Research on Damping Mechanism with Resetting Capability for Axial Vibration Control of Satellite Antenna

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Abstract. With the development of space technology, the large scale space deployable antennas gradually become one of the key research themes of research. The basic requirements for large scale satellite antennas are the characteristics of light in weight and high in profile accuracy. The low-frequency and large-amplitude vibration of the large scale antennas is easily excited when working in an environment with zero gravity. In order to suppress the vibration of large scale deployable satellite antenna, a new type of damping mechanism with resetting capability is presented to improve the ability of vibration energy consumption and ensure the dynamic characteristics of the radial rib structure containing the presented profile accuracy of the antenna. The rod making up the deployment mechanism of the antennas is divided into two parts which connected by using the shape memory alloy (SMA) wires through guiding mechanism. Meanwhile, a metal rubber is fixed and pressed between two parts of the rod by SMA wires. The ability of the friction energy dissipation of the metal rubber is utilized to suppress the axial vibration of the rods. The super elasticity of the SMA wires is used to provide the restoring force for ensuring the dimensional stability of the rod. In this paper, the design principle of the axial self-resetting damping structure is introduced in detail. And, the dynamic characteristics of the radial rib structure containing the presented damping mechanism are investigated by using the software ANSYS. The simulation results show that the vibration amplitude of the radial rib of antennas has been reduced significantly.

1. Introduction

The large-scale flexible automatically expandable mechanism is a significant part of the satellite antenna. The continuous vibration phenomenon exists in the process of opening and flying of the antenna ribs for the satellite antenna. This vibration affects the normal use of the satellite directly to reduce profile accuracy retention and working life of the antenna. It is necessary to consume the vibration energy of the antenna while maintaining the original shape of the antenna. Therefore, the structure of large scale space automatically expandable antennas is required to have the characteristics of light weight, high deployment reliability and profile accuracy. A passive control method that can achieve multiple degrees of freedom and multiple modes vibration control with time-varying effectively for satellite antennas is proposed in this paper. A new type of metal rubber self-resetting friction damper is designed, and the
detailed design method and optimization scheme of the damper are given in this dissertation. The metal rubber damper has been widely used in the field of vibration reduction because of its good damping performance, light weight, simple structure, accessibility to making craft, adjustable stiffness, and so on.

The metal rubber is used as the main energy-consuming material in this paper. The metal wires of the metal rubber squeeze against each other to consume energy to achieve the purpose of vibration reduction when the damper is subjected to axial vibration. The super-elastic properties of SMA are used to provide axial self-resetting preload. The preload of SMA and the hysteresis characteristics of metal rubber are used to ensure that the axial length of the expansion member does not change to ensure the profile accuracy of the antenna when the vibration is attenuated. Metal rubber is a porous elastic material, which is made of metal wire through a special molding process\textsuperscript{1,2}. Wire of a certain quality, stretched and spiral is discharged in the stamping die in an orderly manner, and then the blank must be stamped in the die to achieve the geometric shape and performance required by the structure. Metal rubber material has the characteristics of aging resistance, high strength, great damping property, tunable stiffness, long life etc. compared with traditional viscoelastic rubber\textsuperscript{1,3,4}. Metal rubber has been widely used in various fields such as aerospace because of it plays an extremely important role in damping, power absorption and vibration isolation. The damping and vibration reduction characteristics of metal rubber materials have been widely used in various cushioning and vibration reduction devices as one of the main properties. Hongyuan Jiang and others\textsuperscript{5} designed a new type of squeeze film damper with a metal rubber ring at the end to reduce the vibration caused by the high-speed rotation of the engine rotor. Long YangXiang and others\textsuperscript{6} studied the elastic support structure used for aero-engine rotor vibration reduction, and conducted an in-depth study on its strength characteristics. Hongjie Liu and others\textsuperscript{7} studied a new type of intelligent damping material-memory alloy metal rubber that combines traditional metal rubber preparation technology with shape memory alloy materials, which has good vibration damping and shape memory effects.

2. Design of metal rubber friction damper.

The metal rubber self-resetting friction damper is mainly designed for the axial vibration reduction of the large scale flexible automatically expandable satellite antenna, which can effectively control the axial vibration of the expansion member while realizing the axial self-reset function. The function of axial damping vibration reduction is mainly realized by the metal rubber material as the friction energy dissipation element. Metal rubber has a certain degree of rigidity due to the complex spatial network structure inside, which similar macromolecular structure. Dry friction occurs between the metal wires can dissipate a large amount of energy when vibrating, thereby reducing vibration of antenna. The axial self-reset function uses the super-elastic properties of SMA to provide axial self-reset preload. Due to the preload of SMA and the hysteresis characteristics of metal rubber, the axial length of the expansion member does not change to ensure the profile accuracy of the antenna when the vibration is attenuated.

2.1. Structural design plan

The metal rubber self-resetting friction damper consists of an outer tube, an inner tube (shaft), metal
rubber, and SMA wire. Its structure model is shown in Figure 3 and 4. The structure has the functions of axial vibration reduction and axial self-reset, respectively, which are realized by metal rubber and SMA wire respectively. The SMA wire is braided through the hole of the outer tube and fixed at both ends of the SMA wire with the locking screw to make it in a tensioned state to produce a certain pre-tightening force on the metal rubber. The pre-tightening force can be calculated. The metal rubber block passes through the inner shaft and is placed in the cavity of the outer tube to connect the two components. The metal rubber is compressed under the pre-tightening force of the SMA wire. The axial vibration of the unfolding member is suppressed by the frictional energy of the metal rubber block when the inner and outer tubes slide relatively due to vibration. On account of the preload of SMA and the hysteresis characteristics of metal rubber the axial length of the expansion member does not change when the vibration is attenuated.

