

はやぶさ探査機のイオンエンジンによる深宇宙動力航行

國中 均*

Deep Space Powered Flight of Hayabusa Asteroid Explorer by Ion Engines

By

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Abstract : The Hayabusa spacecraft rendezvoused with the asteroid Itokawa in 2005 after the powered flight in the deep space by the $\mu 10$ cathode-less electron cyclotron resonance ion engines for two years. Though the spacecraft was seriously damaged after the successful soft-landing and lift-off, the xenon cold gas jets from the ion engines rescued it. New attitude stabilization method using a single reaction wheel, the ion beam jets, and the photon pressure was established and enabled the homeward journey from April 2007 aiming the Earth return on 2010. The total accumulated operational time of the ion engines reaches 31,400hours at the end of October 2007. One of four thrusters achieved 13,400-hour space operation.

概 要

日本独自のシステムとして、長寿命・高信頼を特徴とするマイクロ波放電式イオンエンジンが開発され、「はやぶさ」小惑星探査機の主推進に応用された。2年間の深宇宙動力航行の末、2005年に小惑星へのランデブーに成功し、着陸・離陸を実行した。複数の故障に見舞われたが、残る機能を駆使し2010年の地球帰還に向けて、イオンエンジンによる復路軌道変換を実施中であり、帰路の途上にある。2007年10月現在、イオンエンジンの総積算作動時間は3万1千時間、発生軌道変換量1700m/sに達しているが、推進性能および推進剤残量は十分に余力を残している。

I. Introduction

Four $\mu 10$, the cathode-less electron cyclotron resonance ion engines, propelled the Hayabusa asteroid explorer, launched in May 2003, which 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. It rendezvoused with the asteroid Itokawa after the deep space flight in two years with a delta-V of 1,400m/s, 22kg of xenon propellant consumption and 25,800hours of the total accumulated operational time of the ion engines. Though it succeeded in landing on the asteroid on November 2005, the spacecraft was seriously damaged. It delayed the Earth return in 2010

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from the original plan in 2007. Reconstruction on the operational scheme using remaining functions and newly uploaded 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 and Microwave Discharge Ion Engines

Spacecraft

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

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.



Fig.1 Hayabusa asteroid explorer



Fig.2 Microwave discharge ion engine

- 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 $\mu 10$ ion engine with 10cm 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. Figure 2 shows the operation of the ion engine in the laboratory. Four $\mu 10$ are installed on the Hayabusa spacecraft, and three of them can generate thrust simultaneously. The dry mass of IES is 59kg including a gimbal and a propellant tank, which was filled with xenon propellant 66kg. A single $\mu 10$ is rated at 8mN thrust, 3,000sec Isp, and 350W electrical power consumption so that the Hayabusa spacecraft is accelerated 4m/s per a day by the maximum thrust 24mN.

III. Flight Chronology in Outward Journey

Figure 3 shows the flight chronology of the Hayabusa asteroid explorer on the total accumulated operational time and the remaining propellant. The following sections explain the history of the Hayabusa in the space flight.

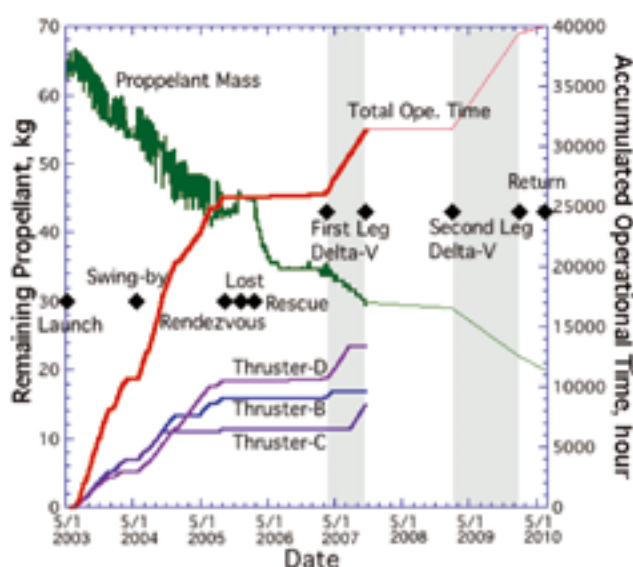


Fig.3 Flight chronology of the Hayabusa

Outward Journey

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 1,400m/s, while consuming 22kg of xenon propellant and operating for 25,800hours. Reference 5 reports the details of the space operation on IES.

