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Reduction of dynamic response of a bar using constrained layer damping composite structure

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Abstract. The bar structure has been widely used in products and equipment. The tool holders of cutting machines and the support bars in processing are prone to vibration under the unstable excitation. Firstly, a universal and general-purpose constrained layer damping composite bar is proposed to reduce dynamic response for the bar structure. The composite bar can reduce vibration through adding the damping ratio and compensates stiffness. The constrained layer damping structure of the composite bar are consisted of constrained layer, damping layer and substrate. Secondly, the modal characteristics of the composite bar are analysed. According to the modal characteristics calculation and the optimization principles of reduction vibration, the geometric parameters of the composite bar are determined. And 42CrMo steel, four viscoelastic materials and the hard metal are chosen as the materials of substrate, damping layer and constrained layer, respectively. Finally, the modal tests for the composite bars with various materials are performed. The constrained layer damping composite structure is optimized by the test result. The optimal constrained layer damping composite bar can increase the damping ratio by 400% and can reduce the vibration obviously.

1. Introduction

The quality of the product is related to the stability during production and manufacturing. The dynamic characteristics of the supporting system affect the acquisition of test data during the test simulation. Tool holders in machining and stings in the wind tunnel are the typical bar structure. The bars with large length-diameter ratio and the long overhang are prone to vibration under the unstable excitations.

Both passive damping and active damping methods have been applied to reduce the dynamic response for the bar structure [1, 2]. A passive damping method will be introduced to reduce the structural vibration and dynamic response of the bar in this paper. The constrained layer damping composite bar is a typical passive damping structure which offers an easier and cheaper approach to solve the problem of structural detrimental vibrations [3].

The composite damping structures have been attracted more attentions in recent years, where the vibration energy can be converted to heat. And the free layer damping structure or the constrained layer damping structure are chosen as the composite structure generally [4, 5].

In this paper, the composite bar combines the damping advantages of metal and viscoelastic materials. The calculation and manufacturing of the three layers composite bar are put forward and improved. The constrained layer damping structure consists of three layers, where the damping layer is



in the middle of the constrained layer and the substrate. The constrained layer can restrict the deformation of the damping layer, which leads to decrease its shear deformation. The damping layer increases the damping ratio of the structure, and the structure stiffness is compensated by the constrained layer.

2. Modal characteristics calculation

The typical and universal structure of the constrained layer damping composite bar was designed by referencing the structure of the tool holder and the sting of the wind tunnel as shown in figure 1. D_1 , D_2 and D_3 are the external diameters of the substrate, damping layer and constrained layer, respectively. L is the suspension length of the composite bar. When the geometrical shape of the composite bar was designed, there was a 0.2mm gap between the layers for splicing. The gap of splice was counted as the thickness of damping layer in modal dynamic analysis.

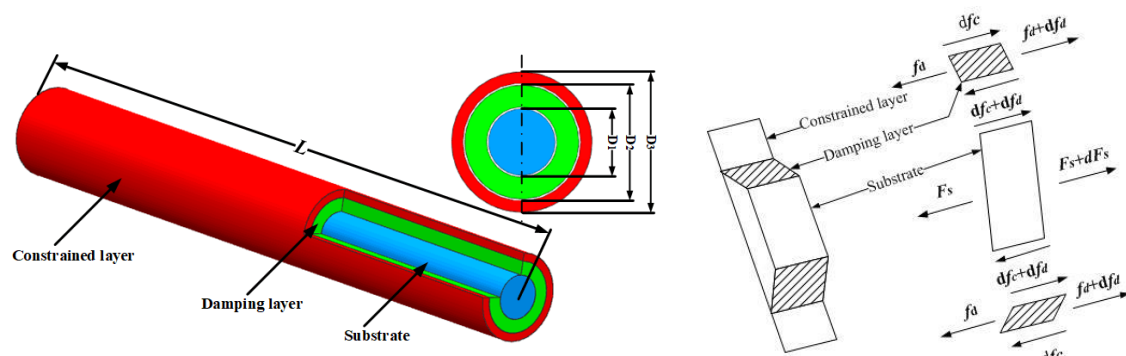


Figure 1. Design of the composite bar and stress as well as deformation for differential elements.

