Flight Demonstration of Electrostatic Thruster Under Micro-Gravity

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Abstract

Based on a new concept, a low power electrostatic thruster is being developed for its application to 50 kg class satellite, which is named "Microwave Engine". The proto-model (PM) of the microwave engine was manufactured and the qualification test (QT) was conducted. The estimated performances are 1250 seconds in specific impulse, 0.36mN in thrust and 10% in thrust efficiency when it is operated at 26.6W. To evaluate the feasibility of its accelerating mechanism, the flight demonstration of a plasma thruster is implemented under microgravity. The demonstrated thruster has an aperture of 19 mm in diameter. The same accelerating mechanism as Microwave Engine is applied to the plasma thruster although there is a difference in the mechanism of generating plasma. The flight demonstrator utilizes the glow discharge while the microwave discharge is applied to Microwave Engine. In this study, the thrust is estimated based on the flight path of the plasma thruster under microgravity, the swing of its pendulum under 1G and the beam theory of its copper wires. These corresponding thrusts are 0.36 mN, 0.20 mN and 0.11 mN, respectively. In addition, a series of its flight images is shown in this paper. As a result, the reasonable flight performance validates the accelerating mechanism of Microwave Engine.

Introduction

At the present time, there is new tendency in which a constellation of small satellites is launched into low earth orbit for their networking operations, instead of launching traditional large geostationary satellites. For this new change, the demand of low power electric propulsion system for an attitude control and station keeping of small satellites is getting larger. Based on this situation, a low power electrostatic thruster has been developed for its application to 50-100 kg class satellite, which is named "Microwave Engine". In this mechanism, the advantage of generating plasma by microwave made the low power operation of Microwave Engine possible. This operational performance was obtained in the previous work [1,2]. In the former part of this paper the microwave engine system and the results of the qualification test are described.

The latter part of this study describes that the flight demonstration of a plasma thruster is implemented under microgravity to evaluate the feasibility of the accelerating mechanism of microwave engine, based on the fact that the plasma thruster has the same accelerating mechanism as microwave engine.

Principle of Microwave Engine

The following characteristics of this new thruster are there. This thruster comprises an ion acceleration chamber and electron emitter (neutralizer). Propellant gas is xenon. The plasma is generated using microwave discharge. Two electrodes are located at upstream and downstream of the discharge chamber, respectively. The neutralized is combined with the electrode of the downstream as well as the hall type accelerator. Applying acceleration voltage between two electrodes, an electrostatic field gradient is formed in the plasma, accelerating ions to generate thrust. The principle of the microwave engine is represented in Fig.1. Figure 2 shows the photograph of the microwave engine head which equips eight neutralizers on the front surface and four igniters inside the discharge chamber. The aperture diameter of the thruster is one centimeter. Figure 3 shows the assembly of the thruster system. Typical performances of the microwave engine are described in Table 1.

