Hayabusa Attitude Control for delta-V Operations

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Abstract

Hayabusa spacecraft started the homeward journey with an ion engine driven in April, 2007 aiming at the Earth return. In 2006, the fuel-free sun-tracking attitude control strategy was established and performed during spin stabilization. Then, the non-spin attitude control has been executed since February 2007. The key point is the balance of the solar radiation torque and the swirl torque of ion engine thrust. This paper reports how those attitude control strategies were carried out, showing flight results.

「はやぶさ」のΔＶ姿勢運用

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概要

小惑星探査機「はやぶさ」は 2007 年 4 月から地球帰還のためのイオンエンジンによるΔＶを開始した。昨年は太陽輻射圧を利用することで燃料を使わないスピン姿勢制御方式を確立し、太陽追尾を実施した。この方式を踏まえて、イオンエンジン運転時に発生する推力軸周りの外乱トルクと太陽輻射によるトルクを拮抗させて、太陽追尾をする三軸姿勢制御を確立し、地球帰還のためのΔＶ運用を開始した。本報告では姿勢制御をどのように実施したか飛行結果を交えて述べる。

1. Introduction

Hayabusa spacecraft was launched targeting on Itokawa, a near Earth asteroid in May 2003, arrived to Itokawa in September 2005, and left for the Earth in April 2007.

Hayabusa has been operated by several ways different from the ones, supposed to be used at the beginning. In July 2005, the control mode with ion-engines was switched to Dual Reaction Wheel Mode because of the failure of one of three reaction wheels. In September, Hayabusa arrived to Itokawa. Three weeks after the science missions started, the attitude control mode was switched to RCS mode due to the failure of the second RW. The rehearsal for touch-down had been repeated three times and then, repeating taking-on/off two times has been successfully done by RCS. Furthermore, the attitude control based on bias-momentum stabilization with the third RW and no thrust of RCS was established and succeeded in estimating the mass of Itokawa.

After the second take-off, however, Hayabusa spacecraft had lost the attitude due to the leakage of RCS and had been out of communication for two months. Instead of the regular actuators out-of-order, the xenon-gas from neutralizers of the ion-engines has been used for spin-down and attitude control along the spin-axis.

These neutralizers (Figure 1) are the devices to neutralize ion-beams by xenon-gas. The torque arms with one meter of the distance from the center of mass are fortunately enough to generate torques required for the maneuvers, even though their thrust is only 20μN.

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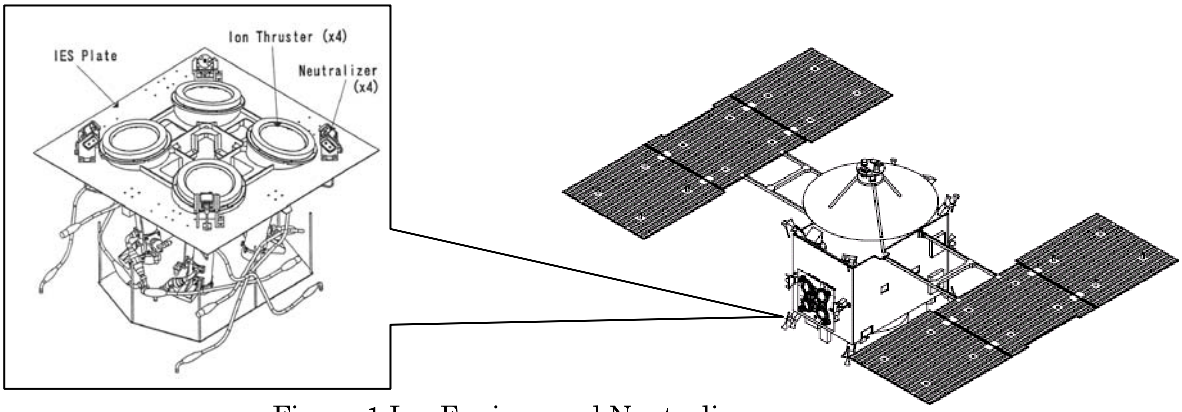

Figure 1 Ion Engines and Neutralizer

Earth return of Hayabusa has been postponed to June 2010 and the generation of ΔV for the return has been started from March 2006. Figure 2 shows the Hayabusa return orbit. To reduce the consumption of xenon-gas required for ion-engine drive, the new technique for passive attitude control by means of solar radiation pressure for sun-tracking with no thrust of xenon-gas has been established [1].

