Design and simulation analysis of an aerospace damper

Q L Wang1,2, Q X Wang1, H J Jiang1, Y H Lin1 and X H Zhou1
1Beijing Institute of Space Mechanics & Electricity, Beijing 100094, China

E-mail: 18001096205@163.com

Abstract. In this paper, viscoelastic materials are used to attenuate vibration for the optical remote sensor and satellite base. Flexible-base single-degree-of-freedom vibration attenuate system model is built considering that the satellite base is not rigid. The transfer ratio of the vibration damping system when the satellite platform foundation is non-rigid is obtained by using the four-terminal parameter method and the mechanical impedance method. Furthermore, the effects of mass ratio, fundamental frequency ratio, basic damping ratio and damper damping ratio on the vibration attenuate efficiency are discussed. According to the properties of integrated space optical remote sensor and satellite base, the optimum parameter combination between damping ratio and vibration attenuate efficiency is obtained. The design schemes of the viscoelastic material damper are refined using the simulation analysis results.

1. Introduction
Vibration problem is an essential issue in the field of aerospace engineering. A modern spacecraft is always in a very complex mechanical environment during transportation from the ground, launch and in-orbit operations, which puts forward more and more tests for the normal work of precision instruments or devices on spacecraft [1-3]. The dynamic characteristics of the spacecraft are significantly related to the stiffness and damping characteristics of the connection structure [4]. Nowadays, a number of spacecrafts at home and abroad use damping vibration reduction technique to solve the vibration problem [5]. The vibration reduction system can adopt different structural forms, such as passive vibration reduction and active vibration reduction, as well as active and passive conjoint vibration reduction. With the advantages of simple structure, easy implementation, and good high-frequency vibration reduction effect, passive vibration reduction does not require external energy. Many passive dampers based on spacecraft applications are studied, such as metal rubber dampers, adaptive variable damping magneto-rheological dampers, viscoelastic material damping dampers, etc [6,7].

During the on-orbit working of space optical remote sensing satellite, the vibration of the remote sensor is caused by space dynamics interference source, which affect the imaging quality of the remote sensor. With the improvement of resolution, suppressing this influence has become an increasingly important factor to be considered in the overall design [8, 9].

In this paper, according to the characteristics of the optical remote sensor and the satellite platform, considering that the satellite base is non-rigid, flexible base single degree of freedom vibration attenuate system model is built. The effects of mass ratio, fundamental frequency ratio, basic damping ratio, and damper damping ratio on vibration attenuate efficiency are discussed based on the four-terminal parameter method and mechanical impedance method. The optimal parameters of damper ratio and vibration suppression effect are obtained. A design scheme of viscoelastic material damping damper is presented and simulated.
2. Evaluation of conventional vibration reduction effect

When evaluating the effect of vibration damping, the traditional theory of vibration damping usually assumes that the foundation is absolutely rigid [10, 11], that is, the rigid body with infinite impedance and mass, the vibration damping body is an ideal mass block without elasticity, and the vibration damping system is composed of an ideal spring and an ideal damper with a zero mass. The single-degree-of-freedom (1DoF) vibration damping system model is shown in figure 1:

![Figure 1. Model of vibration reduction system with a single degree of freedom.](image)

According to the four-terminal parameter method, the theoretical formula of transfer ratio of a 1DoF vibration damping system for rigid foundation can be obtained as follows:

\[
TR = \frac{F_s}{F} = \frac{1 + (2\zeta\lambda)^2}{\sqrt{(1 - \lambda)^2 + (2\zeta\lambda)^2}}
\]  

(1)

Vibration absorption characteristic curve of the single-degree-of-freedom system is shown in figure 2: In the area of \( \lambda > \sqrt{2} \), when \( TR < 1 \), the vibration is reduced. The vibration reduction effect will increase as the \( \lambda \) value increases and the \( TR \) value decreases. However, in the area of \( \lambda < \sqrt{2} \), \( TR > 1 \), the damper’s vibration response is amplified. Even when \( \lambda = 1 \), resonance occurs.

When designing a damper, the resonance peak amplitude can be reduced by appropriately increasing the damper damping. In the vibration absorption zone, increasing the damper damping will reduce the vibration absorption effect. These two aspects should be considered comprehensively in the selection of damper damping, and finally, a compromised value should be used.

