizer's electron emission capability and emission stability matched with the microthruster cluster have basically met the technical indicator requirements. For detailed relevant parameters, see Ref. 10.

3.2. *Microthruster ignition reliability test and working stability test*

The RF microthruster's ignition reliability directly affects the success of the micro-propulsion system, which is the most critical issue. A self-excitation ignition method without a neutralizer that is to realize the self-sustained discharge excitation of RF plasma through a gas breakdown when being hit by instantaneous pressure impact under the strong electric field of grid electrode has been proposed. Such a method is proven feasible; however, the relevant conditions for ignition need to be explored and a reasonable ignition threshold needs to be set to guarantee the ignition reliability.

The ignition reliability problem is solved through experimental research after setting reasonable ignition threshold conditions (gas pressure, orifice aperture, gas path length, gas volume, high-voltage threshold, RF power, RF frequency, etc.). Before the 100 h work stability evaluation test, the thruster engineering prototype was subjected to 300 on–off tests at the average temperature (1 min for each on and off). After the life test, another 500 on–off tests were carried out. It showed no exception, which means that the engineering prototype's ignition reliability reaches 100% at the room temperature. The ignition reliability at high and low temperatures has also been verified through thermal vacuum tests, all of which have been successful.

A mission of a long-term working stability test was carried out to verify the long-term working stability, reliability and changes in the microthruster's performance over time. A 100 h work stability verification test was carried out on the engineering prototype of the microthruster cluster. With the closed-loop thrust output (50 μN) adopted, the thruster was in normal working conditions throughout the process. The carbon nanotube field emission neutralizer's emission performance decreased slightly during the 100 h life test, and it can meet the mission's requirements by making compensation through derating design. See Ref. 14 for details.

3.3. *Mechanical test of microthruster cluster*

The mechanical test mainly checks the internal discharge chamber's ability, acceleration grid and neutralizer components of the microthruster to withstand sinusoidal vibration, random vibration and shock. It is carried out following the requirements of the satellite product environmental test.

The mechanical tests are carried out according to the qualification test conditions. After the sinusoidal and random vibration tests are completed in all directions, carry out 1000 g impact tests twice in each direction, and then perform a structure detection on the spot. The performance test is performed again after the prototype is retrieved. The test results showed that the microthrusters' internal components are free of damage and cracks, and the performance of the microthruster remained the same before and after the test. The comparison of technical parameters is shown in Table 2.

3.4. *Thermal cycle test of the microthruster cluster*

The thermal cycle tests are carried out to assess the system's ability to withstand temperature cycle changes under normal pressure to expose process defects and ensure quality. The microthruster and the neutralizer cannot be energized in the high and low-temperature thermal cycle tests and must be energized under a vacuum environment. Besides, the thermal test under normal pressure shows a slight impact on the neutralizer's emitter. Therefore, it is reasonable to convert the thermal cycle test of the microthruster cluster into the thermal vacuum test during the development process of the engineering prototype.

The thermal vacuum test mainly assesses the ability of the system components to withstand the thermal vacuum environment. The engineering prototype's thermal vacuum test conditions are experiment pressure: less than 1.3×10^{-3} Pa; and test temperature: -20℃–$+45$℃. In the thermal vacuum test stage, the highest vacuum can reach 10^{-5} Pa and maintain below 5×10^{-4} Pa while the thruster is operating, and the vacuum conditions meet the test requirements.

Table 2. Comparison of technical parameters of the microthruster before and after the acceptance level mechanical test.

Thruster number	Test item	Before mechanical test	After mechanical test
A1	RF power (W)	4.98	5.02
	Air pressure (kPa)	11	11
	Positive high voltage (V)	1980	1980
	Beam current (mA)	1.01	0.97
	Thrust (μN)	70.4	67.7
A2	RF power (W)	5.1	5.02
	Air pressure (kPa)	11	11
	Positive high voltage (V)	1980	1980
	Beam current (mA)	0.968	0.988
	Thrust (μN)	67.5	68.9
B1	RF power (W)	5.05	5
	Air pressure (kPa)	11	11
	Positive high voltage (V)	1980	1980
	Beam current (mA)	0.88	0.9
	Thrust (μN)	61.4	62.8
B2	RF power (W)	4.93	5
	Air pressure (kPa)	11	11
	Positive high voltage (V)	1980	1980
	Beam current (mA)	0.98	0.95
	Thrust (μN)	68.4	66.3

In the thermal vacuum test, the microthruster cluster switches among single, double and full working modes; the thrust command is set as 5, 30 and 50 μN, respectively in the closed-loop thrust control mode, and the working state in each mode is normal. The thruster does not encounter the problem of start failure at rather low temperatures, and the thruster's working performance is even better than that at room temperature. That is due to the low Ohmic loss and high efficiency of RF power transmission at low temperatures, thereby presenting a better working performance. Similarly, the RF ion microthruster's performance decreases slightly under a high-temperature environment. During the warming-up process, which is lower than the low-temperature state, the acceleration voltage required to maintain the same thrust is higher. The thruster needs to work continuously for more than half an hour after ignition to achieve thermal equilibrium. The closed-loop thrust control is used to achieve high-precision thrust output without affecting task execution.

