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Calculation of Composite Loss Factor Based on Iterative MSE Method

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Abstract. Modal strain energy (MSE) method is a widely used approximation approach for parameter calculation of damped composite structures. In this paper, iterative MSE method is proposed to calculate the loss factor of composite damping structure by considering the frequency dependence of modulus and loss factor of viscoelastic damping materials. The proposed method is applied to free damping spline, free damping plate and constrain damping plate. The results show that: the proposed method obtains minimum relative errors of less than 5% and less than 20% for nature frequency and composite loss factor. The influence of different material parameters on the calculation results is also discussed. The error is smaller when using the storage modulus and loss factor measured by tensile mode as input parameter. The thickness of the sample to measure the dynamic material parameters has a great influence on accuracy. This work provides a way for the calculation of composite loss fator of damped composite structures with embedded viscoelastic layer.

Keywords. Composite loss fator, iterative modal strain energy method, viscoelastic damping materials

1. Introduction

Viscoelastic damping materials is being used in a variety of different industries for vibration and noise control such as automobiles, aircraft, and ships [1-3]. The loss factor of the composite structure is a key parameter that determines the effect of vibration and noise reduction, and it has a strong guiding role in the engineering application [4-7]. The loss factor of the composite structure is generally obtained by the bending resonance method. However, the sample preparation and cumbersome testing process is very complicated. In particular, due to the limitation of the sample dimensions, it is difficult to obtain more detailed damping of the composite structure in a wide frequency band. To expand the test frequency, it is necessary to re-prepare test samples of suitable size, which greatly increases the workload of sample preparation and testing. In addition, the applicable range of the loss factor of the composite damping structure is generally 10^{-2}~10^{-1}. When the damping loss factor is out of this range, it is difficult to find the resonance peak on the instrument, so the resonance frequency and mode cannot be determined.

There are two main types of modeling methods for damping structures: analytical method and finite element method [8]. The analytical method can directly consider the

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frequency-dependent characteristics of the damping material and obtain the exact solution of the system. However, due to the complexity of the equation, it is currently mostly used in simple two-dimensional structural models and requires a large amount of calculation. The finite element method usually combines the finite element analysis and the modal strain energy method [9-10]. After modal analysis, we get the strain energy of each part of the structure, then the structural loss factor is obtained after considering the material loss. This method is widely applicable, but the modal strain energy method does not consider the frequency-dependent characteristics of damping materials, so the calculation accuracy is greatly affected. Therefore, how to accurately model the vibration characteristics of the additional damping structure considering the frequency-dependent characteristics of the damping material is the key to the analysis of the vibration characteristics of the additional damping structure.

The iterative MSE method is proposed to solve the above problems. According to the characteristics of the viscoelastic damping material modulus changing with frequency, the loss factor of the composite structures at each resonance frequency is calculated through iterative. The composite loss factor of the high damping structure can also be calculated by this method.

2. Theory

2.1. MSE Method

Modal strain energy (MSE) method has been widely used for predicting the modal loss factor of composite structures with damping layers [11-13]. The method enables one to calculate dynamic response without accounting for material damping in the vibration analysis. The basic idea of the modal strain energy method is: when calculating the modal strain energy of a structure with additional damping, it is assumed that the additional damping will not affect the modal mode shape of the structure, then for the same structure, an undamped modal approximation can be used instead of the damped one. Then, through the modal analysis without damping, the SE of the damping layer and the total modal strain energy distribution of the structure in each order mode are obtained. Finally, the energy loss of the damping layer is calculated by the loss factor of the material, then the energy loss of the damping layer is obtained.

The modal strain energy calculation formula is shown in formula (1).

$$U = \frac{1}{2}\int \{\emptyset\}^T [B]^T [D][B]\{\emptyset\}\, dV = \frac{1}{2}\{\emptyset\}^T \int [B]^T [D][B]\, dV \{\emptyset\} = \frac{1}{2}\{\emptyset\}^T [K]\{\emptyset\} \tag{1}$$

where $\{\emptyset\}$ is the real modal vector of the structure and $[K]$ is the structural stiffness matrix.

The strain energy at the i-th modal frequency of the structure is divided into two parts: the strain energy of damping material U_{Di} and the strain energy of non-damping material U_{Ei}:

$$U_{\mathrm{i}} = U_{\mathrm{Di}} + U_{\mathrm{Ei}} \tag{2}$$

According to the energy dissipation mechanism of the damping material, it can be known that the loss strain energy of the structure at the i-th modal frequency is:

$$\Delta U_{\mathrm{Di}} = \beta_{\mathrm{i}} U_{\mathrm{Di}} \tag{3}$$

where ΔU_{Di} is the loss strain energy of the damping layer, and β_{i} is the loss factor of the viscoelastic material at the i-th modal frequency.