In February 2007, Hayabusa spacecraft was switched from spin-stabilization to three-axis attitude control based on bias-momentum and in March, three-axis control with ion-engine drive has been established. This paper reports the results of spin-stabilization and three-axis attitude control based on bias-momentum.

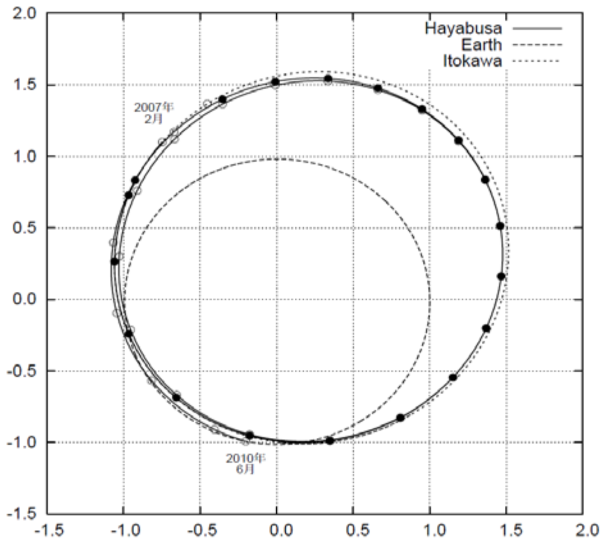

Figure 2 Hayabusa Return Orbit

2. Sun Tracking while spin stabilized

In the passive sun-tracking mentioned in the previous chapter, the solar radiation pressure torque acts on the angular-momentum vector of the spinning spacecraft and then, changes the attitude being based on gyro-effect. Considering the directions of the sun and spin-axis in ecliptic coordinate system, the motion of the sun from Hayabusa's point of view is almost parallel with the longitudinal direction. At this time, pointing the spin-axis to the north/south of the sun, the solar radiation pressure torque is parallel to the daily motion of the sun and proportion to the sun angle.

Because the angular momentum vector of Hayabusa in spin-stabilization is pointing to anti-solar direction (i.e. –z axis direction), it is possible to track the sun by pointing to the north side of the sun in ecliptic coordinate system. The mechanism is as follows: the greater the angle from the optimum increases, the more the solar radiation pressure torque increases and then, it causes the increase of the angular velocity along the spin-axis in proportion to the torque. As a result, the spacecraft moves faster than the sun (figure 3 (a)). When the spin-axis goes in front of the direction of the sun (figure 3 (b)), the solar radiation pressure torque starts pointing to the side which the sun approaches to. It causes the reduction of the angle and then, the angular velocity reduces in proportion to the angle (figure 3 (c)) By repeating this sequence, the sun-tracking attitude control which keeps the sun angle constant has been successfully done without fuel.

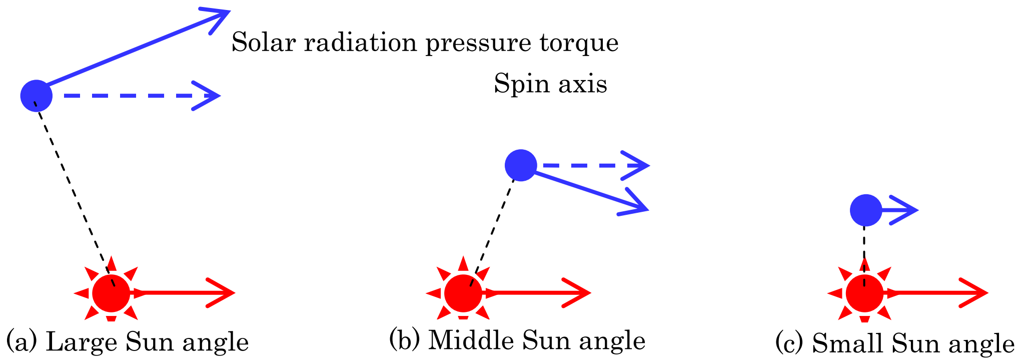

Figure 3 Relation of Sun direction and Spin axis.

