Design and Experiment of Vibration Reduction Scheme for Sensitive Detectors Based on Random Vibration

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Abstract. This work proposes a vibration damping scheme using a metal rubber damper for space camera mechanically sensitive detectors. The feasibility of the scheme is verified by the analysis of the principle of metal rubber damper. According to the relevant test conditions, the relevant parameters of the metal rubber damper are designed, and the vibration damping effect of the scheme is verified by experiments. The research results show that the use of metal rubber damper can play a role in the vibration energy transfer of the space camera, thus effectively reducing the RMS value of the acceleration in the main vibration direction.

1. Introduction

The space camera is a high-precision optical instrument. It carries the detector as an important component to ensure measurement accuracy and image quality. Due to the increasing accuracy of satellite observations, higher requirements are imposed on the accuracy and anti-jamming capability of satellite detectors. Based on such requirements, relevant designers are increasingly faced with problems such as high instrument accuracy requirements, high load quality, and high anti-interference requirements. Under various constraints, the optimization of simple structures was difficult to meet the required accuracy. Therefore, it is necessary to consider the corresponding vibration reduction scheme. This can reduce the influence of the external environment, especially the random vibration on the detector, and ensure the accuracy of the detector. Thereby obtaining accurate and reliable data.

Metal rubber is a kind of special material that is spirally wound by a specific process, and after being stamped and formed, the wires are hooked and joined together to form a rubber-like molecular structure. The metal rubber damper made of this material is a dry friction damping damper [1], which has the characteristics of high damping, excellent energy absorption performance and good environmental adaptability. The vibration damping principle is that when the damper is subjected to various types of loads, the internal wires are in contact with each other to generate dry friction, which absorbs vibration energy, thereby damping the vibration. At present, many researches on the properties and applications of metal rubber materials have appeared at home and abroad [2-7]. Zou Qinglong et al [8] analyzed the micro-element stiffness and hysteresis loop characteristics of metal rubber from microscopic and macroscopic perspectives respectively, and verified the advantages of combined metal rubber through experiments and simulation analysis. In the research of random vibration of metal rubber, Yan Hui, Jiang Hongyuan et al [9] based on the research of dry friction vibration isolation system under random vibration, deduced the formula of random vibration mean square acceleration of metal rubber vibration isolation system, and tested its accuracy by experiment. However, only a comparative study on the RMS
acceleration of random vibration is not sufficient to demonstrate the performance of the metal rubber vibration isolation system.

Based on the mission of a satellite space camera, this paper designs a new damping system based on the dynamic model of the metal rubber damping system. The test compares the RMS value of the random vibration before and after the vibration damping system, and verifies the vibration damping effect.

2. Metal rubber vibration reduction principle
The metal rubber damper vibration type is dry friction damping vibration, so its physical model is shown in Figure 1. According to the model, the relevant dynamic equations are obtained:

\[ m\ddot{x}_1(t) + c\left(\dot{x}_1(t) - \dot{x}_s(t)\right) + k\left(x_1(t) - x_s(t)\right) = 0 \]  

(1)

Where \( m \) is the load mass, \( x_1 \) is the displacement of the load, \( x_s \) is the displacement of the vibration source, \( k \) is the stiffness of the metal damper, and \( c \) is the damping of the metal damper.

Equation (1) performs a Lagrangian transformation. Get the transfer function of the system as

\[ G(s) = \frac{X_s(s)}{X_1(s)} = \frac{cs + k}{ms^2 + cs + k} = \frac{2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \]

(2)

Where the undamped natural circular frequency is \( \omega_n = \sqrt{\frac{k}{m}} \) and the damping ratio is

\[ \zeta = \frac{c}{2\sqrt{km}}. \]

By substituting the virtual variable \( j\omega \) for the complex variable \( s \), the power spectrum density of the vibration subjected to the load is finally obtained as a function of the vibration source, that is, the power spectrum density of the vibration condition is as follows:

\[ |X_s(j\omega)| = |G(j\omega)| |X_1(j\omega)| \]

(3)

According to formula (3), we only need to select a suitable metal damper according to the quality of the load and the installation method. The total RMS value of the vibration subjected to the load will be less than the total RMS value in the vibration condition. In this way, the effect of damping is achieved.

3. Test study on metal rubber damper

3.1. Test conditions
The vibration test device is composed of a computer, a vibration controller, a power amplifier, a vibration generator, a sensor, and the like. As shown in Figure 2, when testing, first use the computer to run the vibration test software and set the vibration parameters. The vibration controller then generates an excitation signal based on the vibration parameters and passes it to the power amplifier. After the excitation signal is amplified by the power amplifier, the vibration generator is transmitted and pushed to start vibrating. At the same time, an acceleration sensor is placed on both the vibrating table and the
test equipment to monitor the acceleration response before and after the vibration damping system. The sensor transmits the acceleration response value back to the vibration controller in real time, and after computer monitoring, processes and stores the test data.

![Figure 2. Vibration test device schematic.](image)

The infrared detector uses a Stirling-cooled short-wave infrared detector. The detector and the refrigerator have a mechanical random vibration test of 18GRMS, and the vibration test site is shown in Figure 3.