Therefore, the calculation formula of the modal loss factor corresponding to the i-order modal frequency of the structure is as follows:

$$\eta_{\mathrm{i}} = \frac{\Delta U_{\mathrm{Di}}}{U_{\mathrm{i}}} = \frac{\beta_{\mathrm{i}} U_{\mathrm{Di}}}{U_{\mathrm{Di}} + U_{\mathrm{Ei}}} \tag{4}$$

where: η_{i} is the loss factor at the i-th mode of the structure.

2.2. Iterative MSE Method

The MSE method will cause large calculation errors when ignored the frequency dependence of viscoelastic damping materials [14-15]. Taking a rubber material as an example, at 23°C, its Young's modulus increases from 40MPa to 160MPa in the frequency range of 10~300Hz, and the loss factor changes from 0.99 to 1.20. To solve this problem, an iterative MSE method can be used to calculate the natural frequencies of the structure. The calculation steps are as follows:

1) First, assume that the i-th order natural frequency of the structure is f_{i};

2) Obtain the Young's modulus and Poisson's ratio of the damping material at frequency f_{i0}, and input them into the software together with the material parameters of the non-damping layer;

3) Calculate the i-th order natural frequency and composite loss factor η_{i} of the structure by the finite element method;

4) If $|f_0 - f_{\mathrm{i}}| \le \varepsilon$, then the i-th order natural frequency is f_{i} ,and the i-th order composite loss factor is η_{i};

5) If $|f_0 - f_{\mathrm{i}}| \ge \varepsilon$, then make $f_{\mathrm{i}} = f_{\mathrm{i0}}$, repeat steps 2) and 3) until $|f_{\mathrm{i0}} - f_{\mathrm{i}}| \le \varepsilon$.

After the calculation of the i-th order natural frequency is completed, the i+1-th order is calculated until the calculation of the N-order natural frequency and the composite loss factor is completed.

3. Experiment

3.1. Sample Preparation

In this paper, the validity of the calculation method is verified by three types of damping structures, including free damping spline, free damping plate, and constrained damping plate.

Free damping spline (FDS) is the most convenient method to measure the composite loss factor of free damped structures with different thickness ratios. According to 'ISO 6721.3-2021', the dimensions of the free damping spline are shown in table 1.

Table 1. Dimension of the free damping spline.

Sample		Length/mm	Width/mm	Thickness/mm
FDS	Based(steel)	200	10	1.05
	DM-3 Damping material	180	10	1.53

Free damping plate (FDP) is a layer of damping material covered on the surface of the steel plate according to a certain thickness ratio, and is widely used because of its simple process. Dimensions are shown in table 2.

Table 2. Dimension of the free damping plate.

Sampl e		Length/mm	Width/mm	Thickness/mm
FDP	Based(steel)	300	300	6
	DM-3 Damping material	300	300	10

The constrained damping plate (CDP) is a high-modulus constrained material covered on the surface of the damping layer, which can improve the shear deformation of the damping layer. It is difficult to measure the loss factor of the restrained damping plate through the damping spline, so it is generally tested by a big sample or a model. Dimensions are shown in table 3.

Table 3. Dimension of constrain damping plate.

Sample		Length/mm	Width/mm	Thickness/mm
CDP	Based(steel)	1000	600	10
	DM-3 Damping material	1000	600	7
	Constrained plate(steel)	1000	600	1.5

3.2. Material Parameter Test

According to 'ISO 6721-6-2019', the storage modulus and loss factor of DM-3 damping material in tensile mode and shear mode at 20°C are tested by METTELER Company STDA861^{e} DMA. The thickness of the sample is 2 mm. The test results are shown in figure 1 and figure 2.

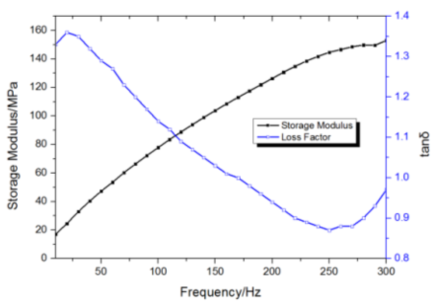

Figure 1. Storage modulus and loss factor in shear mode.