The history of the direction of the spin-axis until ion-engine drive restarted is shown on figure 4. The history of z-axis of the spacecraft in ecliptic coordinate is plotted on the figure. The sun is located around 0 degrees in the ecliptic coordinate system. In March, the spin-axis had pointed to the Earth because the direction is almost the same as the one to the Sun.

To start sun-target-pointing from June, the spin-axis was pointed to +2 degrees of the north side of the sun. In April, to reduce the sun angle, the direction along z-axis had been lowered. After July, the error of the sun angle had been successfully kept within less than 3 degrees and the difference of the longitudinal direction with the one of the sun within ±1 degree.

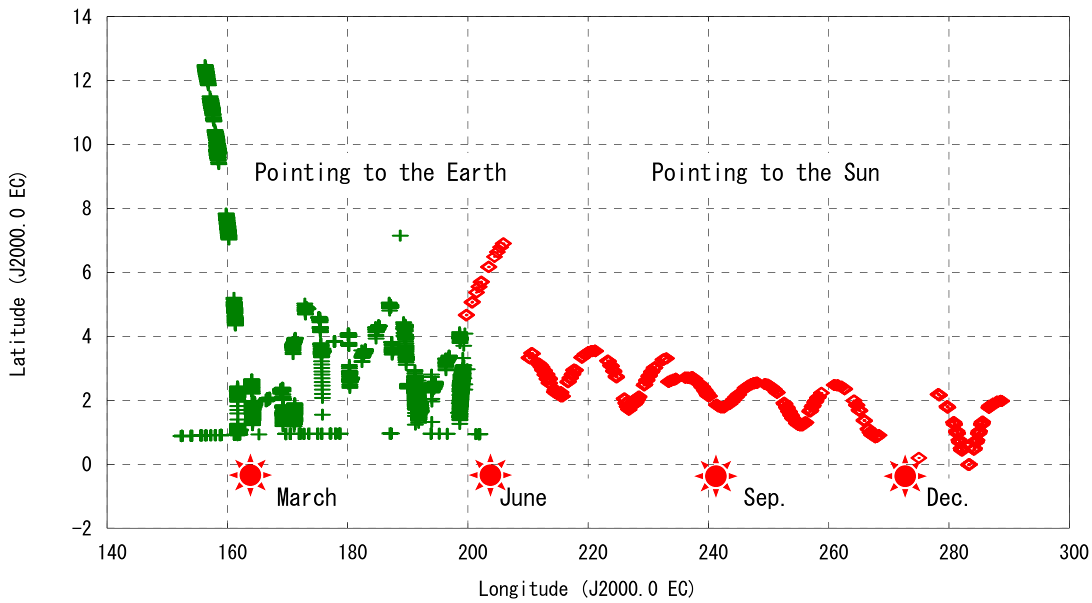

Figure 4 History of Spin Axis

3. Momentum-Biased Attitude Stabilization

To utilize the third/last RW parallel to z-axis, three-axis attitude control based on bias-momentum had been established. In the case when the ion-engines were not in use, Hayabusa tracks the sun by utilizing solar radiation pressure torque and pointing z-axis to the desired direction by thrusting xenon gas from the neutralizers (as same as operation in spin stabilization).

On the other hand, the actuators used in accelerating ion-engines are not only RW but two-axis gimbals to control the thrust axis of ion engines to pass through the center of mass. These gimbals are able to shift the axis from the center of mass to generate torques. One is to keep unloading all the time to hold the rpm of z-axis constant, and another one is to control y-axis directly.

X-axis has been controlled indirectly by two types of torques; (1) the very small, swirl torque along the thrust axis and (2) the solar radiation pressure torque pointing to the opposite direction. The mechanism is shown in figure 5. The swirl torque mentioned above can be generated due to the structure of ion-engines, which mechanism had been already clarified on the way to Itokawa. The second torque can be controlled by adjusting the sun angle with the gimbals of ion-engines. The sun angles balancing with the swirl torque of ion-engines are around 15 degrees when two ion-engines drive and around 3 degrees when only one engine drives.

