FEM-based High-fidelity Solar Radiation Pressure Analysis*

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In medium-Earth-orbit, geostationary, and deep space missions, the effects of solar radiation pressure (SRP) on the motion of a spacecraft are dominant relative to other perturbations. Recently, several spacecraft have actively used SRP torque for attitude control, and the importance of calculating the SRP torque accurately is increasing. The present paper introduces a newly developed SRP analysis tool called the FEM radiation analysis tool (FRAT). This tool uses an element-based ray tracing strategy, and each element is assigned different optical parameters derived from its material properties. This tool calculates the SRP applied to each mesh element taking shadows into consideration. In the present paper, the accuracy of this calculation is evaluated using flight data of the HAYABUSA 2 asteroid exploration spacecraft. Then, two application examples in which FRAT has played an important role are presented. The first example involves HAYABUSA 2, the attitude of which has been stabilized by actively using the SRP. In the second example, the shape of the sail of IKAROS, a solar sail spacecraft, was estimated using FRAT in order to reproduce the flight data.

Key Words: Solar Radiation Pressure Torque, Finite Element Model, FEM Radiation Analysis Tool

Nomenclature

\[ A: \text{ torque parameter} \]
\[ \alpha: \text{ right ascension of the spin vector} \]
\[ \alpha_C: \text{ right ascension of the Sun direction} \]
\[ B: \text{ torque parameter} \]
\[ C: \text{ torque parameter} \]
\[ C_r: \text{ ratio of specular reflection} \]
\[ C_d: \text{ ratio of diffuse reflection} \]
\[ C_a: \text{ ratio of absorption} \]
\[ C_t: \text{ ratio of transmittance} \]
\[ c: \text{ speed of light} \]
\[ D: \text{ torque parameter} \]
\[ dA: \text{ area of mesh element} \]
\[ df: \text{ force applied to area of mesh element} \]
\[ dT: \text{ torque applied to area of mesh element} \]
\[ \delta: \text{ declination of the spin vector} \]
\[ \delta_C: \text{ declination of the Sun direction} \]
\[ E: \text{ torque parameter} \]
\[ F: \text{ torque parameter} \]
\[ f_{S/C}: \text{ force applied to spacecraft} \]
\[ G: \text{ torque parameter} \]
\[ H: \text{ torque parameter} \]
\[ h_{nm}: \text{ weight of sail deformation mode} \]
\[ I: \text{ torque parameter} \]
\[ J: \text{ torque parameter} \]
\[ K: \text{ torque parameter} \]
\[ L: \text{ torque parameter} \]
\[ n: \text{ unit normal vector} \]
\[ \phi: \text{ right ascension} \]
\[ \psi: \text{ rotation angle around Z-axis} \]
\[ R: \text{ distance to Sun} \]
\[ r: \text{ position vector of mesh element} \]
\[ r_\text{i}: \text{ inner radius of the sail} \]
\[ r_\text{o}: \text{ outer radius of the sail} \]
\[ r_{CG}: \text{ position vector of center of gravity} \]
\[ s: \text{ unit vector} \]
\[ T_{S/C}: \text{ torque applied to spacecraft} \]
\[ T_x: \text{ torque component (X-axis)} \]
\[ T_y: \text{ torque component (Y-axis)} \]
\[ T_z: \text{ torque component (Z-axis)} \]
\[ \theta: \text{ declination} \]
\[ W: \text{ solar constant} \]
\[ z: \text{ out-plane deformation of the sail} \]

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1. Introduction

1.1. Background

All spacecraft are affected by solar radiation pressure (SRP). The effect of SRP on the motion of the spacecraft is non-negligible, especially in medium-Earth-orbit (MEO), geostationary, and deep space missions.1) In typical orbit determinations, the SRP force is modeled using a cannonball model,2) in which the spacecraft is modeled as a simple sphere, and coefficients are updated continuously using actual orbit determination results. If the accuracy of this model is insufficient for a mission, such as global positioning system (GPS) missions, a more precise model using the Fourier expansion is applied.3) In actual deep space operations, more precise SRP estimations are required for attitude control,4) as compared to orbit determination, especially in missions involving solar sails with large area-to-mass ratios.

Studies on precise SRP modeling can be classified based
on their use, as follows:

1. Using a theoretical SRP model and fitting coefficients based on flight data,
2. Directly calculating the SRP force using spacecraft shape and surface material models.

