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Effects of Fatigue Characteristics on Static and Dynamic Performance of *Eucommia* Rubber Isolators

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Abstract

This study aimed to investigate the effect of fatigue characteristics on the static and dynamic performance of *Eucommia ulmoides* gum isolators, and to explore the performance changes of *Eucommia ulmoides* gum isolators with different formulations. For this purpose, we used five formulations of *Eucommia ulmoides* gum isolators and set different fatigue test methods to study the static and dynamic performance changes of *Eucommia ulmoides* gum isolators with different formulations by changing the amplitude. The experimental results showed that the addition of *Eucommia ulmoides* gum had an impact on the performance of the isolator, and the number of fatigue cycles would lead to the hardening of the *Eucommia ulmoides* gum isolator and changes in its static and dynamic performance. In the range of two million vibrations, the performance change of the isolator was significant in the early stage and then tended to be flat, indicating that the impact of fatigue on the performance of the isolator would not continue to persist. It is worth noting that the study found that the addition of 30% *Eucommia ulmoides* gum had the least impact on the performance of the isolator under fatigue. Therefore, for long-term use of *Eucommia ulmoides* gum isolators, attention should be paid to their fatigue characteristics to ensure their stability and reliability. Additionally, this study provides a reference for the design and application of *Eucommia ulmoides* gum isolators. In summary, this study provides important reference value for a deeper understanding of the fatigue characteristics of *Eucommia ulmoides* gum isolators and for ensuring their stable and reliable performance.

Keywords

Fatigue Characteristics, *Eucommia* Rubber, Vibration Isolators, Static Performance, Dynamic Performance

1. Introduction

Eucommia gum is a natural polymer material mainly composed of trans-1,4-polyisoprene, which is the same isomer of natural rubber cis-1,4-polyisoprene [1]. *Eucommia* gum has excellent crystallization efficiency and elastomeric binary properties, and can achieve self-crosslinking without adding curing agents. It has good performance such as heat resistance, cold resistance, ozone resistance, aging resistance, etc. *Eucommia* gum has a wide range of applications in medical equipment, national defense and military industry, civil industry, and other fields [2].

A vibration isolator is a device that uses elastic elements to isolate the vibration source from the foundation, thereby reducing or eliminating the transmission of vibration. The dynamic performance of the vibration isolator refers to the mechanical response characteristics of the vibration isolator under different frequencies, amplitudes, and loads, mainly including dynamic stiffness, damping ratio, transfer function, and other indicators. The dynamic performance of the vibration isolator directly affects its isolation effect and service life, and is an important basis for vibration isolator design and evaluation.

Fatigue characteristics refer to the phenomena of damage, hardening, and stress relaxation that occur in materials during repeated loading and unloading processes. Fatigue characteristics can cause changes in the mechanical properties and structural stability of materials, thereby affecting their functions and service life. The fatigue characteristics are affected by factors such as the composition, structure, defects of the material itself, as well as the frequency, amplitude, and form of external loading.

Currently, research on *Eucommia* gum vibration isolators mainly focuses on the influence of material composition, structural form, geometric parameters, and other factors on their dynamic performance, while there is less research on the influence of fatigue characteristics on their dynamic performance. Therefore, this article aims to study different *Eucommia* gum vibration isolators with different material compositions, structural forms, and geometric parameters through fatigue tests and dynamic performance tests, analyze the mechanism and law of the influence of fatigue characteristics on their dynamic performance, and provide theoretical basis and technical guidance for the design and application of *Eucommia* gum vibration isolators.

2. Materials and Methods

2.1. Material and Structure of Vibration Isolator

The material of the *Eucommia* gum vibration isolator is a *Eucommia* gum composite material, which is mainly a mixture of *Eucommia* gum and natural rubber in a certain proportion. In order to investigate whether the content of *Eucommia* gum affects the dynamic performance of the vibration isolator after fatigue testing, different *Eucommia* gum composite materials were designed to make rubber isolators. The proportion of *Eucommia* gum and natural rubber is detailed in

Table 1, and the proportion of other auxiliaries is the same except for the ratio of *Eucommia* gum and natural rubber.

