Panel deployment and retraction using electromagnetic forces in satellite missions

Takaya Inamori, The University of Tokyo
Yasutaka Satou, Tokyo Institute of Technology
Yoshiki Sugawara, Akita University
Hiroyuki Ohsaki, The University of Tokyo

Key Words: Extensible structure, Deployment, Retraction, Electromagnetic force

1. Introduction

These days, more and more space satellites which have extensible structures have been launched for various space applications. Generally, satellite dimension depends on the space of the rocket payload fairing. To achieve a large area in orbits, extensible and deployable structures are commonly utilized in their satellite missions. One of these missions is space solar power (SSP) satellites (Nagatomo 1996). The SSP satellites are space-based solar power plants that generate electrical energy in orbits. To generate larger energy, these SSP missions employ large deployable solar panels. Other space applications with deployable structures are large membrane satellites called "Fuloshiki" satellites (Shimichi Nakasuka et al. 2001) (Shimichi Nakasuka et al. 2006). The membranes are folded in a small volume in rockets and achieve a large area in orbits for space applications such as solar power generation, a large communication antenna, and a large heat radiator. Some applications of large membrane satellites are solar sail satellites which are a form of spacecraft propulsion using the solar radiation pressure with a large membrane (Mori et al. 2008). As shown in these satellites, the deployable structures can be applied to various satellite missions. To achieve the large area with satellite structures, they should be deployed after the launch in orbits. In previous satellites, these structures have been deployed by using an elastic force of boom and truss structures. In spite, these deployment systems have been utilized in many previous satellites, these systems generally make the satellites more complicated, less reliable, and heavier. To ensure the reliability of the deployment, the system can be tested several times on the ground. In addition, satellites cannot confirm the deployment easily and retract the structures after their deployment. In some satellite missions, these structures have been deployed by using a centrifugal force. Although the deployment system with the centrifugal force is useful to achieve a larger area in orbit, the attitude of these deployed structures cannot be controlled precisely. Furthermore, satellites cannot confirm the deployment easily and retract the structures after their deployment as the boom and truss deployment systems.

This research proposed a method to deploy the extensible structures by using an electromagnetic force generated from the electrical wires on the deployed structures (Inamori et al. 2012) (Inamori et al. n.d.). A concept of the deployment using electromagnetic forces has been surveyed in the previous works (Powell et al. 2007) (Powell et al. 2010). The concept of the researches is a deployment system for large extensible structures using an electromagnetic force created by superconducting wires. The focus of these previous works is system design such as thermal and magnetic design of the system, and was not considered the motion of these structures during deployment operation based on satellite dynamics. In addition, superconducting wires cannot be utilized in almost all satellites in the current state of art. This research focused on the application of electromagnetic forces generated from normal conducting wires for common panel deployment. In this system, a satellite can easily confirm the deployment using magnetometers. In addition, the deployed structures can be retracted to a small volume to avoid space debris. Furthermore quasi-static deployment of the panels using electromagnetic forces can reduce an impulsive force exerting the fragile panels caused in the deployment operation. In this paper, Section 2 presents the overview of the proposed deployment and retraction system using an electromagnetic force. This electromagnetic force generated by electrical currents will be formulated by the Biot–Savart law. Sections 3 presents modelling of a satellite with extensible panels using Multibody Dynamics (MBD) and shows the results of numerical simulations.

2. Panel deployment and retraction using magnetic forces

2-1 Overview of the proposed system

As an application of the deployment system, this research focuses on a simple panel deployment satellite as shown in Figure 1. Figure 1a shows a simple wiring pattern on the panels. Although the wiring pattern is simple, this wiring pattern can generate an electromagnetic force only to the one side for the deployment of the panels, because electrical wires which face each other on two panels can only make a repulsion force. To achieve both the deployment and retraction of the panels, the current direction of the electrical wires which face each other should be changed on both sides to generate both attractive and repulsive forces. Figure 1b shows a possible wiring pattern to generate the attractive and repulsive forces. In Figure 1b, electrical currents flowing in the same direction through each wire generate a repulsion force in electrical wires which face each other on two panels, while electrical currents flowing in different directions generate an attractive force. Thus this wiring pattern can achieve both deployment and retraction.
The Japan Society of Mechanical Engineers

The Japan Society

Figure 1 wiring pattern on the panels for the deployment and retraction system. (a) Electrical wiring pattern only for deployment. (b) Electrical wiring pattern for both deployment and retraction.

