Experimental Study on Hysteresis Characteristics of Fluorosilicone Rubber Damper

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Abstract. This study tested the hysteresis characteristics of the damper for determining the damping characteristics. Firstly, dampers with four kinds of hardness, such as 20\textdegree HA, 30\textdegree HA, 40\textdegree HA and 50\textdegree HA, were obtained by vulcanization. Then hysteresis loops of the dampers were tested by cyclic loading method with displacement of ±0.5mm, ±1.0mm and ±1.2mm. The relationship between stiffness of dampers and hardness was obtained, and it was found that the stiffness of dampers changed quadratically with rubber hardness. The ellipse method is used to calculate the damping factor of the damper. The damping factor of the damper varies with the change of loading displacement and rubber hardness.

Key words: Fluorosilicone rubber; Hysteresis loop test; Damping factor

1. Introduction

Fluorosilicone, as a polymer damping material, was originally developed by the US Air Force and Dow Corning in 1951. Fluorosilicone rubber is an elastomer with trifluoropropyl side chain introduced into the main chain of methyl vinyl siloxane. This kind of rubber has not only the resilience, high and low temperature resistance and weatherability of silicone rubber, but also the oil resistance and solubility resistance of fluorine rubber\textsuperscript{[1,2]}.

Damping behavior of rubber macromolecule material is a process of transforming mechanical energy into heat energy dissipation by relative movement of macromolecule chain in rubber under cyclic loading. This kind of damping behavior results in the deformation hysteresis load in the loading process, which forms hysteresis loop under cyclic loading. The envelope area of hysteresis loop represents the energy consumed by the relative motion of molecular chains. A large amount of investigations were conducted on hysteresis loop features of rubber damping materials, for instance, Hu Zhenxian\textsuperscript{[3]} et al. tested the hysteretic loops of natural rubber connectors in automotive shock absorbers with different amplitudes. It was found that the damping and stiffness characteristics of the shock absorber vary nonlinearly with the loading amplitude. Zhang Lixia\textsuperscript{[4]} carried out loading tests at different frequencies for rubber dampers in bogies of fast freight cars. The effects of loading frequencies on rubber hysteresis loops were obtained, and the dynamic stiffness and loss factors of rubber materials were obtained as a function of the excitation frequencies of dynamic loads. Zeng Cheng\textsuperscript{[5]} et al. acquired hysteresis loops of shock response for JXD rubber isolator with low frequency and large displacement on ship equipment by drop hammer impact testing machine at different impact speed and pulse width, and analyzed the
influence of loading parameters on stiffness and loss factor of rubber isolator. Liu Wenwu [6] used simulation analysis method to study the response of rubber products under harmonic load, obtained the hysteresis loop of rubber products, and calculated the dynamic stiffness and loss factor of rubber products. Lei Gang [7] et al. carried out dynamic characteristic test of rubber bushing in automobile by constant amplitude frequency conversion loading method, obtained hysteresis loops of rubber bushing at different frequencies, and then calculated the dynamic stiffness and loss factor of rubber bushing.

J.B. Le Cam [8] studied the hysteresis of natural rubber by experimental method and found that the hysteresis loop of natural rubber is not caused by internal and heat dissipation, but is used to change the microstructure of the material. It is proved that natural rubber can store mechanical energy without converting mechanical energy into thermal energy, which is a realistic method to explain the excellent crack resistance of natural rubber.

T. Bhave [9] et al. studied the effect of nonlinear viscoelastic behavior of automotive synthetic rubber tires on its hysteresis coefficient. The analytical model was first used to predict the hysteresis friction of rubber tires. Then the model results are compared with the test results of rubber tires, and the friction performance evaluation method based on the nonlinear viscoelasticity of rubber tires is obtained.

Lin Song [10] and others tested different temperature, loading frequency and dynamic displacement of butyl rubber viscoelastic damping materials. An M-RT model considering the effects of temperature, frequency and displacement on the dynamic mechanical behavior of materials is proposed.

Fluorosilicone rubber has excellent damping characteristics and environmental resistance, and is suitable for vibration-damping installation of aerospace high-precision electronic equipment. At present, there are few studies on the mechanical properties of fluorosilicone rubber, especially the hysteretic behavior related to material damping. In this paper, for the four hardness fluorosilicone rubber dampers, the material testing machine is used to carry out three kinds of displacement cyclic loading, and the hysteresis loops with different hardness and different loading displacements are obtained. The damping loss factor of fluorosilicone rubber is calculated by elliptic method. The variation of the damping factor of the material with rubber hardness and loading displacement is obtained, which provides technical support for fluorosilicone rubber in vibration isolation installation of aerospace equipment.