![Figure 2. Vibration reduction characteristic curve of a 1DoF system.](image)

3. Influence of foundation impedance of satellite platform on the vibration reduction effect

In the practice of engineering, the satellite platform is not absolutely rigid, but has elasticity and certain damping as a flexible foundation. Using the traditional vibration reduction theory will produce large errors, so the foundation can be regarded as a system of several degrees of freedom, as shown in figure 3:
Figure 3. Model of flexible foundation vibration reduction 1DoF system

According to the four-terminal parameter method, the following transfer ratio formula of 1DoF flexible foundation vibration reduction system can be obtained.

\[
TR = \frac{F_s}{F} = \left| \frac{1 + 2j\zeta \lambda}{1 + 2j\zeta \lambda - \lambda^2 (1 + \frac{1 + 2j\zeta \lambda}{\mu(\alpha^2 - \lambda^2 + j2\zeta \lambda \alpha)})} \right| \quad (2)
\]

where \(\mu\) is the mass ratio of the satellite platform to remote sensor; \(\alpha\) is the base frequency ratio between satellite platform and remote sensor; \(\zeta_s\) is the satellite platform damping ratio; \(\zeta\) is the damper damping ratio; \(\lambda\) is the ratio of vibration frequency and base frequency of remote sensor; TR is the transfer ratio.

3.1. Influence of the mass ratio on the transfer ratio

When the base frequency ratio \(\alpha\), the satellite platform damping ratio \(\zeta_s\), and the damping ratio \(\zeta\) are given, the curve of transfer ratio of flexible foundation damping system TR changing with transfer ratio \(\lambda\) for different mass ratios \(\mu\), is shown in figure 4:

Figure 4. Model of flexible foundation vibration reduction 1DoF system.

The mass ratio has a significant impact on the vibration reduction effect of the system. The larger the mass ratio, the smaller the difference between the transfer ratio curve of the flexible foundation and the transfer ratio curve of the rigid foundation, and vice versa. The first formant is before the formant of the transfer ratio curve of the rigid foundation. The larger the mass ratio, the smaller the resonance peak.

3.2. Influence of fundamental frequency ratio on the transfer ratio

When the satellite platform damping ratio \(\zeta_s\) and the damper damping ratio \(\zeta\) are known for the mass ratio \(\mu\), the evolution curve of transfer ratio of flexible foundation damping system TR and the transfer ratio \(\lambda\) for different mass ratios \(\alpha\) has the form, as shown in figure 5:
3.3. Influence of satellite platform damping ratio on the transfer ratio
When the mass ratio \( \mu \), the base frequency ratio \( \alpha \), and the satellite platform damping ratio \( \zeta_s \) are known, the evolution curve of transfer ratio of flexible foundation damping system \( TR \) and transfer ratio \( \lambda \) for different satellite platform damping ratios \( \zeta_s \) can be constructed, as shown in figure 7:

![Diagram](image)

**Figure 6.** Influence of damping ratio on transfer ratio.

Different foundation damping ratio only changes the magnitude of vibration peak but does not change its position. The peak value of the curve decreases with the increase of the damping ratio. Different foundation damping ratios intersect at a point at a certain frequency ratio after the formant peak and before the anti-formant peak. Finally, the curves converge asymptotically, indicating that when the vibration frequency reaches a certain value, the effect of the foundation damping ratio to system damping tends to be consistent.

3.4. Influence of satellite platform damping ratio on the transfer ratio
When the mass ratio \( \mu \), the base frequency ratio \( \alpha \), and the satellite platform damping ratio \( \zeta_s \) are known, the evolution curve of transfer ratio of flexible foundation damping system \( TR \) and transfer ratio \( \lambda \) for different damper damping ratios \( \zeta \) can be constructed, as shown in figure 7:

![Diagram](image)

**Figure 7.** Evolution curve of transfer ratio for different damper damping ratios.
In the curve of flexible foundation transfer ratio, when the first order formant is before the formant of the rigid foundation transfer ratio curve, the larger the damper damping ratio, the smaller the first order formant. When an anti-resonance peak appears after the peak value, the peak value remains the same when the damping ratio of the damper is changed. At the frequency ratio $\lambda=1.685$, the curves of different damping ratios intersect at one point. When the frequency ratio $\lambda>1.685$, the larger the damping ratio, the weaker the damping effect. For the specific mass ratio, fundamental frequency ratio and foundation damping ratio, there is an optimal value ($\zeta=0.35$) for the damping ratio of the damper. When the frequency ratio $\lambda>0.62$, the transfer ratio will be less than 1, and the remote sensor and satellite platform will not cause a secondary resonance.

