FEM based evaluation of attitude dynamics for spinning spacecraft under influence of SRP

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Abstract

This paper discusses about attitude dynamics for spinning spacecraft under influence of solar radiation pressure (SRP). Generally spinning objects maintain its spin axis with reference to inertial frame. But if disturbance torque like SRP affects this object, the spinning motion indicates a unique behavior due to dynamical coupling between the SRP torque and the spin motion. IKAROS and HAYABUSA launched by Japan Aerospace Exploration Agency (JAXA) positively utilize this phenomenon in actual operation. There are two purposes in this paper. The one is alignment of microscopic theory and macroscopic theory. The other one is considering these remarkable motions theoretically. For this purpose, we construct FEM-model including SRP effects and simulate attitude dynamics numerically. In the results of simulations, two causes were found. The one is surface optical property distribution of spacecraft. The other one is non- flat surface effect of spacecraft. In this paper, we indicate the background of constructing SRP model and the evaluation including flight data of HAYABUSA and IKAROS. Then we discuss about the relationship between simplified attitude models and microscopic models.

太陽光圧影響下での FEM を用いたスピン型宇宙機の姿勢ダイナミクス評価

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摘要

本研究は，太陽光圧を受けるスピン型宇宙機の姿勢運動について論ずる．通常宇宙空間でスピン物体は，慣性系に対してそのスピン軸を維持するが，太陽光圧のような外力トルクを受けるとスピン運動とのカップリングにより特徴的な挙動を示す．ＪＡＸＡによって打ち上げられたはやぶさやＩＫＡＲＯＳはその挙動を積極的に利用して運用されたミッションの例である．本稿の目的は，太陽光圧による姿勢挙動について微視的な理解と巨視的な理解を整合させ，これらの特徴的な挙動に理論的考察を与えることである．そのために光圧に関する有限要素モデルを構築して数値シミュレーションを行った．結果として宇宙機の表面の光学特性が特定の分布を持っていること，および非平面的な形状を有していることが，はやぶさIKAROSの特徴的な姿勢挙動を作り出していることが見出された．本稿は，太陽光圧モデル構築の理論的背景，IKAROS はやぶさの実データをもちいた評価を示し，簡易姿勢モデルと微視的モデルの間の関係について考察をするものである．

1. Introduction

The theme of this study is attitude dynamics for spinning spacecraft under influence of solar radiation pressure (SRP). Generally spinning objects maintain its spin axis with reference to inertial frame. But if disturbance torque like SRP affects this object, the spinning motion indicates a unique behavior. As shown in Fig. 1, the spin axis of the spacecraft trace cycle motion around a certain equilibrium point due to dynamical coupling between the SRP torque and the spin motion. We call this phenomenon SRP drift motion. As past study, interplanetary spacecraft HAYABUSA and IKAROS (Fig.2) launched by Japan Aerospace Exploration Agency (JAXA) utilized this behavior in actual operation. For example, HAYABUSA was kept sun-oriented during spin stabilized phases without fuel utilizing this phenomenon. In the IKAROS mission a method has been developed which controls both attitude and orbital trajectory by SRP. These two are the remarkable examples of how SRP is utilized for fuel-saving operation efficiently.

Seeing actual spin axis motions of HAYABUSA and IKAROS (Fig.3) macroscopically, these motions can be seeing like circular motion, but microscopically, these motions are like spiral behavior. The spiral behavior and wind mill effect which causes acceleration or deceleration of spin rate cannot occur from SRP torque by flat face equipment. These effects are caused by effects of non-flat surface like wrinkle of membrane and asymmetry of the spacecraft. To enable to operate by SRP drift motion correctly, it is essential to understand these causes of remarkable effects correctly. For these purposes, we construct FEM models of HAYABUSA and IKAROS including SRP effects and evaluate the effect of SRP influence attitude dynamics. Using FEM models, it is enable to calculate SRP effects of complicated surface and wrinkle of membrane. In this paper, from FEM models and flight data we calculate three parameters which make it possible to explain SRP drift motion including spiral behavior and wind mill effect. Then, comparing these parameters of only HAYABUSA, we understand correct surface shape and formulate SRP effect.