Generally, satellites with larger areas have a higher collision risk with space debris. Thus extensible structures increase the probability of a collision. In this proposed method, satellites can retract the structures after the warning of the conjunction predicted by Joint Space Operations Center (JSPOC). In addition, the satellites can retract the structures to reduce the inertia of moment of the satellites for their agile attitude control. Furthermore, the electrical wires on the extensible panels can be utilized as large MTQs for their attitude control systems in LEO (Low Earth Orbit). The magnetic field generated from the panels can confirm the deployment operation using on-board magnetometers. With the magnetometers, the satellite can know the panel positions which enable an active control system. In this method, the satellite can control the electromagnetic force for the deployment, thus the satellite can achieve quasi-static deployment of the panels to reduce an impulsive force exerting the fragile panels.

2-2 Electromagnetic force Model

An electromagnetic torque caused between two panels can be calculated by using the Biot–Savart law. As a simple model, we consider an electrical wire of length 2L which is folded at the middle point of the wire as shown in Figure 2. Here, the electromagnetic torque exerts the electrical wire 2 by the magnetic field generated by the electrical wire 1. The electrical wire 1 with a current $I_0$ generates an axial magnetic field as follows:

$$B_0 = \frac{\mu_0 I_0}{4\pi} \int \frac{dz}{r^2 + z^2} \sin \phi$$

$$= \frac{\mu_0 I_0}{4\pi} \frac{1}{\sqrt{x^2 + y^2 + (l - z)^2}} \left( \frac{x}{\sqrt{x^2 + y^2 + z^2}} + \frac{z}{\sqrt{x^2 + y^2 + z^2}} \right)$$

The electromagnetic force at a given point on the electrical wire 2 can be written as follows:

$$dF = -\frac{\mu_0 I_0}{4\pi} \frac{1}{\sqrt{x^2 + y^2 + z^2}} \sin \theta \left( \frac{l - i \cos \theta}{\sqrt{l^2 \sin^2 \theta + (l - i \cos \theta)^2}} + \cos \theta \right) \frac{dz}{di}$$

where $\theta$ is the angle between the electrical wire 1 and the electrical wire 2. With this equation, the electromagnetic torque caused in the electrical wire 2 is calculated as follows:

$$T = \int \frac{\mu_0 I_0}{4\pi} \frac{1}{\sqrt{x^2 + y^2 + z^2}} \left( \frac{l - i \cos \theta}{\sqrt{l^2 \sin^2 \theta + (l - i \cos \theta)^2}} + \cos \theta \right) \frac{dz}{di}$$

This electromagnetic torque makes the electrical wire straight, which can be utilized for the panel deployment. Similarly, an electromagnetic force acts on two separated electrical wires can also be calculated using the Biot–Savart law. We consider two electrical wires as shown in Figure 3. In this figure, the electrical wire 1 carries a current of $I_0$ in the positive x direction, and the electrical wire 2 carries a current of $I_0$ in the direction of the vector $(i, j, k)$. In this model, we calculate the electromagnetic torque in the electrical wire 2 from the electrical wire 1. The magnetic field generated by the electrical wire 1 at an given point $x_m$ as $x_m(x_m, y_m, z_m)$ on the electrical wire 2 can be written as follows:

$$B_0(m) = \frac{\mu_0 I_0}{4\pi} \frac{l_x(x_m, y_m, z_m) + m}{\sqrt{x_m^2 + y_m^2 + z_m^2}}$$

where $(x_m, y_m, z_m) = (x_0 + im, y_0 + jm, z_0 + km)$. The magnetic field at the point $x_m$ is rewritten with a vector form as follows:

$$B_0 = B_0(-y_m - jm, x_0 + im, 0)$$

The electromagnetic force which acts on the electrical wire 2 is,

$$F = \int M B_0(m) I_0 \frac{\mu_0 I_0}{\sqrt{(y_0 + jm)^2 + (x_0 + im)^2}} \left( -k(jm + x_0), -k(im + y_0) \right) \frac{dz}{dm}$$

where $M$ is the length of the electrical wire 2. The electromagnetic torque acting on the electrical wire 2 around the y-axis is written as follows:

$$T = \int r \times dF$$

where $r$ is the distance from the focused point to the y-axis. $r$ can be expressed as follows: $r = (x_0 + im, 0, z_0 + km)$.