4. Thrust Calibration

A set of a micro-newton-level thrust measurement system based on a torsional balance was designed and developed so as to calibrate the microthrusters thrust on the ground. The system adopts a high-precision, high-resolution capacitive displacement sensor as the torsion angle displacement sensing device, uses a high-precision electronic balance to calibrate the electrostatic comb, then uses the electrostatic comb to calibrate the torsional balance to obtain the relationship between thrust and angular displacement, and uses the standard weak force generated by the electrostatic comb to measure the thrust resolution and range of the torsional balance. The system is featured a measurement thrust range of 0–400 μN, a thrust resolution better than 0.1 μN, and a thrust noise power spectral density better than 0.1 $\mu N/\sqrt{Hz}$ (10 mHz–1 Hz), which fully meets the thrust calibration requirements of the microthruster required for this task.[15]

The thrust measurement system was used to calibrate the thrust range, thrust resolution and thrust noise of thrusters A1, A2, B1 and B2. The thrust range and resolution of each thruster are calibrated according to the thrust step measurement method, and the calibration results of each thruster's thrust range are shown in Table 3. The maximum thrust of each thruster exceeds 60 μN, which meets the requirements of the mission. It can be seen from the table that the actual measured thrust is greater than the thrust command value, and the reason is that the thrust command is given in a linear relationship between thrust and voltage. However, the actual thrust output is nonlinear with voltage, resulting in a larger output deviation. The closed-loop thrust output deviation can be guaranteed of less than 2% after correcting the thrust calculation formula according to the calibrated measured thrust values.

The thrust resolution of the thruster mainly depends on the resolution of the positive high voltage output. The four positive high voltage outputs' characteristics are the same, thus ensuring the thrusters' thrust output characteristics. Taking thruster B2 as an

Table 3. Calibration of the thrust range for the microthruster's flying parts.

Thrust range calibration				
Thruster number	Measured thrust (μN)			
	A1	A2	B1	B2
Thrust command: 5 μN	4.5	6.3	5.1	5.2
Thrust command: 10 μN	10.4	12.4	12.4	10.2
Thrust command: 20 μN	22.4	23.4	23.3	23.3
Thrust command: 30 μN	32.9	33.9	32.6	33.8
Thrust command: 40 μN	43.7	44.3	42.9	43.5
Thrust command: 50 μN	53.8	53.9	52.6	54
Thrust command: 60 μN	64.5	64.9	64.9	64.5

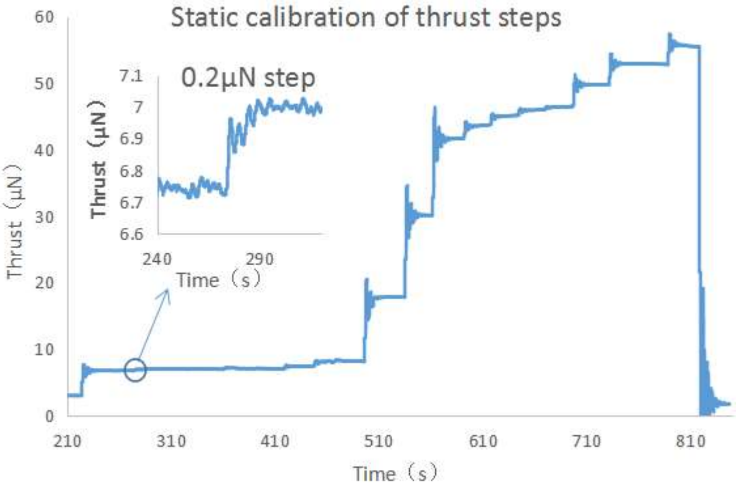

Fig. 2. Thrust range and thrust resolution calibration of thruster B2.

