Energy dissipation of a ring-like metal rubber isolator

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Metal rubber (MR) is a kind of homogeneous poroelastic damping material made of metal wire. In this paper, by analyzing the forces on the MR isolator and the MR element, the hysteresis loops of the force and deformation are studied and verified by experiments. The results show that the force and displacement hysteresis loop of the MR isolator is described by the force and deformation hysteresis loops of the MR elements. In addition, the relationship between the energy dissipation coefficient of the MR element and that of the MR isolator is derived. The energy dissipation coefficient is programmed and calculated by MATLAB using experimental data, and the results are compared with the theoretical value. It is the basis for the design and applied research of the MR isolator in a future study.

Keywords: metal rubber, hysteresis loop, experimental study, energy dissipation coefficient

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1. Introduction

MR is a new type of porous damping material, and it originated from the former Soviet Union in the early 1970s.[1–3] Components made of MR not only have properties of rubber-like elasticity, but also damping through dissipating energy when they are subjected to vibration and shock. An isolator made of MR has a high damping capability and can work at high and low temperatures and high pressure, in a corrosive media environment, a vacuum, and radiation condition.[4–8] So it is widely used in the vibration protection system and its working performance is superior to those of other materials.

Several scholars have studied the application of MR to isolation.[9–12] Based on those studies, some further research is carried out in this paper. In the MR isolator, the MR element dissipates the energy and withstands forces acting on the MR isolator. The relationship of force and displacement hysteresis loop between the MR isolator and the MR element is studied in this paper. The energy dissipation coefficient of the MR isolator is analyzed by this method.

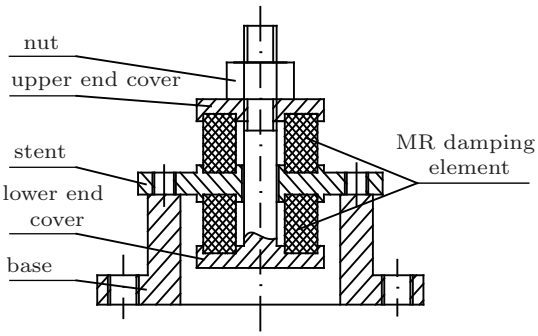
2. Hysteresis loop of the MR isolator

The MR isolator made of 1Cr18Ni9Ti, which is to be studied in this paper, is shown in Fig. 1. Generally, MR only bears pressure, but the MR isolator can withstand either tensile or compressive force when MR elements are installed in the upper and lower layers of the isolator.

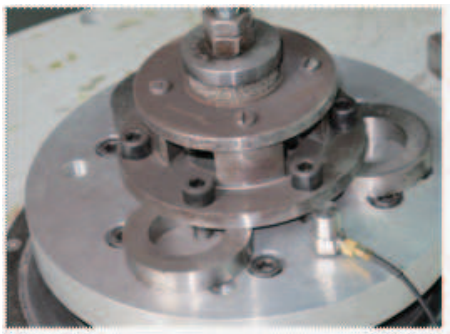
Due to an external load acting on MR, the force analysis of the upper and lower layer MR elements can be used to describe the force and displacement of the isolator. To carry out force analysis, upper end cover, lower end cover, and nut are considered as part 1, the stent and base as part 2, and the influence of gravity can be ignored when it is compared with the forces on the MR element. The force analysis is presented in Fig. 2. In Fig. 2, F is the force (external load) of testing the machine's pressing-head on the isolator, p_1 is the pressure of the lower-layer MR element on the lower end cover (stent), p_2 is the pressure of the upper-layer MR element on the upper end cover (stent) and N is the force of the base on the bottom of the MR isolator.

F_1 and F_2 can be expressed as

$$\begin{cases} F_1 = 0.25\pi(D^2 - d^2)p_1, \\ F_2 = 0.25\pi(D^2 - d^2)p_2, \end{cases} \tag{1}$$



(a)



(b)

Fig. 1. (color online) (a) Schematic illustration of the MR isolator and (b) a photo of the material object.

