Homeward Journey of Hayabusa using Ion Engines

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[Abstract] The μ10 cathode-less electron cyclotron resonance ion engines made the Hayabusa spacecraft rendezvous with the asteroid Itokawa in 2005. Though the spacecraft was seriously damaged after the successful soft-landing and lift-off, the xenon cold gas jets from the ion engines rescued the Hayabusa. New attitude stabilization method using a single reaction wheel, the ion beam jets, and the solar pressure was established and enabled the homeward journey aiming the Earth return on 2010. The total accumulated operational time of the ion engines reaches 29,000 hours at the end of July 2007.

はやぶさ小惑星探査機のイオンエンジンによる帰還運用

［要約］マイクロ波放電式イオンエンジンは、２００５年にはやぶさ探査機を小惑星ランデブーに導いた。探査機は着陸・離陸の際に大きな損傷を受けたが、想定外の運用としてキセノンコールドガスジェットを用いて、復旧を行った。機能残存したリアクションホィール１台とイオンエンジンの推力方向制御、太陽輻射圧トルクを用いた新しい姿勢制御方式を確立し、２００７年から帰還運用を開始した。２０１０年への地球到達を予定している。

I. Introduction

The Hayabusa space mission is focused on demonstrating the technology needed for a sample return from an asteroid, using electric propulsion, optical navigation, material sampling in a zero gravity field, and direct re-entry from a heliocentric orbit. Four μ10, the cathode-less electron cyclotron resonance ion engines, propelled the Hayabusa asteroid explorer, launched in May 2003, aiming at rendezvous, soft-landing, lift-off and Earth return. It succeeded in rendezvousing with the asteroid Itokawa in September 2005 after a 2-year flight, producing a delta-V of 1,400 m/s, while consuming 22 kg of xenon propellant and operating for 25,800 hours. After a series of scientific observations the Hayabusa landed on and lifted off the asteroid in November 2005. Malfunctions of onboard equipment seriously damaged the Hayabusa spacecraft and delayed Earth return in 2010 from the original plan in 2007. Reconstruction on the operational scheme using remaining functions and newly unloaded control logic made the Hayabusa leave for Earth in April 2007. This paper reports the recent status of the Hayabusa space mission.

II. Hayabusa Asteroid Explorer

The Hayabusa space mission aims to retrieve surface material of the asteroid to Earth. Total launch mass of the spacecraft is 510 kg including hydrazine fuel 67 kg. Figure 1 shows its configuration, including the pair of stowed solar cell paddles (SCP), which can generate 2.6 kW electrical power at 1

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AU from Sun. The high gain antenna (HGA) is mounted on the upper surface of the body. The SCP and HGA have no rotational or tilt mechanisms. The ion engine system (IES) is mounted on the side panel perpendicular to the z-axis, with which the HGA aperture is aligned. At high bit rate communication with 8 kbps, the spacecraft orientates the HGA towards Earth without IES firing. In cruise mode, the spacecraft orients the SCP face toward Sun in order to generate electrical power and rotates its attitude around the solar direction to steer the thrust direction of the IES. Three reaction wheels (RW) control the attitude of spacecraft in the original design.

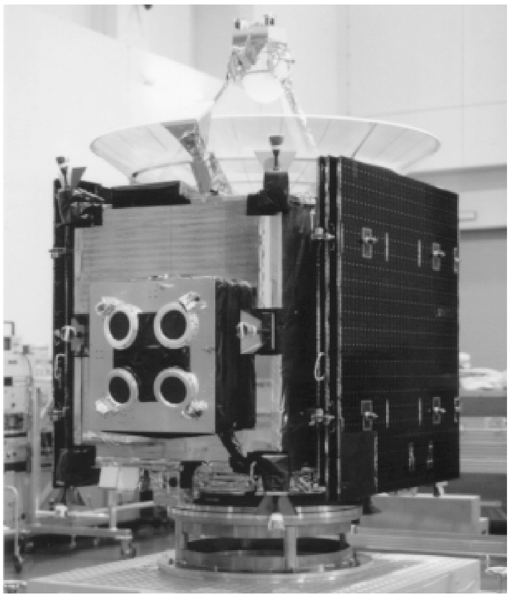

Fig.1 Hayabusa spacecraft in clean room.

