Research on Optimization Design of Local Damping Vibration Reduction

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Abstract. Damping technology is widely used in navigation and aerospace. It is an important research how to achieve weight reduction and efficiency enhancement with damping layer. Reasonable local damping design is an effective method. Based on modal analysis, Ansys software is used as the simulation platform to design a local damping laying based on modal vibration mode. In order to verify the designed performance of local damping weight reduction, a beam with fixed support at both ends was analyzed, and the damping design of local damping and global damping was carried out. The simulation results show that the designed local damping can achieve good damping effect under the condition of reducing the weight of the damping layer, and it has reference value for engineering applications.

1. Introduction
Damping material is the most commonly used technique in modern vibration and noise reduction engineering, including free damping structure and constrained damping structure. Free damping is applied directly to the surface of the vibrating body, while constrained damping is after coating the damping layer, and then attached a layer of metal structure to control the deformation of the free surface. However, the two principles are the same, that is, when subjected to strain; the damping structure consumes vibration energy by bending deformation or shear deformation. Damping materials are the most commonly used viscoelastic materials, which have been studied by a large number of scholars [1-6].

In order to achieve the best vibration damping performance, it is often chosen to dampen the entire vibrating body. However, in engineering applications, especially aerospace equipment, there are strict limits on the weight of the structure. Therefore, the weight of the damping layer must be strictly limited. In this paper, a local damping design method is proposed. In the different damping coating stages, the maximum deformation of modes in different states are analyzed. The damping performance of undamped beam, fully constrained damped beam and local constrained damping are compared and analyzed.

2. Constitutive Equation of Damping Structure
The free damping structure is to directly adhere a layer of material with large damping to the machine parts or structural parts that need to be subjected to vibration and noise reduction treatment. This additional material is called free damping layer, and the structural part is called basic elastic layer. When the structure vibrates, the damping layer vibrates with the structural member, the damping material undergoes alternating tensile and compressive stresses and strains, and the strain lags behind the stress, so that the vibration energy of the structure is lost, then the purpose of vibration reduction is achieved. The longitudinal section of the free-damping composite structure is shown in Figure 1(a).
The constrained damping structure is to stick a layer of damping material on the basic elastic layer, and then firmly adhere a layer of elastic material on the upper part of the damping layer, which is called a constraining layer, and its longitudinal section is as shown in Fig. 1(b). When the basic elastic layer is subjected to bending vibration to elongate the damping layer, the elongation of the constraining layer is much smaller than the elongation of the damping layer. Conversely, when the damping layer is compressed, the constraining layer in turn prevents the damping layer from compressing, so that the covered elastic layer becomes the constraining layer. Since the elongation and compression of the damping layer are hindered by the constraining layer, the upper and lower surfaces of the damping layer respectively generate different deformations of compression and stretching, so that the damping layer is subjected to shear stress and strain, thereby the vibration energy of the structure is dissipated.

The constraining layer, the viscoelastic layer and the elastic layer are denoted by Nos. 1, 2, and 3 respectively, and their thicknesses are $h_i$ ($i = 1, 2, 3$), they are represented by $c$, $v$, and $s$ respectively.

2.1. Elastic Layer Constitutive Relation ($-\frac{h_1}{2} \leq z \leq \frac{h_2}{2}$)

A point is take in the elastic layer, the displacement $z$ is the point from the elastic layer, the initial displacement of the surface in the elastic layer is $u$ and $v$, and the phase shift is $W$. According to the thin shell theory, the point is in the $x$ and $y$ directions respectively. The positive strain is:

$$
\varepsilon_{xx} = \frac{\partial u}{\partial x} - z \frac{\partial^2 W}{\partial x^2}, \quad \varepsilon_{yy} = \frac{\partial v}{\partial y} - z \frac{\partial^2 W}{\partial y^2}
$$

(1)

The shear strain at this point is:

$$
\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} - 2z \frac{\partial^2 W}{\partial x \partial y}
$$