Proximity Operation

The Hayabusa executed the scientific observation⁶ staying around the asteroid in September and October 2005. And in November it succeeded twice touchdowns on the asteroid. Figure 4 is the snapshot taken by the Hayabusa and shows the

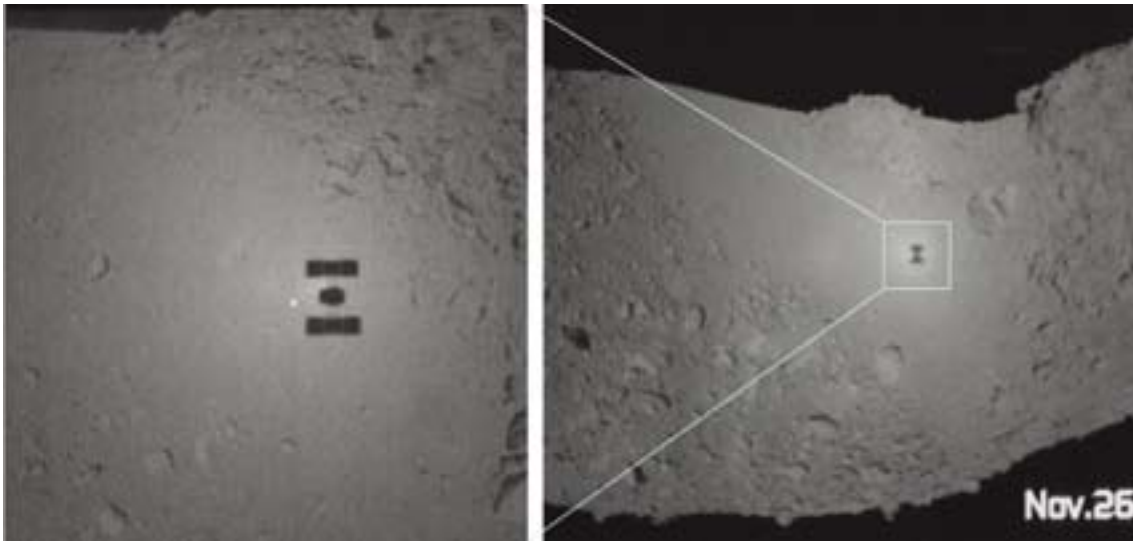


Fig.4 Shadow of Hayabusa on the asteroid surface

surface of the asteroid and the Hayabusa's shadow on it at the touchdowns. The target marker, which was dropped in the previous approach, was seen as a bright spot illuminated by a flash of the Hayabusa in it.

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.5. A set of commands from Earth initiated the Hayabusa again and established the beacon 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

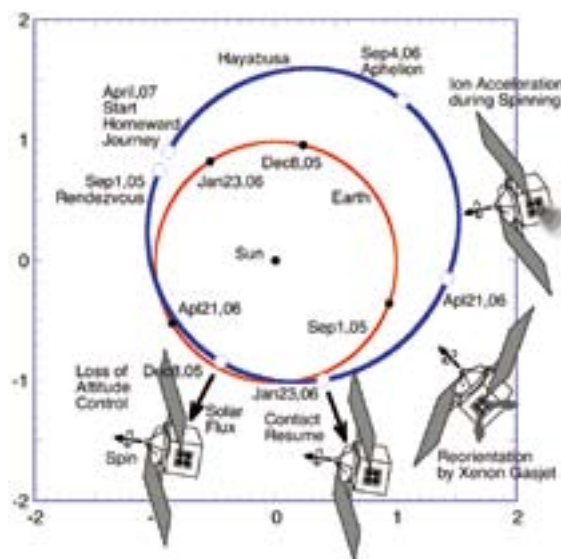


Fig.5 Rescue sequence of Hayabusa due to the orbital motion

and rescued the Hayabusa. The combination of torques from four neutralizers and the timing on the spin cycle enabled to control of the attitude of spacecraft on three axes. Successful reorientation of the spin axis toward Sun and Earth restored the microwave telemetry data with high bit rate on February 25, 2006. On April the checkout operation revealed the wholesome of IES for the ion acceleration. From January to June in 2006 the rescue operations consumed 9kg xenon propellant in the cold gas jets. Figure 3 shows the profile of the propellant consumption and indicates the remainder 35kg, which is enough for the homeward journey to Earth by the electrical-powered IES.

Hibernation

In order to watch and wait for the homeward journey from 2007 the Hayabusa hibernated in the way of the spin attitude stabilization from July 2006 to February 2007. The ion thrust from IES spun down the Hayabusa from 1rpm to 0.2rpm by continuous operation during 3 days on May 2006. And the Hayabusa automatically made the spin axis track toward Sun by mean of the photon pressure torque without any propellant consumption. 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 toward Sun. Then the Hayabusa saved enough propellant for the homeward journey.

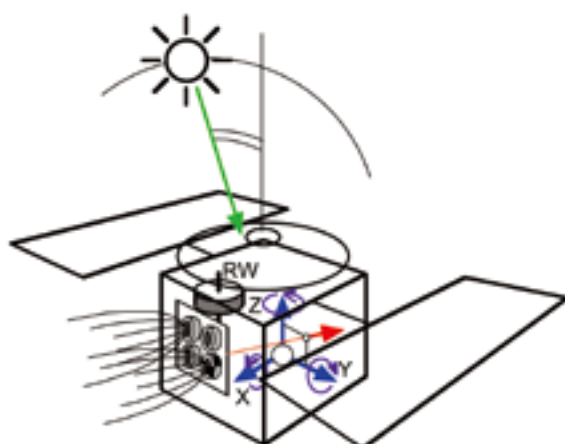


Fig.6 Attitude control by means of RW, IES thrust vector control and photon pressure torque.