The structure vibration is usually caused by an unstable exciter. The vibration is propagated through the substrate to the damping layer and induces the deformation of structure. Due to the low modulus of damping material, both tension and compression deformation of the damping layer are excited, which are suppressed by the constraining layer. The shear deformation is also produced in the damping layer and its vibration energy is mainly dissipated into heat. The analysis of stress and deformation for differential elements was shown in figure 1.

The viscoelastic materials can absorb the vibration energy and decrease the vibration amplitude. Three viscoelastic materials were selected as the materials of the damping layer including the polyurethane, nitrile rubber and butyl rubber [6]. The temperature influence to the viscoelastic material was ignored assumed that the bar working temperature remains unchanged.

Other assumptions were made to analyze the modal characteristics for the bar structure [7-10].

- 1) The bending deformations of the substrate, the damping layer and the constrained layer are consistent in the bar radial direction.
- 2) The substrate, the damping layer and the constrained layer have been spliced firmly and uniformly without relative sliding.
- 3) The material of the damping layer is uniform and isotropic.
- 4) Only the influence of radial force is considered.

According to the material mechanics theory, the static stiffness of the constrained layer damping composite bar is directly proportional to the bending rigidity of the material. It is related to the elastic modulus of the material and the cross section shape of the bar. The static stiffness k can be expressed as by Eq. (1).

$$k = \frac{3(EI)_w}{L^3} \quad (1)$$

where, $(EI)_w$ is the equivalent bending stiffness of the bar hanging section. E is elastic modulus of material. I is the moment of inertia of cross section to curved neutral axis. The equivalent bending stiffness of the bar hanging section can be calculated by Eq. (2).

$$(EI)_w = (EI)_1 + (EI)_2 + (EI)_3 \quad (2)$$

where, $(EI)_1$, $(EI)_2$, $(EI)_3$ are the bending stiffness of the substrate, damping layer and constrained layer, respectively.

The static stiffness of the constrained layer damping composite bar is obtained by the substitution Eq (2) into Eq (1).

$$k = \frac{3\pi[D_1^4 E_1 + (D_2^4 - D_1^4)E_2 + (D_3^4 - D_2^4)E_3]}{64L^3} \quad (3)$$

When the bar is bending, the section of the substrate and the constrained layer is subjected to bending moment and shear force. For the metal elastic layer, the effect of the shear strain can be ignored. Only the bending energy is calculated. The stiffness parameters of the substrate and the constrained layer related to the bending energy dissipation is represented Y as given in Eq. (4).

$$\frac{1}{Y} = \frac{(B_1 + B_3)}{D_3^2} \frac{1}{(EI)_1} + \frac{1}{(EI)_3} \quad (4)$$

$$\text{here, } B_n = \frac{(\frac{D_n - D_{n-1}}{2})^2}{12} (EI)_n \quad (n = 1, 2, 3).$$

In the damping layer, the vibration energy is mainly dissipated by shearing strain and shear stress, ignoring the bending energy dissipation. The shear parameter X of the damping layer related to shear energy dissipation is represented as in Eq. (5).

$$X = \frac{G_2 L}{P^2 (\frac{D_2 - D_1}{2})} \left[\frac{1}{(EI)_1} + \frac{1}{(EI)_3} \right] \quad (5)$$

here, G_2 represents shear modulus of material of damping layer.

$$P^2 = \omega_0 \sqrt{\frac{m}{L(B_1 + B_2 + B_3)}}$$

According to the shear damping theory, the structure damping ratio of the constrained layer damping composite bar η is represented as in Eq. (6).

$$\eta = \frac{\beta XY}{1 + (2 + Y)X + (1 + \beta^2)(1 + Y)X^2} \quad (6)$$

where, β is loss factor of viscoelastic material of damping layer.

The material loss factor for metal elastic material can be ignored in the material optimization process, because it is far lower than that of the damping layer material. The loss factor for viscoelastic material of damping layer was measured by the DMA tester. According to the test results, the material loss factor tended to be stable at the high frequency section and could be considered as a constant when the frequency was over 1500Hz.

