Application of a New-type Damping Structure for Vibration Control in Deployment Process of Satellite Antenna Component

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Abstract. Vibration control of flexible deployable mechanism is seriously significant with the increasing application of it in aerospace field. Satellite antenna must be carried out in folded state due to small space of launch vehicle. In the process of deployment and attitude adjustment, vibration has a great influence on the contour accuracy. Based on transfer matrix method, the deployment structure of large flexible deployable satellite antenna is analysed to obtain its natural frequencies and modes. By solving the first three natural frequencies and modes in different deployment angles, the structure completely deployed is prone to be coupled and has the worst stability. Thus, damping structure to suppress vibration at all modal resonance points of fully deployed satellite antenna is necessarily to be installed. A new-type damping structure, multi-petal friction damping structure with the characteristics of simple structure and wide frequency-band, is proposed in previous paper. The dynamic analysis of deployment process at different angles for deployment component with damping structure is carried out to verify the damping effect and the feasibility of damping structure as well as the rationality of theoretical analysis.

1. Introduction
The development of high-resolution satellites equipped with large-scale deployable antennas is significant to aerospace industry, which is the fundamental part in the development of country's defense industry[1-2]. Limited by the size of the launch vehicle, the antenna of the spacecraft needs to be folded during the launch and transportation phases, and then, Satellite antennas carry out deployment to work as planned after the spacecraft enters the satellite orbit[3]. Due to the weak rigidity and low natural frequency of large-scale self-deployable satellite antennas, coupling resonance is prone to occur during the deployment process. Chen concentrated on the strengthening of masts and low-mass surface to provide two kinds of cable designs to improve natural frequency of a spaceborne flexible coilable antenna[4]. Doussot introduce a short-circuit plane between one of the inner or outer boundaries of the ring and the earth plane to modify the conditions of propagation of the waves between the ring and the earth plane[5]. The antenna locking action and the power interference of the attitude control engine will produce wide-band random vibrations, which will reduce the surface accuracy of deployment antenna and cause friction and wear of the connection pair to suppress the
retention of antenna profile accuracy and life of antenna. With the development of artificial intelligence, a lot of active methods are adopted to improve the profile accuracy. Ahn obtained a method of optimal satellite antenna profile based on reinforce learning\cite{6}. Limited by the fact that losses associated with switch impedance will reduce the efficiency of the driven antenna elements, especially in the folded state of the antenna\cite{7}, it is an urgent need to research a method to control the vibration of the satellite antenna during deployment based on the existing satellite antenna structure. It is necessary to design a vibration suppression structure with light weight, high stability, good effect and good integration. Further study about the dynamic model of deployment satellite antennas should be carried out to overcome the satellite antenna vibration caused by various factors and ensure the stability and surface accuracy of the satellite antenna during operation.

According to the basic deployment components in different configurations of satellite antennas, the current mainstream satellite deployable antennas can be classified into plate satellite deployment antennas, inflatable satellite deployment antennas, radial rib satellite deployment antennas, frame and ring truss satellite deployment Antennas. Limited by factors such as folded volume and launch weight, fewer types of self-deployable antennas are suitable for satellites above 10 meters\cite{8-9}. The current choices are mainly among ring truss antennas, radial rib antennas and inflatable array antennas\cite{10-12}. The large deployment size and high profile accuracy of the large self-deployable satellite antenna put forward higher requirements about the structural design for the deployment structure and the control stability and accuracy of the deployment process. This article analysed the vibration control effect of a lateral friction damping structure, a pre-loaded multi-petal friction damping structure proposed in previous paper, whose structure, damping principle and vibration control effect are simply introduced here\cite{13}. The damping structure of the radial ribs at different deployment angles is analysed and compared to verify the correctness of the transfer matrix theoretical analysis and the effect of vibration control regarding the damping structure by the finite element simulation.

2. Modal analysis for deployment process of satellite antenna component.

Affected by the launch volume, the satellite antenna needs to deploy from the folded state during operation after launched into space. In order to ensure the stability of the satellite antenna deployment process and enable the satellite antenna to deploy smoothly, analysis of the dynamics of the satellite antenna deployment process is seriously necessary.

2.1. Simplified structure of satellite antenna rotating hinge

Rotating hinge of satellite antenna, a key part of deployment operation, plays an important role in controlling the angle, providing power and ensuring synchronization of deployment.