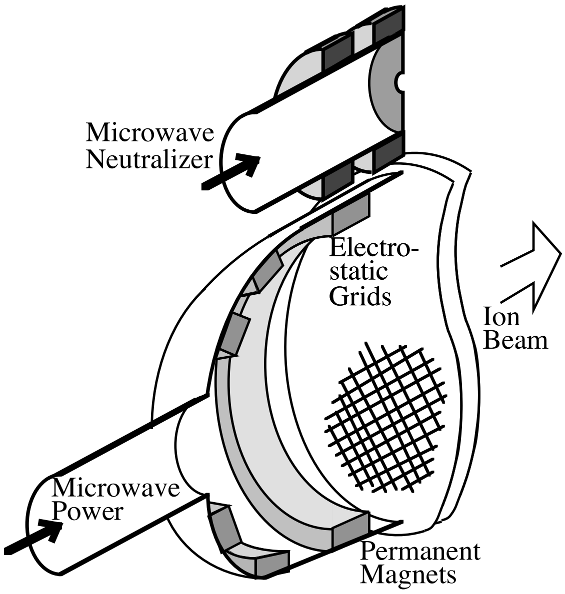

Fig.2 Cross section of the microwave discharge ion engine without solid electrodes.

III. Cathode-less Microwave Discharge Ion Engines

The cathode-less microwave discharge ion engines have the technological features as follows:

1) Xenon ions are generated using ECR (electron cyclotron resonance) microwave discharge without solid electrodes, which in conventional ion engines are the critical parts and the cause of flaking leading to electrical grid shorts. Thus, the elimination of the solid electrodes makes the ion engine more durable and highly reliable.
2) Neutralizers are also driven using ECR microwave discharge. The removal of the hollow cathodes releases IES from heater failures and hollow cathode emitter performance degradation due to oxygen contaminating the propellant, as well as air exposure during satellite assembling.
3) A single microwave generator simultaneously feeds the ion generator and the neutralizer. This feature reduces the system mass and simplifies control logic.
4) DC power supplies for ion acceleration have been reduced to 3. This feature also has the advantage of making the system lighter and requiring simpler operational logic.
5) The electrostatic grid system is fabricated from a carbon-carbon composite. The clearance between the grids is kept stable regardless of the temperature since there is no thermal expansion. This prolongs the life of the acceleration grid due to the low sputtering rate against the xenon ions. Low wettability of carbon seldom causes electrical shorts between the grids.

The cross section of the microwave discharge ion engine is illustrated in Fig.2. The μ10 ion engine with 10 cm effective diameter was developed for in order to dedicate to the Hayabusa space mission. The ground qualification schemes are described in detail in Refs. 1, 2, 3, and 4. Four μ10 are installed on the Hayabusa spacecraft, and three of them can generate thrust simultaneously. The dry mass of IES is 59 kg including a gimbal and a propellant tank, which was filled with xenon propellant 66 kg. A single μ10 is rated at 8 mN thrust, 3,000 sec Isp, and 350 W electrical power consumption so that the Hayabusa spacecraft is accelerated 4 m/s per a day by the maximum thrust 24 mN.

IV. Flight Chronology in Outward Journey

A. Outward Journey and Proximity Operation

The Hayabusa asteroid explorer was launched in May 2003. Since July IES have been continuously accelerating the Hayabusa, which reached a distance of 0.86 AU from Sun in February 2004 and 1.7 AU from Sun in February 2005. These distances are the farthest that an electric propulsion system has yet attained in the solar system. Depending on the solar distance IES was operated between 250W and 1.1kW in electrical power. The Hayabusa succeeded in rendezvousing with the asteroid Itokawa in September 2005 after a 2-year flight, producing a delta-V of 1,400 m/s, while consuming 22 kg of xenon propellant and operating for 25,800 hours. Reference 5 reports the details of the space operation on IES. The Hayabusa executed the scientific observation[6] staying around the asteroid in September and October 2005. And in December it succeeded twice touchdowns on the asteroid.