2. Fluorosilicone Rubber Damper

The damper structure is illustrated in Figure 1. Four kinds of rubber with hardness of 20 HA, 30 HA, 40 HA and 50 HA were obtained through the formulation design of fluorosilicone rubber. According to the structure size of the damper, the damper was made by molding method, and the curing mold was designed. The shrinkage of rubber after vulcanization was considered in the design process of the vulcanization mould. The vulcanization process was designed and conducted hereinafter. Fluorosilicone rubber is a kind of resistant high temperature rubber. In this paper, the vulcanization process of fluorosilicone rubber is as follows: the temperature is 160 °C, the pressure is 20 MPa, and the time of vulcanization is 15 min. The second stage vulcanization temperature is 200 °C and vulcanization time is 4 h. According to the vulcanization process above, the specimens of fluorosilicone rubber damper was made. Four damper specimens were made from each hardness rubber. The corresponding specimen numbers of 20 HA, 30 HA, 40 HA and 50 HA were 11#-14#, 21#-24#, 31#-34#, 41#-44#, respectively, as shown in Figure 2.
3. Hysteresis Characteristic Test

The hysteresis characteristic test of the fluorosilicone damper was carried out by WDW-500 material testing machine, and the displacement control method was used to load at a speed of 1 mm/min. The stiffness and hysteresis characteristics of the damper were tested, respectively. The test system of the hysteresis characteristic of damper was established which shows in Figure 3. In the stiffness characteristic test, in order to avoid damaged the damper, the compression dimension of each sample was controlled to be 0.5 mm. In the hysteresis characteristic test, each sample was loaded with ±0.5 mm, ±1.0 mm and ±1.2 mm, respectively. At least three hysteresis loops for complete cycles are guaranteed. The matrix of hysteresis characteristic is shown in Table 1.

![Figure 3. Hysteresis characteristic test system of damper.](image)

| Rubber No. | Sample No. | Rubber hardness (HA) | Load displacement (mm) | Loading speed (mm·min⁻¹) | 1/
|-----------|------------|----------------------|------------------------|--------------------------|---|
| 1#        | 11#-14#   | 20                   |                        |                          | 0.5/1.0/1.2 |
| 2#        | 21#-24#   | 30                   |                        |                          | 1 |
| 3#        | 31#-34#   | 40                   |                        |                          |   |
| 4#        | 41#-44#   | 50                   |                        |                          |   |

4. Test Results and Analysis

4.1. Stiffness test results and analysis

To prevent the damage of the damper caused by excessive compression during the stiffness characteristic test, the compression of each sample was 0.5 mm. Figures 4, 5, 6, and 7 demonstrate the load-displacement curves of the four hardness dampers. The stiffness of the damper with four kinds of hardness was obtained by fitting the load displacement curve. The stiffness of the damper is 62.6 N/mm for the hardness of 20 HA; the stiffness of the damper is 73.67 N/mm for the hardness of 30 HA; the stiffness of the damper is 118.7 N/mm for the hardness of 40 HA; the stiffness of the damper is 187.6 N/mm for the hardness of 50 HA. Therefore, the relationship between the stiffness \( K_s \) of the damper and the rubber hardness \( HA \) is as follows

\[
K_s = 0.0422(\text{HA})^2 + 1.5069(\text{HA}), \quad R^2 = 0.976
\]

4.2. Hysteresis characteristics test results and analysis

Figure 8 is a load-displacement curve obtained when the 11# specimen was loaded at ±0.5 mm, ±1.0 mm, and ±1.2 mm. When the loading displacement was 0.5 mm, the maximum and minimum loads were 32.975 N and -21.8 N, respectively; when the loading displacement was 1.0 mm, the maximum and minimum loads were 75.225 N and -50.1 N, respectively; when the loading displacement was 1.2 mm, the maximum and minimum loads were 84.625 N and -67.625 N, respectively. The maximum load of the hysteresis loop increases as the loading displacement increases. With the increase of loading displacement, the envelope area of hysteresis loop increases, indicating that the more energy the damper consumes under one cycle loading. The maximum damping force of the damper under three kinds of
loading displacement conditions, that is, the value of the intersection of the hysteresis loop and the Y-axis, respectively \(F_D1,0.5=6.125N\), \(F_D1,1.0=9.325N\), \(F_D1,1.2=9.175N\). According to the standard GB/T 15168-2013 named as vibration and shock isolators measuring method for its static and dynamic characteristics, the loss factor \(\eta\) was calculated using the elastic force \(F_T\) and the damping force \(F_D\) in the hysteresis loop as follows

\[
\eta = \frac{F_D}{F_T}
\]  

The damping loss factors under the three loading displacements can be calculated from equation (2): \(\eta_{0.5}=0.186\), \(\eta_{1.0}=0.124\), \(\eta_{1.2}=0.108\). The damping loss factor of the fluorosilicone damper decreases with the increase of the loading displacement.

