Parametric Studies of the Whole Spacecraft Vibration Isolation

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Nomenclature

c_i = damping coefficient
D = displacement
g_i = nondimensional frequency
I_{pp} = unit matrix
K = stiffness matrix
k = stiffness ratio
k_i = stiffness
m = mass ratio
m_i = mass
R = coordinate vector
T = displacement transmissibility
η = loss factor
ξ_i = damping ratio
Φ = modal matrix
ω = excitation frequency
ω_i = natural frequency

Subscripts

d = modal coordinate
i = structure number
p = physical coordinate at boundary

Introduction

IN space industries two important challenges are the minimum structural mass of a spacecraft and the maximum market of a launch vehicle. A major factor, which determines whether these targets can be reached or not, is the dynamic environment that a launch vehicle can provide to its payloads. The launch stage is the most severe dynamic environment that a spacecraft will experience during its normal mission life. To survive the launch stage, the strength of a spacecraft structure has to be sufficiently high, and this is translated into some extra mass that will be useless in the orbiter for a normal mission. As there are more and more launch service providers in the world, spacecraft owners now have more choices than ever before. From such aspects as reliability and economics, the dynamic environment is a major factor considered in choosing a launch vehicle.

Because the concept was proposed, the whole spacecraft vibration isolation (WSVI) technology has been successfully applied for many times.[1,2] The purpose of the WSVI is to improve the dynamic environment significantly by adding vibration isolators or damping treatment to the payload adaptor fitting (PAF). Currently, the WSVI is considered as the most effective and economic approach for improving the dynamic environment. A direct benefit of the WSVI is to enable a spacecraft, qualified for being launched with a launch vehicle, to fly using another launch vehicle. A major difference between two different launch vehicles usually is their dynamic environments.

The theory and technology of vibration isolation have been studied for many years, and the vibration isolation has become a standard technology in many engineering areas, such as mechanical engineering and civil engineering.[3] In space engineering isolators are widely applied to isolate vibration transmitted from a spacecraft structure to its instruments.[4] Besides studies on active vibration isolation[5] and isolator optimal designs,[6] the coupling effect of the isolation structure with a flexible base was studied extensively.[7,8] In contrast to a rigid base, the flexible base will introduce more degree of freedoms to the system. This will influence the design of an isolation system with or without active control. There is a similar conclusion for the case of a flexible isolated body.[9]

A feature of the WSVI is that the vibration isolation structure is between two flexible structures, that is, the launch vehicle and the spacecraft. The flexibility of these structures has significant influence on the performance of the isolation. To ensure the effectiveness, the analysis and the design of the isolator should be coupled with the whole launch-vehicle isolator spacecraft system.

There are several methods available for the analysis and design of vibration isolation structures. Among them are vibratory power flow method,[8] modal synthesis method,[10] and graphic model technique.[11] As the finite element models of the launch vehicle and the spacecraft are usually given and the corresponding reduced-order models are also often available, modal synthesis method is a better choice for the analysis of the WSVI. In space industries, when integrating the launch vehicle model and the spacecraft model together for the whole system modal synthesis, the super-element model is often used.[12] This is a feature of the launch-vehicle spacecraft-system vibration analysis.

The purpose of this Note is to study influences of design parameters, especially parameters related to the coupling of the isolation and the isolated structure, on the isolation performance. Experiences obtained from this study are used in the design process of adding vibration isolation function to an existing PAF for improving the dynamic environment of a launch vehicle.

Parametric Studies

From the aspect of a practical isolation design process, the first stage usually is the determination of the overall isolation structure stiffness and damping based on some spacecraft structure parameters, such as mass, overall vertical stiffness, and horizontal stiffness, which are available to the launch service provider. This stage is also called primary design that is followed by the detail design stage. In this stage to study the parameters that decide the isolation performance, the isolation spacecraft system can be modeled as a two-degree-of-freedom system that is shown in Fig. 1. Subscripts 1 and 2 denote the spacecraft and the isolation, respectively. The influence of the launch-vehicle structure is represented by the base displacement.