(2)

2.2. Constraint Layer Constitutive Relation ($\frac{h_2}{2} + h_3 \leq z \leq \frac{h_1}{2} + h_2 + h_3$)

A point is take in the elastic layer, the displacement $z$ is the point from the elastic layer, the initial displacement of the surface in the elastic layer is $u$ and $v$, and the phase shift is $W$. According to the thin shell theory, the point is in the $x$ and $y$ directions respectively. The positive strain is:

$$
\varepsilon_{xx} = \frac{\partial u}{\partial x} - z \frac{\partial^2 W}{\partial x^2} + h_2 \frac{\partial \alpha}{\partial x}, \quad \varepsilon_{yy} = \frac{\partial v}{\partial y} - z \frac{\partial^2 W}{\partial y^2} + h_2 \frac{\partial \beta}{\partial y}
$$

(3)

The shear strain at this point is:
\[
\gamma_{cxy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} - 2z \frac{\partial^2 W}{\partial x \partial y} + h_1 \frac{\partial \alpha}{\partial x} + h_2 \frac{\partial \beta}{\partial y}
\]

(4)

2.3. Constraint Layer Constitutive Relation \(\frac{h_1}{2} \leq z \leq \frac{h_1}{2} + h_2\)

A point is taken in the elastic layer, the displacement \(z\) is the point from the elastic layer, the initial displacement of the surface in the elastic layer is \(u\) and \(v\), and the phase shift is \(W\). According to the thin shell theory, the point is in the \(x\) and \(y\) directions respectively. The positive strain is:

\[
\varepsilon_{xx} = \frac{\partial u}{\partial x} - z \frac{\partial^2 W}{\partial x^2} + (z - h_1 / 2) \frac{\partial \alpha}{\partial x}, \quad \varepsilon_{yy} = \frac{\partial v}{\partial y} - z \frac{\partial^2 W}{\partial y^2} + (z - h_1 / 2) \frac{\partial \beta}{\partial y}
\]

(5)

The shear strain at this point is:

\[
\gamma_{cxy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} - 2z \frac{\partial^2 W}{\partial x \partial y} + (z - h_1 / 2) \frac{\partial \alpha}{\partial x} + (z - h_1 / 2) \frac{\partial \beta}{\partial y}
\]

(6)

3. Local Damping Design Method

In practical applications, the vibration of the structure will be required to be controlled within a certain range, but it does not mean that the damping material must be completely coated on the structural surface. If the largest part of the strain of the structural member can be found, the local application of the damping material at this location may also cause the vibration of the structural member to meet the index requirements. Which parts of the structural member are subjected to damping treatment is the core of the local damping design. The basic design process is as follows:

- Determine the design goal of the vibration reduction and give the target value of the vibration reduction effect;
- Through the modal analysis, find the first-order modal deformation, analyze the position of the maximum deformation;
- Appropriate damping materials and constraining layer materials is selected, and local damping parameters such as thickness and length is set initially;
- Perform modal analysis on the construction with first-order local damping, the first-order modal deformation is obtained again, the maximum deformation position is analyzed;
- The vibration damping effect is analyzed;
- If the damping effect has basically reached the target, the first-order modal deformation is analyzed again to study the application of the local damping material;
- The vibration reduction effect is analyzed again;
- If the design goal is reached, the design is completed;
- If the design goal is not reached, return to step (2) and adjust the damping parameters.

The flow chart of the local damping design program is shown in Figure 2.
Start

find the first-order modal deformation, analyze the position of the maximum deformation

Appropriate damping materials and constraining layer materials is selected, and local damping parameters such as thickness and length is set initially

Perform modal analysis on the construction with first-order local damping, the first-order modal deformation is obtained again, the maximum deformation position is analyzed

The vibration damping effect is analyzed

The vibration damping effect is analyzed

No

Yes

Finish

Figure 2. The local damping optimization program flow chart

4. Beam FEM Example
In order to verify the optimized design method of the previous section, a local constrained damping design is applied to a beam. Firstly, it was analyzed by ANSYS software. The beam was installed with fixed support at both ends. The beam length was 5 meters, width was 0.05 meters, and thickness was 0.005 meters. The beam is stainless steel. The modal frequencies of the first few stages and the corresponding vibration modes are shown in Fig. 3.