1) Rotating body; 2) Rotating shaft; 3) Synchronous gear; 4) Connecting body; 5) Scroll spring

Fig. 1. Schematic diagram of rotating hinge
As shown in Figure 1, rotating hinge is composed of scroll spring, synchronous gear, rotating body, connecting body, and rotating shaft. The scroll spring drives the rotating hinge to realize the deployment of antenna from the folded state, and the synchronization gear ensures the stability and synchronization about deployment process of the unfolded mechanism.

The rotating hinge can be seen as a single-degree-of-freedom planar rotating pair according to the structural diagram during the establishing process of the dynamic model of the satellite antenna deployment. The rotating hinge is seen as the concentrated mass of the connection due to the length of rotating hinge can be negligible compared to deployment structure in the process of establishing the transfer matrix. The vector at two different ends of the rotating hinge will change in floating coordinates when passing through the hinge.

2.2. Dynamic model during deployment process

As shown in Figure 2, the deployment between two adjacent beams of the radial rib satellite antenna changes at the same time due to rotating hinge. Meanwhile, the satellite antenna at any position during the deployment process can be equivalently regarded as a static equilibrium state due to its slow deployment speed. The dynamic model of satellite antenna at different deployment angles can be established based on the transfer matrix method, and the change law of the satellite antenna modal parameters during the deployment process can be studied.

![Fig. 2. Schematic diagram of the satellite antenna deployment process](image)

The establishment of dynamic model during the deployment of the satellite antenna is similar to the establishment about the dynamic model of the fully deployed satellite antenna. The establishment of the transfer matrix of the rod and concentrated mass is the same as previous paper [14]. The main difference is the establishment of the corner.

![Fig. 3. Coordinate system conversion at the corner](image)

The transfer matrix at corner is established and the state vector is set as 

\[ S = [u, y, \theta, M, Q, F]^T. \]

As shown in Figure 3, after the establishment of the principal coordinate system at the root of the satellite antenna deployment component, the sub-coordinate systems are set up at the corners respectively. Through the geometric transfer relationship, when the deployment angle is less than 90°,
the sub-coordinate transfer matrix at the corner can be obtained as follows:

\[
\begin{bmatrix}
    u \\
    Y \\
    \theta \\
    M \\
    Q \\
    F_r
\end{bmatrix} =
\begin{bmatrix}
    -\cos \alpha & -\sin \alpha & 0 & 0 & 0 & 0 \\
    \sin \alpha & -\cos \alpha & 0 & 0 & 0 & 0 \\
    0 & 0 & 1 & 0 & 0 & 0 \\
    0 & 0 & 0 & 1 & 0 & 0 \\
    0 & 0 & 0 & 0 & -\cos \alpha & -\sin \alpha \\
    0 & 0 & 0 & 0 & \sin \alpha & -\cos \alpha
\end{bmatrix} 
\begin{bmatrix}
    u \\
    Y \\
    \theta \\
    M \\
    Q \\
    F_r
\end{bmatrix}
\]

(1)

when the deployment angle is more than 90°, the sub-coordinate transfer matrix at the corner can be obtained as follows:

\[
\begin{bmatrix}
    u \\
    Y \\
    \theta \\
    M \\
    Q \\
    F_r
\end{bmatrix} =
\begin{bmatrix}
    -\cos \alpha & -\sin \alpha & 0 & 0 & 0 & 0 \\
    \sin \alpha & -\cos \alpha & 0 & 0 & 0 & 0 \\
    0 & 0 & 1 & 0 & 0 & 0 \\
    0 & 0 & 0 & 1 & 0 & 0 \\
    0 & 0 & 0 & 0 & -\cos \alpha & -\sin \alpha \\
    0 & 0 & 0 & 0 & \sin \alpha & -\cos \alpha
\end{bmatrix} 
\begin{bmatrix}
    u \\
    Y \\
    \theta \\
    M \\
    Q \\
    F_r
\end{bmatrix}
\]

(2)

Set it as follows:

\[S_r = Z_k \cdot S_i \]

(3)

Then, according to the continuous condition, the transfer matrix of the radial rib system under each sub-coordinate system is established as follows:

\[S_n = Z_n \cdot Z_{n-1} \cdots Z_k \cdots Z_{(k-1)} \cdots Z_1 \cdot S_0 = Z \cdot S_0 \]