According to the Eqs. (3) and (6), the static stiffness and damping ratio of the constrained layer damping composite bar are influenced by the structure geometric parameters and the mechanical properties of the materials. The structure geometric parameters can be determined by the calculation with different D_1 , D_2 , D_3 and L . The mechanical properties of the materials mainly include the density, modulus of elasticity, and loss factor of materials, which can be optimized by comparing modal test results of the various composite bars with those for different mechanical properties of materials.

3. Geometric parameter optimization and composite bar manufacturing

According the analysis in the previous section, considering the generality and the difficulty of manufacturing for the composite bar, a constrained layer damping composite bar with length-diameter ratio 8.75 and a suspension length 280mm was designed and manufactured, as shown in figure 2.



Figure 2. Geometry of the constrained layer damping composite bar.

In order to ensure that the viscoelastic materials and metals were spliced firmly and the adhesive was applied evenly, the epoxy resin adhesive was selected. The epoxy resin AB adhesive with the viscosity 5000~8500cps was chosen. Proper viscosity ensured the good liquidity of the adhesive. And the adhesive dispensing machine was used to ensure that the splicing process was reliable and uniform. When the constrained layer damping composite bar was being spliced, the temperature was controlled at 25 °C. This temperature ensured that the adhesive could flow into the parts fully. When the constrained layer damping composite bar has been spliced, the temperature rose to 50 °C. This method made the adhesive cured quickly and ensured the structure spliced firmly as well as the adhesive injected uniformly.

4. Composite bar modal testing and materials selection

The damping property of the constrained layer damping composite bar can be enhanced by the viscoelastic material which has large material loss factor and small elastic modulus. The static stiffness of the constrained layer damping composite bar is increased by the constrained layer with high elastic modulus material. The composite bar can bear a larger load and the damping property of the composite bar is improved.

Considering the material properties, butyl rubber, polyurethane and nitrile rubber were selected as the damping layer materials. The 42CrMo steel was selected as the substrate material. The 42CrMo steel and hard metal were chosen as the materials of the constrained layer [11]. The constrained layer damping composite bars were made by the splicing process in the last section and used for the test. They were listed in table 1 and shown in figure 3.

The modal tests were carried out for composite bar modal characteristics measurement and materials selection. The constraint mode for modal test was adopted an unconstrained free vibration form. The composite bar was freely hanged by a rubber string and was placed horizontally. The three acceleration sensors were placed in the middle and both ends of the composite bar, respectively. The vibration exciter was placed in the middle of the composite bar and at the same height of the composite bar, and provided the impulse excitation. The modal test setup was shown in figure 3.

Table 1. Constrained layer damping composite bars and their materials.

Bars	Substrate	Damping layer	Constrained layer
C-B-C	42CrMo steel	Butyl rubber	42CrMo steel
C-P-C	42CrMo steel	polyurethane	42CrMo steel
C-N-C	42CrMo steel	nitrile rubber	42CrMo steel
C-P-H	42CrMo steel	polyurethane	Hard metal