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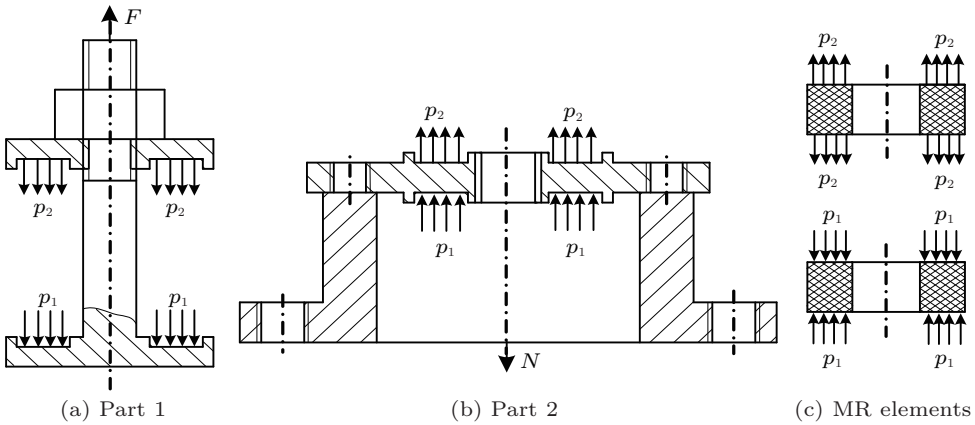


Fig. 2. Force analysis of the MR isolator.

where F_1 and F_2 are the forces acting on the lower and upper MR element respectively, D and d are the outer and inner diameters of the MR element respectively.

The relationship between F_1 and F_2 can be expressed as

$$F - F_2 - F_1 = 0 \Rightarrow F = N = F_2 + F_1. \tag{2}$$

Equation (2) gives a superposed force F, which acts on the upper and lower MR elements. Force and deformation hysteresis loop of the MR element can be converted by coordinate transformation. Before working, MR elements in the isolator will withstand pre-deformation to a certain degree. Regard Q as the pre-deformation of the upper and lower MR elements, A as amplitude isolator bear, x as displacement (or load) of testing the machine's pressing-head, then the deformation range ΔH of the upper and lower MR damping elements will be $\Delta H \in (Q-A, Q+A)$ when $Q > A$ and $\Delta H \in (0, Q+A)$ when $Q \leq A$. The loads on the upper and lower MR elements are contrary, so it is impossible to load and unload simultaneously.

Figures 3 and 4 show the superimposed diagrams of forces converted by upper and lower MR elements when $Q \leq A$ and $Q > A$ respectively. In Figs. 3 and 4, F_{11} and F_{12} are the loading and unloading curves of the lower MR element respectively, F_{21} and F_{22} are the loading and unloading curves of the upper MR element respectively, T_1 and T_2 are the forces when the MR element loaded and unloaded to the amplitude 0 of the isolator respectively, T_3 is the force when MR unloaded to the amplitude A of the isolator, $F_{\max}$ is the maximum force that the MR element can withstand.

The hysteresis loops of the lower and upper MR elements are shown in the I–II and III–IV quadrants respectively in Figs. 3(a) and 4(a). When $Q \leq A$, the maximum forces, which the MR element and the isolator can withstand, are equal. When $Q > A$, the maximum force that the MR element can withstand is larger than the one that the isolator can do, and when Q is much larger than A, the difference between the maximum forces will become greater.

The cyclic tension and compression experiments are carried out on the MR isolator with relative density $\bar{\rho} = 0.22$, and metal wire diameter $d_w = 0.12$ mm and we control pre-deformation $Q = 1.8$ mm. Before the experiments, compression experiments on the upper and lower MR elements have been done. Figure 5 shows the experimental curves of force and deformation of the upper and lower MR elements.

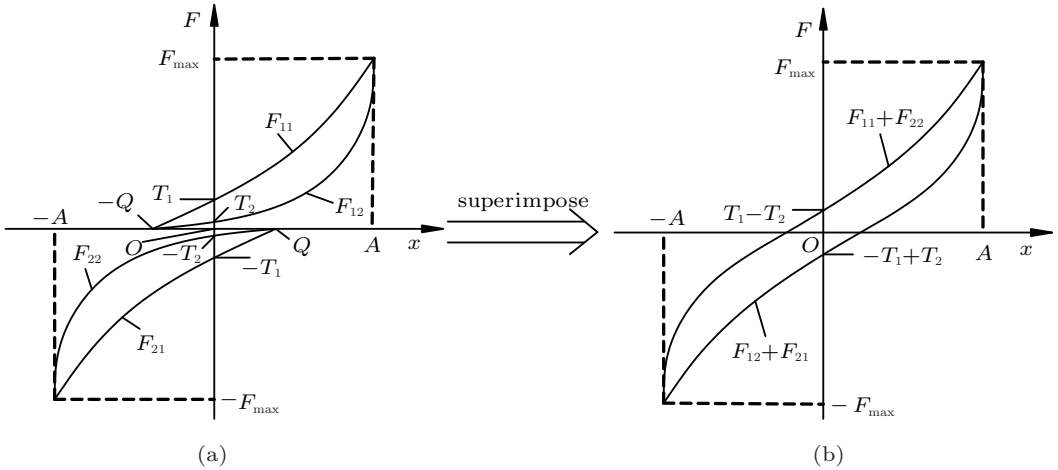


Fig. 3. Superimposed diagrams of forces when $Q \leq A$, showing the relationships between force and displacement of (a) MR element bear and (b) MR isolator bear.