The YS-25 vibration isolator is a compression-type structure, mainly composed of a flat plate and a rubber body. The isolator can withstand large loads in the vertical direction. When carrying loads in the horizontal and longitudinal directions, the rubber is subjected to shear forces, which have a relatively small carrying capacity, as shown in **Figure 1**. The study of the static and dynamic performance of the isolator mainly focuses on its main load-bearing direction, that is, the static and dynamic performance in the vertical direction.

2.2. Experimental Methods

Three vibration isolators were produced for each formulation in **Table 1**. The isolators were processed and tested according to the test conditions specified in GB/T15168-2013. The hardness, static and dynamic performance of the isolators in their initial state were tested, and the hardness, static stiffness at rated load, natural frequency, and damping ratio were recorded. The dynamic stiffness and dynamic-to-static stiffness ratio of the isolator were calculated. To eliminate the influence of discreteness, the average value of each performance parameter of the isolators in each formulation was taken.

The isolators were compressed vertically to the rated load, and a vibration test was conducted with a frequency equal to the natural frequency of the isolator under rated load and amplitudes of 2 mm and 3 mm. During the fatigue test, the hardness, static and dynamic performance of the isolator were measured every 100,000 cycles.

Figure 1. The YS-25 vibration isolator.

Table 1. Proportion of *Eucommia* gum and natural rubber in different formulations.

Type	Number of Parts				
	F1	F2	F3	F4	F5
EUG	0	10	20	30	40
NR	100	90	80	70	60

The time interval between vulcanization and testing for all specimens did not exceed one month. Before each test, the isolator was left to stand for more than 4 hours at room temperature and then tested for its static and dynamic performance to eliminate the influence of endogenous heat on the isolator's performance during fatigue testing. The hardness was measured at the center of the rubber body, with a distance from the edge of not less than 6 mm, and at least five points were taken on each sample to obtain the average value of the five measurement points.

3. Vibration Isolator Performance Test Results

The hardness of the vibration isolator was tested using a portable hardness tester, and the static and dynamic performance and fatigue testing were carried out using an dynamic fatigue testing machine. **Figure 2** shows the loading mode of the vibration isolator on the dynamic fatigue testing machine. During the static test, the isolator was compressed vertically to 3 mm, preloaded twice, and loaded at a rate of 1 mm/min for the third time, and the force value at a deformation of 2.5 mm was taken as the rated load. The static stiffness of the isolator was calculated according to Equation (1).

$$K_j = \frac{F_{1.1} - F_{0.9}}{X_{1.1} - X_{0.9}} \tag{1}$$

In the equation:

$F_{1.1}$ —Force value at 1.1 times the rated load, unit: N;

$F_{0.9}$ —Force value at 0.9 times the rated load, unit: N;

$X_{1.1}$ —Deformation value at 1.1 times the rated load, unit: mm;

$X_{0.9}$ —Deformation value at 0.9 times the rated load, unit: mm.