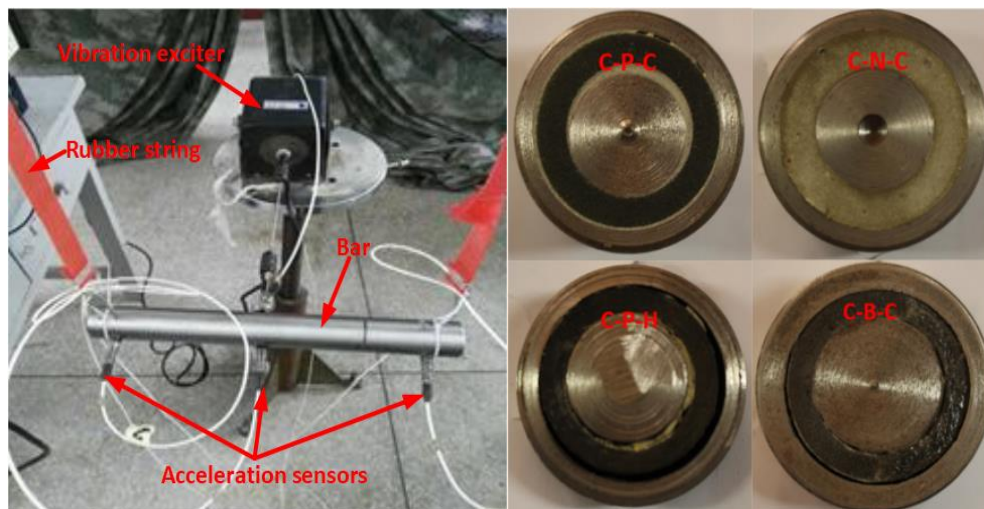


Figure 3. Modal test setup and constrained layer damping composite bars.

Using the LMS test system, the vibration signal was analyzed by the signal analyzer and the test results and the damping ratios were output. Firstly, the tests of the C (a bar without constrained layer damping composite structure), C-B-C, C-P-C and C-N-C bars were tested to compare the performance of different viscoelastic materials of the damping layer. Their frequency response curves were shown in figure 4 and the modal characteristics were collected in table 2.

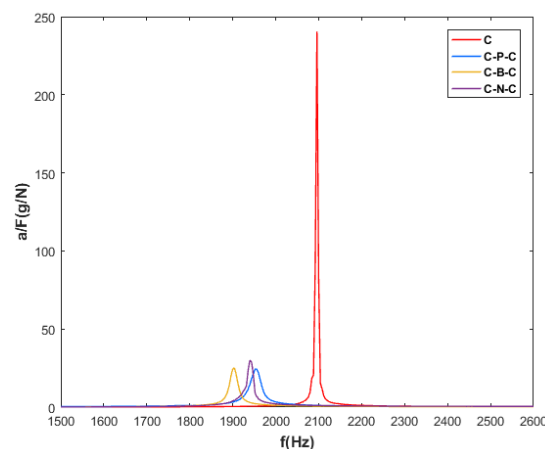


Figure 4. Frequency response curves of the four bars.

Table 2. Modal characteristics of the four bars.

Bars	Damping ratio (%)		First order natural frequency (Hz)	Static stiffness(MN/m)	
	Analytical	Experimental		Analytical	Experimental
C		0.15	2096	5.2	
C-B-C	0.45	0.42	1904	3.0	3.3
C-P-C	0.47	0.43	1956	3.1	3.6
C-N-C	0.41	0.36	1940	3.4	3.8

From figure 4 and table 2, the constrained layer damping composite bars shown better damping effect compared with that for C bar. The experimental results agreed well to the analytical results. Under the same excitation conditions, the amplitude of the composite bars decreased greatly by nearly

7 times compared with that for C bar. The damping ratio for the composite bars also increased by several times. The damping ratio of the composite bar with polyurethane as the material of damping layer increased to 2.8 times as much as for C bar. The vibration attenuation time of the composite bars was greatly shortened. The first order natural frequency of the composite bars only had little change compared with that for C bar, but it moved to the negative direction of the X axis, which reduced the dynamic response of the composite bars in the high frequency field. The static stiffness of the composite bars decreased, especially the composite bar with butyl rubber as the material of the damping layer, which declined by 36%. According to the damping ratio and static stiffness of the composite bars, the polyurethane was preferred as the material of the damping layer.

The test of the C-P-C and C-P-H composite bars were tested to improve the static stiffness of the constrained layer damping composite bar. Their frequency response curves were shown in figure 5. The modal characteristics were collected in table 3.

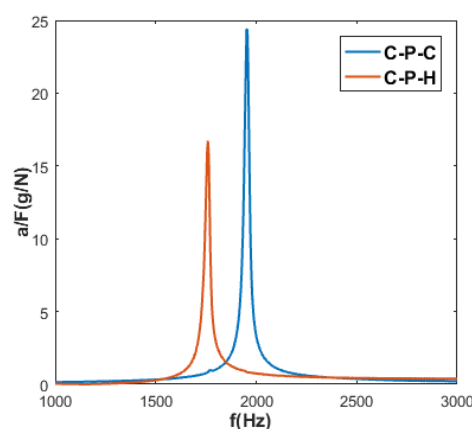


Figure 5. Frequency response curves of the C-P-C and C-P-H composite bars.