Figure 2 Electrical wire of length 2L which is folded at the middle point of the wire

Figure 3 Two separated electrical wires of length L
From these results of the electromagnetic torque acting on the wires, the torque caused between two panels can be calculated. In the wiring pattern shown in Figure 1a, the electromagnetic torque caused from the panel b can be expressed as follows:

\[ T_a = T_{13} + T_{14} + T_{23} + T_{24} \]  

(6)

where \( T_{ij} \) is the electrical magnetic torque caused from the \( j \)th electrical wire to the \( i \)th electrical wire. Here \( T_{13} = T_{24} = T \). The two equal magnitude torques, \( T_{14} \) and \( T_{23} \), act on the panels in opposite directions which cancel their movements each other. Thus the electromagnetic force caused between two panels can be calculated as follows:

\[ T_a = 2T \]  

(7)

Figure 4 Relationship between the angle of two panels and the electromagnetic torque caused by wires with the wire pattern A shown in Equation (7).

Figure 4 shows the relationship between the angle of panels and the electromagnetic torque shown in Equation (7). In this calculation, the length of each electrical wire carrying 1-3A currents on the panels assumed to be 10 cm. An electromagnetic torque between panels is proportional to the squares of a current of the panels. The magnitude of the torque created by the 2A current flow is about \( 1 \times 10^{-7} \) Nm at the angle \( \pi/2 \). With this wiring pattern, the satellite can only deploy the panels. In order to retract the panels, the electrical magnetic force should be generated on both sides. In this research, we consider a magnetic force generated from the wiring pattern shown in Figure 1b as an example for the retraction. An electromagnetic torque caused from the panel b can be expressed as follows:

\[ T_b = \sum_{i=1}^{4} \sum_{j=1}^{8} T_{ij} \]  

(8)

where \( T_{ij} \) is the electrical magnetic torque caused from the \( j \)th electrical wire to the \( i \)th electrical wire. In Figure 1b, the two electrical wires facing each other such as wires 1 and 5; 2 and 6; 3 and 7; 4 and 8 cause torques for deployment or retraction depending on the direction of the current flows with the following strength torque: \( T_{15} = T_{26} = T_{17} = T_{18} = T \). The two electrical wires 1 and 5; 3 and 7; 4 and 8 cause only repulsive torques independent of the current directions. These electromagnetic torques \( T_{16} = T_{15} = T_{38} = T_{47} = T_{2} \) can be calculated using Equation (4) with the parameters: \((i, j, k) = (\sin \theta, 0, \cos \theta)\) and \((x_0, y_0, z_0) = (0, d_1, 0)\). Here \( \theta \) is the angle between two panels. The electromagnetic torque caused between wires 1 and 8; 4 and 5 can be calculated using Equation (4) with the parameters: \((i, j, k) = (\sin \theta, 0, \cos \theta)\) and \((x_0, y_0, z_0) = (0, 2d_1 + d_2, 0)\). The torques can be expressed as follows: \( T_{18} = T_{56} = T_8 \). The two equal magnitude torques; \( T_{17} \) and \( T_{36} \) also act on the panels in opposite directions which cancel their movements each other as follows: \( T_{27} = -T_{26} \). From these calculations, the total torque causing to the panel A from the panel B can be written as follows:

\[ T_b = 4T + 4T_1 + 2T_2 \]  

(9)

3. Numerical simulations

3.1 Simulation Model using MBD

In order to assess the usefulness of the proposed deployment and retraction system using an electromagnetic force, we conducted numerical simulations. In these simulations, the satellite attitude dynamics are modelled in 2D by using Multi Body Dynamics (MBD) as shown in Figure 5.