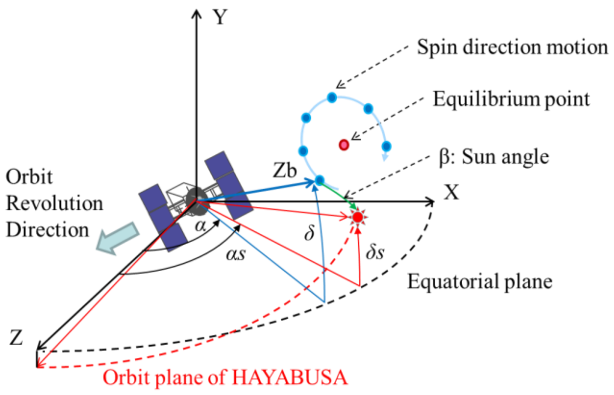

Fig. 1: Spin axis motion of spinning spacecraft under influence of SRP and definition of reference coordinate system and each angle (latitude and longitude) [3].

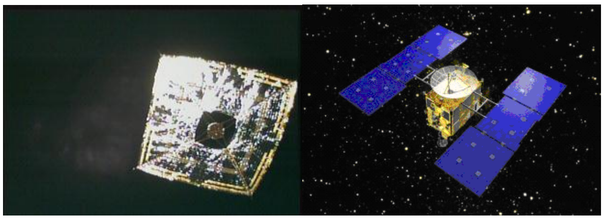

Fig. 2: Interplanetary Kite-craft Accelerated by Radiation Of the Sun: IKAROS launched on 2010 and MUSES-C: HAYABUSA launched on 2003 (JAXA).

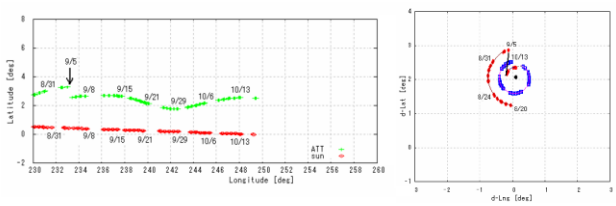

Fig. 3: The spin axis history of HAYABUSA between Sep.15 and Nov.13 2006 in sun-pointing frame[1].

2. Spinning spacecraft attitude dynamics including SRP

First, we indicate the dynamics equation of the spin axis direction motion under influence of SRP. When spinning spacecraft sails under influence of SRP, the attitude dynamics in the spin-free coordinates can be expressed using three parameters. From the paper written by Tsuda et.al.[2], this attitude dynamics are defined as follows;

$$\mathbf{I}\dot{\boldsymbol{\omega}}+\tilde{\boldsymbol{\omega}}\times\mathbf{I}\boldsymbol{\omega}=\mathbf{T} \quad [1]$$

and we can derive;

$$\frac{d}{dt}\begin{bmatrix}\omega_x\\ \omega_y\\ \frac{I_S}{I_T}\Omega\\ \alpha\\ \delta\end{bmatrix}=\begin{bmatrix}\frac{1}{I_T}\left(-I_S\Omega\omega_y+T_x\right)\\ \frac{1}{I_T}\left(I_S\Omega\omega_x+T_y\right)\\ \frac{T_z}{I_S}\\ \frac{\omega_y}{\cos\alpha}\\ -\omega_x\end{bmatrix} \quad [2]$$

Spin-free coordinates is that the z axis correspond to the body frame and x and y axis rotate in synchronization with spin rate.

Additionally, using parameters A, B, and C, the relationships between attitude dynamics and SRP torque are expressed as follows;

$$\begin{bmatrix}T_x\\ T_y\\ T_z\end{bmatrix}=\begin{bmatrix}\cos(\Delta\delta)\sin(\Delta\alpha) & -\sin(\Delta\delta) & 0\\ \sin(\Delta\delta) & \cos(\Delta\delta)\sin(\Delta\alpha) & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}A\\ B\\ C\end{bmatrix} \quad [3]$$

when

$$\Delta\alpha=\alpha_s-\alpha$$
$$\Delta\delta=\delta_s-\delta \quad [4]$$

Originally T_x, T_y, T_z are the external spin-averaged torques of spin-free coordinates. Though, under circumstances of interplanetary spacecraft external torque is almost SRP torque without thruster and reaction wheel. Parameter A, B, and C are determined by configuration and optical parameter of the spacecraft surface.

