Simulation Analysis for Deployment Motion of SMPC Deployable Antenna

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Abstract. In order to predict the deployment time of deployable antenna and whether the deployment of the antenna meets the overall design requirements of the satellite, it is necessary to analyze the whole movement process of the antenna from folding to final unfolding. Before the ground simulation experiment of antenna deployment, the motion analysis of the deployment process is of great significance. In this paper, the deployment process of deployable antenna is analyzed by kinematics. Based on the theoretical model of a single antenna, the differential equation of motion of the deployment process is established. Based on ADAMS virtual prototyping technology, the prototype model of satellite and antenna is established, and the deployment process of the single antenna is simulated. The time-varying curves of the angle and moment during the deployment of the antenna are obtained by simulation. The changes of the position and velocity of the satellite mass center during the deployment of the antenna are studied. The influence of antenna deployment on the position and attitude of satellite body is analyzed.

1. Introduction

Whether the antenna can be successfully deployed after satellite launching is related to whether the future communication system can be established [1]. In order to predict the deployment time of deployable antenna and whether the deployment of the antenna meets the overall design requirements of the satellite, it is necessary to analyze the whole movement process of the antenna from folding state to final unfolding [2]. The analysis of deployment motion can also predict the influence of deployment motion on satellite body posture during antenna deployment [3]. Therefore, before the ground simulation experiment of antenna deployment, the motion analysis of the deployment process is of great significance.

2. Establishment of kinematics equation for antenna deployment

The deployable antenna designed in this paper is composed of several fixed antennas connected by SMPC (shape memory polymer material) hinges. Initially in a folding state, when the satellite is launched into orbit, the release mechanism completes its release. The antenna is driven by an electrically heated hinge and unfolds slowly. Finally the antenna unfolds to form deployable antenna with multiple planar antennas arranged side by side, as shown in figure 1.

The differential equation of motion of the angle change during the deployment of the antenna is obtained through the theoretical modeling of a single antenna. The deployment process of a single
planar antenna can be regarded as a rigid body motion with a single degree of freedom. Establishing the theoretical model can analyze the relationship between the deployment time \( t \) and the deployment angle \( \phi \) of the planar antenna in the deployment process, so as to assist in the analysis of the impact of the deployment process on the overall satellite.

The overall satellite is considered as a rigid body with a degree of freedom of 0. The \( xOy \) coordinate system is established on the overall satellite, as shown in figure 2. The \( OA \) is a planar antenna with a width of \( 2a_0 \) and mass of \( m_0 \). The \( O \) point is the hinge rotation center. Considering the length of the hinge and the mass of the embedded block in the antenna substrate, the geometric center of the antenna does not coincide with the actual center of mass, and the eccentricity is \( e_0 \).

![The satellite body, shape memory hinge, and antenna reflector.](image)

**Figure 1.** Schematic diagram of connected antenna.

**Figure 2.** The coordinate system of overall satellite.

According to the simplified model, the centroid coordinates of planar antenna can be expressed as:

\[
\begin{align*}
x_0 &= (a_0 + e_0) \cos \phi \\
y_0 &= -(a_0 + e_0) \sin \phi
\end{align*}
\]

There \( \phi, x_0, y_0 \) are functions of time \( t \). Equation (1) is derived by quadratic differentiation of time \( t \):

\[
\begin{align*}
x''_0 &= -(a_0 + e_0) [\phi^* \sin \phi + (\phi')^2 \cos \phi] \\
y''_0 &= -(a_0 + e_0) [\phi^* \cos \phi - (\phi')^2 \sin \phi]
\end{align*}
\]

According to Newton's second law, the inertia force is:

\[
\begin{align*}
F_{x_0} &= -m_0 x''_0 = m_0 (a_0 + e_0) [\phi^* \sin \phi + \phi^2 \cos \phi] \\
F_{y_0} &= -m_0 y''_0 = m_0 (a_0 + e_0) [\phi^* \cos \phi - \phi^2 \sin \phi]
\end{align*}
\]

Assuming the inertial radius of the antenna around the mass center is \( \rho_0 \), the inertial moment of the antenna is obtained as follows:

\[
M_0 = -m_0 \rho_0 \phi^*
\]

Let the driving moment of SMPC hinge be \( T_j \), according to the experimental results in [4], through the polynomial fitting with MATLAB, the function of the moment of hinge deployment varying with time is obtained as follows:

\[
T_j(t) = p_1 \cdot t^7 + p_2 \cdot t^6 + p_3 \cdot t^5 + p_4 \cdot t^4 + p_5 \cdot t^3 + p_6 \cdot t^2 + p_7 \cdot t + p_8
\]

There, the coefficients of each order \( p_1 \sim p_8 \) are shown in table 1.

| Coefficient | Value   |
|-------------|---------|
| \( p_1 \)   | 9.8e-14 |
| \( p_2 \)   | -3.7e-11|
| \( p_3 \)   | 5.7e-9  |
| \( p_4 \)   | -4.5e-7 |
| \( p_5 \)   | 2.0e-5  |
| \( p_6 \)   | 4.9e-4  |
| \( p_7 \)   | 6.4e-3  |
| \( p_8 \)   | 3.8e-2  |

(5)
Since there is no friction between the joints in the SMPC hinges, the main resistances are caused by the asynchrony between the two hinges, and the cable between the satellite and the antenna. Because these resistances are relatively small, they can be neglected.