B. Rescue

During the proximity operation with the asteroid the Hayabusa lost the functions of two of three reaction wheels. And just after the lift-off from the asteroid a fuel leak disabled the function of the RCS thrusters and disturbed to control the attitude of spacecraft. Then the Hayabusa was missing on December 8, 2005. It is believed that the Hayabusa without electrical power and all of active controls caused serious nutation motion, which was attenuated to simple spinning by fluid friction of liquefied xenon in the main tank. Revolution motion in the heliocentric space gradually made Sun shine on SCP so that the Hayabusa recovered electrical power as seen in Fig.3. A set of commands from Earth initiated the Hayabusa again and established microwave communication on January 23, 2006 fortunately. The cold gas jets from the canted neutralizers generated enough torque over several tens micro newton meter to control the attitude of spacecraft due to long torque arm as seen in Fig. 4 and rescued the Hayabusa. Combination and timing of cold gas jets from four neutralizers during spinning enabled to change the attitude of spacecraft on each axis as seen in Fig.5. From January to June in 2006 the rescue operations consumed 9 kg xenon propellant in the cold gas jets.

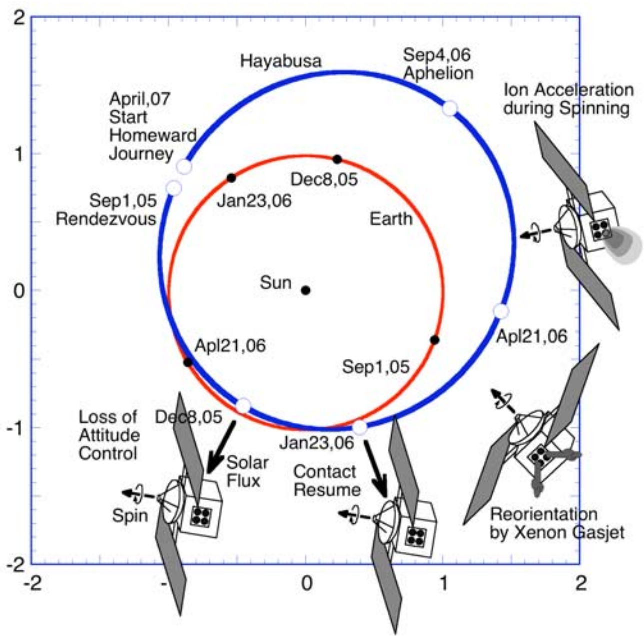

Fig.3 Revival of Hayabusa due to the orbital motion.

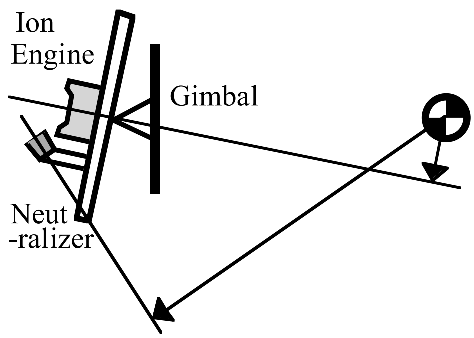

Fig.4 Torque of the xenon gas jets.

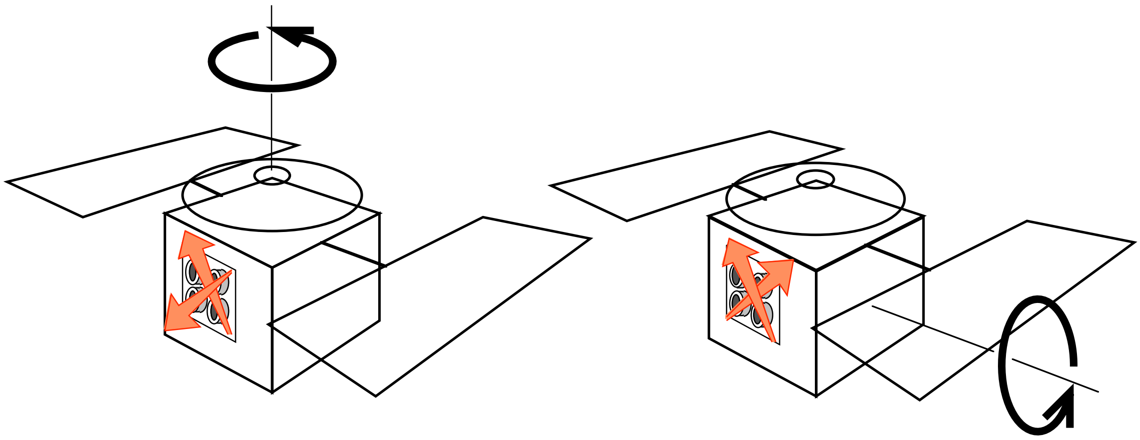

Fig.5 Torque of the xenon gas jets.