(a) First-order vibration mode  (b) Second-order vibration mode
(c) Third-order vibration mode  (d) Fourth-order vibration mode
(e) Fifth-order vibration mode  (f) Sixth-order vibration mode

Figure 3. Modal analysis of fixed beam at both ends.
At different modal frequencies, the maximum response of structural vibration is in different places. Now the damping design of the beam is carried out separately. The following schemes are available:

4.1. Global Constrained Damping Design
A layer of damping material is applied to the entire beam, and then the aluminum alloy beam is used to restrain the damping material above the damping material, so that the freely damped material layer becomes the constrained damping layer. When the structural layer is subjected to bending vibration and the damping layer is compressed or elongated, the deformation of the constraining layer is much smaller than the deformation of the damping layer, so that shear strain and shear stress are generated inside the damping layer, as shown in figure 4.

![Figure 4. Constrained Damping Beam](image)

4.2. Locally Constrained Damping Design
It can be seen from the modal analysis that the violent regions of the modal deformation are distributed at different positions at different modal frequencies. The damping energy is caused by the deformation of the structure. In the place where the structural deformation is relatively small, even if the constrained damping layer is applied, it will not have much effect. If the local damping is performed in a region with a large deformation, it is possible to obtain a better damping effect under the premise of increasing the weight. The local damping layer should cover the area with large vibration mode as much as possible, as shown in Figure 5.

![Figure 5. Local Constraint Damping](image)

The harmonic response analysis is carried out on the beam, the local constrained damping beam and all the constrained damping beams. A force load is applied at the central point of the beam. The
frequency range is 0~200Hz. The frequency response curve of displacement and velocity at the central point of the above three beams are Calculated. The results are as shown in Figure 6 and 7.

**Figure 6.** Comparison of the central point amplitudes of the three beams

![Figure 6](image1.png)

**Figure 7.** Comparison of central point velocity of three beams

![Figure 7](image2.png)

5. Conclusion
In this paper, Ansys software is used as the simulation platform. Based on the results of modal analysis, the constrained damping layer is laid on the region with large mode deformation to reduce the additional weight. It can be seen from the numerical simulation results that the local damping can greatly reduce the area of the conventional global damping layer and excellent performance of vibration reduction effect when the weight of the constrained damping layer is reduced by 80%. This method has a good significance for the design of structural vibration control.

References
[1] Soroka W W. Note on the relations between viscous and structural damping coefficients [J]. Journal of the Aeronautical Sciences, 2012, 16(7): 30-45.
[2] V Pradeep, N. Ganesan. Vibration behavior of ACLD treated beams under thermal environment [J]. Journal of Sound and Vibration, 2006, 292(3-5): 1036-1045.
[3] Mohammadi F, Sedaghati R. Linear and nonlinear vibration analysis of sandwich cylindrical shell with constrained viscoelastic core layer [J]. International Journal of Mechanical Sciences, 2012, 54(1): 156-171.
[4] Zheng C, Cai G, Pau S H, et al. Minimizing vibration response of cylindrical shells through layout optimization of passive constrained layer damping treatments [J]. Journal of Sound and Vibration, 2005, 279(3-5): 739-756.

[5] Lepoittevin G, Kress G. Optimization of segmented constrained layer damping with mathematical programming using strain energy analysis and modal data [J]. Materials and Design, 2010, 31(1): 14-24.

[6] Ninoslav Truhar. An efficient algorithm for damper optimization for linear vibrating systems using Lyapunov equation [J]. Journal of Computational and Applied Mathematics, 2004, 172: 169-182.