Let us then assume that the latitude and longitude of sun angle and spin axis direction are very small. Under this approximation, and using Eq.[2] and Eq.[3], the dynamics of spin axis direction is described as follows;

$$\begin{bmatrix}\alpha_{eq}\\ \delta_{eq}\end{bmatrix}=\begin{bmatrix}\alpha_s\\ \delta_s\end{bmatrix}+\frac{I_S\Omega}{(A^2+B^2)}\begin{bmatrix}A & B\\ -B & A\end{bmatrix}\begin{bmatrix}\alpha_s\\ \delta_s\end{bmatrix} \quad [5]$$

$$\alpha=\alpha_{eq}+D\exp\left(\frac{A}{I_S\Omega}t\right)\cos\left(\frac{B}{I_S\Omega}t+\varphi\right)$$
$$\delta=\delta_{eq}+D\exp\left(\frac{A}{I_S\Omega}t\right)\sin\left(\frac{B}{I_S\Omega}t+\varphi\right) \quad [6]$$

and the rotational dynamics around z-axis is described as follows;

$$T_z=C \quad [7]$$

Equation 6 and 7 indicate that the spiral effect of spin axis direction motion is determined by A, the wind mill effect is defined by C and macroscopically circular motion is driven by B. Therefore, SRP drift motion can be derived correctly by determining A, B and C. In addition, from these equations, the two points are indicated.

1. Spin axis direction move around a certain equilibrium point and if A=0, the motion of spin axis direction is circular without spiral effect.
2. If A is negative, spiral behavior go to equilibrium point and if A is positive, go out from equilibrium point.

In the HAYABUSA, consider only SAP effect of SRP, A and C are zero. Therefore there are no effects of spiral behavior and wind mill effects. In the paper [1], Kawaguchi et.al.[1)] estimate the optical parameter from flight data only considering the effects of SAP SRP. However the flight data of HAYABUSA like Fig.3 show outside spiral behavior. This means parameter A has positive numerical value. This influence does not appear from simplified attitude models considering only flat surface effects. Therefore it is necessary to consider the detailed model including the HGA and others.

3. Numerical analysis using FEM

3.1 The expression of SRP

Next, we indicate numerical analysis method using FEM model including SRP effects of the spacecraft. In order to calculate more detailed model, we construct the FEM model of HAYABUSA and IKAROS, and calculate SRP and SRP torque of each element. Adding SRP effects of each element, we get the total SRP and SRP torque of the spacecraft. In the calculation, we use SRP equation as follows;

$$\mathbf{p} = -P(\mathbf{s}\cdot\mathbf{n})\left[(C_a + C_d)\mathbf{s} + \left\{2(\mathbf{s}\cdot\mathbf{n})C_s + \frac{2}{3}C_d\right\}\mathbf{n}\right] \quad [7]$$

and we consider shade and shadow effects of each element, but do not consider effects of secondary-reflection of sun light.

3.2 Structure and FEM model

In this calculation, we construct only surface equipments of the spacecraft. We do not construct inner equipments and do not calculate dynamic equation such as vibration equation. In the FEM model of HAYABUSA for example, equipments we construct are SAP, HGA, spacecraft body, ion thruster (simple structure), sampler horn (simple structure) and capsule (Fig. 4). Obviously, simple equipment is constructed by coarse elements and complex equipment is configured by fine elements. We model each element including area, position, normal direction, and optical parameter without mass which is not used for calculation. Fig. 5 indicates FEM model of HAYABUSA for example.

