Attitude Control of Hayabusa2 using Sun-Tracking Motion under Solar Radiation Pressure

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Abstract

An attitude model for a biased-momentum 3-axis stabilized spacecraft "Hayabusa2" under the influence of solar radiation pressure is presented. It is confirmed from "Hayabusa" and "IKAROS" that the angular momentum vector of spacecraft can track Sun direction automatically and this motion is called Sun-tracking motion. Past studies revealed mechanism of Sun-tracking motion only for the spin-stabilized spacecraft, so this study extends these analyses to biased-momentum 3-axis stabilized spacecraft. Attitude control using Sun-tracking motion efficiently increases redundancy and saves fuel consumption of spacecraft.

It is shown that Sun-tracking motion of biased-momentum spacecraft is characterized by 9 parameters. Analyzing the flight data of "Hayabusa2", 9 parameter values are estimated.

太陽光圧下における太陽追尾運動を用いた小惑星探査機はやぶさ 2 の姿勢制御

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摘要

3 軸姿勢安定人工衛星「はやぶさ２」の太陽光圧下における姿勢挙動のモデルを示す。太陽光圧下において人工衛星の角運動量ベクトルが太陽方向を自動で追尾する運動、通称太陽追尾運動が、「はやぶさ」及び「IKAROS」にて確認されている。本研究はそれらスピン型の人工衛星にて確認された太陽追尾運動を、3 軸姿勢安定人工衛星に応用することが目的である。太陽追尾運動を利用することで、人工衛星の冗長性を高め、姿勢制御に利用する燃料消費を抑えることができる。

3 軸姿勢安定人工衛星における太陽追尾の挙動は 9 つのパラメータで特徴づけられる。「はやぶさ２」のフライトデータを解析することで、その 9 つのパラメータを推定する。

Nomenclature

$\boldsymbol{H}$	:	Angular momentum vector
$\boldsymbol{T}$	:	Torque vector
Σ	:	Coordinate frame
$\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}$	:	Orthogonal basis vectors
$\beta_{out} = -\phi$	:	Out-orbit angle
$\beta_{in} = \theta$	:	In-orbit angle
ψ	:	Rotation angle
$\boldsymbol{h}_W$	:	Inner angular momentum vector
$\boldsymbol{\omega}_{A.B}$	:	Angular velocity vector of frame A with respect to frame B
$\boldsymbol{I}$	:	Inertia tensor

Subscript

I	:	Inertia frame
O	:	Orbit-fixed frame
B	:	Body-fixed frame
SRP	:	Solar Radiation Pressure

1. Introduction

In interplanetary missions, solar radiation pressure (SRP) is a major disturbance to a spacecraft. Some missions, however, utilize this SRP disturbance to stabilize the spacecraft attitude. Two typical examples are; the emergency operation of Hayabusa[1,2] and the attitude control demonstration of IKAROS[3,4].

In these missions, it is confirmed that angular momentum vector of a spacecraft can track Sun direction automatically, in spite of orbital motion with properly settings, and this motion is called Sun-tracking motion. See Fig.1 and Fig.2. Working only one reaction wheel along the axis that needs to be pointing in Sun direction, the spacecraft will roughly point towards that direction. By actively using SRP, this improved attitude control system is realized and efficiently increases redundancy and saves spacecraft fuel consumption. In contrast with the fact that the past missions used this technique exclusively to spin-stabilized spacecraft[5], this paper attempts to extend this Sun-tracking technique to a biased-momentum 3-axis stabilized spacecraft, Hayabusa2.