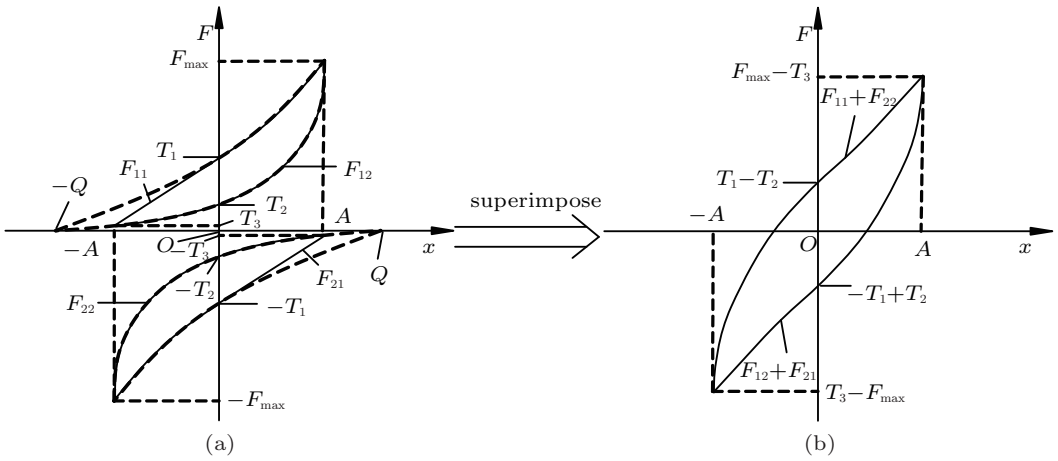


Fig. 4. Superimposed diagram of forces when $Q > A$, showing the relationships between force and displacement of (a) MR element bear and (b) MR isolator bear.

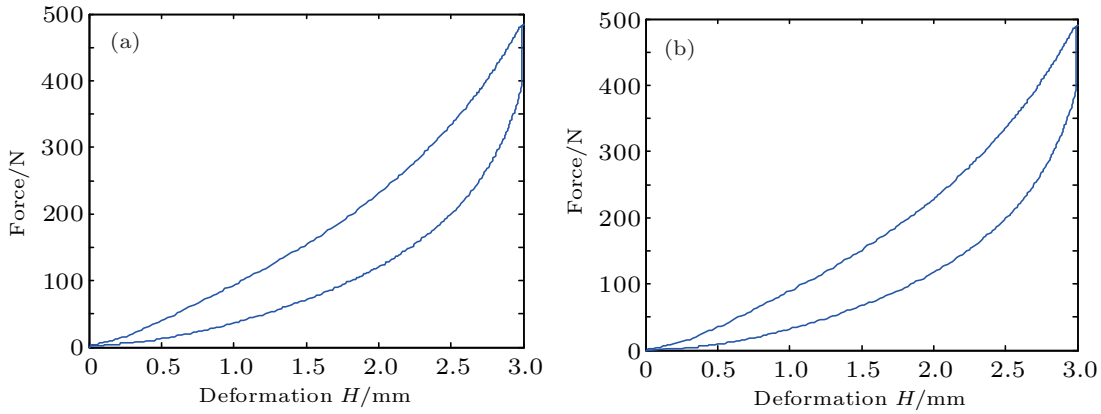


Fig. 5. (color online) Experimental curves of force and deformation of (a) upper and (b) lower MR elements.

Figure 6 shows the force and displacement hysteresis loops of the MR isolator, where the solid and dotted lines represent the experimental curves and the superimposed curves respectively. The superimposed curve is calculated using the force and deformation experiment data in Fig. 5 and coincides with the experimental curve basically. It indicates that it is feasible to describe the force and displacement hysteresis loop of the MR isolator using the force and deformation hysteresis loops of the upper and lower MR elements.