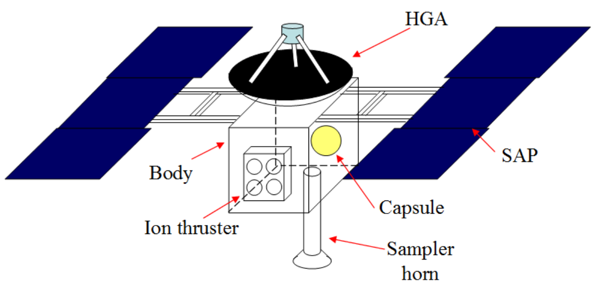

Fig. 4: Equipments we construct for calculating SRP and SRP torque.

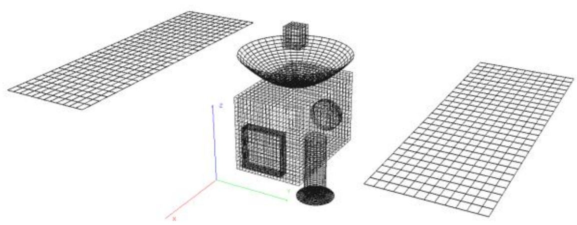

Fig. 5: FEM model of HAYABUSA.

4. Analysis results of HAYABUSA operation

As first analysis of effect of SRP, we chose HAYABUSA. The reason is that there are enough flight data in HAYABUSA operation and structure of HAYABUSA is relatively simple.

4.1 Flight data of HAYABUSA

In order to compare the flight data with the FEM model, it is necessary to estimate parameters A, B and C derived in chapter 2 from flight data of HAYABUSA. In estimation of A, B and C, parameter A and B are derived from the spin axis direction history in sun-pointing frame and parameter C is derived from spin rate history. Because parameter A is responsible for the spiral effect, the A can be estimated from the increase or decrease of radial gradient of spin axis history. Similarly, because parameter B is responsible for the period of SRP drift motion, the B can be estimated from the phase of the history. Therefore, dividing flight data into each component, we employ least squares method to each to estimate each parameter. We use two terms flight data: one is from Aug.1st to Aug. 15, 2008 (Fig. 6) and other one is from Nov. 2nd to Nov. 18, 2008 (Fig. 7). As the results of estimation, parameter A, B and C are derived from two terms as follows;

- Between Aug.1st to Aug. 15, 2008:

$$\begin{aligned} A &= (-9.439 \pm 0.067)\times 10^{-7} \\ B &= (2.697 \pm 0.002)\times 10^{-5} \\ C &= (-5.531 \pm 0.032)\times 10^{-8} \end{aligned} \quad [8]$$

- Between Nov. 2nd to Nov. 18, 2008:

$$A = (-7.132 \pm 0.032) \times 10^{-7}$$
$$B = (2.762 \pm 0.001) \times 10^{-5} \quad [9]$$
$$C = (-6.910 \pm 0.035) \times 10^{-8}$$

In these parameters sun distance corrects to 1 [AU]. Fig. 6 and Fig. 7 show the original flight data history and the results of least squares method. In the flight data from Aug.1st to Aug. 15, 2008, spin rate is 0.0113[rad/sec], sun distance is 1.29 [AU], D is 0.00696 and φ is -35.76 [deg]. On the other hand, from Nov. 2nd to Nov. 18, 2008, spin rate is 0.0104[rad/sec], sun distance is 0.95 [AU], D is 0.0153 and φ is 222.46 [deg].

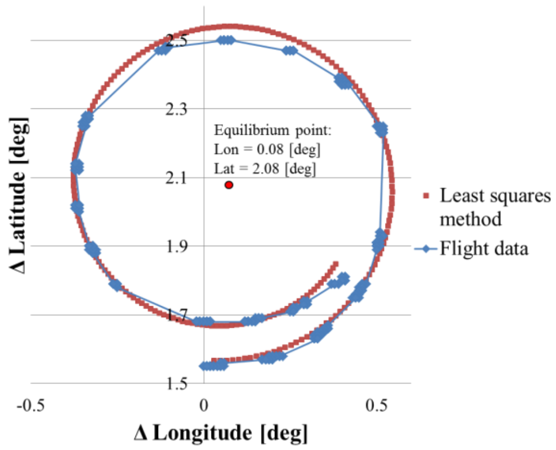

Fig. 6: Plot of spin axis direction motion of HAYABUSA: The results of least squares method and original flight data from Aug.1st to Aug. 15, 2008. X-axis is longitude and Y-axis is latitude from sun point.

