Effect of Damping Parameters on Vibration Response of Cantilever Plate with Viscoelastic Constrained Layer Damping Treatment

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Abstract: Viscoelastic constrained layer damping (CLD) treatment can effectively improve system damping, which is an important means of suppressing structure vibration and noise in modern industrial area. In this paper, The effects of CLD material and damping parameters on vibration response of cantilever plate treated with viscoelastic constrained layer damping are investigated. Using complex modulus model to represent the constitutive law of viscoelastic material, the finite element model of CLD treated plate is established and the effectiveness of the calculating model was verified by tests. Furthermore, The vibration response of cantilever plate with viscoelastic constrained layer damping treatment is conducted by the finite element method (FEM) and tests and the effect of CLD material on vibration response has been analyzed under different load conditions. Subsequently, FEM is adopted to analyze the contributions of thickness and modulus of CLD material on resonance frequency and model loss factor. The results indicated that CLD material can control the resonance frequency and minimize the peak value of the composite structure effectively, in addition, various of the layer thickness and modulus are the main effecting factors in this study.

Keywords: Cantilever Plate; Viscoelastic Constrained Layer Damping; Vibration Response Analysis; Damping Parameters

1 Introduction

Thin-walled structures are widely used in the aerospace, aeronautical and automotive industries for their high strength and stiffness-to-mass ratio. These environments are often vibration rich, which can make fatigue problematic and adversely affect passenger comfort. A common mitigation technique is to damp vibrations via methods such as constrained layer damping (CLD) treatment, which consist of a thin layer of viscoelastic material adhered to the vibrating structure and a constraining stiff layer on its surface. Viscoelastic damping material is one of the most widely used polymer materials, which has both elastic and viscous properties.

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When subjecting to external force, the polymer will be stretching, bending or shear deformation inside, the mechanical energy acting on the polymer elastic component can be stored as potential energy, when the external force is removed, the deformation will be restored. This process releases external force and thereby working, reflecting the elasticity of viscoelastic damping material. However, the mechanical energy acting on the viscous component cannot return to the outside, which is converted into heat energy or dissipated, and the deformation cannot be restored.

For the analysis of vibration of plate, domestic and foreign scholars have done a lot of research. Rayleigh-Ritz method is one of the methods to solve the cantilever plate structure,which proposed by Leissa[1], Using superposition method, Gorman[2] accurately solved the free vibration problem of anisotropic cantilever plate. In recent years, thin plate vibration theory is adopted to analyze the control equations established by some scholars[3,4] for the cantilever plate model. Rossi et al.[5] solved the vibration problem of rectangular plate by finite element method, XU[6] established the expression of vibration curve while deduced the frequency equation and the corresponding vibration curve of the rectangular cantilever plate. Zhong et al [11] presented a theoretial solution for the elastic cantilever rectangular thin plate derived by symplectic geometry method.

In last decades, many investigations on viscoelastic damping structure have been carried out. Yim et al.[8] analyzed the dynamic response of viscoelastic beams, Yang et al.[9] investigated the vibration characteristic and dynamic stability of traveling sandwich beam using the finite element method. Cortés and Elejabarrieta[10] analyzed the vibration of beam, unconstrained damped beam and beam structure with constrained damping layer. Shariyat[11-13] expended the FE model to perform the dynamic buckling analysis using a double-superposition global–local theory for the sandwich/multilayer plates. Kumar and Singh[14] investigated the vibration and damping characteristics of curved panel treated with constrained viscoelastic layer. Manconi[15] imported a spectral finite element method (SFEM) to analyze the elastic guided waves in composite viscoelastic plates. Taupin[16] investigated the dispersion and damping characteristics of viscoelastic laminate plates via a wave finite element method. The dynamic control equation for a rotating laminated circular plate was derived by Li et al.[17] adopting Hamilton principle. Based on the classical zig-zag theory, Akoussan et al.[18] presented a numerical mode performed by the asymptotic numerical method and automatic differentiation technique and obtained the damping properties of the material fibers orientation. Araújo [19] established a finite element model to conduct the vibration performances of sandwich laminated plates with a soft core and composite laminated face layers. Huang et al. [20] developed an efficient sandwich modeling technique to deal with the vibration and damping characteristics of the PLCD plate. Khalfi and Ross [21] presented a model to predict the effect the parameter of partial constraining layer damping (PCLD) material on the harmonic response of a rectangular plate. Yang et al. [22] investigated the panel flutter of composite plate with viscoelastic mid-layer in supersonic airflow and discovered the viscoelastic damping of the soft mid-layer presents dual effect.

