Engineering-Model Development of the Miniature Ion Propulsion System for the Nano-satellite HODOYOSHI-4

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A miniature ion propulsion system is currently developed by the University of Tokyo collaborating with the Next Generation Space Technology Research Association (NESTRA) in Japan. This miniature propulsion system is installed on 50-kg nano-satellite "HODOYOSHI-4" developed by NESTRA under the Japanese government funded project, "New Paradigm of Space Development and Utilization by Nano-satellite". An engineering model of the miniature ion propulsion system was developed to verify its nominal performance and durability to the vibration, thermal change, radiation, and vacuum environment. All of the components of the propulsion system were assembled into one module on a double-deck plate. The present specifications of the engineering model was evaluated as the weight of 7.9 kg (dry:6.9 kg), volume of 39 cm×26 cm×15 cm, power consumption of 39 W, and thrust of 300 μN with specific impulse of 1200s.

Nomenclature

AOBC  = Attitude control On-Board Computer
APS   = Accelerator Power Supply
BBM   = Bread Board Model
EM    = Engineering Model
GMU   = Gas Management Unit
HVPS  = High Voltage Power Supplies
ITU   = Ion Thruster Unit
MCU   = MIPS Control Unit
MIPS  = Miniature Ion Propulsion System

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I. Introduction

Research and development of small spacecraft have extensively grown up in the world and a number of small spacecraft have been successfully launched and operated. Moreover, an increasing number of planned small spacecraft missions are in need of propulsive capability. Propulsion devices supply the spacecraft with attitude control, station keeping, and orbit transfer. The arrival of propulsion devices suitable for small spacecraft, namely micro-propulsion, is awaited [1].

Ion thrusters [2] are promising propulsion devices not only for standard-sized spacecraft but also for small spacecraft. Their characteristics of high specific impulse, high thrust efficiency, and usage of inert propellant (xenon) meet the requirements for small-spacecraft missions. In spite of these benefits, however, miniature ion thrusters have not been employed on small spacecraft yet. This has been mainly impeded by two reasons: limitation of electrical power available on small spacecraft and difficulty to develop a miniature neutralizer suitable for a miniature ion thruster.

A miniature and low-power ion thruster was developed using an ECR (electron cyclotron resonance) plasma by 4.2-GHz microwave to overcome the problems. ECR plasma gives advantages of longer life time and simplified structure for ion thrusters [3,4]. These features are suitable for down-scaling of the ion thrusters. However, the scale-down of plasma inherently leads to high ion production cost [5,6]. This problem was solved by a new antenna design for a small-sized cavity and a miniature ECR plasma was driven by microwave as low as 1.0 W [7]. This technique enabled to develop a miniature ion source and a miniature electron source, namely neutralizer, driven by 1.0 W microwave power respectively, and a miniature and low-power ion thruster was developed [8-12].

Since 2011, developing a small propulsion system installing that ion thruster has started at the University of Tokyo, collaborating with the Next Generation Space Technology Research Association (NESTRA) in Japan.

![Image of HODOYOSHI-4 (CAD)](image_url)

Fig. 1. HODOYOSHI-4 (CAD). The miniature ion thruster is installed on the negative-x panel.

<table>
<thead>
<tr>
<th>Table 1 Specifications of HODOYOSHI-4</th>
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</thead>
<tbody>
<tr>
<td>Size</td>
</tr>
<tr>
<td>Mass</td>
</tr>
<tr>
<td>Orbit</td>
</tr>
<tr>
<td>Descending node local time (22:00 – 23:00)</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Maximum: 100 W</td>
</tr>
<tr>
<td>DC-Bus Voltage: 28V unregulated</td>
</tr>
<tr>
<td>Communication</td>
</tr>
<tr>
<td>Mission data downlink: X-band (10-100 Mbps)</td>
</tr>
<tr>
<td>Propulsion</td>
</tr>
<tr>
<td>Mission</td>
</tr>
<tr>
<td>Store and Forward, Formation flight with HODOYOSHI-3</td>
</tr>
</tbody>
</table>
The propulsion system is named as MIPS (Miniature Ion Propulsion System) and installed on a 50-kg nano-satellite, HODOYOSHI-4. The specification of the HODOYOSHI-4 was summarized in Fig. 1 and Table 1. The nano-satellite series, HODOYOSHI-1 to 4, are developed under the Japanese government funded project, "New Paradigm of Space Development and Utilization by Nano-satellite"[13-17]. The project focuses on the technological innovation, strategy, and utilization of Nano-satellites, and HODOYOSHI-4 will install several innovating technologies for small spacecraft and one of those technologies is a miniature ion propulsion system.