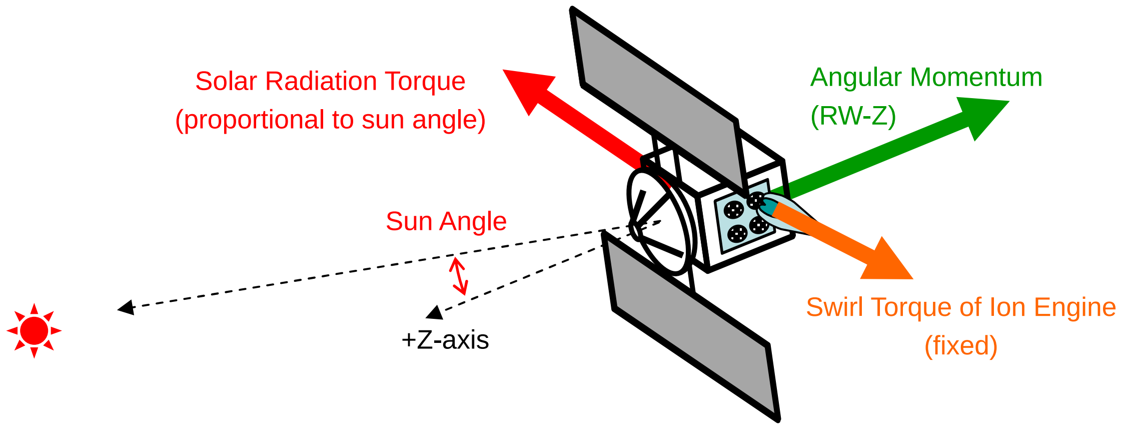

Figure 5 Solar Radiation Torque and Swirl Torque of Ion Engin

4. Flight Results

The history of the solar direction and z-axis of the spacecraft in ecliptic coordinate system from the beginning of March 2007 to the end of July is shown in figure 6. At the beginning of March (around 50 degrees in ecliptic longitude), z-axis had pointed to the north side of the sun to determine the orbit prior to driving ion-engines, based on the same idea as spin-stabilization. From March 12, the ion-engines have been restarted. To balance with the torque generated by the engines, z-axis was pointed to the south side of the sun and then, the test for attitude stabilization with solar radiation pressure torque was performed.