Strategy (1) has been used in several MEO, geostationary, and deep space missions. This approach supplies sufficient SRP profiles for such missions, but the SRP model can be obtained only after launch, and a substantial amount of time is required to update the modeling factor.

Strategy (2) can supply SRP profiles before launch and can be used to precisely take into account the effect of shadow, which is dependent of changes in Sun angle. Ziebart and Dare\(^5\) developed a direct SRP calculation tool using a pixel-based ray tracing strategy, and Tichy et al.\(^6\) also developed this type of tool using OpenGL and GPUs. In both tools, the shadow and secondary intersection effects are considered.

1.2. Objective

The objective of the present study is to construct a new SRP calculation tool called the FEM radiation analysis tool (FRAT), which uses an element-based ray tracing strategy. This tool was originally developed to calculate SRP profiles applied to a solar sail, which deforms due to its flexibility. Therefore, in order to evaluate the SRP profiles applied to each deformation of the solar sail, it is necessary to perform quickly calculation numerous times.

In FRAT, a spacecraft model is generated using the finite element model (FEM), and each element is assigned different optical parameters derived from its material properties. Table 1 provides a comparison between SRP calculation strategies. Sunlight calculation is performed by element-based ray tracing in FRAT, and FRAT can be run on general personal computers.

In the element-based ray tracing strategy, the calculation accuracy depends on the mesh number of the spacecraft model, i.e., the calculation accuracy can be managed when the spacecraft model is structured. In the pixel-based ray tracing strategy, on the other hand, the calculation accuracy depends directly on the pixel resolution.

When considering sensitivity analyses, in the element-based ray tracing strategy, it becomes possible to efficiently increase the calculation accuracy of the interested components simply by increasing the mesh number of the model. In the pixel-based ray tracing strategy, the calculation accuracy is uniform and is determined by the pixel resolution. Therefore, accuracy-sloped calculation cannot be realized.

The effect of shadow is considered in FRAT, as in other tools, although secondary intersection effects are not considered. Ziebart and Dare\(^5\) shows that the secondary intersection effect is less than 1% of the result. This value is smaller than other errors, such as the optical property measurement and modeling errors. This simplification realizes a reduced computational cost.

In the present paper, we first introduce an algorithm of FRAT. Next, actual flight data and calculation results are compared in order to evaluate the calculation accuracy. Finally, FRAT is applied to two actual space missions, in which active SRP attitude control operations are described.

2. Structure of FRAT

2.1. Overview

Figure 1 shows a screenshot of FRAT. In FRAT, the SRP torque is calculated in the following process:

Step 1 Creating a finite element model,
Step 2 Setting calculation parameters,
Step 3 Beginning calculation.

The calculation parameters are the distance of each element from the center of mass with respect to the origin of a body-fixed coordinate system, the solar constant, the distance to the Sun, and the Sun direction with respect to the body-fixed coordinate system. Figure 2 shows an example of the SRP force calculation.

2.2. Finite element model

FRAT can construct simplified finite element models via a graphical user interface (GUI) using the following six fundamental components:

1. Box
2. Circular truncated cone
3. Hollow circular truncated cone
4. Parabola
5. Prism
6. Membrane

Figure 3 shows the shapes of these fundamental components along with their surfaces divided into small quadrangular mesh elements for analysis by FRAT. An approximate spacecraft model can be constructed by combining these fundamental components. In this approach, no technical knowledge is required to make the spacecraft model.

Figure 4 shows an example of the finite element model construction process. In this example, the spacecraft was

| Table 1. SRP calculation strategies. |
|-------------------------------------|
| Matteomoto | Ziebart | Tichy  |
| Unit       | Element | Pixel  |
| Hardware   | CPUs    | (Not mentioned) GPUs |
| Secondary intersection | Not considered | Considered | Considered |

Fig. 1. Screenshot of FRAT.
constructed using three boxes, where one box is the body of the spacecraft and the other two boxes are the solar array paddles. In order to construct the more precise model, the optical properties of each component on the ground must be measured.

### 2.3. SRP model

The SRP model used in FRAT consists of the typical SRP equations given by Ref. 7:

\[
df = \frac{W/R^2}{c} (s \cdot n) dA \left[ (C_a + C_d) s + \left\{ 2C_s (s \cdot n) - \frac{2}{3} C_d \right\} n \right],
\]

(1)

\[
dT = (r - r_{CG}) \times df,
\]

(2)

\[C_s + C_a + C_d + C_t = 1,
\]

(3)

\[F_{S/C} = \sum df,
\]

(4)

\[T_{S/C} = \sum dT.
\]

(5)

Equation (1) is used to calculate the SRP force applied to each mesh element. The SRP torque applied to each mesh element is calculated as the cross product of the force applied to the element and the position of the mesh element relative to the center of mass, as shown in Eq. (2). This calculation procedure is illustrated in Fig. 5. Equation (3) shows that the transmittance is also defined in FRAT. The total SRP force and torque applied to the spacecraft can be calculated as the sum of all forces and torques acting on individual mesh elements, as shown in Eqs. (4) and (5), respectively.