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**Figure 4.** Load-displacement curve with 20HA.

**Figure 5.** Load-displacement curve with 30HA.

**Figure 6.** Load-displacement curve with 40HA.

**Figure 7.** Load-displacement curve with 50HA.

**Figure 8.** Hysteresis loop of 11 # damper under different loading displacements.

**Figure 9.** Hysteresis loops of four hardness dampers under ±0.5mm loading displacement.

Figure 9 is the load displacement hysteresis loop obtained by the four hardness dampers under ±0.5mm loading displacement. The maximum load of hysteresis loop increases as the rubber hardness increases; the damping force of the damper increases as the rubber hardness increases; With the increase...
of rubber hardness, the envelope area of hysteresis loop increases, which indicates that the high hardness damper consumes more energy under one cycle loading. Detailed results can refer to Table 2.

**Table 2** Statistical of elastic force, damping force and damping factor of Hysteresis Loop of Dampers

| Sample No. | $F_{T0.5}$ (N) | $F_{T1.0}$ (N) | $F_{T1.2}$ (N) | $F_{D0.5}$ (N) | $F_{D1.0}$ (N) | $F_{D1.2}$ (N) | $\eta_{T0.5}$ | $\eta_{T1.0}$ | $\eta_{T1.2}$ |
|------------|----------------|----------------|----------------|----------------|----------------|----------------|--------------|--------------|--------------|
| 11#        | 32.975         | 75.225         | 84.625         | 6.125          | 9.325          | 9.175          | 0.186        | 0.124        | 0.108        |
| 12#        | 32.250         | 60.175         | 70.725         | 4.625          | 11.138         | 12.600         | 0.143        | 0.185        | 0.178        |
| 13#        | 32.825         | 72.100         | 103.275        | 6.800          | 11.725         | 15.300         | 0.207        | 0.163        | 0.148        |
| 14#        | 31.350         | 64.775         | 73.45          | 4.563          | 8.263          | 10.975         | 0.146        | 0.128        | 0.149        |
| Avg        | 32.350         | 68.069         | 83.019         | 5.528          | 10.113         | 12.013         | 0.171        | 0.149        | 0.145        |
| 21#        | 40.600         | 83.725         | 89.475         | 9.525          | 12.850         | 15.850         | 0.235        | 0.153        | 0.177        |
| 22#        | 43.375         | 89.125         | 108.00         | 9.100          | 12.275         | 13.925         | 0.210        | 0.138        | 0.129        |
| 23#        | 38.200         | 82.450         | 109.600        | 10.100         | 9.638          | 14.450         | 0.264        | 0.117        | 0.132        |
| 24#        | 38.325         | 82.625         | 99.890         | 8.125          | 11.800         | 15.150         | 0.212        | 0.143        | 0.152        |
| Avg        | 40.125         | 84.481         | 101.741        | 9.213          | 11.641         | 14.844         | 0.230        | 0.138        | 0.146        |
| 31#        | 55.300         | 123.675        | 136.225        | 11.650         | 14.275         | 18.100         | 0.211        | 0.115        | 0.133        |
| 32#        | 73.625         | 153.375        | 159.175        | 21.525         | 22.425         | 19.200         | 0.292        | 0.146        | 0.121        |
| 33#        | 64.250         | 135.575        | 136.013        | 14.738         | 20.925         | 19.775         | 0.229        | 0.154        | 0.145        |
| 34#        | 66.013         | 131.100        | 182.792        | 15.400         | 16.600         | 21.550         | 0.233        | 0.127        | 0.118        |
| Avg        | 64.797         | 135.931        | 153.551        | 15.828         | 18.556         | 19.656         | 0.244        | 0.137        | 0.128        |
| 41#        | 84.000         | 214.975        | 289.975        | 14.388         | 17.850         | 22.000         | 0.171        | 0.083        | 0.076        |
| 42#        | 106.625        | 241.125        | 319.100        | 17.363         | 14.175         | 17.750         | 0.163        | 0.059        | 0.056        |
| 43#        | 113.225        | 225.975        | 254.625        | 20.600         | 22.400         | 23.875         | 0.182        | 0.099        | 0.094        |
| 44#        | 86.975         | 83.800         | 189.15         | 15.825         | 10.425         | 17.150         | 0.182        | 0.124        | 0.091        |
| Avg        | 97.706         | 191.469        | 263.213        | 17.044         | 16.213         | 20.194         | 0.174        | 0.085        | 0.077        |