In this dissertation, the effect of CLD material and damping parameters on vibration response of cantilever plate with CLD material are investigated, Complex

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modulus model is adopted to establish the finite element model of CLD treated plate, and the correctness of the model is verified by calculation and experiment. Subsequently, The resonance frequencies, loss factors, vibration responses of cantilever plate before and after pasting CLD material are conducted by the finite element method (FEM) and tests, and the effect of CLD material on vibration response has been analyzed under different load conditions. Finally, the contributions of thickness and modulus of CLD material on resonance frequency and model loss factor are conducted by FEM.

2 Finite element modeling of CLD treated plate

2.1 Constitutive relation of viscoelastic material

The constitutive relation model of viscoelastic damping material is very important. In the present research, there is no unified constitutive relation model, which can accurately characterize the dynamic mechanical properties of viscoelastic damping material and solved easily. Most of constitutive relations of viscoelastic damping materials are mostly based on theoretical, empirical, experimental and numerical simulation.

Dynamic elastic modulus of the viscoelastic material can be expressed in the plural form, therefore, the constitutive relation can be expressed by complex constant modulus model:

$$\sigma = G^{*}\varepsilon = G^{'}(1+i\eta)\varepsilon \tag{1}$$

The complex modulus is defined as:

$$G^{*} = G^{'} + iG^{''} = G^{'}(1+i\eta) \tag{2}$$

Where $G^{'}$ is the real part of complex modulus, called storage modulus, $G^{''}$ is the imaginary part of complex modulus, called loss modulus, $i=\sqrt{-1}$ is the unit of imaginary part, η is the loss factor of the viscoelastic damping material

In present analysis, the loss factor of viscoelastic damping material is defined by

$$\eta = G^{''}/G^{'} \tag{3}$$

In complex modulus model, the frequency dependent characteristic of viscoelastic damping material has not considered and all the quantities are constant, thus, the model is suitable for the situation of small frequency dependent and the dynamic mechanical properties of viscoelastic material can characterized better under harmonic excitation.

2.2 Finite element model of plate with CLD treatment

The cantilever plate shown in Fig. 1 is taken as the object of study. The geometrical parameters and material properties of each layer of CLD treated plate are shown in Table 1.

Using complex modulus model to represent the constitutive law of viscoelastic material, the finite element model of CLD treated plate is established, as shown in Fig. 2

and the finite element analysis of the cantilever plate with the viscoelastic constrained layer damping is carried out.

Table 1. Material and geometrical parameters of the CLD treated plate

Structure layer	Length (m)	Width (m)	Thickness (mm)	Modulus (Pa)	Density (kg/m^3)	Poisson's ratio
Matrix layer	0.133	0.11	1.35	1.138×10^{11}	4420	0.31
Damping layer	0.133	0.11	0.05	1.2×10^{7}	1200	0.495
Constrained layer	0.133	0.11	0.13	7×10^{10}	2700	0.3