### 2.4. SRP calculation considering the shadow effect

After the SRP applied to each mesh element is calculated, the shadow is determined using the ray tracing strategy, as shown in Fig. 6. The algorithm is as follows:

1. **Step 1** Tracing the ray from the center of a mesh (Mesh A) toward the Sun direction,

2. **Step 2** If the ray crosses another mesh (Mesh B, defined by P1, P2, P3, and P4) to which sunlight is applied, then the sunlight is judged not to be applied to Mesh A.

The accuracy of the shadow calculation depends on the mesh size. In other words, the size of the mesh element directly affects the accuracy of the SRP calculation. Figure 7 shows an example of a FRAT model after shadow calculation process. Since the sunlight is intercepted by the solar array paddles, a
portion of the spacecraft body is hidden by the shadow. In order to verify this effect, simple SRP calculations were performed using the satellite model shown in Fig. 5, which is a 500-mm cubic spacecraft. Calculation conditions are summarized in Fig. 8 and Table 2. Figure 9 shows plots of the force and torque applied to the spacecraft. As the mesh number increased, the calculated values converged. Note that the difference in the calculated values between Calculation number (1) and Calculation number (6) is small (0.1 to 0.3%). Figure 10 shows plots of the calculation errors of the force and torque. In this figure, the calculation results of Calculation number (6) are used as true values. This figure suggests that the accuracy of the calculated SRP profiles is high, even if the mesh number of the spacecraft model is small. In the application for the actual mission, therefore, it is not necessary to use a finite element model with a large mesh number.

3. Evaluation

In this section, the accuracy of FRAT is first discussed using HAYABUSA 2 flight data. Typical and meaningful SRP calculation results are then explained. The first example is a fuel-free attitude control strategy that actively uses the SRP in the HAYABUSA 2 mission. The second example involves IKAROS, the world’s first solar sail spacecraft. In the IKAROS mission, a large thin-film membrane, which is subjected to a large SRP, was deployed.
3.1. Comparison with HAYABUSA 2 flight data

HAYABUSA 2 is an asteroid exploration spacecraft that was launched in 2014. The finite element model is shown in Fig. 11. In order to verify the FRAT calculation results, SRP torque measurement was performed as an on-orbit operation. In this operation, the declination $\theta$ was set to be 3 deg, and the right ascension $\phi$ was a parameter. During this operation, the attitude of the HAYABUSA 2 spacecraft was fixed by attitude feedback control. Actual SRP torque was calculated based on the change in the reaction wheel rotation speed. Figure 12 shows the SRP torque measured by this operation along with the calculation results using FRAT. In this figure, three calculation results are described: a full-model calculation considering the shadow effect, a full-model calculation without considering the shadow effect, and solar-array-paddle-only-model (SAP-only-model) calculation. This figure shows that full-model calculation with the shadow effect corresponds to the flight data. The calculation error is described in Fig. 13. This figure shows that the calculation error is in the range of 1 to 15%. For most rotation angles, the error is nearly 5%. The error is composed of the optical properties error and the modeling error.

As mentioned earlier, in FRAT, the resolution of the finite element model can be changed. For example, as shown in Fig. 11, the resolution of the SAP is quite low. Since there is no component that casts a shadow on the SAP, it is not necessary to set the SAP resolution to be high for accurate calculation. Figure 14 shows the contribution ratio of each component in the SRP calculation. This figure indicates that the torque contribution of thrusters is quite small, for example. This indicates that the resolution of the thrusters can be reduced.

3.2. Application 1: HAYABUSA 2 attitude control

The HAYABUSA 2 actively uses the SRP torque for Sun-pointing attitude control. In a newly developed theory, referred to as the generalized sail dynamics model (GSDM), for the HAYABUSA 2 mission, such attitude motion can be described by nine parameters based on the shape and optical properties of the spacecraft.4) The GSDM was verified using FRAT before the launch of HAYABUSA 2.