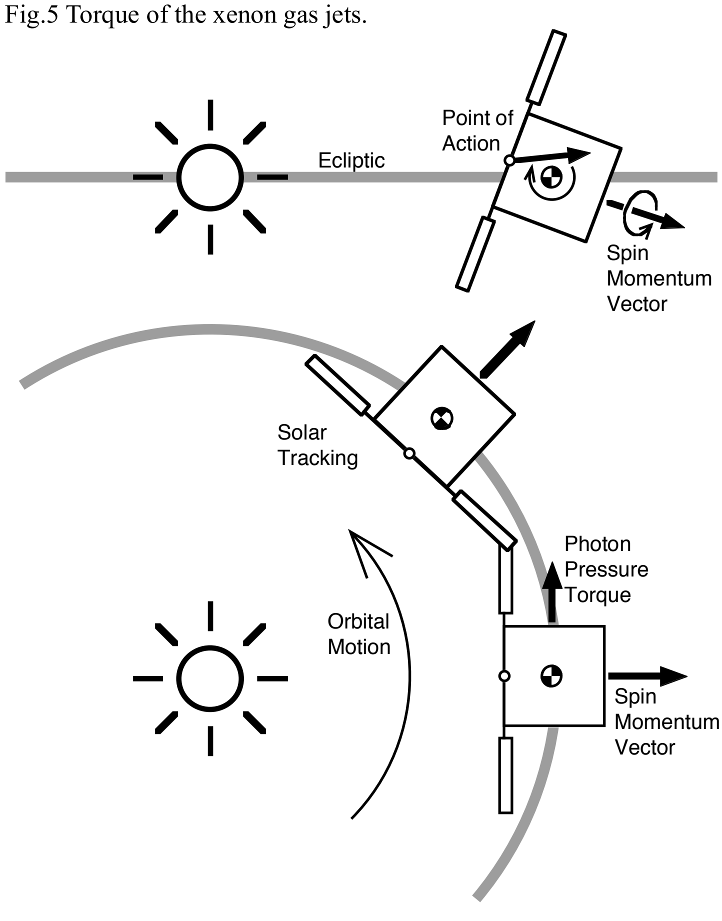

Fig.6 Torque of the xenon gas jets.

In April 2006 some of IES were turned on again and exhausted the ion beams. The spacecraft was spun down from 1 rpm to 0.2 rpm by the ion jets with three-day continuous operation. And then it was operated under hibernation from May 2006 to February 2007, in which the solar tracking of the spin axis was controlled by the photon pressure torque so as to save the propellant consumption. The mechanism on the photon pressure torque is illustrated in Fig.6.

C. Homeward Journey

In order to execute the homeward journey the non-spin attitude control scheme using the RW-Z and IES was established. The only available reaction wheel RW-Z, which is set along the z-axis as seen in Fig.7, takes a biased momentum of the spacecraft. The thrust vector control of IES by the gimbal can actively generate torques around the y- and z-axes in order to cancel disturbance torques. The following section describes in detail the IES torque force around the thruster along the x-axis of the spacecraft. Because the center of gravity on the spacecraft does not meet with the action point of the solar pressure, the lean attitude against Sun results in the torque, which is devoted to track the Z axis to Sun. The torques around three axes are adjusted independently by the thrust vector control of IES and the solar pressure.

After the test operation the Hayabusa spacecraft left the asteroid for Earth in April 2007. By the end of July IES achieve the total accumulated operational time 29,000 hours and total delta-V 1,500 m/s. One of four thrusters, which has been most frequently used, reaches 13,000 hours in space operation. The Hayabusa will come back Earth in 2010 after two revolutions around Sun as seen in Fig.9. For the return trip IES is requested 10,000-hour operation, 700 m/s delta-V, and 10 kg propellant. Hayabusa still keeps enough propellant 30 kg.