4. Design and simulation analysis of damper

4.1. Damping mechanism of viscoelastic materials

A viscoelastic material is a kind of high molecular polymer material with both viscous liquid and elastic solid properties. It produces alternating strain when subjected to alternating stress, which has both the storage capacity of elastic material and the effect of energy loss or conversion of viscous liquid. The treatment of constraint damping layer is the main structure form of viscoelastic damping vibration reduction, the viscoelastic composite structure is formed by bonding viscoelastic materials between the surface of the structural substrate and the restraint layer. The basic mechanism is that the structure bends and deforms during vibration to obtain damping. This method has the characteristics of wide-band and multi-peak resonance response control, and has high reliability, which will not significantly change the stiffness and mass of the system [12].

4.2. Design and simulation analysis of damper

4.2.1. Structure design of damper: The main structure of damper is titanium spring and damping rod with viscoelastic damping layer, as shown in figure 8. Titanium spring used to meet the requirements of the axial stiffness, damping rod is loaded along the axis with a cylindrical structure. The shear plane of viscoelastic material inter-layer is ringing, when relative movement occurs between coats and the mandrel, viscoelastic materials are deformed by shear, to increase structural damping, inhibit the action of the structural vibration.
4.2.2. Modal analysis of damper. The finite element model of the damper is shown in figure 9, and the modal analysis results are shown in figure 10. According to the results of modal analysis, the first order frequency of viscoelastic material damping damper is 210.9 Hz, which can meet the stiffness requirements. By adjusting the viscoelastic material and metal structural parameters of the damper, the damping ratio of the damper is designed to be 0.35, which can reduce the resonance peak and has a good effect on suppressing the vibration of the optical remote sensor caused by satellite platform.

![Figure 9. Finite element model of the damper.](image)

![Figure 10. Modal analysis results of the damper.](image)

5. Conclusion
In this paper, considering the flexibility of satellite platform based on the system, the influence of the flexible vibration system model of single degree of freedom was established, from the point of view of mechanical impedance, the four-terminal parameters method is adopted to get the transfer ratio calculation formula of flexible foundation, researched the influence of the foundation mass ratio, the frequency ratio, the damping ratio, and the damper damping ratio on the vibration reduction effect. According to the characteristics of the remote sensor and the satellite platform, the damping ratio of the damper is determined to be 0.35. A design scheme of the viscoelastic material damper is presented and the modal analysis is carried out. The analysis results show that the damper can meet the stiffness requirements, reduce the resonance peak, and increase the damping ratio of the system, which lays a foundation for the detailed design and engineering application of the damper.
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References
[1] Zhou L W, Zhou J and Li W H 2006 Active vibration control of flexible spacecraft during attitude maneuver Fire Control and Command Control 31 31-2
[2] Zhao C, Shen G Z and Wen C Y 2001 Study on modeling and simulation of docking control process of some spacecraft System Simulation 13 280-1
[3] Zhang P F, Cheng W, Wang H and Zhao Y 2010 Disturbance modeling and parameters identification of reaction wheel assembly on spacecraft Beijing University of Aeronautics and Astronautics 36 879-80
[4] Lin Y H, Li L, Wang C H, Zhao Y and Wang W Q 2012 Application of vibration suppression and assembly stress unloading technology for a space optical remote sensor Spacecraft Recovery & Remote Sensing 33 25-31
[5] Wang K and Gu Y D 2006 Study of the passive vibration isolation system for the space scientific experimental rack Chin. J. Space Sci. 26 470-6
[6] Zhou C G and Li D X 2009 Experiment of vibration suppression for large flexible space truss structures of satellite Aerospace Control 27 45-9
[7] Wang Y, Liu Z M and Li S Q 2010 Vibration temperature-increase research of viscoelastic material applied on constrained damping vibration isolator Vibration Engineering 23 587-90
[8] Zheng G T 2007 Advances in spacecraft vibration isolation and attenuation Symp of the 9th National Conference on Vibration Theory and Application (Hangzhou: China) pp 17-19
[9] Liu T X, Hua H X et al 2002 Study on the model of finite element of constrained layer damping plate Chin. J. Mech. Eng. 38 108-13
[10] Xie G M 2007 Mechanics of Vibration (Beijing: National Defence Industry Press)
[11] Wu C J 2003 Engineering Vibration and Control (Xi’an: Xi’an Jiaotong University Press)
[12] Ren H Y 2007 The application of viscoelastic damping vibration suppression for shock-isolation structure of multistage missile Astronautics 28 1494-9