The SRP force and torque were calculated using FRAT, and a table that includes a number of different attitudes with respect to the Sun and corresponding SRP torques was generated. Nine parameters can be calculated using this table because the relationship among the parameters, the SRP torque, and the spacecraft attitude with respect to the Sun is described in the GSDM as follows4):

$$
\begin{bmatrix}
T_x \\
T_y \\
T_z
\end{bmatrix} =
\begin{bmatrix}
D & E & F \\
G & H & I \\
J & K & L
\end{bmatrix}
\begin{bmatrix}
\cos \psi & \sin \psi & 0 \\
-\sin \psi & \cos \psi & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\alpha - \alpha_s \\
\delta - \delta_s \\
1
\end{bmatrix}.
$$

(6)

The left-hand side of the equation denotes the torque around each axis of the body-fixed coordinate system, and the right-hand side of the equation denotes the nine parameters, $D$, $E$, $F$, $G$, $H$, $I$, $J$, $K$, and $L$, related to the attitude angles of the spacecraft with respect to the Sun. Since the attitude angles and torque are input and output to and from FRAT, respectively, and are therefore known, these nine parameters can be calculated by the least-squares method. Subsequently,
the attitude motion was predicted analytically by substituting the values of the nine parameters into an equation derived in the GSDM.

Another method by which to predict the attitude motion is to use the result of FRAT directly in a numerical dynamics simulation. In the numerical simulation, the SRP torque calculated by FRAT was interpolated and added to the equations of attitude motion as an external torque. The interpolation was necessary because the result generated by FRAT was discrete.

The attitude motions of HAYABUSA 2 predicted by these analytical and numerical methods using FRAT are shown in Fig. 15, where the origin of the figure is the Sun direction. The figure indicates that the Z-axis of the body-fixed coordinate system rotates around an equilibrium direction near the Sun direction due to the SRP torque. The period of this motion is approximately nine days. The small difference in the predictions is due to the effect of shadow. In the GSDM, it is assumed that there is no shadow and that all parts of the spacecraft are illuminated by sunlight. The nine parameters calculated in the analytical method are, therefore, assumed to be constant for all attitudes with respect to the Sun. In reality, however, shadows do exist, and the SRP torque is not exactly equal to that given by Eq. (6). This causes the difference in Fig. 15 because the SRP torque incorporating the effect of shadow is used directly in the numerical simulation, as opposed to the analytical solution that assumes the nine parameters to be constant. The two predictions are, nevertheless, nearly identical. This result reveals that FRAT was useful in the verification of the GSDM theory as well as in terms of attitude prediction of HAYABUSA 2 before launch.

### 3.3. Application 2: IKAROS

IKAROS is the world’s first spinning solar power sail and was launched in 2010. An image of IKAROS taken on orbit is shown in Fig. 16. This spacecraft has a 14-m by 14-m rectangular solar sail deployed only by centrifugal force. Through this mission, a new solar sail attitude motion model, the generalized spinning sail model (GSSM), was constructed as follows:

\[
\begin{bmatrix}
T_x \\
T_y \\
T_z
\end{bmatrix} = \begin{bmatrix}
A & -B & 0 \\
B & A & 0 \\
0 & 0 & C
\end{bmatrix} \begin{bmatrix}
\alpha - \alpha_s \\
\delta - \delta_s \\
1
\end{bmatrix}. \tag{7}
\]

In this model, the attitude motion induced by the SRP is expressed in terms of three parameters, A, B, and C, each of which represents different sail deformation modes. In the IKAROS mission, these parameters have been determined by the parameter fitting strategy.\(^{(10)}\) Using FRAT, the unknown sail shape of IKAROS that reproduces the in-flight attitude motion can be estimated.

This shape estimation problem is an underdetermined problem. In other words, there are an infinite number of sail shapes that reproduce the degenerated flight data in terms of A, B, and C. In this problem, the Chebyshev polynomials are natural functions to describe the structure, are used to describe the sail shape. The advantage of using FRAT is that FRAT can calculate the SRP torque even though the shape of the sail is quite complex. Since FRAT uses the element-based ray tracing strategy, a detailed analysis that including the shadow effect and the components attached to the sail can be performed.