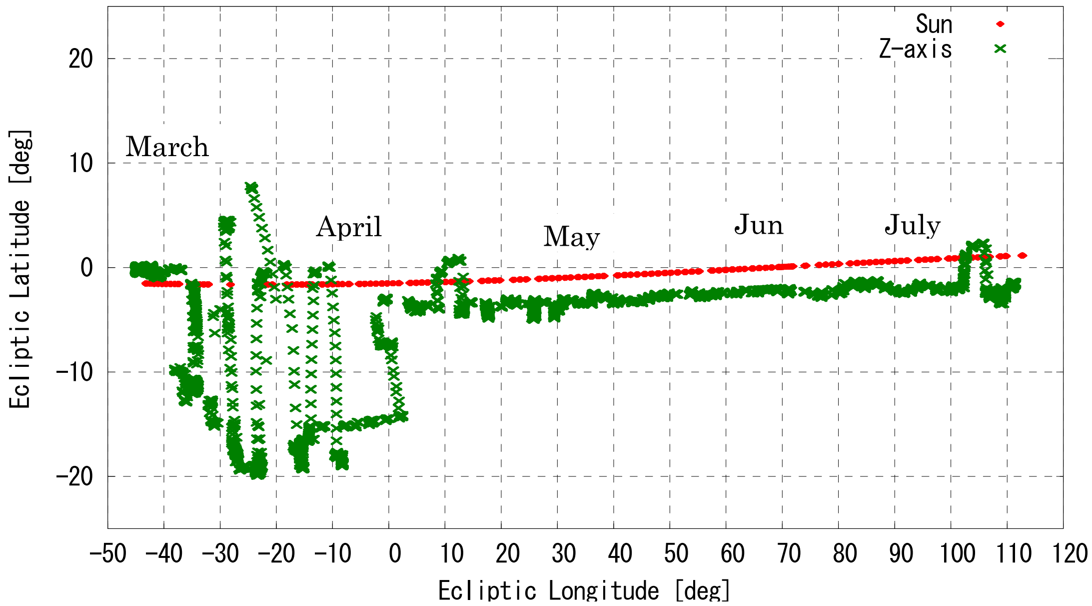

Figure 6 Sun direction and Z-axis history

After the test, the ion-engines have been driven keeping the sun angle constant from the middle of April (ecliptic longitude of around -15 degrees). Then, at the end of April (ecliptic longitude of 0 degree), the control mode was switched to one ion-engine drive and the sun angle was reduced. To determine the orbit at the beginning of May, the spin-axis had been pointed to the north side of the sun again without ion-engine drive. After restarting ion-engine drive, the attitude had temporally drifted by reducing rpm of RW from 3,200rpm to 2,000rpm in the middle of May (ecliptic longitude of 30 degrees approximately). After that, it recovered back to the stable attitude pointing to the south side of the sun. To determine the orbit at the end of July, the spin-axis pointed back to the north of the sun, which was stable even with no thrust of ion-engines. The details of the remarkable ΔV operations are descrived in the followings.

4.1. Momentum-Biased Attitude Stabilization without Thrusting

In the middle of February, spin-down and nutation-dump had been performed and then, three-axis attitude control started. Before starting ion-engine drive, the orbit was determined while keeping the control with no thrust. At this time, the passive attitude control for sun-tracking with pointing z-axis to the north of the sun without xenon-gas thrust had been successfully performed, based on the same idea as spin-stabilization. The history of z-axis at this time is shown on figure 7. This figure shows the history of z-axis with respect to the sun in ecliptic coordinate system. In about a week from 2nd to 9th of Marth, it goes around the direction of 1 degree of the north side of the sun. It satisfies the requirements of the attitude accuracy to guarantee the communication with the Earth.

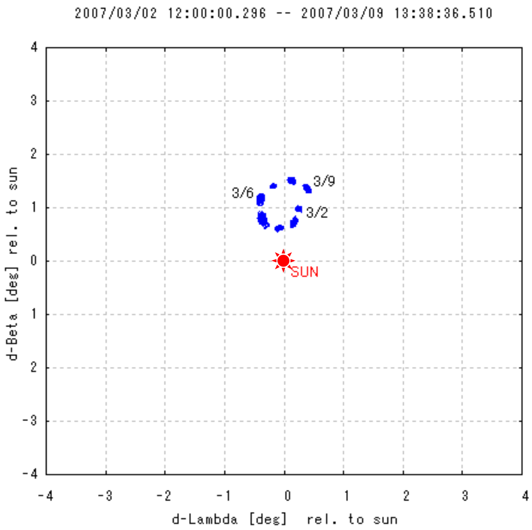

Figure 7 +Z axis history without thrust (Sun Tracking)

4.2. Momentum-Biased Attitude Stabilization with Thrusting

After determining the orbit, flight plan was updated and ion-engine drive re-started. The torque generated by ion-engine is on the ecliptic plane because the direction of ΔV is almost on the same plane. On 12th of March, the axis was pointed to 10 degrees apart from the south side of the sun by thrusting ion-engines and operating gimbals. Then, the torque of ion-engine thrust axis could be balanced with solar radiation pressure torque by increasing the elongation with the sun. The change of drift is shown in figure 8 and table 1. After that, the optimum sun angle was determined and in April, stabilization with ion-engine drive around 17 degrees from the south side of the sun had been successfully done. It had been required for attitude control to keep the direction of ΔV within 5 degrees and successfully satisfied.