Up to date, a cold gas thruster or a pulsed plasma thruster has been possible propulsion systems for small spacecraft (< 50 kg). However, their delta-V abilities are limited mainly due to the low specific impulse or geometrical limitation of the propellant respectively. On the other hand, ion thrusters, if they can be applied to the small size and power, readily provide large delta-V over 100 m/s for 50-kg spacecraft. This new capability can wholly change the maneuvers possible by small spacecraft. This paper addresses the current development status of the miniature ion propulsion system.

II. Miniature Ion Propulsion System

A. Structure of MIPS

The MIPS consists of four units: an ion-thruster unit (ITU), a power-processing unit (PPU), a gas-management unit (GMU), and a MIPS-control unit (MCU). All of the units are installed on a MIPS-supporting structure (MSS). A simplified block diagram of the system is given in the Fig. 2. The MIPS is considered a module to the entire spacecraft system. Electrical interface with the spacecraft is the MCU and mechanical interface is the MSS.

B. Ion Thruster Unit

An ion thruster unit, ITU, consists of an ion beam source, a neutralizer, a thruster valve, a gas distributor, a gas isolator, and DC-blocks. Both of the ion beam source and the neutralizer employ ECR-plasma sources driven by microwave injection and both sources have almost identical design. Both plasmas need the same amount of microwave power, typically 1.0 W each other. The detail of the discharge chamber was described in the reference [3-8]. Downstream end of the discharge chamber differentiates the ion beam source and the

Fig. 2. Bock diagram of the miniature ion propulsion system.

Fig. 3. Ion thruster unit (engineering model) for the MIPS. The ion beam source (bottom) has 211 apertures exhausting ion beam.

Fig. 4. Electrical connections between the high voltage power supplies and the ion thruster unit.
neutralizer. The ion beam source installs a two-grids system to accelerate and exhaust ions. The neutralizer installs a multiple-holed orifice, instead of the grid system, for electron emission. Contrasting to the microwave power, lower gas conductance of the neutralizer orifice than the ion grid causes the operation of the neutralizer by half gas flow of the ion beam source. The engineering model of the ITU (ITU-EM) was designed based on a laboratory-model thruster [8]. The ITU-EM has modifications on the structure of the grid system to reduce the size and weight. The assembled ITU-EM is shown in Fig. 3.

Applying three types of DC voltages to the ITU generates thrust by ion beam exhaust and its neutralization by electrons. The three voltages are provided by a screen power supply (SPS), an accelerator power supply (APS), and neutralizer power supply (NPS). Electrical connections of those supplies are shown in Fig. 4. Thrust generated by the ITU was calculated using measured beam current by

\[ T = \gamma \tau I_b \sqrt{2M V_b/e}, \]  

where \( \gamma \) is the thrust coefficient (0.90), \( I_b \) is the ion beam current, difference between the SPS and APS currents, \( M \) is the mass of ion particle, \( V_b \) is the beam voltage, equal to the SPS voltage, and \( e \) is the elementary charge. The NPS applies negative voltage to the neutralizer to emit electrons from it. The voltage of the NPS is controlled such that the NPS current equals to the SPS current. The NPS does not necessarily need for the ion propulsion system if we allow the potential drop of the spacecraft as much as the contact voltage. Actually, a number of ion propulsion systems were operated without this power supply and electrons are emitted by a slight potential drop of the spacecraft. The reasons we employ the NPS for the MIPS is to reduce the potential drop as low as possible and also to monitor the status of the neutralizer (health-check).

C. Power Processing Unit

A power processing unit consists of a high voltage power supply (HVPS) generating thrust and a microwave power source (MPS) generating plasma.

The high voltage power supplies: HVPS includes the screen power supply (SPS), the accelerator power supply (APS), and the neutralizer power supply (NPS). All the power supplies are operated by unstable 28 V (typically 24-32 V). Output voltage of the SPS is 1.5 kV and its typical current is at 5.0 mA. Output of the APS is set at -350 V and its typical current is less than 0.1 mA. Output of the NPS can range from 0 to -80 V depending on the required current and the plasma status. The typical voltage is from -10 to -40 V and this voltage is often referred to as contact voltage. The HVPS-EM had the conversion efficiency of 50% to 60% depending on the output current, where the efficiency means summation of the output powers of three supplies over the input unstable 28 V. The picture of the HVPS-EM is shown in Fig. 5.

The microwave power supply (MPS) outputs the total microwave power of 2.2 W. The MPS includes an oscillator of 4.25-GHz microwave, high-efficiency amplifiers, dividers, and isolators. The output 2.2 W microwave is divided into two lines, which are transmitted to the ion source and neutralizer respectively. Microwave isolators are used after the divider on the both lines to prevent unexpected coupling by reflected waves.