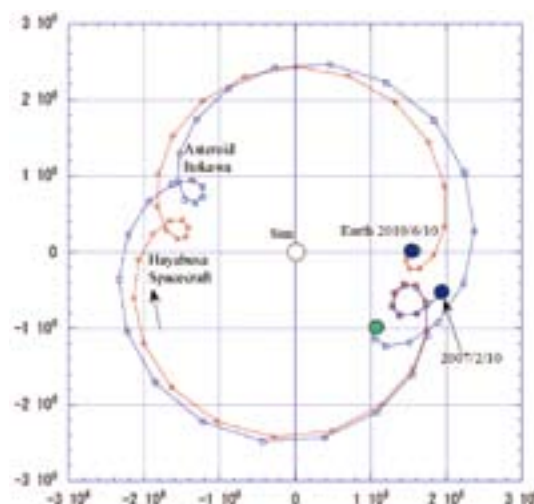


Fig.7 Orbit plan to Earth

Homeward Journey

In order to execute the homeward journey the non-spin attitude control scheme using the RW-Z, IES thrust vector control and the photon pressure torque was established. The only available reaction wheel RW-Z, which is set along the z-axis as seen in Fig.6, 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. The IES torque around the z axis is dedicated to unload the RW-Z. After the test operation the Hayabusa spacecraft left the asteroid for Earth in April 2007. By the end of October IES achieve the total accumulated operational time 31,400 hours and total delta-V 1,700m/s. One of four thrusters, which has been most frequently used, reaches 13,400hours in space operation. The Hayabusa will come back Earth in 2010 after two revolutions around Sun as seen in Fig.7. For the return trip IES is requested 8,000-hour operation and 400m/s delta-V.

IV. Summary

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 $\mu 10$, 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 250W and 1.1kW in electrical power. It succeeded in rendezvousing with the asteroid Itokawa in September 2005 after a 2-year flight, producing a delta-V of 1,400m/s, while consuming 22kg of xenon propellant and operating for 25,800hours. 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 photon pressure was established and enabled the homeward journey aiming the Earth return on 2010. The total accumulated operational time of the ion engines reaches 31,400hours at the end of October 2007.

References

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- ¹ Kuninaka, H. and Satori, S., "Development and Demonstration of a Cathode-less Electron Cyclotron Resonance Ion Thruster", *Journal of Propulsion and Power*, Vol.14, No.6, November/December 1998, pp.1022-1026.
 - ² Funaki, I., Kuninaka, H., Toki, K., Shimizu, Y., and Satori, S., "Development of Microwave Discharge Ion Engine System for Asteroid Sample and Return Mission MUSES-C", *Journal of Space Technology and Science*, Vol.13, No.1, 1999, pp.26-34.
 - ³ Funaki, I., Kuninaka, H., Toki, K., Shimizu, Y., Nishiyama, K., and Horiuchi, Y., "Verification Tests of Carbon-Carbon Composite Grids for Microwave Discharge Ion Thruster", *Journal of Propulsion and Power*, Vol.18, No. 1 January/February 2002, pp.169-175.
 - ⁴ Kuninaka, H., Nishiyama, K., Funaki, I., Shimizu, Y., Yamada, T., and Kawaguchi, J., "Assessment of Plasma Interactions and Flight Status of HAYABUSA Asteroid Explorer Propelled by Microwave Discharge Ion Engines", *IEEE Transaction of Plasma Science*, Vol.34, No.5, October 2006, pp.2125-2132.
 - ⁵ Kuninaka, H., Nishiyama, K., Funaki, I., Yamada, T., Shimizu, Y., and Kawaguchi, J., "Powered Flight of Electron Cyclotron Resonance Ion Engines on Hayabusa Explorer", *Journal of Propulsion and Power*, Vol.23, No.3, May-June 2007.
 - ⁶ Fujiwara, A., Kawaguchi, J., Yeomans, D.K., Abe, M., Mukai, T., Okada, T., Saito, J., Yano, H., Yoshikawa, M., Scheeres, J., Barnouin-Jha, O., Cheng, A.F., Demura, H., Gaskell, R.W., Hirata, H., Ikeda, H., Kominato, T., Miyamoto, H., Nakamura, A.M., Nakamura, R., Sasaki, S., and Uesugi, K., "The Rubble-pile Asteroid Itokawa as Observed by Hayabusa," *Science*, Vol.312, No.5778, June 2006, pp.1330-1334.