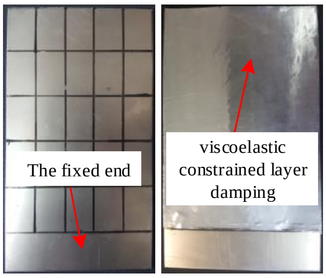

Fig. 1. The cantilever plate

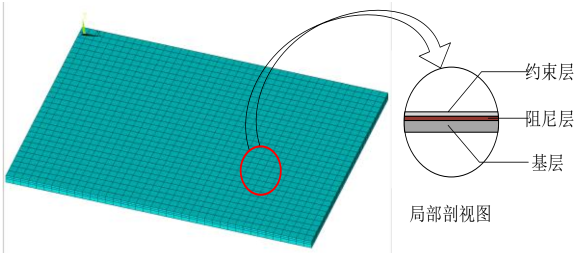

Fig. 2. FE model of CLD treated plate

2.3 Simulation model validation

In order to confirm the accuracy of the calculated model, the natural frequencies of the cantilever plate before and after pasting the CLD material are calculated by FEM and tests. The results are shown in Table 2.

As shown in Table 2, comparing with the results obtained by FEM and tests, the errors of natural frequencies of the plate without CLD treatment, except the 5 and 7 order, are less than 3%; the errors of natural frequencies of the CLD treated plate, except the 1 and 5 order, are less than 3%; It can be considered that the accuracy of the solution was high and the model can be used for subsequent analysis

Table 2. Natural frequencies of plate before and after pasting the CLD material obtained by FEM and tests

Order	Base Plate (Hz)			Plate with CLD Treatment (Hz)		
	FEM	Tests	Error	FEM	Tests	Error
1	64.8	63.5	2.04%	69.2	60.9	13.62%
2	183.8	189	2.75%	194.2	197.6	1.72%
3	401.1	396	1.28%	423.9	422.5	0.60%
4	642.4	658	2.37%	672.6	679.9	1.07%

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5	701.5	764	8.18%	740.6	851.4	13.1%
6	1136.8	1134	0.25%	1183.8	1151	2.85%
7	1249.1	1296	3.62%	1297.2	1266	2.46%
8	1378.2	1399	1.49%	1427.6	1406	1.54%

3 Effect of CLD material on structural vibration response

Vibration response and fatigue life of the structure are related to damping parameters and inherent characteristics of system. Therefore, the characteristic parameters such as natural frequency, damping ratio and vibration amplitude are selected as the indexes to evaluate the damping efficiency of damping materials.

3.1 Vibration response analysis with finite element method

As shown in Fig. 3, finite element method is used to obtain the modal damping ratio of the first to six order of plate before and after pasting the CLD material. It can be seen that the modal damping ratio of the cantilever plate is increased after pasting the CLD material.

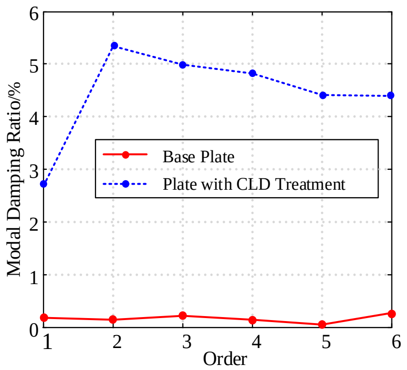

Fig. 3. Damping ratio of the 1 to 6 order of plate before and after pasting CLD material

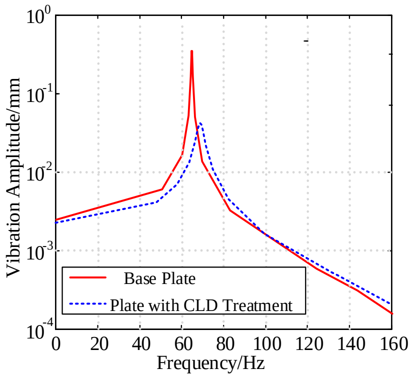

Fig. 4. First order harmonic response curves of plate before and after pasting CLD material

Fig. 4 shows the first order harmonic response curves of the plate before and after pasting CLD material. It can be seen from Fig. 4 that the peak value of harmonic response curve of the plate without viscoelastic constrained layer damping treatment is 0.3485mm, while after pasting the CLD material, the peak value of harmonic response curve is 0.03963mm. The result indicated that the CLD material can significantly improve the damping of the system.