The dynamic equation of motion of the model is

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - c_1\dot{x}_2 - k_1x_2 = 0 - c_1\dot{x}_1 - k_1x_1 + m_2\ddot{x}_2 + (c_1 + c_2)\dot{x}_2 + (k_1 + k_2)x_2 = c_2\dot{u} + k_2u \tag{1}$$

The displacement transmissibility from the base to the isolated structure is

$$T_{ux_1} = \frac{x_1}{u} = \frac{(c_1s + k_1)(c_2s + k_2)}{\left(m_1s^2 + c_1s + k_1\right)\left[m_2s^2 + (c_1 + c_2)s + k_1 + k_2\right] - (c_1s + k_1)^2} \tag{2}$$

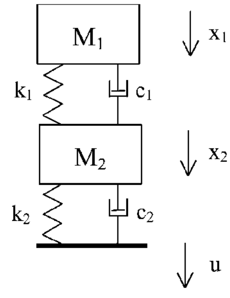

Fig. 1 Simplified model for the primary isolation design.

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By substituting the parameters mass ratio $m = m_1/m_2$, stiffness ratio $k = k_1/k_2$, and damping ratio $\xi_i = c_i/2\omega_i m_i$ into Eq. (2), a equation of the transmissibility with the preceding parameters is obtained as

$$T_{ux_1} = \frac{(1+2\xi_1 g_1)(1+2\xi_2 g_2)}{\left(1+2\xi_1 g_1+g_1^2\right)\left[(1+k)+2\left(\xi_2+\xi_1\sqrt{km}\right)g_2+g_2^2\right]-k(1+2\xi_1 g_1)^2} \tag{3}$$

where $g_i = j(\omega/\omega_i)$ is nondimensional frequency and $\omega_i = \sqrt{k_i/m_i}$.

It can be seen from Eq. (3) that the stiffness ratio k plays an important role in the isolation performance. Generally, there are two types of isolation: "soft ride" and "hard ride," which are defined by the stiffness ratio of the isolated structure and the isolation k. If $k > 1$, the isolation is a soft ride, and if $k < 1$ the isolation is a hard ride. With a different type of isolation, influences of design parameters are different, especially that of the damping ratio. In engineering applications there are three approaches toward realizing the WSVI, that is, replacing the PAF with an isolator, installing an isolator on the top or at the bottom of the PAF, and adding damping to the PAF. The first two approaches are soft ride. Although, strictly speaking, the last approach is a way of vibration attenuation, it is often considered as an important technique of the WSVI, especially when there is strict restriction on the payload room inside a fairing or any decrease in the stiffness of the PAF is not allowed. This approach is a typical hard ride.

With this model for the primary design, by numerical analysis some conclusions about the parameters can be deduced as follows:

1) With a hard ride, damping can significantly decrease the transmissibility at the resonance frequencies of the isolated structure but might increase it at some other part of the frequency axis.

2) A large mass ratio can decrease the transmissibility from the base to the isolated structure. This indicates that a lightweight isolation is of benefit to the vibration isolation.

3) If the stiffness of an isolation is lower than that of the isolated structure (soft ride), the transmissibility is less than one almost everywhere.

4) In the case of soft ride, the damping will increase the transmissibility at any frequency.

Practical Application

When a satellite, which was qualified for being launched by an old type of launch vehicle, was going to be launched with a new type of launch vehicle, there was a margin in the dynamic environments, especially in the horizontal direction, which these launch vehicles can provide. To ensure the reliability of the satellite during the launch, the WSVI was proposed. For ensuring the payload room and also because of the shape of the satellite as shown in Fig. 2, a constraint of the isolation is that the overall stiffness of the existing PAF should not be decreased, and for reducing the design and manufacture cost the original structure also should not be varied. As the existing PAF has a very high stiffness compared with that of the satellite, it requires that the WSVI has to be a hard ride. It is known from the preceding discussion that with a hard ride damping can decrease the transmissibility effectively at the satellite natural frequencies. Therefore, an increase in the PAF damping was chosen as the approach. The damping increase was realized by putting a constrained viscoelastic layer (CVL) on the outer surface of the PAF to increase the damping.