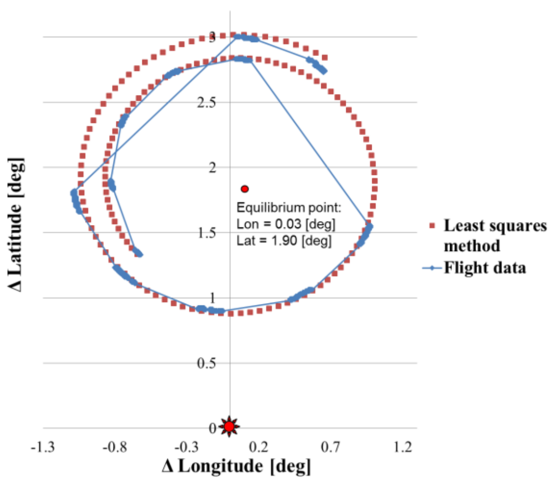

Fig. 7: Plot of spin axis direction motion of HAYABUSA: The results of least squares method and original flight data from Nov. 2nd to Nov. 18, 2008. X-axis is longitude and Y-axis is latitude from sun point.

4.2 Parameter of equipments

In previous section, we derived A, B and C from the flight data. Then, we calculate each parameter from FEM model of HAYABUSA. In order to calculate parameters, equipments introduced in section 3.2 are constructed. Sizes of each equipment are shown in Fig. 8, and optical parameters we use are shown in Table 1. In order to calculate SRP and SRP torque correctly, it is necessary to consider effects of disagreement between center point and gravity point and between Z-axis in body frame and spin axis. The disagreement problem of gravity point can be solved using Eq. [10] values;

$$GPx = 2.019[mm]$$
$$GPy = 1.583[mm] \quad [10]$$
$$GPz = 574.94[mm]$$

These values of Eq. [10] are gravity point from coordinates frame indicated Fig. 8. Subtracting these values from each position of equipments, the origin of this coordinate can be transformed to gravity point.

The spin axis problem can be solved by using the direction cosine matrix (DCM) of Eq. [11] which transforms coordinate from body frame into spin axis frame;

$$DCM = \begin{bmatrix} 0.9983041 & 0.0000061 & 0.0582137 \\ -0.0006227 & 0.9999439 & 0.0105743 \\ -0.0582104 & -0.010593 & 0.9982481 \end{bmatrix} \quad [11]$$

For this DCM, the spin axis inclines about 3 degrees.

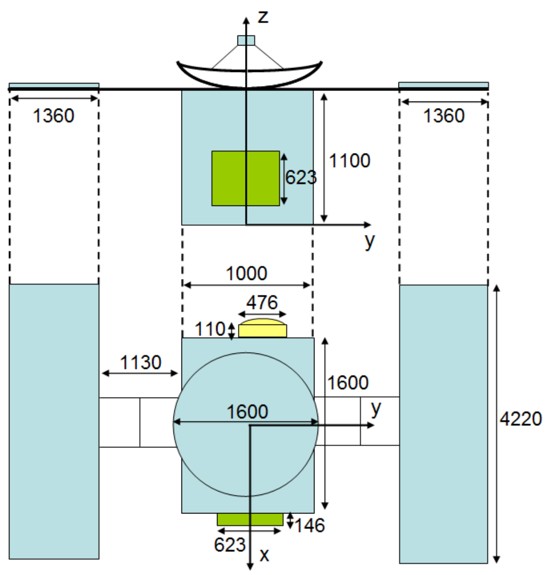

Fig. 8: Sizes of each equipment and body axis of HAYABUSA. This frame is not body frame. The body frame of HAYABUSA is described by including gravity point.