SRP torque working on Hayabusa2 is approximately described by 9 parameters and analytical attitude model is established using them. It is also confirmed that these 9 parameters are related with spacecraft shape. Attitude motion is mainly depending on 6 parameters and the change of inner angular momentum is mainly decided by the other 3 parameters. Analytical attitude motion is combination phenomenon of precession, torque-induced main attitude motion, and nutation, torque-free circular motion around the angular momentum vector. Interestingly, the equilibrium direction of precession is not exactly Sun direction and the history of precession draws elliptic circle. The equilibrium direction has certain offset from the exact Sun direction and it depends on the shape of spacecraft and its rotational angle. The radius of elliptic circle may converge or diverge depending on attitude conditions. These new phenomenon is unique to 3-axis stabilized spacecraft and not observed in spin-stabilized spacecraft.

These 9 parameter values are obtained from real flight data of Hayabusa2, using least-square method. It becomes possible to estimate attitude motion using obtained 9 parameters. Analytical model is compared with the real spacecraft behavior and it agree well with it, so the analytical model of Sun-tracking motion is proven to be reasonable and this newly derived model

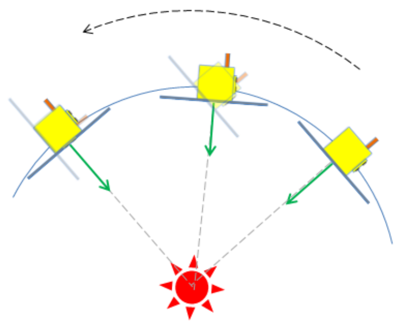

Figure 1. Image of Sun-tracking motion

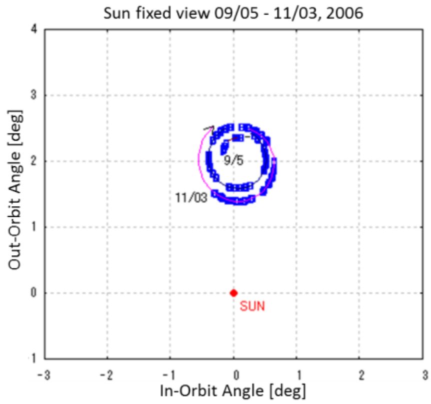

Figure 2. Attitude history of Hayabusa in emergency operation

is sufficiently effective for prediction of future attitude motion of Hayabusa2.

This analytical model is not restricted to Hayabusa2 but is applicable to various 3-axis stabilized spacecraft. Furthermore, this control method is so simple and does not need any new algorithm that Sun-tracking motion can be applied to various interplanetary missions in future.

2. Sun-Tracking Motion

Sun-tracking motion is roughly the same mechanism as the motion of spinning top. Both motions are the combination of precession and nutation. Precession is a torque-induced motion of the angular momentum vector, whereas nutation is a torque-free circular motion of the rotation axis around the angular momentum vector. The precession motion of a spinning top is induced by gravity torque. In the case of a spinning or biased-momentum spacecraft, in interplanetary missions, it is induced by the SRP torque. Precession is described by Euler equation:

$$\left.\frac{d\boldsymbol{H}}{dt}\right|_I = \boldsymbol{T} \quad (1)$$

This equation says that the angular momentum vector is inclined to the external torque vector direction. The gravity torque field on the spinning top draws a circle around the vertical vector to the ground, and the SPR torque field also draws a circle around Sun direction. In the result, the angular momentum vector also draws a circle around Sun direction automatically; this motion is, so called, Sun-tracking motion.

In addition, in the case of orbiting spacecraft, inertia torque generated by orbital motion works on spacecraft. Because of that, the center of Sun-tracking motion, which is the equilibrium point where total torque is zero, is shifted in the out-orbit direction. In the result, the angular momentum vector of spacecraft draws a circle around that shifted equilibrium point. This phenomenon is common to spinning spacecraft and biased-momentum spacecraft.