Assuming that an imaginary displacement angle is $\delta \varphi$ when the antenna is deployed, the virtual displacement at the mass center of planar antenna is:

$$
\begin{align*}
\delta x_0 &= -(a_0 + e_0) \sin \varphi \cdot \delta \varphi \\
\delta y_0 &= -(a_0 + e_0) \cos \varphi \cdot \delta \varphi
\end{align*}
$$

According to the principle of virtual work, the following equation can be obtained:

$$
F_x \delta x_0 + F_y \delta y_0 + M_o \delta \varphi + T_j \delta \varphi = 0
$$

Substituting equations (3) ~ (6) into equation (7), and the result is as follow:

$$
m_o \varphi^* \left[ (a_0 + e_0)^2 - \rho_0^2 \right] + T_j = 0
$$

Equation (8) is a two-order differential equation. Substituting the relation equation of the deployment moment with the deployment angle of the hinge, the rule of the variation of deployment angle of single antenna plate with time can be obtained.

3. Simulation analysis of planar deployable antenna deployment with ADAMS

3.1. Establishment of virtual prototype for deployable antenna mechanism

There are three main steps to build simulation model with ADAMS:

3.1.1. Establishment of structural model. The antenna deployment structure is formed by connecting the satellite body with the antenna veneer through SMPC hinges (see figure 1). The deployment of SMPC hinges are driven by large deformation of SMPC. Because the large deformation structure cannot be simulated by ADAMS, so the SMPC hinge is simplified to rigid hinge connection. Each hinge is composed of a main hinge and an auxiliary hinge, and the main and auxiliary hinges are respectively connected with the satellite body and the antenna substrate. The single antenna is simplified to a rigid body.

3.1.2. Definition of connection mode. According to the simplified design of the hinge structure mentioned above, the hinge connection is defined as a rotating pair connection.

3.1.3. Loading of driving moment. Selective moment acts between two objects. Because the unfolding moment of SMPC hinge is a variable quantity, it needs to be defined by function. There are many ways to define functions in ADAMS. The STEP functions used in this paper are briefly introduced below.

STEP function is a cubic polynomial approximation function, its basic format is $\text{STEP}(x, x_0, h_0, x_1, h_1)$. Whereas $x_0$ is a variable, $x_0$ and $x_1$ are the initial and end values of independent variable, respectively, and $h_0$ and $h_1$ are the initial and end values of function, respectively. In practical application, STEP function in ADAMS is generally used in two ways: embedded and incremental. Because incremental is more convenient, incremental is adopted here.

Select eight representative values [4] (see table 2) to establish STEP function

| Serial number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------------|---|---|---|---|---|---|---|---|
| Time/s        | 0 | 10| 29| 39.2| 48.8| 80.2| 88.7| 107.1|
| Moment /N·mm  | 37.6| 68.9| 68.8| 70.0| 58.6| 41.3| 34.2| 4.8|
Running according to the input STEP function, the function curve is drawn as shown in figure 3(a), which is close to the hinge expansion moment measured by experiment (Figure 3(b)) [4].

![Figure 3. Comparisons of applied and measured moment curves](image)

3.2. Simulation of antenna deployment and result analysis

When \( t=0 \), the antenna is in a folding state, and the bending angle of the hinge is 90°, and the angle between the antenna and the \( x \)-axis is 0°. When deploying \( (t>0) \), the antenna rotates around the \( z \)-axis, and finally 90° with the \( x \)-axis and 0° with the \( y \)-axis. The whole deployment process is only 22.3s. The unfolding process and time are shown in figure 4 and figure 5.

![Figure 4. Antenna deployment process diagram.](image)  
![Figure 5. Relation of output torque of rotating pair and time.](image)

Through simulation, the relationship between the deployment angle of antenna and time during deployment is shown in figure 6. It can be seen that the deployment angle of the antenna increases with time, and the deployment angle increases faster and faster.

In the deployment process, it is necessary to consider the influence of some satellite accessories, such as solar wing and deployable antenna, on the satellite's position and attitude. Based on the above simulation of single antenna deployment, the influence of antenna deployment on satellite body can be further studied. The curves of coordinate values in \( x \), \( y \), \( z \) directions of the satellite body varying with deployment time are extracted, as shown in figure 7. It can be seen that the maximum displacement along the \( x \)-axis is 2.5 mm, along the \( y \)-axis is 2.5 mm, and along the \( z \)-axis is 0.
In addition to studying the influence of antenna deployment on the position of the satellite body, it also needs to analyze the moving velocity of the satellite body in the deployment process. Influenced by the deployment velocity and angle of the antenna, the satellite body will also be subject to a variable inertial force. Therefore, in the course of antenna deployment, the satellite body will have a variable moving velocity. Figure 8 shows the velocity curve of the satellite body in the directions of x, y, z during the antenna deployment. It can be seen that the maximum unidirectional velocity is only 0.4 mm/s. It can also be seen that the deployment process of the antenna is smooth and the impact on the satellite body is small.

In order to analyze the attitude change of the satellite itself with the antenna deployment, the angle changes of the satellite around the x, y, and z axes are obtained, respectively, as shown in figure 9. It can be seen that in the 22.3s course of the antenna deployment, the angle of rotation of the satellite around the x-axis and y-axis is almost zero, and only 0.34° around the z-axis.

### 4. Conclusion

The deployment process of deployable antenna is analyzed by kinematics. Based on the theoretical model of a single antenna, the differential equation of motion of the deployment process is established. Based on ADAMS virtual prototyping technology, the prototype model of satellite and antenna is established, and the deployment process of the single antenna is simulated, the whole deployment process is only 22.3s. The time-varying curves of the angle and moment during the deployment of the antenna are obtained by simulation. The changes of the position and velocity of the satellite mass center during the deployment of the antenna are studied. The influence of antenna deployment on the position and attitude of satellite body are analyzed. It provides a basis for the improvement of antenna structure in the future, and also provides a reference for future experiments.

### References

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