	Ca	Cd	Cs	Ct
SAP	0.910	0.080	0.010	0
Body(MLI)	0.370	0.255	0.375	0
Body(Rad)	0.100	0.200	0.700	0
HGA	0.320	0.050	0.030	0.600
Horn	0.920	0.080	0	0
Ion thruster	0.100	0.200	0.700	0
Capsule	0.370	0.255	0.375	0

Table 1: Optical parameters of each equipment of HAYABUSA. Ca is absorption coefficient, Cd is diffuse reflection coefficient, Cs is specular reflection coefficient and Ct is transmission coefficient.

4.3 Calculation results from FEM model

We can calculate A, B and C from FEM model of HAYABUSA using parameters of previous section. In order to calculate A, B and C, it is essential to calculate spin average SRP torque in spin-free coordinate. This coordinate is defined as that sun direction is on the plane made Z and X axis of this coordinate. That is to say, the spin-free coordinate is not affected from spinning, like inertial coordinate. For calculating spin average SRP torque, the spacecraft or sun direction is rotated around spin axis on fixed sun angle. Then, each SRP torque of calculation is averaged in spin-free coordinate. Next, we calculate parameter A, B and C from the spin average SRP torque. From Eq.[3], assume that sun angle direction is very small, the relationship between the spin average SRP torque and A, B and C is derived as follows;

$$\begin{bmatrix} Tx \\ Ty \\ Tz \end{bmatrix} = \begin{bmatrix} \Delta\alpha & -\Delta\delta & 0 \\ \Delta\delta & \Delta\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} \qquad [12]$$

In this way, we define $\Delta\alpha = 0$ and $\Delta\delta = \beta$, so Eq. [12] is derived as follows ;

$$\begin{bmatrix} \mathrm{A} \\ \mathrm{B} \\ \mathrm{C} \end{bmatrix} = \begin{bmatrix} \mathrm{Tx}/\beta \\ \mathrm{Ty}/\beta \\ \mathrm{Tx} \end{bmatrix} \qquad [13]$$

Using Eq.[13], we indicate results of A, B and C for $\beta = 0-10$ [deg] in Fig. 9. The detailed evaluation of A, B and C indicated Fig. 9 is described on this figure explanation. We also indicate some calculation results of SRP torque in Fig. 10. In description of this model, each element is collared by SRP or SRP torque value. From this figure, we can understand SRP effects visually, for example shade effect can be understood easily.