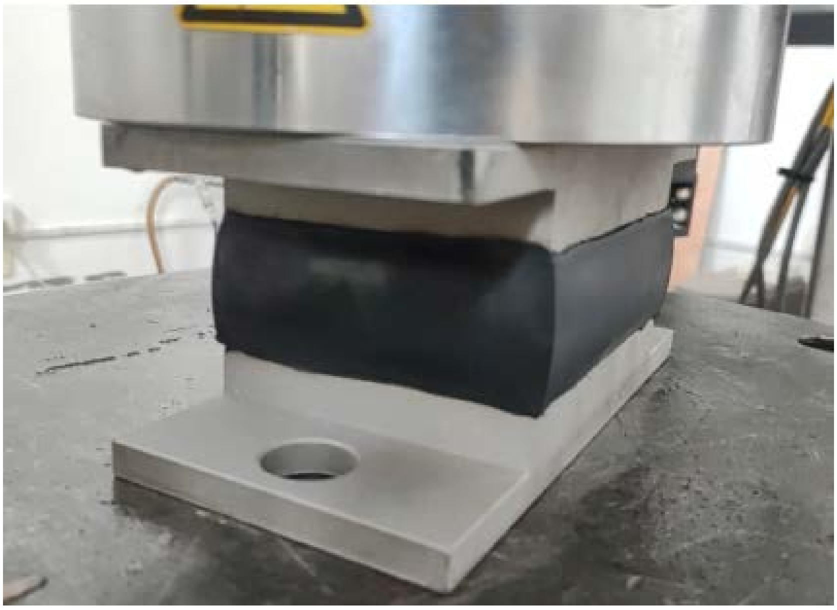


Figure 2. Static performance test in the vertical direction of the vibration isolator.

After the fatigue test, the rated load of the vibration isolator was still tested statically according to the rated load in its initial state. During the dynamic test, the isolator was compressed to the rated load, with an amplitude of 0.7 mm. The isolator was scanned for frequency, with an initial frequency of 1 Hz, an end frequency of 20 Hz, and a step size of 0.1 Hz. After the scan was completed, the point with the maximum transmissibility was read from the result file, and its corresponding frequency was taken as the natural frequency of the isolator under rated load, and half of the corresponding damping factor was taken as the damping ratio of the isolator. **Tables 2-6** show the hardness, static stiffness, dynamic stiffness, damping ratio, and dynamic-to-static stiffness ratio of the isolators produced from each formulation.

Table 2. Hardness of the vibration isolators after fatigue testing.

Number of fatigue cycles (in ten thousands)	The hardness of the vibration isolator with an amplitude of 2 mm (HA)				
	F1	F2	F3	F4	F5
0	54	58	62	66	70
10	54	58	62	66	70
20	54	58	62	66	70
30	54	58	62	66	70
40	54	58	62	66	70
50	55	58	62	66	70
80	55	59	62	66	70
110	55	59	63	67	70
150	55	59	63	67	71
200	55	59	63	67	71
Number of fatigue cycles (in ten thousands)	**The hardness of the vibration isolator with an amplitude of 3 mm (HA)**				
	F1	F2	F3	F4	F5
0	54	58	62	66	70
10	54	58	62	66	70
20	54	58	62	66	70
30	54	58	62	66	70
40	55	58	62	66	70
50	55	58	62	66	70
80	55	59	63	66	70
110	55	59	63	67	71
150	55	59	63	67	71
200	55	59	63	67	71

Table 3. Static stiffness of the vibration isolators after fatigue testing.

Number of fatigue cycles (in ten thousands)	Static stiffness of the vibration isolator with an amplitude of 2 mm (HA)				
	F1	F2	F3	F4	F5
0	2614	2995	3431	3673	4208
10	2280	2625	3002	3211	3666
20	2279	2602	2987	3208	3670
30	2284	2613	2976	3225	3682
40	2304	2635	3002	3187	3695
50	2323	2657	3079	3248	3729
80	2328	2667	3066	3255	3736
110	2280	2626	2984	3208	3677
150	2301	2653	3019	3225	3707
200	2288	2627	3001	3258	3683
Number of fatigue cycles (in ten thousands)	Static stiffness of the vibration isolator with an amplitude of 3 mm (HA)				
	F1	F2	F3	F4	F5
0	3012	3451	3694	4232	3012
10	2386	2731	2911	3352	2386
20	2375	2708	2899	3342	2375
30	2410	2756	2905	3401	2410
40	2396	2733	2915	3382	2396
50	2369	2710	2896	3347	2369
80	2377	2731	2921	3364	2377
110	2335	2684	2869	3277	2335
150	2348	2702	2893	3319	2348
200	2344	2688	2874	3303	2344

Table 4. Natural frequency of the vibration isolators after fatigue testing.