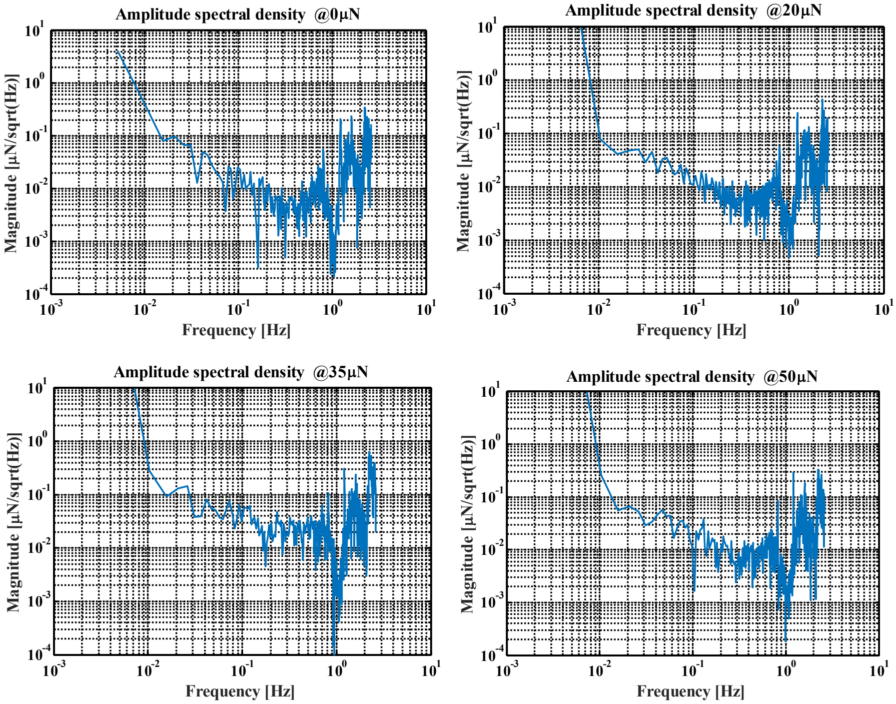

Fig. 3. Thrust noise power spectral density (@0 μN, 20 μN, 35 μN and 50 μN) of Thruster B2.

example, its thrust resolution is better than 0.2 μN, as shown in Fig. 2. At the same time, its thrust noise is better than 0.2 μN/√Hz in the 10 mHz~1 Hz frequency band (see Fig. 3). Due to the short measurement time, only 5 minutes of experimental data are recorded in each thrust step; some thrust steps exceed 0.2 μN/√Hz at 10 mHz but are also lower than 0.5 μN/√Hz. The rise and fall time of the output thrust from the microthruster is not measured directly on the measuring device; instead, it is evaluated based on the high-voltage module's voltage and current response time. The open-loop thrust rise and fall time evaluated by the high-voltage output characteristic are less than 20 ms, which meets the mission's requirements.

While completing the RF ion microthruster engineering, the engineering studies on the matching neutralizer, the mass flow controller and the electronics module are also completed, and the engineering prototype of the RF ion micro-propulsion system is successfully developed. As the primary actuator of the drag-free control system of the Taiji-1 satellite, the RF ion micro-propulsion system has been flying in orbit for more than one year and has reached the requirements of design life evaluation. At present, the RF ion micro-propulsion system has completed the on-orbit function and performance evaluation and supported the "Taiji-1" satellite to complete China's first drag-free control function verification, and the mission was a complete success.[16]

5. Conclusion

In response to the demand of the high-precision, continuously adjustable micronewton-level thrust output on the spacecraft micro-propulsion system proposed by Taiji-1 satellite, the forerunner of China's "Taiji Program in Space" for detection of gravitational waves in space, a set of engineering prototype of micronewton-level RF ion thruster cluster was designed and developed based on the principle of inductively coupled self-sustained discharge of RF plasma. This set of engineering prototypes has undergone mechanical tests and thermal vacuum tests, and its operating performance is relatively stable. In the ground calibration test and evaluation, all the four thrusters can achieve 5–60 μN continuously adjustable thrust output with their thrust resolution better than 0.2 μN, their thrust noise better than 0.2 uN/√Hz, and their open-loop thrust rise and fall time of less than 20 ms, which is better than mission evaluation indicators. As the primary actuator of the drag-free control system of the Taiji-1 satellite, it has completed the on-orbit function and performance evaluation and the drag-free control function verification, and the mission is a complete success. However, the development cycle of the RF ion micro-propulsion system load was restricted to only 10 months due to the task's urgency. In order to reduce the difficulty of project implementation, the system scheme was greatly simplified; therefore, the microthruster's performance and service life were sacrificed to a certain extent. The engineering prototype's performance are of considerable potential for improvement through the subsequent optimization design. It is expected to meet the ultimate technical indicator requirements of the gravitational wave detection mission in space.

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