First, the sail shape is decomposed into two orthogonal functions, as follows:

\[
z(r, \phi) = R(r)\Phi(\phi) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} h_{nm} T_n(r^*) \Phi_m(\phi) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} h_{nm} T_n(r^*) \sin(m\phi + \frac{\pi}{2}), \tag{8}
\]

\[
T_0(x) = 1, \quad T_1(x) = x, \quad T_2(x) = 2x^2 - 1, \quad \ldots
\]

\[
T_n(x) \text{ with } x \in [-1, 1] \text{ is the } n\text{-th order Chebyshev polynomial of the first kind. In order to change the domain from } x \in [-1, 1] \text{ to } r \in [r_a, r_b], \text{ the modified radius } r^* \text{ defined by } r^* = \frac{2}{r_b - r_a} r - \frac{r_b + r_a}{r_b - r_a} \tag{9}
\]
is used.

In order to estimate the sail shape, it is necessary to determine the weight \(h_{nm}\) of each sail deformation mode. The principle of this determination is the superposition of the
three parameters \( A, B, \) and \( C. \) First, the three parameters are calculated for each sail deformation mode using FRAT,

\[
z_{nm}(r, \phi) = T_n(r^*) \sin \left( m\phi + \frac{\pi}{2} \right) \rightarrow \text{FRAT} \to \begin{bmatrix} \hat{A}_{nm} \\ \hat{B}_{nm} \\ \hat{C}_{nm} \end{bmatrix}.
\]  

(10)

In this calculation,
- the weight \( h_{nm} \) is set to be unit (\( h_{nm} = 1 \)),
- the distribution of optical properties is considered, and
- the shadow effect is considered.

The finite element model used is shown in Fig. 17. In this calculation, SRP calculation should be performed several times in order to evaluate the shape effect of each sail deformation mode. The optical properties of the devices attached to the solar sail were measured on the ground. The hat parameters \( \hat{A}_{nm}, \hat{B}_{nm}, \) and \( \hat{C}_{nm} \) indicate the contributions from each sail deformation mode defined by \( m \) and \( n \) to the actual parameters \( A, B, \) and \( C, \) respectively. The actual parameters can be represented by the superposition of the hat parameters with the weight up to the \((N, M)\)-th order, as follow:

\[
\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} \hat{A}_{11} & \hat{A}_{12} & \cdots & \hat{A}_{NM} \\ \hat{B}_{11} & \hat{B}_{12} & \cdots & \hat{B}_{NM} \\ \hat{C}_{11} & \hat{C}_{12} & \cdots & \hat{C}_{NM} \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ \vdots \\ h_{NM} \end{bmatrix}.
\]  

(11)

By solving this equation, the weight \( h_{nm} \) can be determined. The simplest way to solve this equation is the inverse strategy:

\[
x = M^T(MM^T)^{-1}y, \quad \text{(12)}
\]

\[
y = \begin{bmatrix} A \\ B \\ C \end{bmatrix}, \quad \text{(13)}
\]

\[
x = \begin{bmatrix} h_{11} \\ h_{12} \\ \vdots \\ h_{NM} \end{bmatrix}, \quad \text{(14)}
\]

\[
M = \begin{bmatrix} \hat{A}_{11} & \hat{A}_{12} & \cdots & \hat{A}_{NM} \\ \hat{B}_{11} & \hat{B}_{12} & \cdots & \hat{B}_{NM} \\ \hat{C}_{11} & \hat{C}_{12} & \cdots & \hat{C}_{NM} \end{bmatrix}. \quad \text{(15)}
\]

Figure 18 shows the estimated sail shape with \((N, M) = (30, 30)\) used to reproduce the flight data of the torque parameters \( A, B, \) and \( C, \) as shown in Table 3, which was calculated based on the spacecraft attitude history. In this case, the norm of \( x \), which is an indication of sail flatness, is 66 mm.

In this section, an example of a series of analyses using FRAT is described. In this process, a number of fundamental shapes, as defined by Eq. (10), should be calculated as a sensitivity analysis. The simplicity of the finite element modeling contributes to the realization of efficient calculations of several shape models. Comparison of the estimated shape and the actual shape is an important and interesting topic, which although beyond the scope of the present paper, is described in Ref. 10).

4. Conclusion

In the present study, a new strategy for SRP calculation was proposed considering the shape and surface material properties of a spacecraft and the effect of shadow using the element-based ray tracing strategy. In this algorithm, the resolution of the model becomes a variable parameter, which can be set to reduce the computational cost and to calculate the SRP with sufficient accuracy. The accuracy of this calculation is nearly 5%, based on the flight data of HAYABUSA 2, and the effectiveness of this algorithm
was also verified by actual deep space mission analyses involving HAYABUSA 2 and IKAROS. These results revealed that it was possible to calculate the SRP with sufficient accuracy for actual mission analyses.

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