![Figure 3. Vibration test site.](image)

The random vibration test adopts the average control method. The random vibration test of the hyperspectrum imager is divided into five stages. The power spectrum density is shown in Table 1, and the control spectrum is shown in Figure 4.

| Frequency (Hz) | PSD (g²/Hz) |
|---------------|-------------|
| 10~50         | +6dB/oct    |
| 50~110        | 0.35        |
| 110~150       | 0.35~0.04   |
| 150~450       | 0.04        |
| 450~2000      | -18 dB/oct  |
| Total RMS     | 6.92GRMS    |

![Table 1. Power Spectrum Density](image)
3.2. Vibration reduction design

The through-hole cylindrical metal rubber used in the vibration damping scheme is formed by folding and winding stainless steel. Due to space constraints, the metal rubber damping pad is designed to have a height of 3.5mm, an inner diameter of 3mm and an outer diameter of 6mm, as shown in Figure 5. The damper test has a theoretical natural frequency of 130 Hz and an overall stiffness value of $2\times10^5$N/m. When the total deformation of the test piece is less than or equal to 4 mm, the vibration damping performance is better. Assume that the entire damping system is made up of N test pieces in parallel, and each test piece is made up of two metal rubber pads in series. The entire damping system shares a load of 3.7 kg, and each test piece bears $3.7/N$ kg.

According to the vibration theory, the natural frequency of the metal rubber damper is:

$$f_n = \frac{1}{2\pi} \left( \frac{k}{m} \right)^{\frac{1}{2}} = \frac{1}{2\pi} \left( \frac{kN}{3.7} \right)^{\frac{1}{2}} \quad (4)$$

In the formula, $m$ is the load mass of each test piece, and $N = 12.3$ is calculated. In order to ensure the reliability of the project, a margin of 30% is added in this number. Therefore, it was finally determined that the number of metal rubber dampers in the vibration damping system was 16.

Substituting $N=16$ into equation (4) gives the overall stiffness value $K=1.54\times10^5$N/m in this state.
According to Hooke's law, the overall stiffness of the metal rubber damper is:

\[ k = \frac{E_s S}{\Delta s} \]  

Substituting the maximum allowable deformation amount \( \Delta s = 4 \text{mm} \) into equation (5), the elastic modulus of the metal rubber is \( E_s = 728 \text{Mpa} \).

The simulation parts before and after the improvement of the support scheme are shown in Figure 6. Eight metal rubber dampers are added between the detector, the refrigerator and the infrared focal plane assembly. In this way, the influence of the vibration energy transmitted by the box on the detector and the refrigerator is reduced.

![Before](image1.jpg) ![After](image2.jpg)

**Figure 6.** The simulation parts before and after the improvement.

### 3.3. Analysis of test results

In order to ensure consistent input, we test the simulated parts before and after the improved support scheme under the same vibration platform and the same vibration conditions. The excitation signals are applied in three directions of X, Y and Z respectively. The sensor uploads the acceleration value from the detector measurement point and the refrigerator measurement point respectively, and then converts to the acceleration RMS value after computer processing.

Table 2 shows the RMS response of the main vibration direction of the detector and the refrigerator under different excitation directions before and after the improvement. The RMS value of the acceleration characterizes the vibration energy of the system. The metal rubber damping system can absorb the vibration energy and also transfer the energy of the main vibration direction, thereby reducing the corresponding acceleration RMS response. Comparing the test results, it is known that before the improvement of the support scheme, the rms acceleration of the detector and the refrigerator exceeds the 18 Grms limit of the factory mechanical test in some main vibration directions. After the improvement of the damping scheme, the RMS value of the main vibration direction of the focus is reduced. However, due to the structural characteristics of the metal rubber of this scheme, the vibration reduction in different directions has different effects. At the same time, the RMS value of some main vibration directions has increased due to the transfer of vibration energy by the vibration damping system. The RMS values of all accelerations of the detector and the chiller are normal, so the vibration damping system can ensure the normal operation of the mechanically sensitive detector.

| Measuring point | Response result (Grms) |
|-----------------|------------------------|
|                 | X  | Δ   | Y  | Δ   | Z  | Δ   |
| Detector        |    |     |    |     |    |     |
| Before          | 19.7| 29.39%| 20 | 51.00%| 11.2|13.56%|
| After           | 13.9| 9.8  | 9.7|     |     |     |
| Refrigerator    |    |     |    |     |    |     |
| Before          | 21.7| 20.28%| 14.6| 86.10%| 13.6|-28.24%|
4. Conclusion
Based on the mission of a satellite space camera, this paper designs the corresponding vibration reduction scheme. The vibration reduction effect of the scheme is verified by comparing the total RMS value of the random vibration before and after the vibration damping system.

(1) According to the research on the vibration damping principle of metal rubber, the idea of using metal rubber damper for vibration reduction is proposed. Combined with relevant test parameters, the related parameters of the vibration reduction scheme and metal rubber damper are determined.

(2) The vibration test was used to verify the effect of the vibration reduction scheme. After using the vibration reduction scheme, the mechanical response of the main vibration direction can be generally reduced by more than 20%, and the RMS value of the main vibration direction that is mainly concerned meets the requirements of the factory test. This paper provides a feasible direction for the study of vibration reduction of mechanically sensitive detectors for large-caliber space optics cameras in the future.

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