This study reveals, only in the case of biased-momentum 3-axis stabilized spacecraft, that the equilibrium point is shifted not only in the out-orbit direction but also in the in-orbit direction, and that precession motion is not necessary perfect circle, but it would be elliptic, and diverge or converge. It is because the additional SRP is working on biased-momentum spacecraft due to its complex shape, optical properties and so on. In the case of spinning spacecraft, SRP working on spacecraft is averaged due to high frequency spinning, so it is assumed that upper surface of spacecraft is roughly flat and SPR always radiates on the center of upper surface. However, in the case of biased-momentum spacecraft, which is not spinning, the deviation of radiated surface and optical properties on each surface or component is generated. Then they generate small, but important, additional torques. Consequently, these additional SRP torque shifts the equilibrium point in certain direction, which is depending entirely on the shape and optical properties of spacecraft, and distort Sun-tracking circular attitude motion.

3. Analytical Model of Sun-Tracking Motion

In this section, attitude motion of biased-momentum 3-axis stabilized spacecraft under the SRP, which is so called Sun-tracking motion, is modeled analytically.

3.1. Definition and Assumption

In order to express spacecraft attitude, three coordinate frames, inertia frame, orbit-fixed frame, and body-fixed frame are introduced. In regards to orbit-fixed frame, $\boldsymbol{k}_O$ is always pointing in Sun direction, $\boldsymbol{i}_O$ pointing in opposite direction of orbital motion and $\boldsymbol{j}_O$ is standing up right to orbital plane. In regards to body-fixed frame, in the case of Hayabusa2, $\boldsymbol{i}_B$ is thruster injection direction, $\boldsymbol{k}_B$ is solar array panels' (SAP) normal vector and $\boldsymbol{j}_B$ is configured to form the right-handed system. See Fig.3 and Fig.4.

The attitude of body-fixed frame with respect to orbit-fixed frame is represented 2-1-3 $(\theta - \phi - \psi)$ Euler expression, in modeling attitude motion. In figuring the spacecraft attitude, however, the in-orbit angle β_{in} and the out-orbit angle β_{out} are used for easily understanding where $\boldsymbol{k}_B$ directs. They are angles when spacecraft is looked at behind Sun. See Fig.5

3.2. One Wheel Control

In Hayabusa2 mission, Sun-tracking motion is used in order to save fuel consumption and increase redundancy. As the attitude control actuator, four RWs are mounted on spacecraft in X-Y-Z1-Z2 arrangement, which is very unique configuration. However, spacecraft uses only one RW along vector $\boldsymbol{k}_B$ and the other RWs are not operated. This control mode is called, one wheel control (OWC) mode. The only active RW is driven utilizing exactly the same control logic as is used by the ordinary three-axis stabilization controller to hold the attitude about vector $\boldsymbol{k}_B$, and it realizes Sun-tracking motion. The other axes, $\boldsymbol{i}_B$ and $\boldsymbol{j}_B$ are passively maintained taking advantage of Sun-tracking motion. During OWC mode, rotation angle around $\boldsymbol{k}_B$, which is ψ, is maintained constant with only one active RW control. So in this study, it is assumed that rotation angle ψ is always controlled constant.

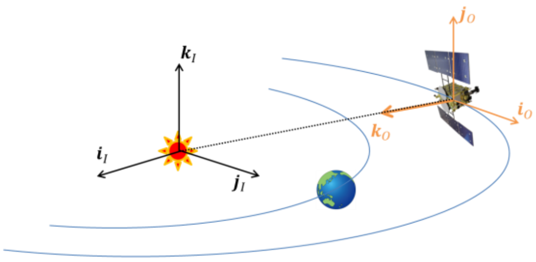

Figure 3. Orbit-fixed frame

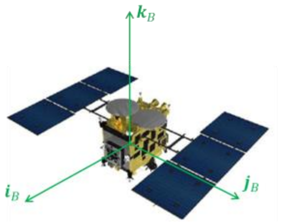

Figure 4. Body-fixed frame

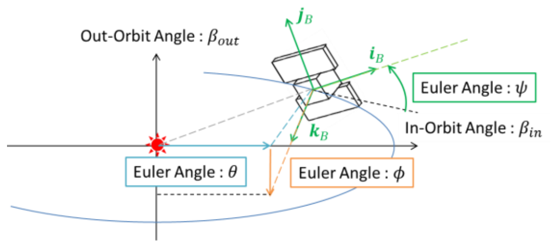

Figure 5. Euler angle expression and angles when looking at spacecraft behind Sun