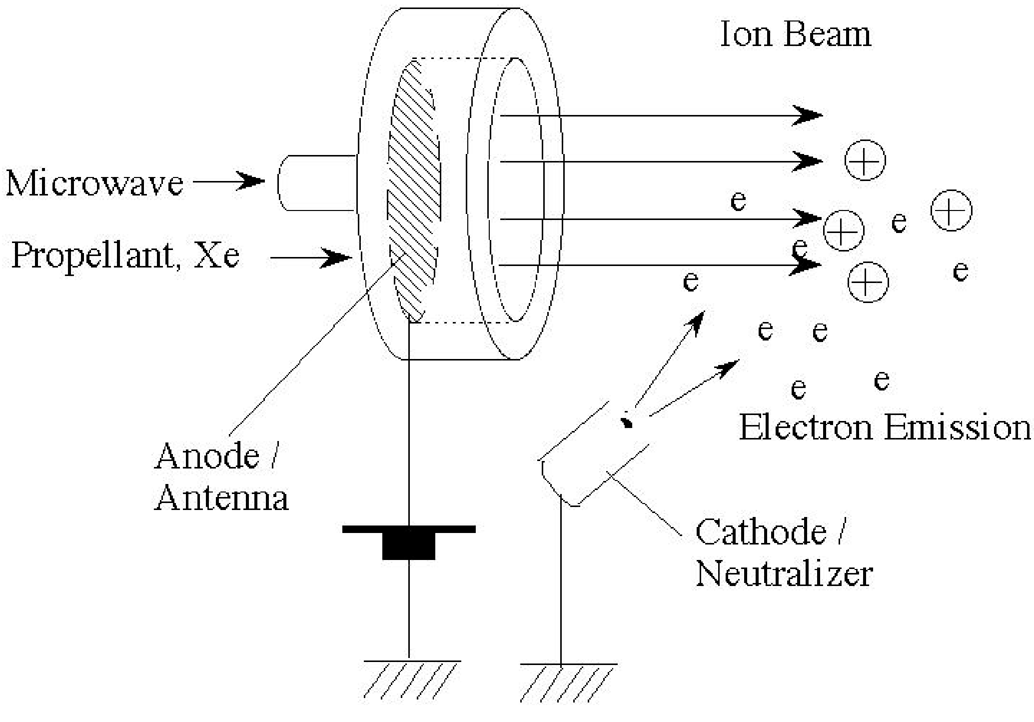

Fig.1 Principle of Microwave Engine

Fig.2　Microwave Engine Head

Fig.3　Assembly of Microwave Engine System

Fig.4　Operation of Microwave Engine in Vacuum Chamber

Table 1　Performances of Microwave Engine System

Propellant	Xenon
Propellant Mass Flow Rate	0.3 sccm
Thrust	0.36mN @0.3sccm
Specific Impulse	1250 sec
Power Consumption	26.6 watts nominal
Weight	Engine Head : 94 g
Size	Engine Head : 46 mm x 57 mm x 89 mm
Vibration Level	20 Grms
Operation Tempareture	-10C to +50C
Operation Voltage Input	12V DC
Life	>5000 hours continuous firing (TBD)
Status	PM

Block Diagram and Interface

The thruster system consists of engine head, propellant management unit, microwave power unit, acceleration power unit, neutralizer power unit, ignition power unit, interface unit and onboard computer (including CPU over-current protection circuit). The operation status is directed by the command via the interface unit and the onboard computer controls each electric device in accordance with the programmed sequence. The telemetry monitors success/ unsuccess of each sequence, acceleration voltage, beam current, thruster temperature, propellant tank pressure and so on.

Figure 6 represents the electrical circuits for the neutralizer power supply and the ignition circuit, and the propellant control circuit is shown in Fig.7.