Table 3. Modal characteristics of the C-P-C and C-P-H composite bars.

Bars	Damping ratio (%)		First order natural frequency(Hz)	Static stiffness(MN/m)	
	Analytical	Experimental		Analytical	Experimental
C-P-C	0.47	0.43	1956	3.1	3.6
C-P-H	0.76	0.75	1760	4.0	4.6

From figure 5 and table 3, the C-P-H composite bar had a less dynamic response and better damping performance compared with the C-P-C composite bar. The damping ratio was 1.74 times that of C-P-C composite bar and 5 times that of the C bar. The C-P-H composite bar further reduced the amplitude and the vibration in the high frequency section. And the static stiffness of the C-P-H composite bar was 1.3 times that of C-P-C composite bar and only lost 12% compared with the C bar. The hard metal improved the damping performance and compensated the static stiffness of the composite bar.

5. Conclusions

A universal constrained layer damping composite bar was designed and developed. The static stiffness and damping ratio of the composite bar were analyzed. The geometric parameters of the composite bar was optimized and length-diameter ratio of 8.75 was determined. The splicing process of the composite bars was determined. The material optimization of the constrained and damping layers was carried out by the modal test. The experimental results corresponded to the analytical results and the C-P-H composite bar had more excellent damping performance and a less dynamic response. The polyurethane as a viscoelastic material of the damping layer improved the damping property, and the

hard metal as a high stiffness material of the constrained layer increased the damping property and compensated the static stiffness. Compared with the bar without the constrained layer damping structure, the damping ratio of the C-P-H composite bar was increased by 400% and the static stiffness was lost 12%.

Acknowledgments

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References

- [1] Jang J L, and Tarng Y S 1999 A study of the active vibration control of a cutting tool *J Mater Process Tech* **95**(1) 78-82
- [2] Munoa J, Beudaert X, Dombovari Z, Altintas Y, Budak E, Brecher C and Stepan G 2016 Chatter suppression techniques in metal cutting *Cirp Ann-manuf Techn* **65**(2) 785-808.
- [3] Song Q, Shi J, Liu Z, Wan Y and Xia F 2016 Boring bar with constrained layer damper for improving process stability *The International Journal of Advanced Manufacturing Technology* **83**(9-12) 1951-1966
- [4] Yi S, Ahmad M F and Hilton H H 1996 Dynamic responses of plates with viscoelastic free layer damping treatment *J Vib Acoust* **118**(3) 362-367
- [5] Yim J H, Cho S Y, Seo Y J and Jang B Z 2003 A study on material damping of 0 laminated composite sandwich cantilever beams with a viscoelastic layer *Composite Structures* **60**(4) 367-374
- [6] Hsu S, Mor M, Stirling B and Glaese R 2010 Reduction of Dynamic Response of a Wind Tunnel Sting Mount Using Co-cured Composite and Viscoelastic Materials *InProceedings of the 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, AIAA* **1308** 1-8
- [7] Liu Y, Liu Z, Song Q and Wang B 2016 Development of constrained layer damping toolholder to improve chatter stability in end milling *Int J Mech Sci* **117** 299-308
- [8] Zhang S H and Chen H L 2006 A study on the damping characteristics of laminated composites with integral viscoelastic layers *Composite Structures* **74**(1) 63-69
- [9] Cupiał P and Nizioł J 1995 Vibration and damping analysis of a three-layered composite plate with a viscoelastic mid-layer *J Sound Vib* **183**(1) 99-114
- [10] Granger D and Ross A 2009 Effects of partial constrained viscoelastic layer damping parameters on the initial transient response of impacted cantilever beams: Experimental and numerical results *J Sound Vib* **321**(1) 45-64
- [11] Ćurčić D, Samardžić M, Marinkovski D, Rajić Z and Anastasijević Z 2016 Model sting support with hard metal core for measurement in the blowdown pressurized wind tunnel *Measurement* **79** 130-136