Fig. 5. The high voltage power supply (engineering model) for the MIPS, which includes three supplies: a screen power supply (1.5 kV), an accelerator power supply (-0.35 kV), and a neutralizer power supply (-80 V).

Fig. 6. The microwave power supply (engineering model) for the MIPS; two output ports with 1.1 W power.
The final stage amplifier of the MPS is a GaN-FET to attain high conversion efficiency. The conversion efficiency of the MPS-BBM showed the maximum efficiency of 48% from three DC powers to the output microwave power (single output). Three DC voltages are 24 V to the FET drain, -5 V to the FET gate, and 5.0 V for the oscillator. Flight operation of the MPS needs to consider more two efficiencies. DC/DC conversion from unstable 28 V, which is supplied from the satellite bus, to the regulated those three has typical efficiency around 80%. Splitting and isolating the output microwave power has efficiency around 80%. As a result, around 30% of the total efficiency (0.48×0.80×0.80) is feasible for the MPS. The picture of the MPS-EM is shown in Fig. 6.

D. Gas Management Unit

A gas management unit, GMU, controls the xenon flow rate by a “bang-bang control”. Pressurized xenon is stored in a CFRP (carbon fiber reinforced polymer) tank (Teijin, ALT764J). This tank has the capacity of the 1100 mm³, the mass of 0.70 kg, and the service pressure of 19.6 MPa. The nominal charging pressure of the MIPS is scheduled at 7.0 MPa. At the temperature of 20 °C, the xenon mass more than 1.0 kg can be stored in this tank.

The GMU has two-staged regulation to control the mass flow rate of 22.5 μg/s. The system diagram of the GMU is shown in Fig. 7. First, high pressure gas is regulated down to 0.1 MPa by a pre-fixed pressure regulator. Secondly, the 0.1 MPa gas is further regulated down to around 0.03 MPa by the bang-bang control using a solenoid valve and a low pressure tank as an accumulator (second pressure regulation). An example of this pressure control is shown in Fig. 8. The low pressure tank extends the time interval of opening the solenoid valve (typical interval is 10 min.). The exit of the low pressure tank is connected to the ITU through a flow restrictor. Those components of the GMU are commercially available products (COTS).

E. MIPS Control Unit

A MIPS control unit is to receive commands from the attitude control on-board computer (AOBC) of the satellite, control the on/off of the each units and valves, and send telemetries received from all of the units to the AOBC. The control of second pressure regulation of the GMU is included in the function of the MCU. No device except for the MCU is connected to the AOBC and the bus-power line. The picture of the MCU is shown in Fig. 9.

F. MIPS Supporting Structure

All of the components of the MIPS are installed in a MIPS supporting structure having two decks: middle deck and lower deck. The picture of the MIPS-EM is shown in Fig. 10. The ITU, MIPS, and GMU are installed on the
middle deck. The MPS was located at the closest place to the ITU to reduce the microwave transmission loss. Components of the GMU (tank, valve, tube, and joints etc.) are distributed on the middle deck to minimize the total volume. The HVPS and MCU are installed on the lower deck. Seven posts connect the middle deck to the satellite frame and the lower deck is held by inserting it between the posts and satellite frame.

At the initial stage of the development, the structure had only the middle deck on which all of the components were installed. However, the HVPS and MPS generated higher power dissipation than the initial plan and temperatures of the supplies increased up to those rating temperature before thermal steady state was achieved. Adding the lower deck and installing the HVPS and MCU on it reduced the heat source on the middle deck and decreased the maximum temperature.

III. Operations of the MIPS

A. Coupling Tests of the Components

Before assembling the MIPS, each unit was coupled to the ITU and basic functions of the unit were confirmed. In this coupling test, some components were placed outside chamber. During this stage, a major problem was the failure of the pressure regulation by the MCU and severe gas leakage of the GMU. The MCU includes both of the digital circuit for the communication with the AOBC and analogue circuit for the secondary pressure regulation of the GMU. Mixture of the ground lines between digital and analogue parts caused severe noise for the pressure measurement and failed to control the solenoid valve. Separating the ground lines between analogue and digital parts solved this problem. The gas leakage was due to inexperience assembling gas system for the vendors. Establishing an assembling and checking procedures solve this problem.

B. Assembling and Operating the MIPS-EM

All of the units and components were assembled into one system: MIPS, as shown in Fig. 10. The CRFP tank of the GMU was charged up to 4.0 MPa at 25°C by xenon gas and all the operations of the MIPS were performed using this gas. Installing the MIPS inside a vacuum chamber requires only two-types of feed lines: communication lines of the MCU to the ground support equipment (GSE, simulating the AOBC) and 28-V power line.