(4)

Boundary conditions are as follows:

\[S_0^k = [0, 0, 0, M, Q, F]^T, S_0^q = [u, y, 0, 0, 0]^T \]

(5)

System transfer matrix coordinates in the sub-coordinate system is transformed to obtain its relationship in the primary coordinate system, and the matrix transfer relationship between the initial and final states of the satellite antenna is as follows:

\[
\begin{bmatrix}
    H_{11} & H_{12} & H_{13} & H_{14} & H_{15} & H_{16} \\
    H_{21} & H_{22} & H_{23} & H_{24} & H_{25} & H_{26} \cdot 0 \\
    H_{31} & H_{32} & H_{33} & H_{34} & H_{35} & H_{36} \cdot 0 \\
    H_{41} & H_{42} & H_{43} & H_{44} & H_{45} \cdot H_{46} & M \\
    H_{51} & H_{52} & H_{53} & H_{54} & H_{55} \cdot H_{56} & Q \\
    H_{61} & H_{62} & H_{63} & H_{64} & H_{65} \cdot H_{66} & F_0
\end{bmatrix}
\]

(6)

Equation (2) is set with a non-zero solution, then:

\[\Delta = \begin{bmatrix}
    H_{41} & H_{45} & H_{46} \\
    H_{54} & H_{55} & H_{56} \\
    H_{65} & H_{65} & H_{66}
\end{bmatrix} = 0 \]

(7)

The natural frequency about different deployment angles of the satellite antenna can be obtained. Then the initial and final state vectors of the system and other modal parameters such as the mode shape and amplitude-frequency characteristics can be solved.
2.3. Numerical simulation of satellite antenna at different deployment angles

A radial rib of a satellite antenna with 9m diameter is taken as an example. A radial rib is composed of 5 deployment component and connectors. The material is carbon fiber T700. The physical parameters such as dimensions are shown in Table 1.

| Implications of parameters | Deployment component | Connector |
|---------------------------|----------------------|-----------|
| Length/m                  | 0.5                  | 0.07      |
| Diameter/mm               | Φ23*1                | Φ25*1.5   |
| Density/(kg/m³)           | 1780                 | 1780      |
| Elastic modulus/Pa        | 2.45e11              | 2.45e11   |

The dynamic analysis about the satellite antenna with deployment angle of 30°, 60°, 90°, 120°, 150° and 180° was carried out as example. The natural frequency and mode shape of the satellite antenna during the deployment process is obtained to analyze the amplitude and frequency characteristics. Through the MATLAB calculation program, the first three-order natural frequencies at different angles can be obtained as shown in Table 2.

| Deployment angles | Natural frequencies (Hz) |
|-------------------|--------------------------|
|                   | First  | Second | Third  |
| 30°               | 13.58  | 27.84  | 40.31  |
| 60°               | 16.36  | 38.76  | 106.99 |
| 90°               | 8.23   | 92.87  | 119.92 |
| 120°              | 2.59   | 16.55  | 55.57  |
| 150°              | 1.80   | 11.36  | 32.49  |
| 180°              | 1.62   | 10.17  | 28.47  |

The first-order natural frequency of the satellite antenna deployment component first increases and then decreases with the increase of the angle. It reaches maximum when the deployment aperture of the satellite is half of full deployment. In the deployment process, the natural frequency of the completely deployed satellite antenna is the smallest and prone to coupling vibration in this state, which should be severely paid attention to.

The fluctuation amplitude of the mode shape first decreases and then increases during the antenna deployment process according to the mode diagram, and the satellite antenna has the worst system stability after being fully deployed can be acquired. Thus, it is most necessary to install dampers at each mode resonance point of the fully deployed satellite antenna to suppress vibration, and perform dynamic analysis after deployment.

![Graph a) Deployment angle 30°](image1)

![Graph b) Deployment angle 60°](image2)
3. Finite element analysis for deployment process of component

Under the vibration characteristics of coupling vibration and low natural frequency for large-scale flexible satellite antenna, a preloaded thin-walled multi-petal friction damping structure is proposed in the previous articles as shown in figure 5 and 6\textsuperscript{[13]}. The energy dissipation mechanism of the damping structure is that microscopic relative sliding friction of the contact surfaces between the outer wall of the petals and the inner wall of the deployment component produces energy loss\textsuperscript{[13]}. Through the numerical analysis of the model, the loss energy is obtained, which is 0.3326.