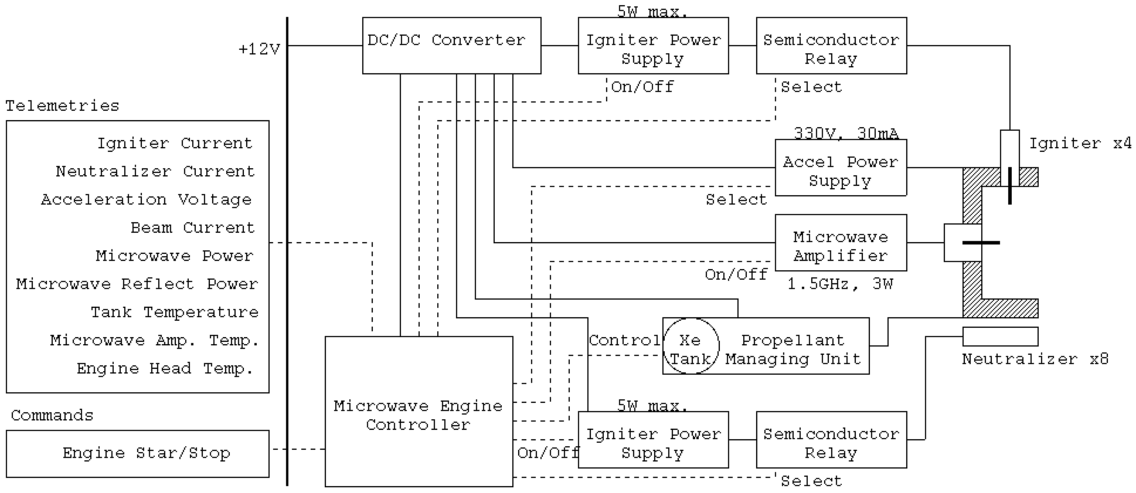

Fig. 5 Block Diagram of Microwave Engine System

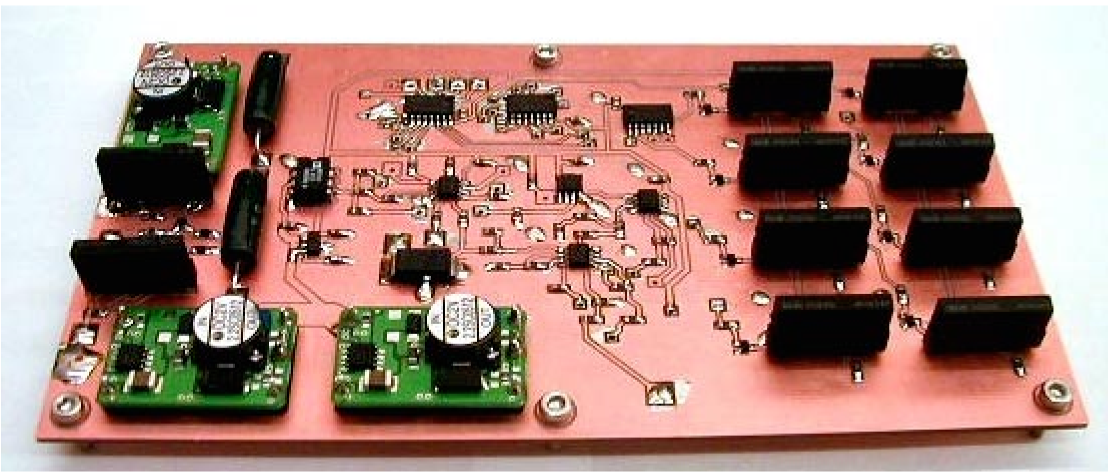

Fig.6 Neutralizer Control Ciruit

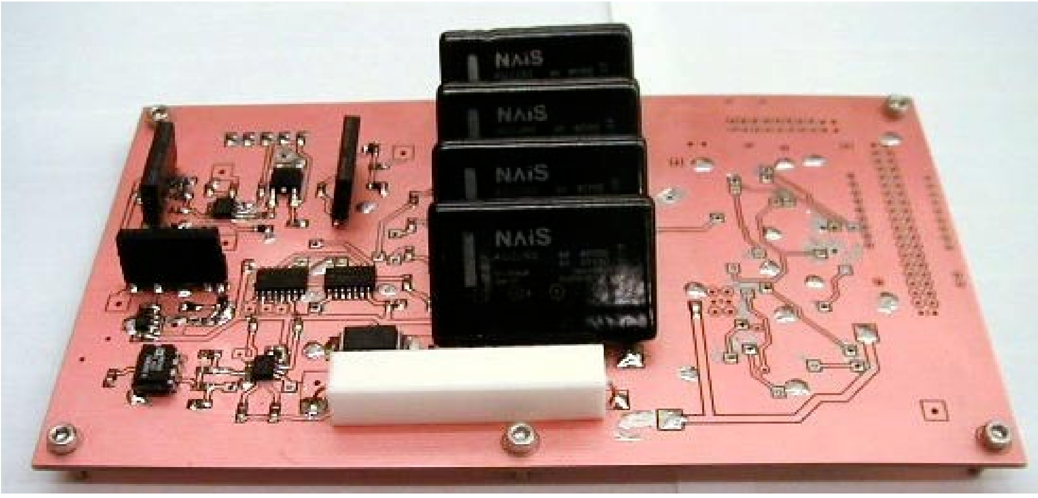

Fig.7 Ignition and Propellant Control Circuits

The engine system requires two kinds of DC 12 volts power lines, one for a main power line and another for an ignition power line, respectively.
The specifications of these electrical requirements are summarized in Table 2 and 3. Table 4 represents the details of power consumption required by each component.

Table 2 Requirement of Main Power Line

DC Voltage	12 V +/- 0.5 V
DC Current (Nominal)	2.21 A
CD Current (Maximum)	2.70A
Power (Nominal)	26.6 Watts
Power (Maximum)	31.7 Watts
Rush Current (less than 5 msec)	3.0 A

Table 3 Requirement of Ignition Power Line

DC Voltage	12 V +/- 1V
DC Current (Maximum)	1.6 A
Power (Maximum)	17.5 Watts
Duration per an ignition	1 sec +/- 0.01sec

Table 3 Power Requirement Breakdown

Module	Current [A]		Rush current [A]	Power [W]	
	Nominal	Max.	Max.	Nominal	Max.
Microwave power unit	1.03	1.13		12.40	13.00
Acceleration power unit	0.60	0.90		7.20	10.80
Neutralizer power unit	0.32	0.38		3.89	4.38
Propellant management unit	0.12	0.13		1.44	1.60
Interface unit	0.11	0.12		1.27	1.40
CPU	0.03	0.04		0.35	0.47
TOTAL	2.21	2.70	3.0	26.6	31.7

Thermal Design

Microwave engine configuration is shown in Fig.8. The engine head is made of steel where magnets are located. The engine is mounted to spacecraft through GFRP mounting brackets.

The key thermal design of the microwave engine is to maintain the magnets temperature below 110 degrees centigrade under any possible microwave engine flight configuration. These condition includes:

1) The microwave engine is thermally decoupled from spacecraft
2) The microwave engine engine could be in any orbital orientation and could experience any orbital fluxes input
3) The microwave engine has a constant power dissipation of 3W

To ensure the thermal design and analysis of the microwave engine will work in all the potential LEO orbits, we have studies the following 5 orbital environment for determining orbital flux inputs to engine as follows (see Figure 8 for coordinate definition for this thermal analysis):

A) Engine +Z face direct solar radiation
B) Engine -Z face direct solar radiation
C) Engine +X face direct solar radiation
D) Engine -X face direct solar radiation
E) Engine +Y face direct solar radiation

We assumed that the engine is mounted to a spacecraft on its –Y face bracket and the spacecraft panel is sufficient large to block any direct solar radiation to the engine. For all the orbital fluxes computation, the following orbital thermal conditions are assumed:

(i) Orbital attitude = 650 km
(ii) Solar constant = 1420 W/m^2
(iii) Albedo = 0.36

To minimize the orbital flux influence and maximize the engine heat rejecting capability, we decided to apply white paint to all surfaces of the engine assembly.