The total dry mass of the MIPS-EM was 6.9 kg and charging xenon up to 1.0 kg leads to the wet mass of 7.9 kg. The Table 2 summarizes the mass distributions in the MIPS. The GMU primarily dominates the mass, 40% of the total, and the MSS is the secondary, 17%. The heavy weight of the GMU is mainly due to the legal regulation, High Pressure Gas Safety Act in Japan. Any components utilizing high pressure (> 1.0 MPa) have to clear the regulation. It prevents to introduce original parts with light weight. The weight of the MSS depends on the power dissipation on the system. The present structure enlarged to provide enough heat pass from the MIPS to the satellite rather than to provide enough stiffness. Increasing the conversion efficiency of the MPS and HVPS leads to the reduction of the structure mass.
The operation of the MIPS-EM has been conducted a number of times, before and after any tests (oscillation, thermal, and thermal-vacuum tests) and any modifications. Fig. 11 shows the time history of the telemetry data acquired by the MCU during a typical operation. The performances of the propulsion system at this test were summarized in the Table 3.

The largest problems appeared in the operations were heat rejections, which prevented the continuous operation of the MIPS up to a couple of hours. Adding the lower deck and re-arranging the units’ configuration extended the operable time. Nonetheless, the temperature reached to the rating temperatures before the thermal steady state (then the operation stopped). The major causes are narrow thermal pass from a transformer inside the HVPS and low energy conversion efficiency of the MPS. Modifications for these problems are scheduled to be incorporated in the development of the flight model.

C. Compatibility Test with the HODOYOSHI-4 EM

The operation of the MIPS incorporated in an engineering model of the HODOYOSHI-4 was conducted to clarify potential problems lying under the on-board operation. An AOBC of the satellite is directly connected to the MIPS and is the most sensitive device against electrical noises. Hence the coupled operation was focused on the interaction of the AOBC and MIPS. The HODOYOHI-4 EM used here includes only bus systems (including the AOBC) and no mission devices.

The compatibility test was conducted using a 1.0-m-diameter chamber in which the satellite of a 50-cm cubic can be installed. Firstly, the MIPS was installed into the HODOYOSHI-4 EM and all the communication and power lines of the MIPS are connected to the satellite-bus system. Then the HODOYOSHI-4 EM was moved inside the vacuum chamber and the chamber evacuated less than 10 mPa over 12 hours to reduce the outgas from the system. Installation and operation of the compatibility test is shown in Fig. 12.

The MIPS operation was successful and no special problem was found in this test. This first compatibility test was performed under the connection of the satellite frames (potential base) to the ground (the vacuum chamber). As a next step, isolating the whole satellite system from the ground is planned to simulate the situation in the space more.

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Table 3 Specifications of the MIPS-EM.

<table>
<thead>
<tr>
<th>Name</th>
<th>Total volume</th>
<th>Total mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>39 cm × 26 cm × 15 cm</td>
<td>7.9 kg (incl. 1.0 kg xenon)</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>39 W</td>
<td></td>
</tr>
<tr>
<td>Thrust</td>
<td>300 μN</td>
<td></td>
</tr>
<tr>
<td>Specific impulse</td>
<td>1200 s</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Mass distribution of the MIPS-EM.

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass/kg</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITU</td>
<td>0.62</td>
<td>Incl. a high-voltage DC-block (0.45 kg)</td>
</tr>
<tr>
<td>HVPS</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>MPS</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>MCU</td>
<td>0.56</td>
<td>Dry weight</td>
</tr>
<tr>
<td>GMU</td>
<td>2.40</td>
<td></td>
</tr>
<tr>
<td>MSS</td>
<td>2.04</td>
<td>Middle/lower decks, side cover, &amp; posts</td>
</tr>
<tr>
<td>Others</td>
<td>0.27</td>
<td>Including instrument wiring and screws</td>
</tr>
<tr>
<td>Xenon</td>
<td>1.00</td>
<td>Assuming 7.14 MPa at 30°C</td>
</tr>
<tr>
<td>MIPS Total</td>
<td>7.86</td>
<td></td>
</tr>
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</table>

Fig. 12. Compatibility test of the MIPS-EM and the HODOYOSHI-4 EM.
IV. Conclusion

This paper addressed development of an engineering model of a miniature ion propulsion system (MIPS). The development is intended for the installation on the 50 kg spacecraft; HODOYOSHI-4. The development of the engineering model was successfully finished and a number of operations of the MIPS have been conducted. The specifications of the engineering model was currently evaluated as the weight of 7.9 kg (dry:6.9 kg), volume of 39 cm × 26 cm × 15 cm, power consumption of 39 W, and thrust of 300 μN with specific impulse of 1200s.

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References