Fig. 5. Schematic diagram of satellite antenna deployment component with damping structure

Fig. 6. Thin-walled multi-petal damping structure

A three-dimensional solid model is established according to the size of the geometric model about radial rib flexible deployable antenna, and the harmonic response of the satellite antenna component was analyzed at 30°, 60°, 90°, 120°, 150° and 180° of deployment angle by finite element method.
The deployment angle of 60° is taken as an example and the modeling is shown in Figure 7 below. One end is set to be fixed, and then the first three natural frequencies are 5.35 Hz, 20.99 Hz, 29.08 Hz obtained through modal analysis and the spectrum of the unfolded component can be obtained through harmonic response analysis. Due to accuracy problems, the amplitude corresponding to the first natural frequency may be lower, and the first-order natural frequency is analyzed separately in accuracy of 0.001Hz as shown in Figure 8.

The finite element analysis results about the first three-order natural frequencies and the first-order amplitude are recorded in Table 3. The first-order natural frequency has a downward trend as the deployment angle increases. The frequency is the lowest to be prone to coupling when fully expanded, which is basically the same as the theoretical analysis result of the transfer matrix. The amplitude corresponding to the first-order natural frequency first increases and then decreases, and the amplitude is the largest when the expansion angle is 120°. Thus, the analysis for vibration control effect of damping structure when fully deployed and deployment angle 120° is necessary to be focused on.
The loss factor of the damping structure can reach 0.3326 according to previous paper. The deployment structure with damping structure is analyzed, and the natural frequency is basically the same as the state of that without damping structure. The response amplitude obtained by the harmonic response analysis is recorded in Table 3, and the influence of the damping structure on the first-order response amplitude can be obtained. The amplitude reduction rate can reach more than 80% at different deployment angles. The amplitude reduction rate is greater than 95% when fully deployed and deployed angles at 120°. Thus, the damping structure has a obvious vibration reduction effect.

Table 3. The natural frequency and amplitude of different angles of deployment component

| Deployment angles | Natural frequency (Hz) | Amplitude of first order (m) | Amplitude of first order (m) | Amplitude drop rate |
|-------------------|------------------------|----------------------------|----------------------------|--------------------|
|                   | First                  | Second                    | Third                      | First              |                      |
| 30°               | 9.388                  | 19.876                    | 36.923                     | 4.03E-05           | 10.822              | 6.49E-06             | 0.839               |
| 60°               | 5.348                  | 20.986                    | 29.079                     | 1.56E-04           | 5.843               | 1.04E-05             | 0.934               |
| 90°               | 3.855                  | 21.751                    | 27.351                     | 1.02E-03           | 4.002               | 5.20E-05             | 0.949               |
| 120°              | 3.168                  | 19.266                    | 36.388                     | 4.60E-03           | 3.349               | 1.53E-04             | 0.967               |
| 150°              | 2.847                  | 17.739                    | 48.307                     | 1.63E-03           | 2.912               | 9.62E-05             | 0.941               |
| 180°              | 2.752                  | 17.255                    | 48.385                     | 9.79E-04           | 3.376               | 3.30E-05             | 0.966               |

4. Conclusion

In this paper, through the transfer matrix and finite element analysis of the deployment process of a radial rib of the flexible self-deployment satellite antenna, in the fully expanded state, the natural frequency is the lowest and the system stability is poorest. Through the finite element analysis of deployment component, the natural frequency is basically consistent with the theoretical analysis, and the system is prone to coupling to cause poor system stability in the fully deployment situation. Through the harmonic response analysis, the amplitude is the largest when the deployment angle is 120°. Therefore, it is necessary to focus on the vibration control analysis when the damping structure is fully deployed and the deployment angle is 120°. Through the finite element dynamic analysis of the deployment component with damping structure proposed, the amplitude reduction rate can reach more than 80% under different expansion angles, and the amplitude reduction rate is greater than 95% when fully deployed and deployment angle is 120°, which proves that the damping structure has an excellent vibration reduction effect. The multi-petal frictional damping structure proposed in previous paper provides a simple method that easy to manufacture and an effective method to control vibration that produced in the deployment process of a radial rib, which attach a profound impact on the development and application of large flexible antennas and even on the aerospace industry.

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