Hayabusa Attitude Control by Xe Gasjet for Rescue Operations

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Abstract
After the completion of the Hayabusa touchdown operation onto the asteroid Itokawa, the telemetry link with the Earth station was interrupted due to the spacecraft attitude loss, of which reason was thought to be the attitude disturbance by the onboard RCS fuel leak. When the radio beacon was acquired four days after the loss, the spacecraft was in a condition that RCS thrusters normally used for the attitude control were not working. Then, to cope with this circumstance Hayabusa operation team developed the attitude control scheme which utilizes the weak thrust generated by the cold Xenon gas ejection from ion engine neutralizer nozzles. The adopted scheme enabled the attitude control, the telemetry link recover and the Earth/Sun tracking.

In this paper the newly developed attitude control using cold Xenon gas jet is outlined and the operation result up to the present is reported.

1. Introduction
After the final touchdown and sampling operation, the operation which returns Hayabusa to the normal operation mode was executed on November 27th, 2005. During the course of the returning operation, the communication link with the spacecraft was lost. On December 1st, i.e. forth day after the spacecraft loss, the beacon from the spacecraft was successfully acquired by the ground station antenna. The spacecraft is designed so that the spacecraft entered into spinning mode with spin rate of 0.6 degrees/second by the onboard safe-hold logic when the attitude malfunctions occur. However, the observed spin rate by the Doppler data after the acquisition was 8 degrees/s, and the spin rate continued decreasing due to the existing attitude disturbances (see Fig.1). The observation showed the exponential spin rate decay, but the possibility of the spin direction reversal was not excluded at that time. When the spin rate approaches to zero, attitude became unstable and will be easily tumbled by the weak disturbances, a fear to loss the attitude again. Furthermore, none of reaction wheels or RCS thrusters was available at that time.

Only actuators available were ion engines. The solution derived by the operation team was to generate the control torque by ejecting cold Xenon gas from neutralizer nozzles with higher pressure than the normal operation, of which actuator was named as “Xenon Gasjet”. Four neutralizer nozzles are equipped for each ion engine as shown in Fig.2. The thrust level is
approximately 20μN when pressured. Utilizing the DHU’ automation and autonomous functions spin rate monitor and spin rate hold-control functions by the Xenon Gasjet were devised. Just completed the preparation for the rescue and started the regular operation, the second attitude loss occurred on December 7th.

Spacecraft search operation was continued and the beacon was acquired again on January 23rd, 2006 finally. When discovered, Sun-Spin angle (Sun angle) was about 60 degrees, and spin rate 7 degrees/s. The data analyses revealed the spin direction was reversed to that of before the attitude loss. In this paper, the outline of the rescue operations from re-acquisition through September 2006 is reported mainly.

2. Rescue Operations after Second Attitude Loss

The time profile of the spin rate and Sun angle through the rescue operations are shown in Fig.3 and Fig.4. The operations up to the present are comprised with Initial Sun Acquisition, Fine Sun Acquisition, Ecliptic Acquisition, Earth Acquisition and Sun Tracking.
2.1. Initial Sun Acquisition

The purpose of the initial Sun acquisition is to align the spin axis to the Sun direction and acquire the stable solar power. As the usage of the two-dimensional sun sensor (TSAS), which has the field of view in +Z direction, is limited at larger Sun angle, coarse sun sensor (CSAS) for the safe-hold attitude control purpose was used for the spin-axis precession.
control (lamb-line method) using Xenon Gasjet. The fields of view of TSAS and CSAS are depicted in Fig.5. For a week precession control was continued and the sun angle was reduced from initial 60 degrees down to 30 degrees. As the telemetry condition was not good enough to receive and decode the telemetry data, the Earth-spin angle (Earth angle) was estimated by changing MGA gimbals angle and its corresponding radio receiving level (See fig.6). As the Earth and the Sun seen from the spacecraft were almost in the same direction, the Earth angle was assumed to represent the Sun angle. The driving signal and corresponding torque by Xenon Gasjet is shown in Fig.7. The figure shows nozzle pair with opposite polarity torque was driven in each half spin period. The time constant is about 50 seconds for the thrust level decay after the valve closure, which is nearly equals to the spin period and so the next nozzle drive is started before the reach to zero thrust level. The thrust characteristics is such that the phase delay is 70 degrees and gain 1/3, resulting in an inefficient control. Although the efficiency would be improved if the spin rate was lowered, the high spin rate and then the stiffness by angular momentum against the recurring accidental attitude disturbance was given the first priority and then spin rate of 7 degrees/s was kept in spite of the fuel(Xenon Gas) loss disadvantage.

![Figure5. Sun Sensor Fields of View](image)

![Figure6. MGA Gimbals Angle and Receiver Level (Example)](image)

![Figure7. Xenon Gasjet Generate Torque Profile](image)

### 2.2. Fine Sun Acquisition

Switching the sun sensor from CSAS to TSAS for the lamb-line control for further 1 week operation, telemetry data became acquired. By using the fine Sun angle from the telemetry, the spacecraft attitude and tilt (direction of the moment of inertia axis on the spacecraft) were estimated. As the Earth angle obtained from the Doppler shift was not accurate for the attitude determination use, the attitude was determined by the cone method utilizing the Sun angle variation caused by the spacecraft orbital motion around the Sun, ceasing the lamb-line control for four days. The cone method provide two
solutions (Northern and Southern), the proper one (Northern solution) was selected and confirmed from the order of the Earth and the Sun on the spin plane, the Doppler data, autonomous function and so forth.