Figure 5 Model for the panel deployment simulation using MBD

In this model, the position of the main satellite and the \( k \)th panel are defined as \((x_k, y_k)\) and \((x_{nk}, y_{nk})\), respectively. The attitude of the satellite and the \( k \)th panel are defined as \( \theta_k \) and \( \theta_{nk} \), respectively. In this model, the main satellite and the panels are assumed to be rigid bodies. Here, the generalized coordinates can be expressed as follows:

\[ q = [\theta_1 \ldots \theta_L \ldots \theta_k \ldots \theta_{nk}]^T \]  

and

\[ \theta_k = (\theta_k_1 \ldots \theta_k_j \ldots \theta_k_n) \]  

where \( \theta_k = (x_k, y_k, \theta_k, \theta_k_1 \ldots \theta_k_n) \). In this model, the constraint equation is written as follows:

\[ C = [C_{11} \ldots C_{1k} \ldots C_{1n}] \]  

where

\[ C_{1k} = x_k + L_k \cos \theta_k - (x_n - L_n \cos \theta_n)C_{1y} = y_k + L_k \sin \theta_1 - (y_n - L_n \sin \theta_n) \]

With this constraint equation, the Jacobian matrix of this model can be calculated as follows:

\[ C_q = dC/dq \]  

Here the external force term \( \vec{G} \) can be written as follows:

\[ \vec{G} = [F, F_{x}, F_{y}, F_{z}, r_{x}, r_{y}, r_{z}, \tau_{x}, \tau_{y}, \tau_{z}] \]  

where \( F_{ki} \) is a force acting on the \( k \)th panel to the \( i \) axis, and \( \tau_{ki} \) is a torque acting on the \( k \)th panel. While the inertia matrix of this system can be written as follows:

\[ M = \text{diag}(m_1, m_2, m_3, m_4, m_5, m_6, m_7, m_8, m_{1L}, m_{2L}, m_{3L}, m_{4L}, m_{5L}, m_{6L}, m_{7L}, m_{8L}) \]  

which \( m_i \) and \( J_k \) are the mass and the moment of inertia of the \( k \)th panel, respectively. With these equations, the differential algebraic equation of this system can be written as follows:

\[ \begin{bmatrix} \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} M_C & C_q \\ C_q^T & 0 \end{bmatrix}^{-1} \begin{bmatrix} \dot{q} \\ \dot{\theta} \end{bmatrix} \]  

(10)

where \( \lambda \) is a Lagrange multiplier. In this equation, the generalized coordinate \( q \) involves both independent and dependent generalized coordinates, which increase the cost of the calculation. In order to reduce this cost of the calculation, the differential algebraic equation should be formulated using only the independent generalized coordinate. Here another generalized coordinate is introduced which is denoted by \( q = [\bar{q}_G, \bar{q}_D]^T \). Here \( \bar{q}_G \) and \( \bar{q}_D \) are independent and dependent generalized coordinates which can be expressed as follows:

\[ \bar{q}_G = [x_k, y_k, \theta_k, \theta_k_1 \ldots \theta_k_n] \]  

and

\[ \bar{q}_D = [x_1, x_2, \ldots, x_N, y_N] \]  

The
The relationship between the generalized coordinates $q$ and $\ddot{q}$ are written as follows: $q = T \ddot{q}$, where $T$ is a transformation matrix providing the relationship between $q$ and $\ddot{q}$. From Equation (10), the differential algebraic equation can be rewritten as follows:

$$[M \quad 0 \quad 0] \dot{\ddot{y}} = [C_y \quad 0 \quad 0] \ddot{y}$$

(11)

where $M = T^T M T$, $C_y = C_y T$, $\ddot{y} = T^T \ddot{y}$. Here, the differential algebraic equation expressed using only the independent generalized coordinate $\ddot{y}$ can be written as follows:

$$\ddot{\ddot{y}} = \ddot{y}$$

(12)

where $M_{\ddot{y}}$ and $C_{\ddot{y}}$ are written as follows:

$$M_{\ddot{y}} = M - M_y C_y^{-1} C_y^{-1} C_y - C_y^{-1} C_y^{-1} (M_y - M_y C_y^{-1} C_y - C_y^{-1} C_y)$$

and

$$C_{\ddot{y}} = C_y^{-1} C_y^{-1} (M_y - M_y C_y^{-1} C_y - C_y^{-1} C_y) \cdot \ddot{y} = (M_{\ddot{y}})^{-1} C_{\ddot{y}}$$