Number of fatigue cycles (in ten thousands)	Natural frequency of the vibration isolator with an amplitude of 2 mm (HA)				
	F1	F2	F3	F4	F5
0	2614	2995	3431	3673	4208
10	2280	2625	3002	3211	3666
20	2279	2602	2987	3208	3670
30	2284	2613	2976	3225	3682

Continued

40	2304	2635	3002	3187	3695
50	2323	2657	3079	3248	3729
80	2328	2667	3066	3255	3736
110	2280	2626	2984	3208	3677
150	2301	2653	3019	3225	3707
200	2288	2627	3001	3258	3683
Number of fatigue cycles (in ten thousands)	Natural frequency of the vibration isolator with an amplitude of 3 mm (HA)				
	F1	F2	F3	F4	F5
0	3012	3451	3694	4232	3012
10	2386	2731	2911	3352	2386
20	2375	2708	2899	3342	2375
30	2410	2756	2905	3401	2410
40	2396	2733	2915	3382	2396
50	2369	2710	2896	3347	2369
80	2377	2731	2921	3364	2377
110	2335	2684	2869	3277	2335
150	2348	2702	2893	3319	2348
200	2344	2688	2874	3303	2344

Table 5. Damping ratio of the vibration isolators after fatigue testing.

Number of fatigue cycles (in ten thousands)	Damping ratio of the vibration isolator with an amplitude of 2 mm (HA)				
	F1	F2	F3	F4	F5
0	2614	2995	3431	3673	4208
10	2280	2625	3002	3211	3666
20	2279	2602	2987	3208	3670
30	2284	2613	2976	3225	3682
40	2304	2635	3002	3187	3695
50	2323	2657	3079	3248	3729
80	2328	2667	3066	3255	3736
110	2280	2626	2984	3208	3677
150	2301	2653	3019	3225	3707
200	2288	2627	3001	3258	3683

Continued

Number of fatigue cycles (in ten thousands)	Damping ratio of the vibration isolator with an amplitude of 3 mm (HA)				
	F1	F2	F3	F4	F5
0	3012	3451	3694	4232	3012
10	2386	2731	2911	3352	2386
20	2375	2708	2899	3342	2375
30	2410	2756	2905	3401	2410
40	2396	2733	2915	3382	2396
50	2369	2710	2896	3347	2369
80	2377	2731	2921	3364	2377
110	2335	2684	2869	3277	2335
150	2348	2702	2893	3319	2348
200	2344	2688	2874	3303	2344

Table 6. Dynamic-to-static stiffness ratio of the vibration isolators after fatigue testing.

Number of fatigue cycles (in ten thousands)	Dynamic-to-static stiffness ratio of the vibration isolator with an amplitude of 2 mm (HA)				
	F1	F2	F3	F4	F5
0	2614	2995	3431	3673	4208
10	2280	2625	3002	3211	3666
20	2279	2602	2987	3208	3670
30	2284	2613	2976	3225	3682
40	2304	2635	3002	3187	3695
50	2323	2657	3079	3248	3729
80	2328	2667	3066	3255	3736
110	2280	2626	2984	3208	3677
150	2301	2653	3019	3225	3707
200	2288	2627	3001	3258	3683
Number of fatigue cycles (in ten thousands)	Dynamic-to-static stiffness ratio of the vibration isolator with an amplitude of 3 mm (HA)				
	F1	F2	F3	F4	F5
0	3012	3451	3694	4232	3012
10	2386	2731	2911	3352	2386
20	2375	2708	2899	3342	2375
30	2410	2756	2905	3401	2410

Continued

40	2396	2733	2915	3382	2396
50	2369	2710	2896	3347	2369
80	2377	2731	2921	3364	2377
110	2335	2684	2869	3277	2335
150	2348	2702	2893	3319	2348
200	2344	2688	2874	3303	2344

The stability of the vibration isolator's static and dynamic performance parameters is a key factor in determining its effectiveness in vibration isolation. We analyzed the relationship between the dynamic and static performance parameters and the number of fatigue cycles in **Tables 2-6**, as shown in **Figure 3**.

From **Figure 3**, it is clear that the addition of *Eucommia ulmoides* gum has an impact on the performance of the vibration isolator, mainly in the following aspects:

1) After the addition of *Eucommia ulmoides* gum, the hardness of the vibration isolator will increase to a certain extent, and the more *Eucommia ulmoides* gum is added, the higher the hardness will be.