The baseline design is to apply white paint on all the surface of the microwave engine assembly. The resulted maximum engine head temperature is 81 C including the +/- 5 C modeling uncertainty, the maximum engine head (including magnets) will be 86 C, well below the specified temperature limit of 110 C.

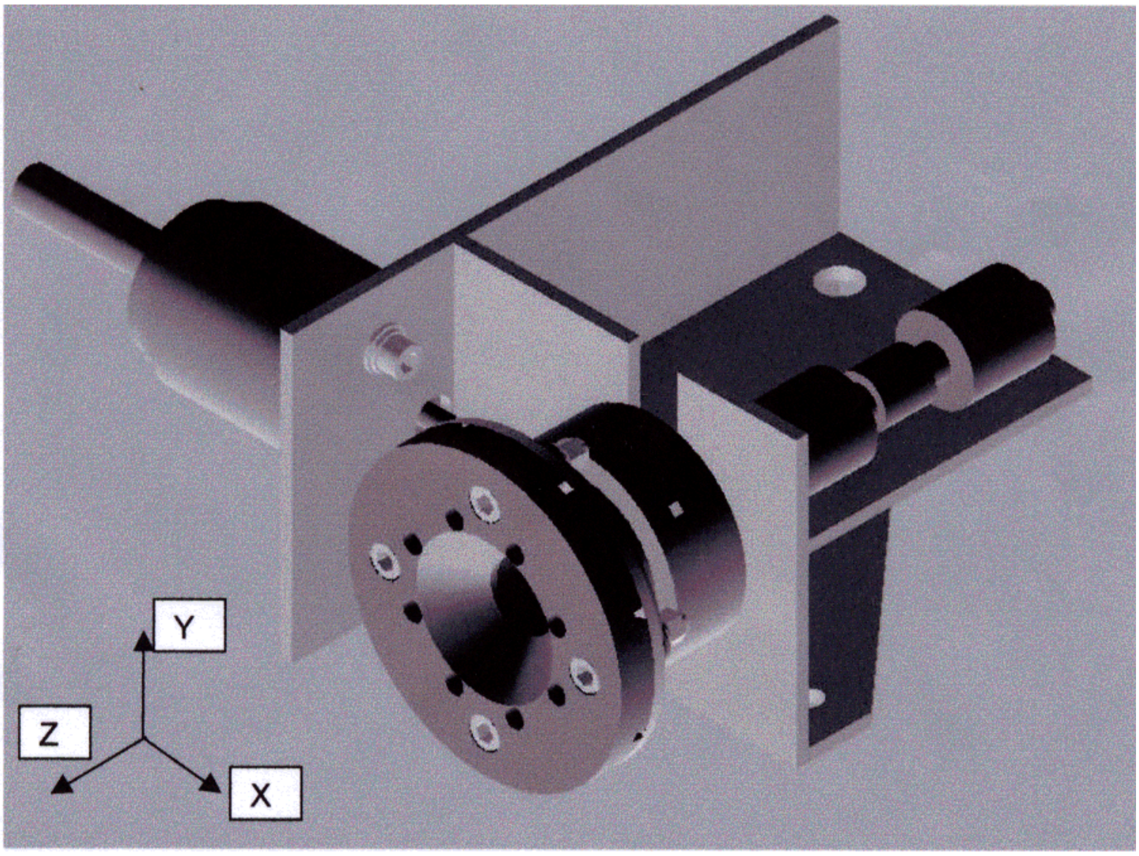

Fig.8 Coordinate for Thermal Analysis

Table 4 Predicted Temperature (Baseline Design)

ITEM	NODE	+Z FACE SUN 3W	-Z FACE SUN 3W	+X FACE SUN 3W	-X FACE SUN 3W	+Y FACE SUN 3W
NEUTRALIZER SUPPORT	1001	79.5	71.6	72.5	63.0	54.3
NEUTRALIZER PCB	1011	80.3	74.1	74.4	65.0	56.1
CHAMBER (INCLUDE MAGNET A&B)	**1101**	**81.0**	**76.5**	**76.3**	**67.1**	**58.0**
PREINUM CHAMBER	1201	70.9	70.2	67.6	59.7	50.0
GFRP BRACKET PLATE	2001	40.0	42.3	46.0	43.8	42.3
GFRP BRACKET PLATE	2021	37.1	43.0	48.0	44.3	27.0
GFRP BRACKET PLATE	2041	35.3	39.2	51.1	51.3	29.3
GFRP BRACKET PLATE	2051	31.8	36.5	48.6	52.0	23.8
GFRP BRACKET PLATE	2061	65.0	67.3	61.6	54.9	44.2
GFRP BRACKET PLATE	2071	63.2	64.8	61.1	54.7	45.0
GFRP BRACKET PLATE	2081	41.1	41.9	52.2	58.0	28.4
GFRP BRACKET PLATE	2091	40.3	41.2	49.3	55.5	27.0
SPACECRAFT DECK	7777	40.0	40.0	40.0	40.0	40.0