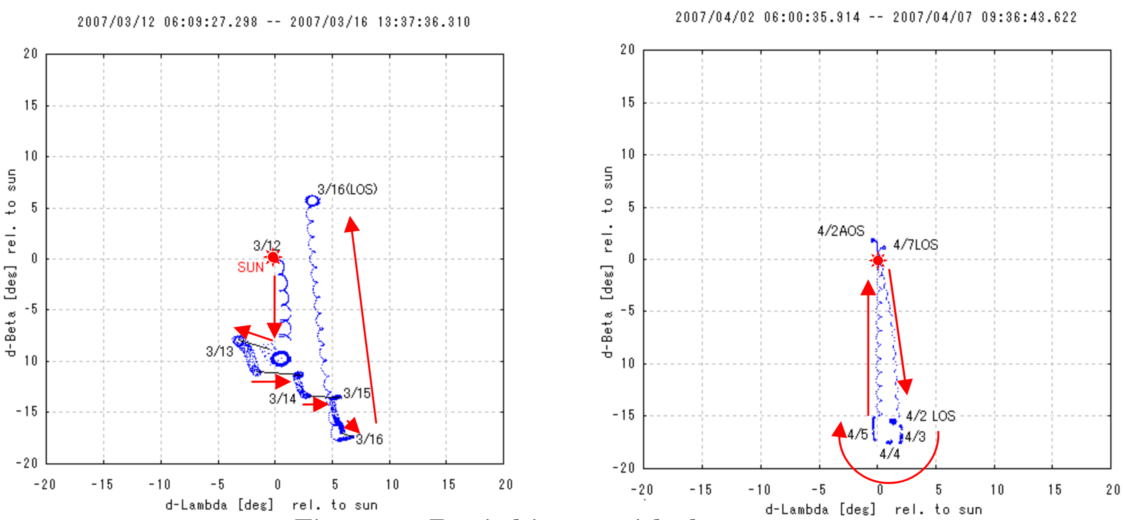

Figure 8 +Z axis history with thrust

Table 1 Change of drift

Date	IES and Spin axis direction	Drift
3/12	One engine、South, 10deg	Left, 3deg
3/13	Two engines、South, 12deg	Right, 4deg
3/14	Two engines、South, 14deg	Right, 3deg
3/15	Two engines、South, 17deg	Right, 1deg

4.3. Precise Attitude Control

Afterwards, the Earth return journey has been started by changing two-engine drive to one-engine drive. During the operation, it was clarified that the balancing point of thrust axis torque and solar radiation pressure torque could be changed by the influence of the small change of ion-engine thrust to the thrust-axis torque.

Approaching to the perihelion, it became apprehensible that the temperature at the baked point might exceed the baking temperature. In the worst scenario, the attitude might be disturbed by out-gas. In this case, out-gas could be a very large disturbance for Hayabusa spacecraft, which controls the attitude by adjusting very small sun angle.

Because it becomes clear that the temperature increase is proportion to the solar incidence angle on +X side panel, the decision to expose solar heat flux on –X side panel was made on 16th of May. Figure 8 shows the history of TSAS-X corresponding to the solar incidence angles from 5th of May to 30th of June. +side means that the plane of incidence is +X side panel and –side for -X side panel. Approaching to perihelion at the solar distance 0.95AU on Jun 9 (The lower side of figure 9), this constraint for attitude control had become more severe. In the most cases, the operation with the precision of 0.3 deg/day has been achieved. In the cases with the stable thrust of ion-engines, the precision of 0.1 deg/day could be achieved. Afterwards, Hayabusa has been operated with the precision of 1 degree of the relative attitude to the sun.

5. Concluding Remarks

Three axis attitude control strategy using solar radiation torque was developed and has been used to control the spacecraft for delta-V operation. The two axes were directly controlled using single reaction wheel and two gimbals on the ion engines table, and another axis was indirectly controlled applying a balance between the swirl torque of the ion engine thrust and the solar radiation torque proportional to the sun angle. It was realized two factors. First, the swirl torque was as small as solar radiation torque with small sun angle. Secondly, the difference torque was effective in controlling the angular momentum generated by Z-axis reaction wheel.

It was successful that the pointing accuracy was achieved within 0.3deg/day. The attitude has been kept the sun tracking since the delta-V operation. On the other hand, the strategy was established by operational experience and was still not enough study. These techniques and experience will be useful for future solar powered sail mission, so that we will continue to be conducted the attitude control strategy.

Reference

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