2.3. Ecliptic Acquisition

As the preparation before going to the Earth acquisition, the attitude maneuver to bring the spin axis into the ecliptic was carried out for three days. As the directions of the Earth and Sun changes due to the spacecraft and the Earth orbit motion around the Sun, the target direction was chosen ahead of the Earth direction on the ecliptic. The spin axis time history is shown in Fig.10.

2.4. Earth Acquisition

The Earth acquisition was continued by the middle of May 2006. During the period, the detailed diagnoses of the onboard equipment including the ion engines and baking operations for the purposes of removing outgas were carried out. Also during the period, tool to acquire the Doppler data and estimate the Earth angle based on its Doppler amplitude in real time, and tool to estimate the spacecraft attitude combining the Sun angle from the telemetry were prepared for the improvement of the operability. The snap shots are shown in Fig.11, in which the Earth angle (upper graph), the spacecraft attitude in the ecliptic coordinate (lower left), and attitude in the Earth fixed coordinate (lower right). The two solutions by the cone method are plotted with different colors. Typical daily operation is such that the reorientation maneuver is conducted to bring the spin axis to the predicted Earth position for two to three days per week, then wait for the Earth comes to that position.
Up to the present, the robustness against the attitude disturbance was given the first priority and the spin rate was kept at 7 degrees/sec, but after the completion of the outgas-baking, the fear of the attitude loss was removed. Then, the spin rate was lowered down to 1.2 degrees/sec to save the Xenon gas. As the effect of the Xenon Gasjet time delay is also reduced, the control efficiency is more than simply reducing the angular stiffness. As the spin rate increase was observed large (probably due to SRP windmill torque), the spin rate control was carried out using the ion acceleration inherent in the ion engines instead of Xenon Gasjet. The principle of the spin down by the ion engines is shown in Fig. 12. The Xenon consumption is 1/20 lowered compared with the Xenon Gasjet owing to the lower tank pressure and higher thrust, i.e. higher torque level (TLgas=20μN×1m=20μNm@11sccm, TLion=8mN×1cm=80μNm@3sccm).

2.5.2. Sun Tracking using Solar Radiation Pressure

The spacecraft spin axis would move along the circle with the Sun at its center if the Sun direction was fixed. Actually the Sun direction seen from the spacecraft is not fixed because of the spacecraft orbit motion around the Sun. If the
spin-axis drift by solar radiation pressure is tuned to this orbital displacement, the spin axis will follow the Sun. The Sun angle which corresponds to the spin rate of 1.2 degrees/sec was estimated as 4 degrees from the flight data, and the spacecraft spin axis was moved at this position. After this maneuver the spin axis nearly followed the Sun direction.

**Figure 13**  Principle of Sun Tracking Utilizing Solar Radiation Pressure

### 2.5.3. Spin Rate Tuning and Attitude Trim

As another problem, as the separation angle between the Sun and the Earth became larger, the telemetry receiving condition became worse. To keep the telemetry link it needed switching from the LGA to MGA. As a result, once per spin, that is, the spin phase when MGA with the side pattern points to the Earth, the telemetry data were received. Then, spin rate was further reduced down to 0.6 degrees on June 30th to increase the duration when MGA pointed toward the Earth. On September 5th, attitude was trimmed and approached to the stationary point relative to the Sun (“frozen point”). The trajectories of the spin axis and the direction of the Sun on the celestial sphere from June to September are plotted in Fig.14. The attitude controls conducted during this period were only three: (1) Sun angle Tuning, (2) Spin rate reduction down to 1/2, and (3) Attitude Trim, and the Sun Tracking was achieved almost with no Xenon consumption. The spin axis trajectory at before and after the attitude trim is shown in the Sun fixed coordinate in Fig.15. After the trim the spin axis circled with radius of 0.2 degrees with its center at the frozen point. In the figure, the attitudes are estimated and plotted based on the simple dynamic model, in which, assuming spin axis drift by the SRP is proportional to the Sun angle, the initial attitude and proportional constant were estimated using the time history data (batch estimation once per two to three weeks). The Sun angle data used are plotted in Fig.16 (curves are derived from the model calculation).

**Figure 14. Attitude History (Ecliptic Coordinate)**
3. Concluding Remarks

After the touch down operation, the Hayabusa attitude was lost probably due to the leaks of the RCS fuel and associated large attitude disturbances. The control scheme which utilizes Xenon gas as actuators was developed newly, and by this the spacecraft attitude was recovered and the communication link with the Erath station was established again. The outgas baking and ion engine health confirmation were completed. Now in September 2006, though the spacecraft is in the severe condition such that the normal attitude control equipment is not available at all, the efforts are continued to return the spacecraft to the Earth in 2010.