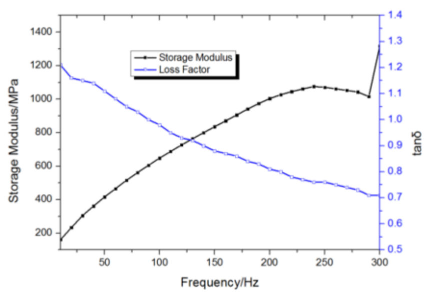

Figure 2. Storage modulus and loss factor in tensile mode.

3.3. Composite Loss Factor Test

3.3.1. Free Damping Spline

According to ISO 6721.3-2021', the prepared composite damping splines are tested. By measuring the bending resonance curve of the sample in the cantilever state, the bending resonance frequency and resonance peak width of the sample are obtained, then, the loss factor of the sample is calculated. The calculation formula is as follows:

$$\eta_i = \frac{\Delta f_i}{f_i} = \frac{f_{Hi} - f_{Li}}{f_i} \tag{5}$$

In formula (5), f_i is the i-th order resonance frequency of the sample, $\Delta f_i$is the half-power bandwidth of the i-th order formant, $f_{Hi}$is the upper limit frequency of the i-th order formant half-power band, $f_{Li}$is the i-th order formant half-power band lower limit frequency,η_i is the loss factor at the i-th order resonance frequency of the sample.

The test results are shown in table 4.

Table 4. Loss factor of the free damping spline.

Sample	Order	Natural frequency/Hz	Composite loss factor/%
FDS	2	142.3	9.6

3.3.2. Free Damping Plate and Constrained Damping Plate

According to 'ISO 7626-2-2015' Mechanical vibration and shock-Experimental determination of mechanical mobility-Part 2: Measurements using single-point translation excitation with an attached vibration exciter' to conduct vibration response test, then we can get the natural frequencies, natural mode shapes and mode of the structure to identify modal damping ratio. For small damped structures, the composite loss factor is twice the modal damping ratio. The test results of the free damping plate and the constrain plate are shown in table 5 and table 6.

Table 5. Loss factor of the free damping plate.

Sample	Order	Natural frequency//Hz	Composite loss factor/%
FDP	1	214.6	15.1
	2	328.1	15.8
	3	388.9	14.5
	4	560.1	13.0
	5	959.1	10.3

Table 6. Loss factor of the constrain damping plate.

Sample	Order	Natural frequency//Hz	Composite loss factor/%
CDP	1	87.6	4.6
	2	89.1	7.3
	3	192.4	8.1
	4	231.8	7.5
	5	244.8	6.1

4. Calculation Results and Discussion

4.1. Calculation of Free Damping Spline

There are two ways to input the Young's modulus of rubber materials into the finite element method. The first way is to directly input the modulus measured in the tensile mode. The second is to treat the rubber as a linear viscoelastic material, then the Young's modulus can be converted by formula (6).

$$G = \frac{E}{2(1+\nu)} \tag{6}$$

Rubber is nearly incompressible materials with Poisson's ratio close to 0.5, so Young's modulus is about 3 times the shear modulus.

The material parameters obtained by two methods are respectively input into the program for calculation, the results are shown in table 7.

Table 7. Calculations of the free damping spline.

	Second order natural frequency			Composite loss factor		
	Experiment	Calculated	Error	Experiment	Calculated	Error
Tesion Mode	142.3 Hz	148 Hz	4.0%	9.6%	10.6%	10.4%
Shear Mode*3		144.9 Hz	1.8%		4.8%	50.0%

As shown in table 7, the resonance frequencies of the two modes both are close to the experiment values while the composite loss factor is quite different. The storage modulus and material loss factor in the calculation process are extracted as shown in the table 8.

Table 8. Storage modulus and loss factor at second order frequency.

	Young's Modulus/MPa	Material loss factor
Tesion Mode	856.9	1.02
Shear Mode*3	307.8	1.16

It can be seen that when the measured modulus of DM-3 damping material in tensile mode is used as input, it is two times the modulus which converted by shear mode, so the composite loss factor is also two times higher than shear mode and is much closer to the test value.

4.2. Calculation of Free Damping Plate

Input the sample dimension and material parameters into the program for calculation. The calculation results are shown in table 9.

Table 9. Calculations of the free damping plate.