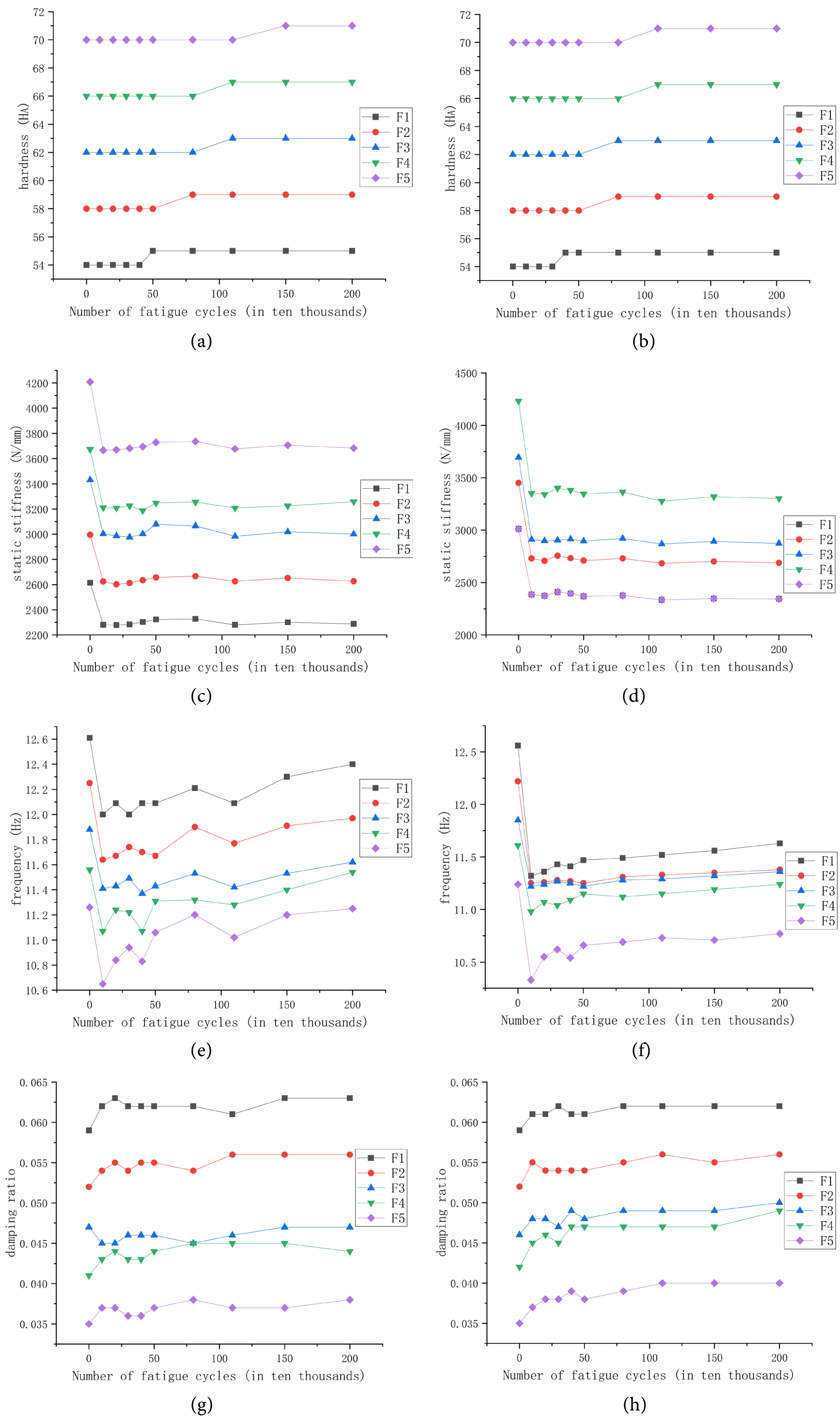
2) After the addition of *Eucommia ulmoides* gum, the damping ratio can be reduced to a certain extent, the dynamic-to-static stiffness ratio can be lowered, and the vibration isolator can obtain a lower natural frequency.