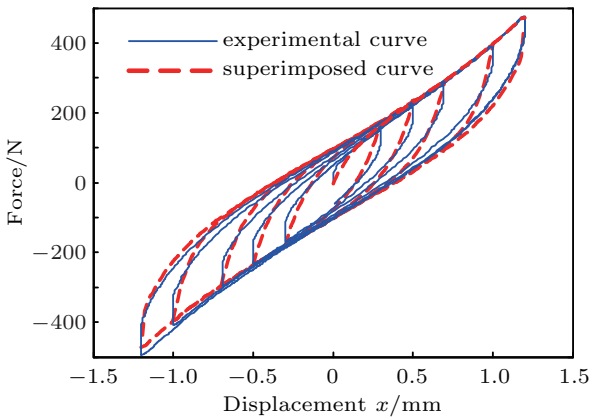


Fig. 6. (color online) Force and displacement hysteresis loops of the MR isolator.

3. Energy dissipation coefficient analysis of the MR isolator

The area of the hysteresis loop represents the dissipation energy. As the force and the displacement hysteresis loop of the MR isolator can be obtained by superposing the force and deformation hysteresis loops of MR elements, it is deduced that the energy dissipation coefficients of the MR isolator can be achieved by using those of the MR element. Regarding the amplitude of the MR isolator as A, then the maximum deformation of the MR element will be $A+Q$. The energy dissipation coefficients corresponding to the MR element and isolator are Ψ_1 and Ψ_2 respectively (Ψ_2 is the ratio between the energy that the MR element dissipates in the isolator and the variable elastic potential energy).

As shown in Figs. 3 and 4, the hysteresis loop areas of the upper or lower MR element and MR isolator are S_1 and S_2 respectively. S_1 and S_2 can be expressed as

$$S_1 = \int (F_{11} - F_{12})\,\mathrm{d}x = \int (F_{22} - F_{21})\,\mathrm{d}x, \tag{3}$$

$$S_2 = \int ((F_{11} + F_{22}) - (F_{12} + F_{21}))\,\mathrm{d}x = \int (F_{11} - F_{12})\,\mathrm{d}x + \int (F_{22} - F_{21})\,\mathrm{d}x. \tag{4}$$

Their relationship is written as

$$S_2 = 2S_1. \tag{5}$$

When $Q \le A$, Ψ_1 and Ψ_2 can be expressed as

$$\Psi_1 = \frac{S_1}{0.5F_{\max}(A+Q)}, \tag{6}$$

$$\Psi_2 = \frac{S_2}{0.5F_{\max}A} = \frac{2S_1}{0.5F_{\max}A}, \tag{7}$$

and their relationship is written as

$$\Psi_2/\Psi_1 = 2 + 2Q/A. \tag{8}$$

When $Q > A$, Ψ_1 and Ψ_2 can be expressed as

$$\Psi_1 = \frac{S_1}{0.5(F_{\max} - T_3)2A} = \frac{S_1}{(F_{\max} - T_3)A}, \tag{9}$$

$$\Psi_2 = \frac{S_2}{0.5(F_{\max} - T_3)A} = \frac{4S_1}{(F_{\max} - T_3)A}, \tag{10}$$

and their relationship is written as

$$\Psi_2/\Psi_1 = 4. \tag{11}$$

Loaded tests are carried out on MR elements with $d_w = 0.12$ mm and $\bar{\rho} = 0.24$. Tension and compression tests are done on the MR isolator with those parameters and $Q = 1.05$ mm. Then Ψ_1 and Ψ_2 are obtained by the test data processed by MATLAB. The results are shown in Table 1.

Table 1. Energy dissipation coefficients and their ratios for different amplitudes when $Q = 1.05$ mm.

A/mm	Ψ_1	Ψ_2	Ψ_2/Ψ_1	Theoretical values of Ψ_2/Ψ_1
0.3	0.606	2.3713	3.9129	4
0.5	0.5951	2.0647	3.4697	4
0.8	0.4835	1.7355	3.5893	4
1.2	0.3883	1.4252	3.6699	3.75
1.5	0.3599	1.2402	3.4459	3.4
1.8	0.3202	1.0802	3.3741	3.1667

From Table 1 it follows that there exist deviations of the theoretical values given by Eqs. (8) and (11) from the experimental data. The deviations arise due to two reasons. The first one is the inherent characteristics of the MR element, which result in poor control of pre-deformation; the second one is the empirical formula used in the calculation, which has an inherent error.

4. Conclusions

In this paper, forces of the MR isolator and the MR element are analyzed and the results revealed that the force and displacement hysteresis loop of the MR isolator can be derived by superimposing the force and deformation hysteresis loops of MR elements, which is in good agreement with the experimental result. Based on this method, the relationship between the energy dissipation coefficient of MR and that of the MR isolator is deduced, and the theoretical and experimental results are basically consistent with each other. It is the basis for the optimal design and applied research of the MR isolator in complex environments.

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