3.3. Analytical Model

In the case that there is no other disturbance except SRP, Euler equation Eq.1 is rewritten as:

$$\left.\frac{d\boldsymbol{H}}{dt}\right|_I = \left.\frac{d\boldsymbol{H}}{dt}\right|_B + \boldsymbol{\omega}_{B.I} \times \boldsymbol{H} = \boldsymbol{T}_{SRP} \quad (2)$$

$$\boldsymbol{H} = \boldsymbol{I} \cdot \boldsymbol{\omega}_{B.I} + \boldsymbol{h}_W \quad (3)$$

It is revealed that SRP torque working on biased-momentum 3-axis stabilized spacecraft is expressed in 9 parameters, in small angle approximation, as:

$$^{B}\boldsymbol{T}_{SRP} = \begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix}$$

$$\begin{aligned} T_x &= P_1 + P_{4A}(\theta \sin\psi + \phi\cos\psi) \\ &\quad + P_7(\theta\cos\psi - \phi\sin\psi) \\ T_y &= P_2 + P_8(\theta\sin\psi + \phi\cos\psi) \\ &\quad + P_{4B}(\theta\cos\psi - \phi\sin\psi) \\ T_z &= P_3 + P_5(\theta\sin\psi + \phi\cos\psi) \\ &\quad + P_6(\theta\cos\psi - \phi\sin\psi) \end{aligned} \quad (4)$$

Then, substituting Eq.3, 4 into Eq.2, the analytical model of Sun-tracking motion is derived. That motion is divided into two parts; one is the motion of equilibrium point that is hardly moves, the other is the small motion around that equilibrium point. They are described as $\theta = \tilde{\theta} + \Delta\theta, \phi = \tilde{\phi} + \Delta\phi$, and each part is written as below, in the case of rotation angle ψ is 90deg constant:

Equilibrium point

$$\tilde{\theta} = \frac{h_W\omega_0(P_7 \sin^2\psi - P_8\cos^2\psi - (P_{4A} - P_{4B})\sin\psi\cos\psi) - P_2P_{4A}\cos\psi - P_1P_{4B}\sin\psi}{P_{4A}P_{4B}}$$
$$\tilde{\phi} = \frac{h_W\omega_0(P_{4A}\sin^2\psi + P_{4B}\cos^2\psi + (P_7 + P_8)\sin\psi\cos\psi) + P_2P_{4A}\sin\psi - P_1P_{4B}\cos\psi}{P_{4A}P_{4B}} \quad (5)$$

Attitude motion around equilibrium point

$$\Delta\theta = A_P\, exp\left(\frac{P_7 - P_8}{2h_W}t\right)\sqrt{\frac{P_{4B}}{P_{4A}}} sin\left(\frac{\sqrt{P_{4A}P_{4B}}}{h_W}t - tan^{-1}\left(\frac{P_7 - P_8}{\sqrt{4P_{4A}P_{4B}}}\right) + \delta_P\right) \quad (6)$$
$$\Delta\phi = A_P\, exp\left(\frac{P_7 - P_8}{2h_W}t\right) cos\left(\frac{\sqrt{P_{4A}P_{4B}}}{h_W}t + \delta_P\right)$$

where A_P, δ_P are integral constants and decided by initial condition, and inner angular momentum h_W is assumed constant because SRP working along $\boldsymbol{k}_B$ is sufficiently small. In Sun-tracking motion of biased-momentum 3-axis stabilized spacecraft, there are three important and unique features.

1. Attitude motion around equilibrium point will converge or diverge due to $P_7 - P_8$.
2. Attitude motion around equilibrium point may be elliptic due to $\sqrt{P_{4B}/P_{4A}}$.
3. There is a phase difference between the out-orbit angle and the in-orbit angle.