3.2 Vibration response analysis by texts

Using shaking table, The vibration response of the plate before and after pasting the CLD material were carried out by experiments. Table 3 shows the resonance frequencies and response peaks of plate before and after pasting the CLD material obtained by experiments under different exciting forces, As shown in Table 3., the excitation accelerations of shaking table are 1g, 2g, and 3g respectively.

Table 3. Resonance frequencies and response peaks obtained by experiments

Order	Exciting force	Base Plate		Plate with CLD Treatment	
		Frequency	Response peak	Frequency	Response peak
2	1g	182.3 Hz	0.151 g	192.5 Hz	0.077 g
	2g	182.3 Hz	0.336 g	192.5 Hz	0.198 g
	3g	182.3 Hz	0.51 g	192.5 Hz	0.270 g
3	1g	395.7 Hz	12.04 g	427 Hz	4.211 g
	2g	395.7 Hz	20.03 g	427 Hz	7.436 g
	3g	395.7 Hz	35.07 g	427 Hz	11.82 g

Data from table 3 showed that the resonant frequencies of the plate with viscoelastic constrained layer damping treatment were increased and independent of the force of exciting, the second order resonance frequency increased from 182.3Hz to 192.5Hz, up by 5.60%, the third order resonance frequency increased from 395.7Hz to 427Hz, up by 7.91%. Moreover, the response peak of the CLD treated plate was decreased and it is related to the exciting force, the vibration peak of second order changed from 0.336g to 0.198g, down by 41.07%; the vibration peak of the third order decreased from 20.03g to 7.436g, down by 62.87%. The result showed that the vibration response value of the structure is proportional to the magnitude of the exciting force, the response peak of CLD treated plate decreased obviously while the resonant frequency increased a little.

Table 4 shows the fixed-frequency response of plate before and after pasting the CLD material obtained by experiments.

Table 4. fixed-frequency response obtained by experiments

	Base Plate		Plate with CLD Treatment	
	Frequency	Response peak	Frequency	Response peak
First order	63.47 Hz	47.08 g	60.8 Hz	28.86 g
Third order	395.8 Hz	31.62 g	428.1 Hz	9.775 g
Non-resonance frequency	71.64 Hz	3.17 g	71.64 Hz	2.184 g

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It can be seen from Table 4 that the vibration response of the CLD treated plate under resonant frequencies and non-resonant frequency are obviously decreased. In the first order, for example, the resonance response peak decreased from 47.08g to 28.86g, down by 38.70%, which indicated that the viscoelastic constrained layer damping material has obvious damping effect on the structure.

4 Effect of damping parameters on inherent characteristics of CLD treated plate

4.1 Effect of thickness of damping layer on inherent characteristics of CLD treated plate

The natural frequency and the loss factor of the CLD treated plate are calculated under different thickness of damping layer. Wherein the thickness of damping layer is changed from 0.05 mm to 0.5 mm, the remaining parameters are assumed to be constant. The results are shown in Fig. 5.

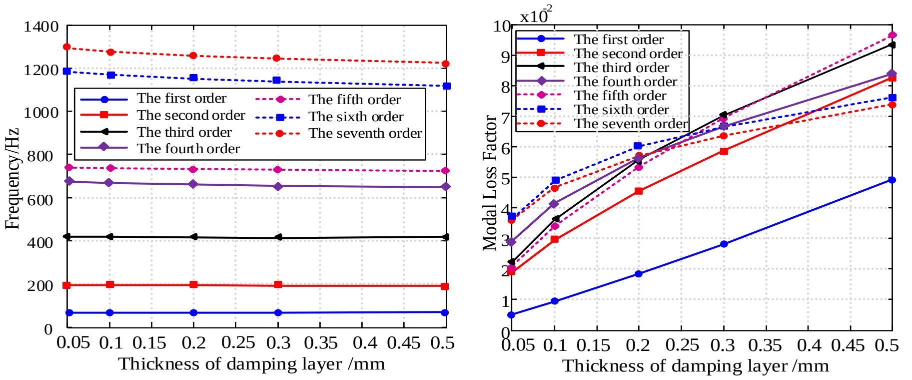

Fig. 5. Effect of thickness of damping layer on natural frequency and loss factor of CLD treated plate