![Fig. 3. Structure drawing of metal rubber damper](image)

![Fig. 4. Damping component structure diagram](image)

2.2. **Structural performance analysis**

The stiffness change of metal rubber presents a hysteresis loop with memory characteristics. Through Y.G. Zhou et al.\cite{9} research on the hysteresis characteristics of metal rubber, a nonlinear damping model of metal rubber was established. As shown in Figure 5, it is the hysteresis loop diagram of metal rubber. Expression of loss factor of metal rubber:

\[
\eta = \frac{2\pi f_{osc} T_{loss}}{F_{max}}
\]

where $f_{osc}$ is the oscillation frequency, $T_{loss}$ is the loss time, and $F_{max}$ is the maximum force.
Fig. 5. Metal rubber hysteresis curve

\[ \eta = \frac{\Delta W}{2\pi W} \]  

(1)

\( \Delta W \)—the area of the ellipse loop is the energy dissipated by the rubber in a period, N-m.

\( W \)—The area of the triangle enclosed by the midline of the hysteresis loop and the horizontal axis is the maximum elastic potential energy stored in the metal rubber during the deformation process, N-m.

The curve actually measured is not a standard ellipse, due to the metal rubber material has nonlinear restoring force characteristics. The area of the hysteresis loop, the energy dissipation effect of the damper, and the loss factor increase as the preload of the metal rubber material increases. Metal rubber no longer has the performance of friction energy consumption as the preload increases to a certain value. Therefore, research on the pre-tightening force range and the best pre-tightening force of metal rubber is necessary.

The rigidity of metal rubber is closely related to process parameters such as the relative density of metal rubber, the diameter of the metal wire, the middle diameter of the spiral coil, the height of the specimen and the bearing area due to the special material characteristics of metal rubber. The stiffness of the metal rubber will increase with the increase of the preload. But the metal rubber is compressed to a certain extent as the preload increases to a certain value, the gap between the metal wires becomes smaller. The energy dissipation capacity of the metal wire to limit the relative sliding friction will decrease. The relationship between preload and stiffness of metal rubber can be obtained through experimental methods due to the complexity of its material properties. In this way, the initial pretension of the SMA wire can be determined.

2.3. Minimum length of SMA wire

The minimum length of SMA wire needs to be calculated to determine the size of the inner and outer tubes of the damper. Determination of the size of other parts of the damper according to the minimum length of the SMA wire that meets the requirements.

Suppose the minimum length of the SMA wire is \( L_{\text{min}} \), the given excitation force is \( F \), the pre-strain force of 6 SMA wires is \( F_0 \), and the frictional force that the friction block can provide is \( F_f \), then:

\[ 6F_0 + F_f = F \]  

(2)

Then the prestress of SMA wire is:

\[ \sigma_0 = \frac{F_0}{A} = \frac{F - F_f}{6A} \]  

(3)

The prestrain at the prestress \( \sigma_0 \) is determined according to the numerical results of the stress-strain curve of the SMA wire simulated by Simulink. It can be known the pre-strain is \( \varepsilon_0 \) from the stress-strain curve at the tensile stage. The maximum recoverable strain of the SMA wire is taken as \( s \) and the amplitude is \( k \), then:

\[ L_{\text{min}} = \frac{k}{s - \varepsilon_0} \]  

(4)

In order to maximize \( L_{\text{min}} \), \( \varepsilon_0 \) should be the largest, that is, \( \sigma_0 \) the maximum value. At this time, the
excitation force is equal to the friction force. The pre-strain at this time \( \varepsilon_0 \) can be obtained according to the stress-strain curve of the SMA wire at the tensile stage. Pre-strain \( \varepsilon_0 \) is brought back to formula (4) to obtain the minimum SMA wire length.

3. Finite element analysis of metal rubber damper

The radial rib with four axial self-resetting damping structure was analyzed in the finite element software ANSYS, and the structure model is shown in Figure 6. The density of the metal rubber material we used is 1.5g/cm³. The material of the metal rubber is stainless steel 304 with a wire diameter of 0.1 mm. The finite element model of the radial rib is shown in Figure 7. The first three natural frequencies of the structure are obtained through modal analysis in the case of undamped structure as shown in Figure 9. The first-order natural frequency is 1136Hz. The frequency spectrum of the structure obtained through harmonic response analysis that the load is 100N is shown in Figure 8, and the amplitude of the first-order natural frequency is 2.2mm.

The first three natural frequencies of the radial rib with metal rubber damper with zero pre-tightening force are obtained through modal analysis is shown in Figure 10, and the first natural frequency is 237
Hz. The frequency spectrum of the structure obtained through harmonic response analysis is shown in Figure 11, and the amplitude of the first-order natural frequency is 0.12mm. Simulation results show that the damping structure is effective obviously with the amplitude reduction rate reaches 94.4%.

![Frequency Spectrum](image)

**Fig. 11. Spectrogram with damping structure**

**4. Conclusion**

A new type of axial self-resetting friction damping structure with dual functions of self-resetting and frictional energy dissipation for the large-scale space deployable satellite antenna is presented in this thesis. The unfolding member of the antenna is designed as two parts connected by the presented self-resetting friction damping mechanism which is with both large damping energy dissipation and elastic recovery capacity to ensure the profile accuracy of the antenna. Compared with the general damping mechanism, the presented damping mechanism has advantages such as simple structure, light in mass, wide frequency band of vibration control, large energy dissipation, and self-resetting capability. The results of finite element simulation show that the dynamic response amplitude of the radial rib can be reduced by 94.4% with the presented damping mechanism. This provides a high performance method for the vibration control of the large scale deployable antennas.
Acknowledgment
This work was supported by National Defense Equipment Pre-Research Foundation of China (Grant NO.61402100103)

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