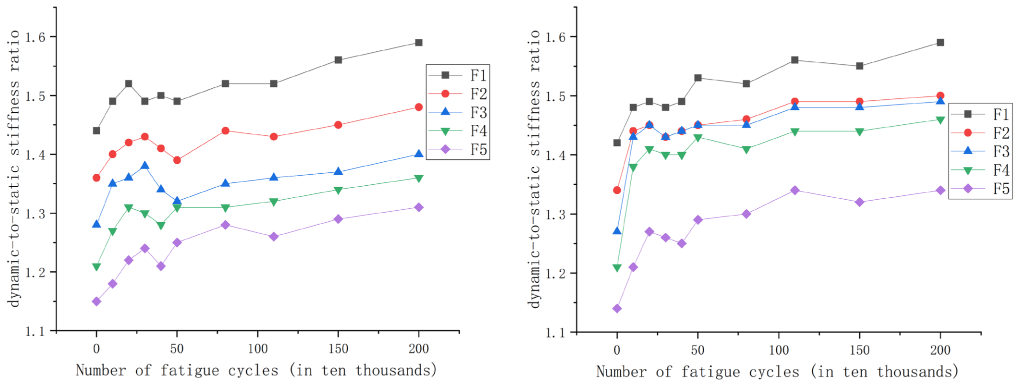
3) After the addition of *Eucommia ulmoides* gum, the fatigue performance of the vibration isolator is improved, making the static and dynamic performance of the vibration isolator relatively less affected. When the proportion of *Eucommia ulmoides* gum added is 30%, the fatigue performance of the vibration isolator is the best, and the static and dynamic stiffness of the vibration isolator are least affected. As the displacement amplitude increases, the changes in the static and dynamic performance of the vibration isolator become more significant, but after a certain degree, the tendency of change tends to be stable.

4. Analysis of Reasons and Principles

Eucommia ulmoides gum has a trans-1,4-isoprene structure and shows significant rubber-plastic dual characteristics. The addition of *Eucommia ulmoides* gum can increase the hardness of the rubber material to a certain extent, especially at low temperatures, where its plastic properties are more prominent [3].

Compared with natural rubber, *Eucommia ulmoides* gum has a higher degree of molecular flexibility and can better absorb dynamic stress and vibration energy, thereby reducing the material's loss factor [4]. *Eucommia ulmoides* gum is a trans structure with microcrystals, which can further reduce the damping ratio. The combined effect of these factors makes the dynamic-to-static stiffness ratio of the composite material with added *Eucommia ulmoides* gum lower in the vibration isolator.


hardness (HA)
Number of fatigue cycles (in ten thousands)
F1
F2
F3
F4
F5
(a)
hardness (HA)
Number of fatigue cycles (in ten thousands)
F1
F2
F3
F4
F5
(b)
static stiffness (N/mm)
Number of fatigue cycles (in ten thousands)
F1
F2
F3
F4
F5
(c)
static stiffness (N/mm)
Number of fatigue cycles (in ten thousands)
F1
F2
F3
F4
F5
(d)
frequency (Hz)
Number of fatigue cycles (in ten thousands)
F1
F2
F3
F4
F5
(e)
frequency (Hz)
Number of fatigue cycles (in ten thousands)
F1
F2
F3
F4
F5
(f)
damping ratio
Number of fatigue cycles (in ten thousands)
F1
F2
F3
F4
F5
(g)
damping ratio
Number of fatigue cycles (in ten thousands)
F1
F2
F3
F4
F5
(h)



(i) (j)

Figure 3. Relationship between the static and dynamic performance of the vibration isolator and the number of fatigue cycles. (a) The change in hardness of the vibration isolator with an amplitude of 2 mm; (b) The change in hardness of the vibration isolator with an amplitude of 3 mm; (c) The change in static stiffness of the vibration isolator with an amplitude of 2 mm; (d) The change in static stiffness of the vibration isolator with an amplitude of 3 mm; (e) The change in natural frequency of the vibration isolator with an amplitude of 2 mm; (f) The change in natural frequency of the vibration isolator with an amplitude of 3 mm; (g) The change in damping ratio of the vibration isolator with an amplitude of 2 mm; (h) The change in damping ratio of the vibration isolator with an amplitude of 3 mm; (i) The change in dynamic-to-static stiffness ratio of the vibration isolator with an amplitude of 2 mm; (j) The change in dynamic-to-static stiffness ratio of the vibration isolator with an amplitude of 3 mm.