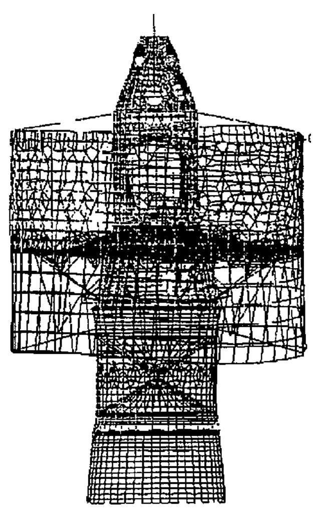

Fig. 2 Finite element model of the PAF-satellite structure.

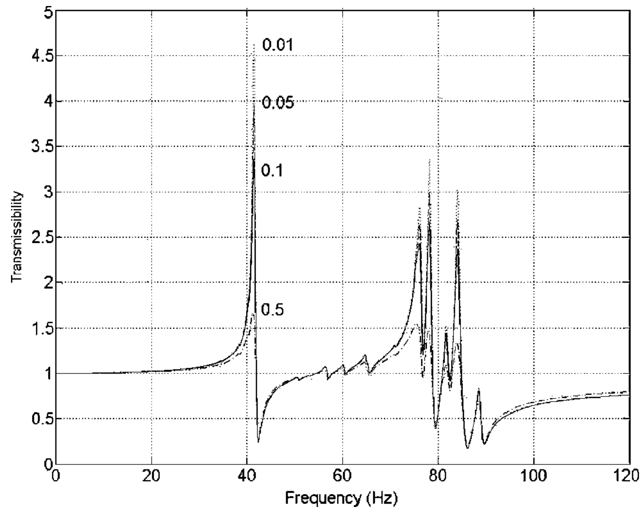

Fig. 3 Influence of the damping on the transmissibility in the vertical direction.

With the CVL any increase in the damping will be at the cost of PAF mass increase. The design process is to choose a proper increase in the damping level.

Because the data of the satellite were provided in the form of super element, in conducting the coupling analysis and designing the CVL the finite element model of the PAF is first transformed to a superelement model. Only physical coordinates on the interfaces between the satellite and the launch vehicle were retained; the number of the modal coordinates are determined by the model order.

Let the new coordinate vector be

$$R = \left\{R_d^T, R_p^T\right\}^T$$

then in generating the super elements the transformation matrix of the coordinate has the form of

$$\Phi = \begin{bmatrix} \Phi_{\mathrm{dd}} & \Phi_{\mathrm{dp}} \\ 0 & I_{\mathrm{pp}} \end{bmatrix}$$

where p denotes the retained physical coordinates at boundaries and d denotes the modal coordinates. In the study the damping is expressed with the loss factor η in the complex stiffness that is defined as $\bar{K} = (1+\eta j)K$. The displacement transmissibility is from the bottom to the top of the PAF.

It is known from the parametric study that by the damping treatment, with a hard ride, the displacement transmissibility can only be reduced at the natural frequencies of the structure. It can be seen from Figs. 3 and 4 that a loss factor 0.5 can significantly reduce the transmissibility close to one. In addition to the decrease of the transmissibility, an important contribution of the damping treatment is an increase in the damping level of the whole PAF-satellite structure. This can attenuate the satellite structure vibration at its resonance frequencies. However, a penalty of increasing the damping level is an increase in the mass of the PAF. With a constraint on the mass increase, the damping increase should be limited in a given range.