4. Comparison with Flight Data

Figure 6 shows the flight data of Hayabusa2 during OWC mode, in this period rotation angle ψ was kept about 90deg, from 9th to 20th February, 2015. The red line is attitude history of $\boldsymbol{k}_B$, which is combination of precession and nutation, and the green line is precession history extracted by averaging red line every nutation cycle, which is just Sun-tracking motion. It is obvious that Sun-tracking motion drew ellipse around the equilibrium point, which is about $\beta_{in} = 1.2$[deg], $\beta_{out} = 2.7$[deg].

By least-square method, 9 parameter values are decided, shown in Tab.1, and analytical model using such obtained values are overlaid on flight data. See Fig.7. It seems to be fitted well, and it confirmed that analytical model is reasonable.

5. Conclusion

SRP torque working on 3-axis stabilized spacecraft is expressed in 9 parameters. Then, using such 9 parameters, analytical attitude model of Sun-tracking motion is constructed. Sun-tracking motion of biased-momentum 3-axis stabilized spacecraft is divided into two parts, one is the

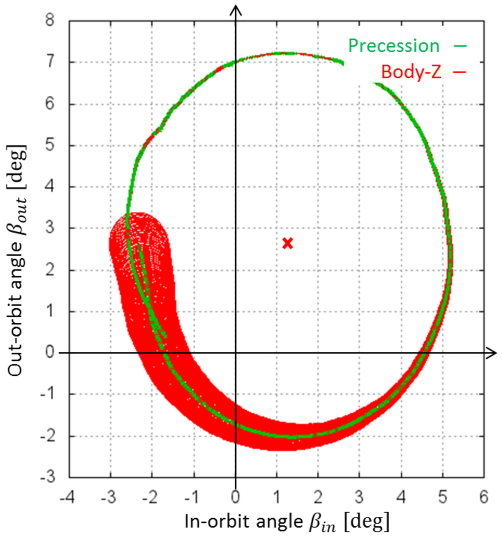

Figure 6. Flight data of Hayabusa2 Feb. 9th-20th

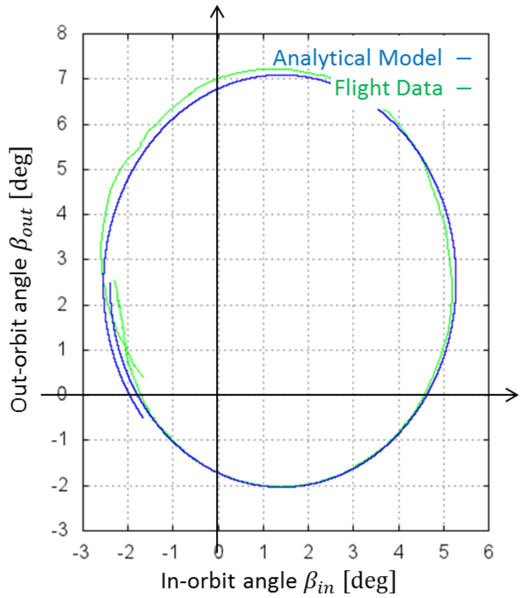

Figure 7. Comparison of analytical model with flight data

Table 1. Parameter values from flight data

P_1	-5.68×10^{-7}
P_2	-1.25×10^{-6}
P_3	-2.33×10^{-7}
P_{4A}	2.37×10^{-5}
P_{4B}	1.71×10^{-5}
P_5	4.34×10^{-9}
P_6	3.44×10^{-6}
P_7	3.97×10^{-7}
P_8	1.51×10^{-7}

equilibrium point, which is shifted not only in the out-orbit direction but also in the in-orbit direction, and the other is ellipse around that equilibrium point, which may either diverge or converge. Finally, this analytical model is confirmed reasonable by comparison with real flight data.

6. Acknowledgments

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