	Natural frequency/Hz			Composite loss factor		
Order	Experiment	Calculated	Error	Experiment	Calculated	Error
1	214.6	199.7	6.9%	15.1%	11.6%	23.2%

2	328.1	298.6	9.0%	15.8%	13.7%	13.2%
3	388.9	388	0.2%	14.5%	17.6%	21.7%
4	560.1	550.4	1.7%	13%	14%	7.7%
5	959.1	1001	4.4%	10.3%	8.1%	21.9%

Comparing the calculation results and test results, the calculation accuracy of the program for the natural frequency of the free damping plate is still high, but the error of the composite loss factor of the structure is large.

The error is mainly caused by inaccurate input of material parameters. The thickness of the free damping plate is 10mm while the material parameter test sample is 2mm. In order to eliminate the error, referring to 'ISO 6721-6-2019', the VFH-104 high frequency viscoelastic spectrometer is used to test a sample with a diameter of 30 mm and a thickness of 10 mm. The storage modulus and loss factor of the DM-3 damping material are re-tested by plate compress mode. The test result is compared with the data measured in the tensile mode, as shown in figure 3.

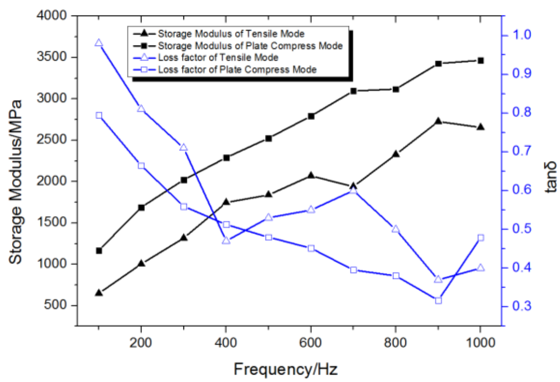

Figure 3. Comparison of Storage modulus and loss factor measured by different thickness.

As shown in figure 3, the storage moduli measured by the two modes are quite different, especially in the high frequency part. The calculation is recalculated using the test data of the 10mm thickness sample, as shown in table 10.

Table 10. Modified calculations of the free damping plate.

	Natural frequency/Hz			Composite loss factor		
Order	Experiment	Calculated	Error	Experiment	Calculated	Error
1	214.6	208.9	2.7%	15.1%	14.4	4.4%
2	328.1	314.0	4.3%	15.8%	15	5.1%
3	388.9	402.8	3.6%	14.5%	16.4	13.4%
4	560.1	575.5	2.7%	13%	11.6	11.0%
5	959.1	1016	6.0%	10.3%	9.0	12.9%

It can be seen that the calculation accuracy of the composite loss factor is significantly improved after the test data of the 10mm sample is used, and it is close to the experiment value. As the composite loss factor of the damping structure is relatively small, the absolute value error is within 2%.

In conclusion, when calculating the composite loss factor of the damping structure, if the test results of the storage modulus and loss factor of the thin specimen are still used as input, the calculation accuracy of the composite loss factor will be greatly affected. In order to improve the calculation accuracy, it is necessary to test samples with approximation thickness.

4.3. Calculation of Constrained Damping Plate

The sample dimension shown in table 3 and material parameters in figure 3 are used as input for the calculation program. Comparison between the calculated value and the experiment value is made, as shown in table 11. The result indicates that the iterative MSE method program also has high accuracy for the constrained damping structure.

Table 11. Calculations of constrain damping plate.

	Natural frequency/Hz			Composite loss factor		
Order	Experiment	Calculated	Error	Experiment	Calculated	Error
1	87.6	83.5	4.7%	4.6%	4.9%	6.5%
2	89.1	84.5	5.2%	7.3%	6.3%	13.2%
3	192.4	186.4	3.1%	8.1%	8.1%	0.2%
4	231.8	225.4	2.8%	7.5%	6.8%	10.1%
5	244.8	237.7	2.9%	6.1%	5.4%	10.5%

5. Conclusion

In this paper, the iterative modal strain energy method is proposed to improve the accuracy of the composite loss factor calculation by taking the frequency dependence of viscoelastic damping materials into account. Comparison between the calculated value and the experiment value verifies the effectiveness of the program: the calculation accuracy of natural frequency is about 5%, the accuracy of composite loss factor is less than 20%. The conclusive analysis of the data also leads out the following rule:1) For viscoelastic damping materials, the modulus and loss factor measured by different test methods of the same damping material are much different, and the modulus measured in tensile mode does not have a three-times relationship with the modulus measured in shear mode. 2) The calculation accuracy of the composite loss factor will be greatly affected by material parameters. The calculations will be more accurate when using the modulus measured in tensile mode as input and it is necessary to test samples with approximation thickness.

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