According to GB/T 15168-2013 standard, the maximum elastic force and corresponding damping force of each specimen under three loading displacements were calculated. The damping loss factors of the damper were determined via Equation (2). The results can refer to Table 2. The average values of the test results of four specimens under each hardness were used to express the maximum elastic and damping forces of the damper under this hardness, and their loss factors were calculated. Taking the hardness of the damper as the transverse axis and the calculated loss factor as the longitudinal axis, the hardness-loss factor curves of the damper under different loading displacements were drawn, as shown in Figure 10. When the loading displacement was 0.5 mm, as the hardness of the rubber increases, the damping loss factor of the damper first increases and then decreases; when the loading displacement was 1.0 mm, as the hardness of the rubber increases, the damping loss factor of the damper decreases, but the middle section decreases very slowly; when the loading displacement was 1.2 mm, as the rubber hardness increases, the damping loss factor of the damper increases slightly and then decreases rapidly. However, when the three curves were fitted by quadratic polynomials, the quadratic coefficients of the fitted curves were all negative, indicating that the damping loss factor of the rubber has a maximum value in a certain range of hardness, which can guide the design of the damper. Under the same hardness, the damping loss factor at 0.5 mm loading displacement is greater than the loss factor of 1.0 mm and 1.2 mm, while the loss factors of 1.0 mm and 1.2 mm loading displacement are not much different. The fitting curves are also very close. It shows that the damper should be designed to control the maximum
amount of deformation within the appropriate range to obtain the best damping loss factor.

Figure 10. Curve of damping factor of damper with rubber hardness and loading displacement.

5. Conclusion
In this paper, the stiffness and hysteresis characteristics of fluorosilicone rubber under different hardness are studied. The relation between the stiffness of the damper and the hardness of the rubber, and the relation between the loss factor variation of the damper and the rubber hardness, and loading displacement are determined. The conclusions are as follows

1. The stiffness $K_s$ of the damper increases quadratically with the increase of rubber hardness $HA$; the maximum load of the damper also increases with the increase of rubber hardness;
2. The single loading loop energy consumption of the damper increases as the hardness of the rubber increases;
3. The damping loss factor of the damper increases first and then decreases with the increase of the rubber hardness, and the loss factor of the damper has a maximum value within a certain hardness range;
4. The damping loss factor of damper decreases with the increase of loading displacement, but it remains unchanged when the loading displacement is large, indicating that the optimum damping loss factor can be obtained only when the maximum deformation is controlled in a proper range in the design of cushion.

References
[1] FLITNEY B. Extending the application of fluorosilicone elastomers[J]. Sealing Technology, 2005, (2):6-11
[2] Ye Xiawang, Guo Jianhua, Zeng Xingrong. Research progress of fluorosilicone rubber[J]. China Elastomerics, 2017, 27(2):60-66
[3] Hu Zhenxian, Gu Liang. Shocker Mount Dynamic test and property analysis[J]. Transactions of Beijing Institute of Technology, 2010, 30(4):400-414
[4] Zhang Lixia. Static and dynamic analysis of rubber isolators on rapid wagon[D]. Chengdu: Southwest Jiaotong University, 2013
[5] Zeng Cheng, Hua Hongxing. Study on shock response characteristics of nonlinear rubber isolator[J]. Noise and Vibration Control, 2012, 4:20-24
[6] Liu Wenwu, Weng Xuetao, Lou Jingjun, et al. Study on the harmonic response method to analyse the dynamic characteristics of rubber products based on ANSYS[J]. Journal of Wuhan University of Technology (Transportation Science & Engineering), 2010, 34(5): 966-968
[7] Lei Gang, Liu Ying, Hu Peng, et al. A study on dynamic characteristics of rubber bushing[J]. Science Technology and Engineering, 2015, 15(7):74-78
[8] J.B. Le Cam. Energy storage due to strain-induced crystallization in natural rubber: The physical origin of the mechanical hysteresis[J]. Polymer, 2017, 127(3):166-173
[9] T. Bhave, M. Tehrani, M. Ali, et al. Hysteresis friction and nonlinear viscoelasticity of rubber composites[J]. Composites Communications, 2018, 9:92-97
[10] Lin Song, Gao Qing. Dynamic Constitutive study for viscoelastic damping material[J]. Atomic Energy Science and Technology, 2008, 428:584-587