Qualification Random Vibration Test

The purpose of this test was to subject the units to the Qualification Random Vibration Test. The unit has subjected following spectrum:

AT Level : All axis Duration: 1 minute

Frequency [Hz]	PSD [G2/Hz]	Slope [dB/oct]	Tolerances
10 - 100	0.0004 – 0.04	+6.0	10-1000 Hz: +- 1.5 dB 1000 Hz over : +- 3.0 dB
100- 800	0.04	0	
800 - 2000	0.04 – 0.006	-6.0	
Over All	6.97 Grms	-	

QT Level : All axis Duration: 3 minutes

Frequency [Hz]	PSD [G2/Hz]	Slope [dB/oct]	Tolerances
10 - 100	0.007 – 0.75	+6.0	10-1000 Hz: +- 1.5 dB 1000 Hz over : +- 3.0 dB
100- 800	0.75	0	
800 - 2000	0.75 – 0.121	-6.0	
Over All	30.18 Grms	-	

At first, the unit has subjected to the AT level for every axis. After AT vibration, the unit has subjected to the QT level for every axis. Each axis is defined as follows.

1) X Axis – At random radially to the engine head

2) Y Axis – Mutually perpendicular to

the X and Z axis.

3) Z Axis – Parallel to the direction of the thrust vector

The test configuration is shown in Fig. 9 and 10.