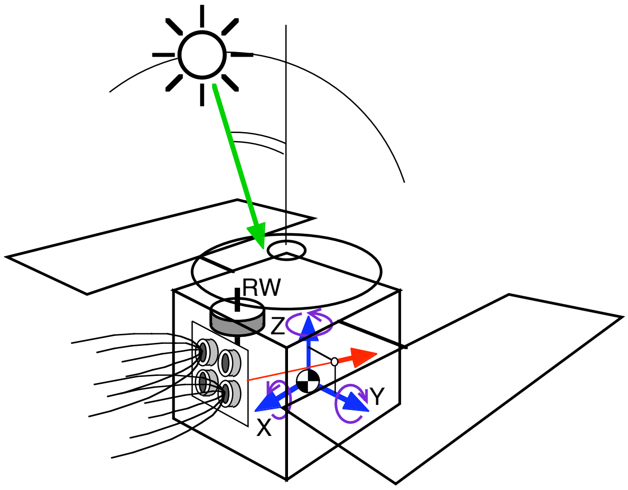

Fig.7 Attitude stabilization using a reaction wheel, thrust vector control of IES, and solar pressure torque.

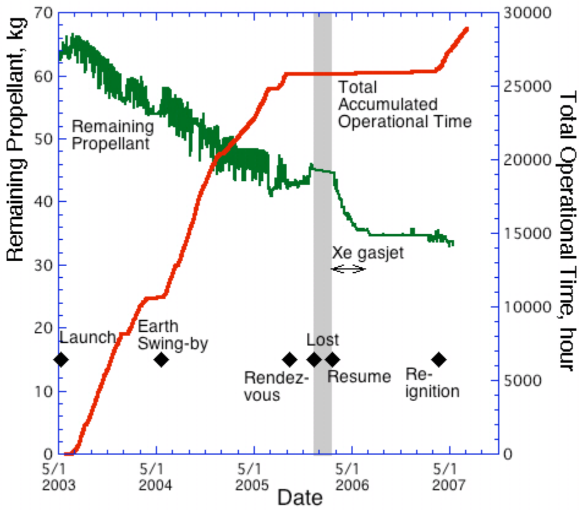

Fig.8 Histories on accumulated operational time and propellant consumption.

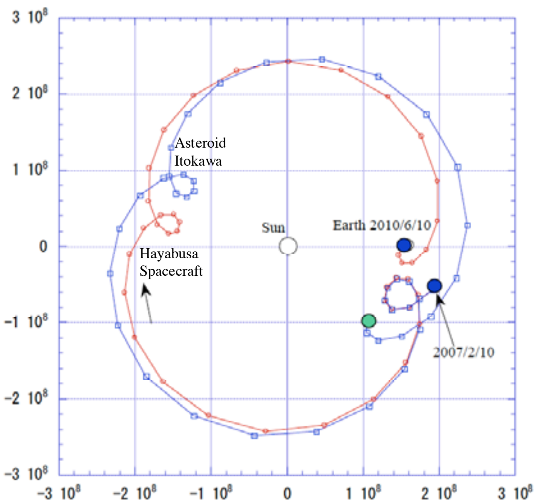

Fig.9 Return orbit to Earth in the rotational coordinate system. Red line shows the planned orbit of Hayabusa. Blue means the trace of asteroid Itokawa.

V. Conclusion

The Hayabusa space mission is focused on demonstrating the technology needed for a sample return from an asteroid and was launched in May 2003. Four μ10, the cathode-less electron cyclotron resonance ion engines, which were developed by the Electric Propulsion Laboratory ISAS/JAXA, propelled the Hayabusa asteroid explorer. It reached a distance of 0.86 AU from Sun in February 2004 and 1.7 AU from Sun in February 2005. These distances are the farthest that an electric propulsion system has yet attained in the solar system. Depending on the solar distance IES was operated between 250 W and 1.1 kW in electrical power. It succeeded in rendezvousing with the asteroid Itokawa in September 2005 after a 2-year flight, producing a delta-V of 1,400 m/s, while consuming 22 kg of xenon propellant and operating for 25,800 hours. After a series of scientific observations the Hayabusa landed on and lifted off the asteroid in November 2005. Though the spacecraft was seriously damaged after the successful proximity operation, the xenon cold gas jets from the ion engines rescued the Hayabusa. The new attitude stabilization method using a single reaction wheel, the ion beam jets, and the solar pressure was established and enabled the homeward journey aiming the Earth return on 2010. The total accumulated operational time of the ion engines reaches 29,000 hours at the end of July 2007.

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