The components of the matrices $M_{\ddot{y}}$ and $C_{\ddot{y}}$ can be calculated as follows:

$$\ddot{y} = \begin{bmatrix} M_{\ddot{y}} & \ddot{y} \end{bmatrix}, \quad \ddot{y} = \begin{bmatrix} C_{\ddot{y}} \ddot{y} \end{bmatrix}$$

With Equation (12), the generalized coordinate of the satellite and panels can be calculated in numerical simulations. In the following subsection, we conducted numerical simulations using the model shown in Equation (12).

3-2 Numerical simulations

In this subsection, we conducted numerical simulations using the dynamics model introduced using MBD in the previous subsection. In this simulation, a small satellite is assumed to have extensible structures. Table 1 shows parameters in the simulations.

<table>
<thead>
<tr>
<th>Table 1 Parameters for the numerical simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation ID</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Simulation time (s)</td>
</tr>
<tr>
<td>Integration method</td>
</tr>
<tr>
<td>Main satellite</td>
</tr>
<tr>
<td>Satellite mass (kg)</td>
</tr>
<tr>
<td>Satellite moment of inertia (kgm²)</td>
</tr>
<tr>
<td>Number of panels</td>
</tr>
<tr>
<td>Wire pattern</td>
</tr>
<tr>
<td>Panel</td>
</tr>
<tr>
<td>Panel moment of inertia (kgm²)</td>
</tr>
<tr>
<td>Electrical current (A)</td>
</tr>
<tr>
<td>Damping coefficient (Nms)</td>
</tr>
</tbody>
</table>

In these simulations, a 20 cm cubic size micro satellite deploys and retracts two extensible panels. In these simulations, the differential algebraic equation shown in Equation (12) is integrated using 4th-Order Runge Kutta (RK4). Two panels are connected to the main satellite. 2-3A currents are assumed to flow in the panels, which generate an electromagnetic force shown in Equation (7) and (9).

Figure 6 Results of numerical simulations representing the panel angle of a satellite in the panel deployment operation (up) and (down) with the parameters a and (down) the parameters b in Table 1.

Figure 6a, b shows results of the simulations representing the panel deployment when the currents are 2A and 3A, respectively. In both cases, it takes around 1000 seconds to deploy the panels. The stronger magnetic force makes the panels vibrate in higher frequencies. These satellites have several options to enlarge the magnetic forces between extensible panels: flowing larger amount of currents, improving the electrical wiring pattern, and utilizing magnetic materials for the panels. These results of the numerical simulations allow us to conclude that the satellite can deploy the extensible structures slowly to reduce an impulsive force exerting the fragile panels caused in the deployment operation.

4. Conclusions

These days, more and more satellites which have extensible structures have been launched for various space applications. This research proposed a new method to deploy and retract extensible panels using an electromagnetic force in orbits. In this system, the deployed structures can be retracted to a small volume to avoid space debris in these satellites. The quasi-static deployment of the panels using electromagnetic forces reduce an impulsive force exerting the fragile panels caused in the deployment operation. In addition, the satellite can easily confirm the deployment using magnetometers. From the result of the calculations using the Biot-Savart law, the strength of the electromagnetic torque generated from the simple magnetic wiring pattern shown in Figure 1 is about 1 x 10⁻⁷Nm with 2A currents at the angle π/2 between two panels. To assess the usefulness of the proposed method, we conducted numerical simulations using the MBD model with the calculated electromagnetic torque. From these simulations, the satellite can deploy the panels in 1000 sec with 2A currents in 20 cm small satellites.

5. Acknowledgement

This research was supported by JSPS KAKENHI (grant number 24-10554) and by The Hattori Hokokai Foundation.

6. References


---

"Application of a magnetic planner actuator to extensible structure control in a Fuloshiki satellite." In Proceedings of the Space Sciences and Technology Conference.