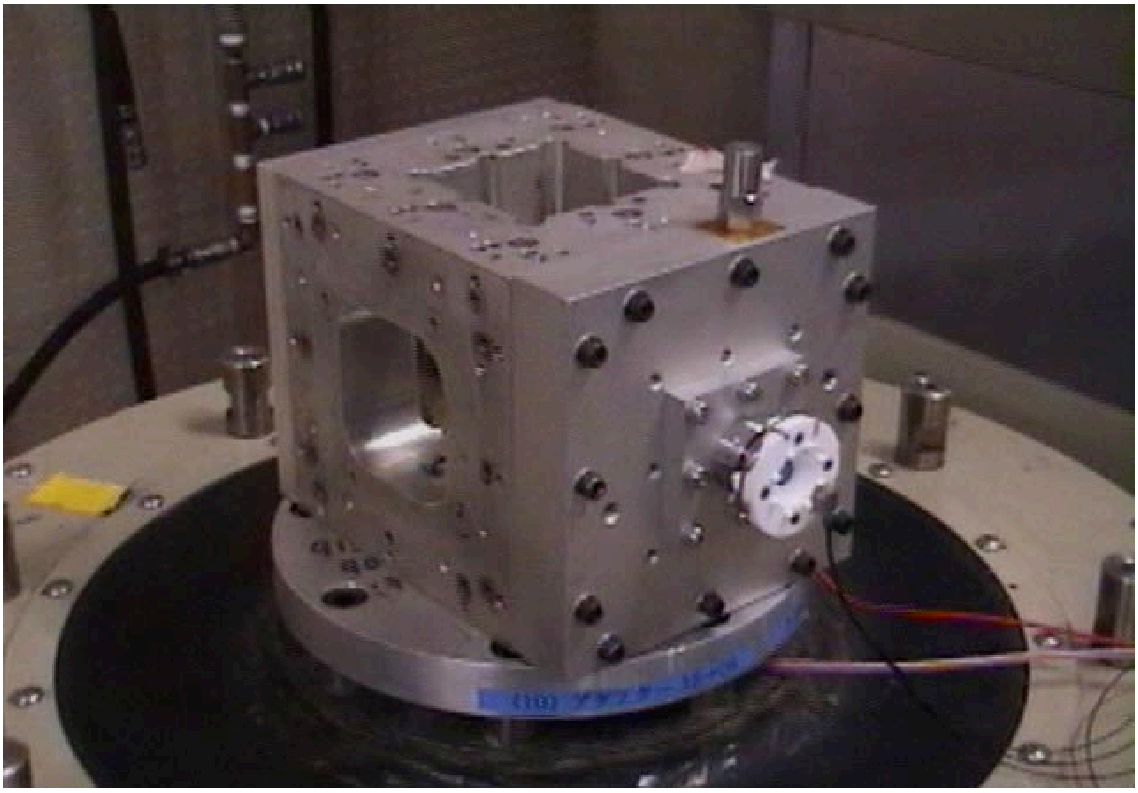

Fig.9 Y-axis Vibration Setup

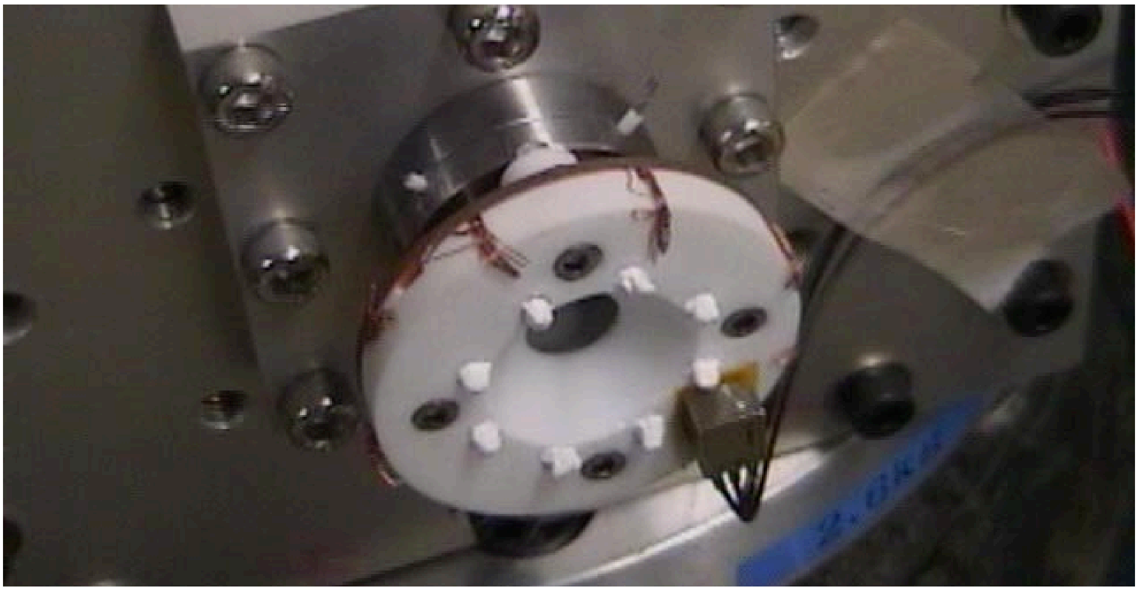

Fig. 10 Y-axis Vibration Setup (closed up)

Examination of the unit after completion of testing disclosed no visible damage or deterioration as a result of the test conditions. The unit was considered to have passed the qualification random vibration test. Figure 11 shows the vibration input PSD for Z axis, respectively.

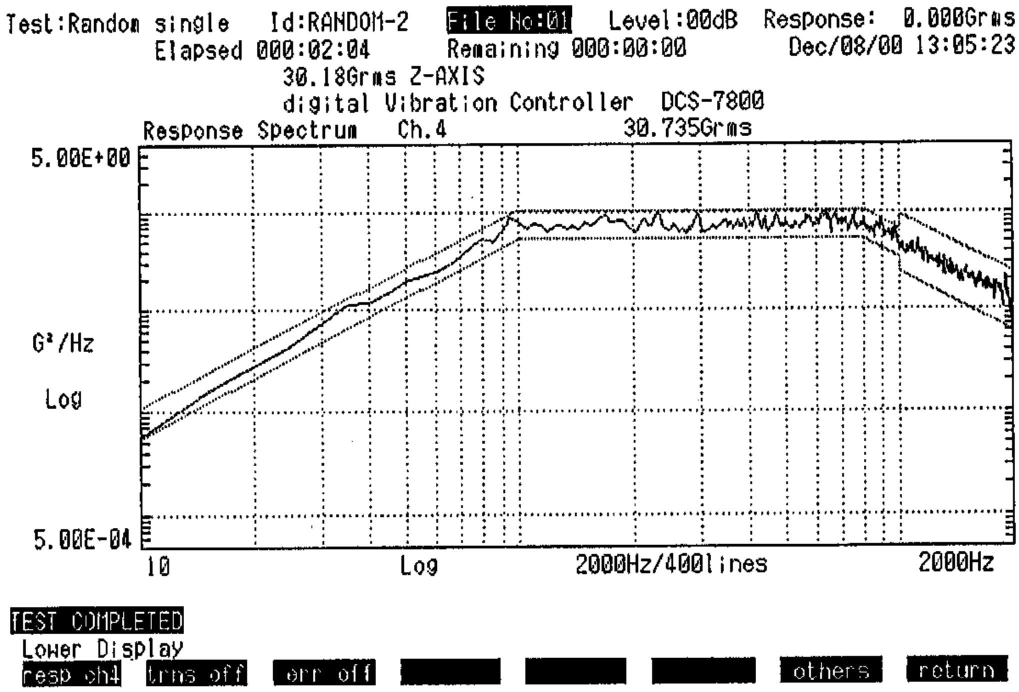

Fig.11 Vibration Input PSD for Z axis.

Flight Demonstration under Microgravity

The flight demonstration of a plasma thruster is implemented under microgravity to evaluate the feasibility of the accelerating mechanism of Microwave Engine, based on the fact that the plasma thruster has the same accelerating mechanism as Microwave Engine. Figure 12 illustrates the schematic of the flight demonstration and the mechanism of the plasma thruster. The demonstrated thruster has an aperture of 19 mm in diameter and 5 g in weight. The plasma thruster consists of an ion acceleration chamber and electron emitter (neutralizer). The applied acceleration voltage between two electrodes can make an electrostatic field gradient in the plasma while ions are accelerated to generate the thrust. The difference between the plasma thruster and Microwave Engine is that the plasma thruster generates plasma by glow discharge while Microwave Engine generates plasma by microwave.