In this application the vertical and the horizontal transmissibility were used to evaluate the performance of the WSVI. Figure 3 is the vertical transmissibility that is defined as

$$T_V = \left|\frac{D_V}{D_{\mathrm{base-V}}}\right| \tag{4}$$

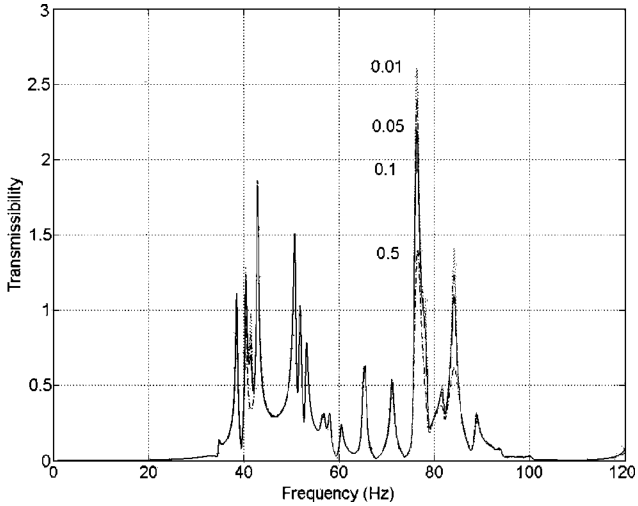

Fig. 4 Influence of the damping on the transmissibility in the horizontal direction.

where D_V is the displacement on the top of the PAF in the vertical direction and $D_{\text{base}-\text{V}}$ is the displacement at the bottom of the PAF in the vertical direction. The definition of the horizontal transmissibility shown in Fig. 4 is

$$T_V = \left|\frac{D_H}{D_{\text{base}-\text{V}}}\right| \tag{5}$$

where D_H is the displacement on the top of the PAF in the horizontal direction.

When the loss factor is about 0.1, the dynamic environment of the new launch vehicle is better than that of the old type, and the satellite is qualified for being launched. Together with some other factors such as launch cost and technical feasibility, the loss factor was finally chosen as 0.1. By this damping treatment the satellite was qualified to be launched with the new launch vehicle.

Conclusions

The WSVI is a direct and effective approach toward the improvement of the dynamic environment that a launch vehicle can provide to its payload. Although effect of adding damping to the PAF for generating a hard ride is not as good as other methods, it is cheap and fast, especially when there is strict constraint on the spacecraft room inside the fairing.

Coupling analysis is essential in designing the WSVI, especially when the damping is involved. In the primary design for choosing the overall stiffness and damping of the isolation the study can be carried out with a simplified model, as shown in Fig. 1.

The soft ride can significantly decrease the transmissibility. Although in the case of soft ride, the damping of the isolator will increase the transmissibility, because of the coupling effect damping can have an important contribution to the vibration isolation. Moreover, damping is essential to the isolation of shocks. With a hard ride the damping can effectively reduce the vibration amplitude of the isolated structure at resonance frequencies.

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Optimal Design of the Optical Pickup Suspension Plates Using Topology Optimization

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I. Introduction

IN this work we deal with the design optimization of the suspension plates of a high-speed optical pickup used in DVDs or CD-ROMs. Figure 1 shows a typical pickup assembly with the bobbin and the suspension plates. The four suspension plates are made identical to minimize unwanted motions. The structural design issues and related references on this subject can be found in Kim et al.[1] and Kim and Lee.[2] The specific design target here is to increase the torsional eigenfrequency of the pickup as high as possible while keeping the focusing eigenfrequency between 25 and 35 Hz and the tracking eigenfrequency between 43 and 57 Hz. These frequency ranges are set to meet design constraints such as servocontrollability. To find an optimal plate shape, we employ the topology optimization methodology.[3,4] Specifically, the multiscale topology optimization method[5] will be used to enhance the solution efficiency.

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