It can be seen from Fig. 5 that with the thickness of damping layer increasing, the natural frequency of CLD treated plate reduced slowly and the loss factor increased quickly up to several times of the original even. The second order natural frequency and loss factor of plate are taken as an example (the red curve), the natural frequency of the CLD treated plate decreased from 193.538 to 192.835, down by 0.36%; the loss factor increased from 0.0294 to 0.0454, up by 54.43%. The results indicated that the thickness of the damping layer can significantly improve the damping of the system, meanwhile, the quality and volume of the system are enlarged, which leads to the decrease of the natural frequency

4.2 Effect of modulus of damping layer on inherent characteristics of CLD treated plate

The natural frequency and the loss factor of the CLD treated plate are calculated under different storage modulus of damping layer. Wherein the modulus of damping layer is changed from 0.01 MPa to 10 MPa, The remaining parameters are assumed to be constant. The results are shown in Fig. 6.

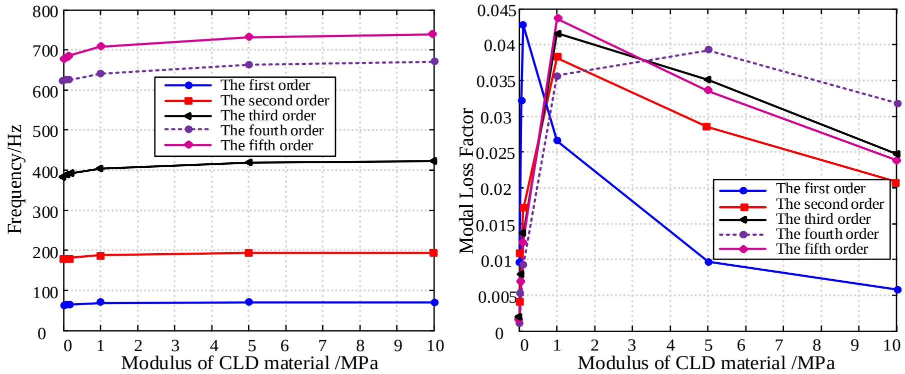

Fig. 6. Effect of modulus of damping layer on natural frequency and loss factor of CLD treated plate

It can be seen from Fig. 6 that with the modulus of damping layer increasing, the loss factor increased to its peak then decreased while the natural frequency increased a little. The results indicated that the modulus of damping layer can significantly improve the loss factor of the CLD treated plate.

4.3 Effect of thickness of constrained layer on inherent characteristics of CLD treated plate

The natural frequency and the loss factor of the CLD treated plate are calculated under different thickness of constrained layer. Wherein the thickness of constrained layer is changed from 0.1 mm to 0.5 mm, the remaining parameters are assumed to be constant. The results are shown in Fig. 7.

It can be seen from Fig. 7 that with the thickness of constrained layer increasing, the natural frequency increased a little while the loss factor is proportional increased

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up to several times of the original even. The second order natural frequency and loss factor of plate are taken as an example (the red curve), the natural frequency of the CLD treated plate increased from 191.747 to 199.609, up by 4.10%; the loss factor increased from 0.01287 to 0.03451, up by 168%. The results indicated that the thickness of the constrained layer can significantly improve the damping of the system.