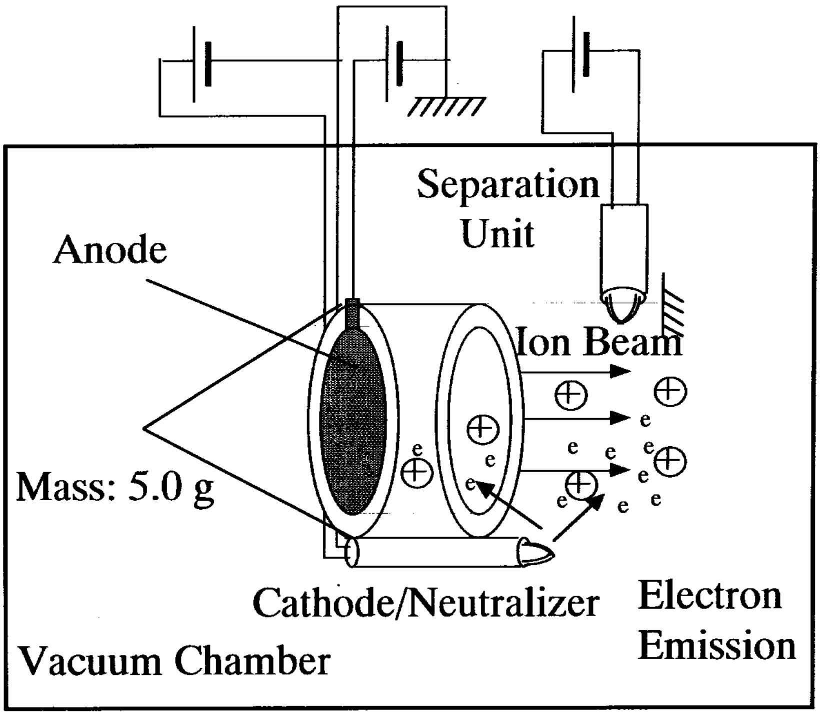

Fig.12 Mechanism of plasma thruster

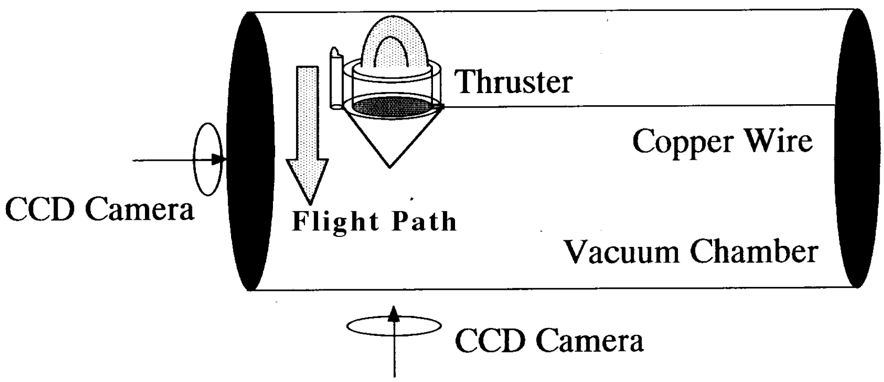

Fig.13 Schematic of Flight Demonstration

In this study, the microgravity experiment was conducted in Japan Microgravity Center (JAMIC), Kamisunagawa in Hokkaido where the microgravity condition could be made for about 10 seconds by free falling. The schedule of this experiment is shown in Table 1. First, the glass chamber was vacuumed by the rotary pump for about 2 hours. Next, the process of heating the neutralizer was started at 2 minutes 23 seconds before starting its free falling, so that the current of the neutralizer could reach the highest value at the beginning of falling. At 2 seconds after falling, the plasma thruster was separated from the launching base by cutting the acrylic wire and ignited. Then, the plasma thruster flew by its ion accelerating mechanism for about 8 seconds under microgravity while the flight pass was recorded with two CCD cameras.

Table 5 Time Schedule

1	-185 min	Start Vacuum Pump
2	-165 min	Neutralizer Preparative Ignition
3	-65 min	Stop Vacuum Pump
4	-60 min	Deliver Experimental Apparatus
5	-3 min 23 sec	Turn On Neutralizer
6	0 min	Drop Starts
7	+2 sec	Separation and Ignition

Table 6 Result of Estimated Thrusts

	Microgravity	Beam Theory	Pendulum
Thrust (mN)	0.36	0.11	0.20

Figure 14 shows the flight path of plasma thruster under microgravity. As shown in these pictures, the area of the generated plasma got small as the time went by because the vacuum level got worse. The generated thrust was calculated, based on the flight path of the plasma thruster under microgravity, the swing of its pendulum under 1G and the beam theory of its copper wires. These corresponding results are summarized in Table 2. Each result had the same order as the others. In addition, the obtained images indicated that the static balance of copper wires was located at the same position as the separation unit of plasma thruster. Thus, these two results validate that the plasma thruster did not move by the spring force of copper wires but by its generated thrust.