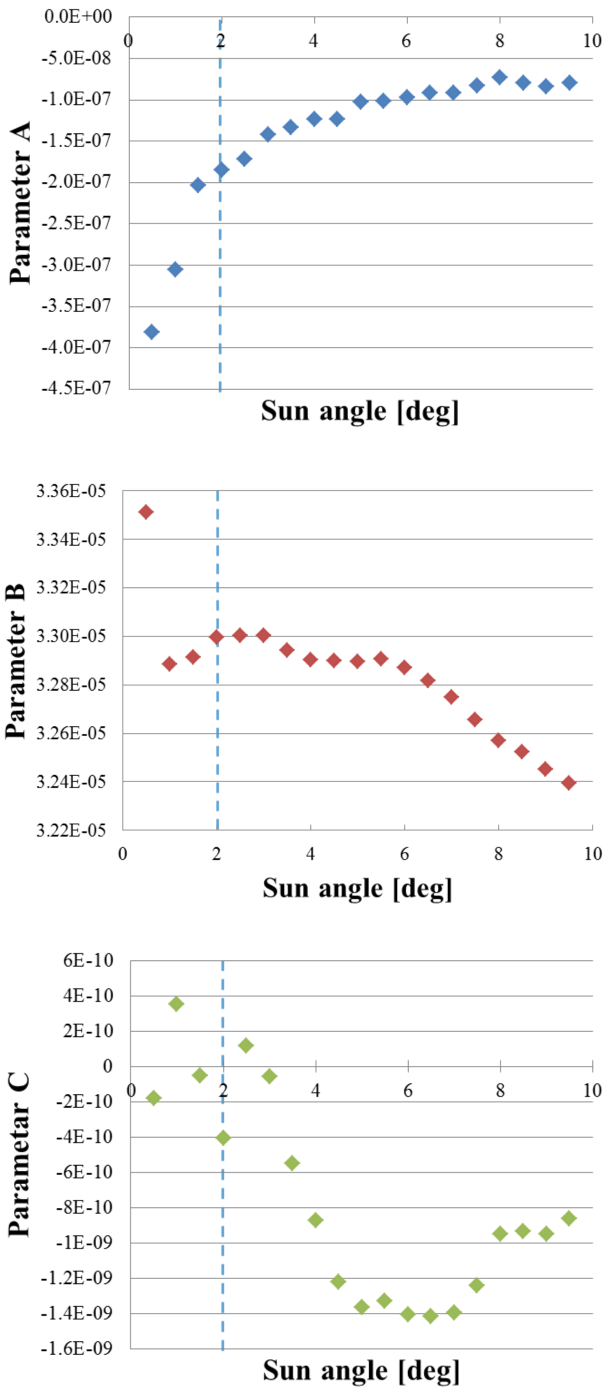

Fig. 9: Plots of sun angle vs parameters A, B and C. In these figures, the absolute value of A is decreased when sun angle is increased, B is almost constant in each sun angle and C fluctuates between 0 and 4 degree. The cause of fluctuation of C is probably that the wind mill effect is very small from virtual structure of HAYABUSA (In actuality, this effect is more lager.). The blue dot-lines are average sun angle in actual operation.

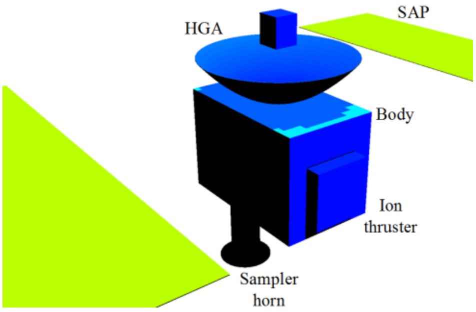

Fig. 10: The result of calculating SRP from FEM model. Using this method, effects of SRP can be understood visually. This figure encourages correct understanding of SRP effects.

4.3 Compare FEM results to flight data using A, B and C

From flight data, we define average sun angle is 2 degree. In this sun angle, A, B and C from FEM model of HAYABUSA are calculated as follows;

$$A = -1.851 \times 10^{-7}$$
$$B = 3.300 \times 10^{-5} \quad [14]$$
$$C = -4.060 \times 10^{-10}$$

There are some suppositions which explain the disagreement between FEM model and flight data, for example straining of SAPs due to any accident, but there are no clear evidences to explain these suppositions. So the truth is veiled.

In this calculation of FEM model, we calculate each effect of equipments. We show the percentage of A, B and C of each equipment in Fig. 11.

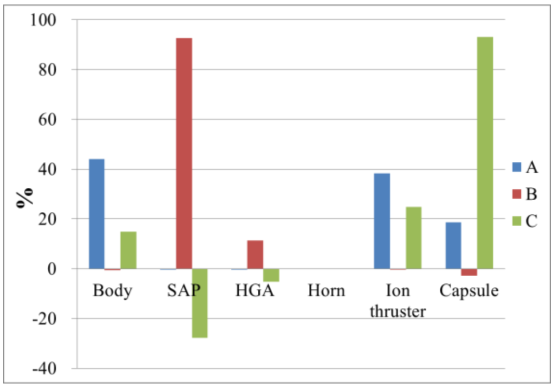

Fig. 11: The percentages of A, B and C of each equipment. It is clear that SAP effect is most strong in B. On the other hand, A is occurred from body and Ion thruster mostly. C is occurred from Capsule mostly. However, if SAPs strain the SAPs effect occur A and C.

5. conclusion

We indicate the method which evaluate the effects of SRP and evaluate HAYABUSA operation. These results of evaluation indicate that the shape and optical parameters dominate spinning dynamics including SRP effect. Therefore, it is important to estimate the shape of spacecraft and understanding what deformation makes these effects dominant. We continue to analyse these matters mainly.

References

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