Natural rubber is a natural polymer compound mainly composed of isoprene, and its molecular weight has a bimodal distribution. *Eucommia ulmoides* gum has a single structure, low internal friction, and low heat generation. Its low molecular weight and narrow distribution range reduce resistance under external force, thereby reducing damping. Low damping reduces heat generation during fatigue. Moreover, in the blend of *Eucommia ulmoides* gum and natural rubber, the microcrystal effect can absorb the thermal energy generated by periodic bending motion, and the microcrystal structure delays and hinders the formation of cracks, thereby improving the fatigue performance of the vibration isolator [5].

Adding an appropriate amount of *Eucommia ulmoides* gum can enhance the elasticity, toughness, and oxidative resistance of rubber, thereby improving the fatigue performance of the rubber vibration isolator. However, excessive addition of *Eucommia ulmoides* gum can lead to problems such as increased hardness and reduced wear resistance of rubber materials, thereby reducing the service life of rubber vibration isolators. When the addition ratio is 30%, the interaction between *Eucommia ulmoides* gum and natural rubber is optimal, forming the most stable chemical bonds, thereby giving the rubber vibration isolator the best mechanical and fatigue performance.

The increase in displacement amplitude is due to the fact that the increase in amplitude causes greater deformation and stress of the rubber material, thus accelerating the material's fatigue damage. The increase in amplitude causes an increase in the amount of deformation of the rubber material. When the amplitude increases, the amount of deformation of the rubber material also increases. This will cause larger changes in the molecular structure within the rubber material, thereby accelerating the aging and fatigue damage of the material. The increase in amplitude also causes an increase in the stress of the rubber material. The increase in amplitude causes the rubber material to be subjected to greater force, which increases the internal stress of the material. When the stress exceeds the load-bearing capacity of the rubber material, it causes fatigue damage to the material. Finally, the increase in amplitude causes the temperature of the rubber material to rise. The increase in amplitude causes an increase in friction and energy loss in the rubber material, resulting in an increase in the temperature of the material. High temperature accelerates the aging and fatigue damage process of the rubber material.

5. Conclusions

1) The crystal characteristics of *Eucommia ulmoides* gum at room temperature can increase the hardness of the elastic body of *Eucommia ulmoides* gum vibration isolator, and the higher the proportion of *Eucommia ulmoides* gum, the higher the hardness.

2) The crystal characteristics of *Eucommia ulmoides* gum at room temperature and its higher degree of molecular flexibility make the loss factor of *Eucommia ulmoides* gum composite materials smaller, and can produce vibration isolators with lower damping ratio and dynamic-to-static stiffness ratio.

3) The single structure of *Eucommia ulmoides* gum results in less friction and lower heat generation, and its microcrystal effect can absorb the thermal energy generated by periodic bending motion. Adding an appropriate amount of *Eucommia ulmoides* gum can enhance the elasticity, toughness, and oxidative resistance of rubber, thereby improving the fatigue performance of the rubber vibration isolator. Excessive addition of *Eucommia ulmoides* gum can lead to problems such as increased hardness and reduced wear resistance of rubber materials, thereby reducing the service life of rubber vibration isolators. When the addition ratio is 30%, the interaction between *Eucommia ulmoides* gum and natural rubber is optimal, and the fatigue performance of the vibration isolator is the best.

4) An increase in displacement amplitude can cause larger changes in the molecular structure within the rubber material, increase the stress of the rubber material, and raise the temperature of the material, thereby accelerating the aging and fatigue damage process of the rubber material.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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