In this experiment, the flight demonstration of the plasma thruster was implemented under microgravity and the generated thrust was estimated, based on the flight pass of the plasma thruster under microgravity, the swing of its pendulum under 1G and the beam theory of the copper wires. Each estimated thrust had the same order as the others, while the obtained images indicated no contribution of the copper wires on the movement of the plasma thruster. Thus, the flight of the plasma thruster was achieved only by the generated thrust.

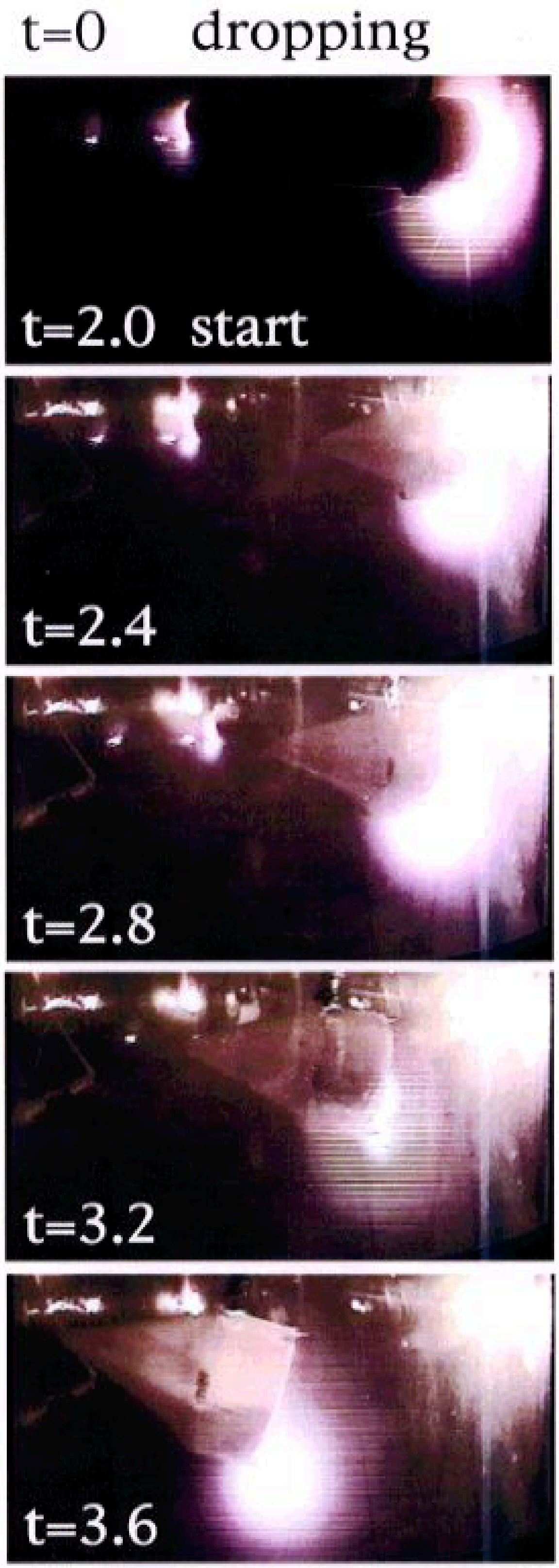

Fig.14 Flight Path of Plasma Thruster Under Microgravity

Conclusions

Proto Model of the microwave engine was built and its qualification test was conducted. Following performances were obtained: thrust of 0.36 mN, specific impulse of 1250 seconds, total power of 26.6 at nominal condition.

The thermal analysis concluded to apply white paint to all surface of the microwave engine assembly and use the engine mounting bracket as radiator surfaces. This desigin gives a maximum on-orbit temperature of the engine head (including both magnets) of 86 C, well below the maximum temperature limit of 110 C.

The random vibration test of the microwave engine head was conducted. No visible failure was observed and its tolerance on the mechanical environment was confirmed.

The flight demonstration of the plasma thruster was implemented under microgravity and the generated thrust was estimated, based on the flight pass of the plasma thruster under microgravity, the swing of its pendulum under 1G and the beam theory of the copper wires. Each estimated thrust had the same order as the others, while the obtained images indicated no contribution of the copper wires on the movement of the plasma thruster.

Reference

[1] Satori, S., Okamoto, H., Sugiki, T.M., and Aoki, Y., “NEW ELECTROSTATIC THRUSTER FOR SMALL SATELLITE APPLICATION”, July 2000, AIAA-2000-3

[2] Satori, S., Okamoto, H., Aoki, Y., Nagata, A. and Sugiki, T.M., "Design Status of Engineering Model of Microwave Discharge Electrostatic Thruster", 3rd International Conference on Spacecraft Propulsion, Cannes-France, Oct. 2000