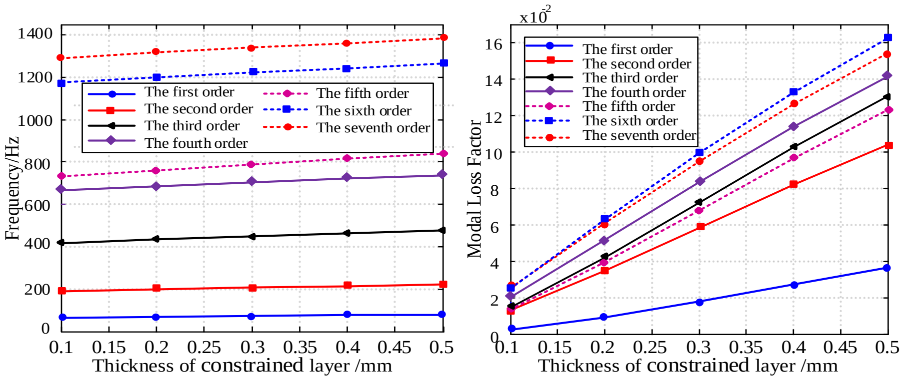

Fig. 7. Effect of thicknesses of constrained layer on natural frequency and loss factor of CLD treated plate

4.4 Effect of modulus of constrained layer on inherent characteristics of CLD treated plate

The natural frequency and the loss factor of the CLD treated plate are calculated under different storage modulus of constrained layer. Wherein the modulus of constrained layer is changed from 30Gpa to 200Gpa, the remaining parameters are assumed to be constant. The results are shown in Fig. 8.

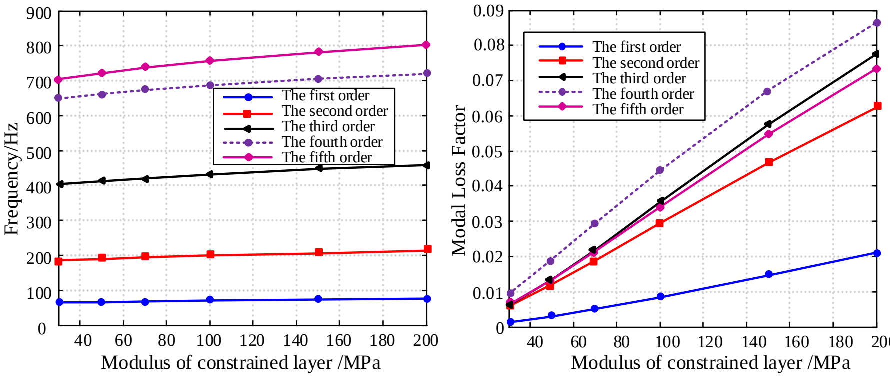

Fig. 8. Effect of modulus of constrained layer on natural frequency and loss factor of CLD treated plate

It can be seen from Fig. 8 that with the modulus of constrained layer increasing, the natural frequency increased a little while the loss factor is proportional increased up to several times of the original even. The second order natural frequency and loss factor of plate are taken as an example (the red curve), the natural frequency of the CLD treated plate increased from 196.161 to 201.324, up by 2.63%; the loss factor increased from 0.0189 to 0.0295, up by 168%. The results indicated that the modulus of the constrained layer can significantly improve the loss factor of the system.

5 Conclusions

In this dissertation, the effect of CLD material and damping parameters on vibration response of cantilever plate treated with viscoelastic constrained layer damping are investigated, it mainly included:

(1) Complex modulus model is adopted to establish the finite element model of CLD treated plate, and the correctness of the model is verified by calculation and experiment.

(2) The vibration responses of cantilever plate before and after pasting CLD material are conducted by the finite element method (FEM) and tests, and the effect of CLD material on vibration response has been analyzed under different load conditions. The result showed that the vibration response of the plate is proportional to the magnitude of the exciting force and the response peak of CLD treated plate decreased obviously while the resonant frequency increased a little.

(3) For the cantilever plate with CLD treatment, with the thickness of damping layer increasing, the natural frequency of the structure reduced a little while the loss factor increased quickly; with the modulus of damping layer increasing, the loss factor increased to its peak then decreased while the natural frequency increased a little; with the thickness or the modulus of constrained layer increasing, the natural frequency increased a little while the loss factor is proportional increased up to several times of the original even.

The results indicated that CLD material can control the resonance frequency and minimise the peak value of the composite structure effectively, moreover, various of the layer thickness and modulus are the main effecting factors of vibration reduction in this study.

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