Application of Magnetorheological Elastomer (MRE) for Smart Vibration Systems

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Abstract Magnetorheological elastomers are intelligent materials in which many scientists have recently been interested in innovative vibration systems. MRE is made by embedding micro-sized iron particles into an elastomer such as natural rubber. MRE has overcome the disadvantages of magnetorheological fluids (MRF), such as deposition problems, leak problems, and response only under velocity. MRE-based devices have many outstanding advantages in intelligent vibration systems, such as MRE-based isolators, absorbers, and MRE sensors. Mechanical properties, especially the modulus, change remarkably when a magnetic field is applied. MRE-based devices combine with a semi-active controller so that the system can avoid resonance, isolate excitation vibrations, or absorb existing vibrations. These systems can be remarkably effective in car suspension, construction sites, and mechanical systems. This paper aims to provide a comprehensive overview of MRE application aspects, including fabrication methods, properties of MREs, modeling, and applications of MREs in vibration systems.

Keywords Magnetorheological elastomer · Vibration control system · Semi-active control

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1 Introduction

Magnetorheological (MR) materials have become important intelligent materials in industrial potential [1]. MR materials can adjust dynamic modulus and viscosity under an external magnetic field. MR materials include MR—Foam (MR foam), MR—Gel (MRG), MR—Fluid (MRF), and MR—Elastomer (MRE). MRE is an intelligent material consisting of micrometer-sized magnetic particles dispersed in a polymer elastomer. Among them, natural rubber has excellent mechanical properties and other comprehensive properties that are the ideal base material for the preparation of MRE. MRE has many advantages, such as fast response, good reversibility, and controllability. Therefore, the application of MRE in suspension systems and integrated semi-active controllers has great research value and potential for application in engineering.

The MRE's viscoelastic properties significantly depend on the magnetic field strength [2]. Therefore, modeling the MRE characteristics is a major challenge, especially in the design of semi-active controllers. Many researchers have proposed different models such as The Kelvin-Voigt, the Dahl, the LuGre friction, the Bouc-Wen, smooth Coulomb friction models [3–5].

The semi-active suspension system can adjust the stiffness and operating mechanism of the system. A system using an MRE-based device needs to integrate a semi-active controller. There are many control methods [6–10], such as optimized control methods, self-adaptive control methods, fuzzy logic control methods, sky-hook, PID, Fuzzy, Clip-optimal, Bang-bang, Lyapunov, adaptive algorithms, and neural network control methods. This study presents problems related to magnetorheological elastomers, including fabrication methods, MRE properties, modeling, and applications. A single degree of freedom system was simulated to evaluate the effectiveness of the material.

2 MRE Material Overview: Fabrication, Properties, and Modeling

2.1 Fabrication of MRE Materials

The fabrication of MRE is almost the same as that of the curing of rubber. The material composition includes silicon rubber, silicon oil, and iron particles (10 μm) with a ratio of 60%:2%:38%, respectively. The material was mixed into a homogeneous mixture using a centrifugal mixer for 10 min. After mixing, the mixture is placed in a low-pressure chamber to remove air bubbles inside the material for about 20 min. Then the mixture is then poured into a plastic mold and cured at room temperature for 24 h. The mixture is placed in a magnetic field of strength 0.5 T to form an anisotropic material during curing. MRE samples has been fabricated (Fig. 1).

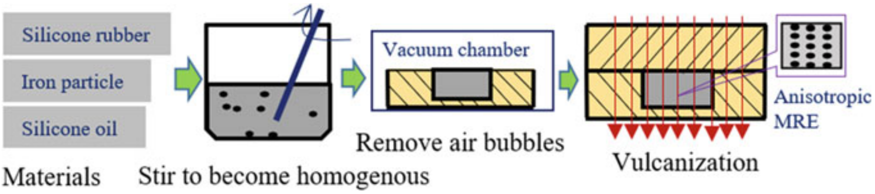

Fig. 1 The MRE fabrication process

2.2 Experiment Set up

In this study, the MRE property measurement system is used to test the dynamics properties of the MRE, as shown in Fig. 2. The system consists of a fixed iron core mounted with a force sensor. The movable core with the integrated coil is attached to the vibrating table to perform harmonic oscillation. The coil with a diameter of 1 mm is wound 650 turns to create an electromagnet in the movable iron core. The movable core is attached to the vibration table, while the stationary core is connected to a force sensor to measure the strain response force of the material (Piezoelectronic PCB, Model: 208C02). Two samples of MRE material are placed between two electromagnet cores. Direct current (DC) power supplies current to the coil to change the strength of the magnetic field passing through the material. A laser sensor for measuring table displacement (laser displacement sensor KEYENCE LB-02). The force and displacement sensors are connected to the oscilloscope to measure the force–displacement responses. A servo motor drives an eccentric wheel. In this study, we used two eccentric wheels with deviations of 0.4 and 0.8 mm, respectively. Eccentricity is the amplitude of the vibration. The table is heavy enough to ensure that the table is always in contact with the eccentric wheel. The servo motor's speed is also the table's vibration frequency and can be adjusted. To further investigate the influence of the magnetic field on the mobility characteristics of the MRE, in this study, the frequency excitation is performed from 1 to 30 Hz, and the magnetic field from 0 to 350 mT corresponds to the voltage current. Use from 0 to 5 A. The oscillation amplitude is 0.4 to 0.8 mm, corresponding to the shear strain of 4 to 14%.

2.3 Numerical Model and Properties of MRE

It is necessary to develop a numerical model to represent the dynamic characteristics of the MRE to design systems using the MRE. Many researchers in recent years have exploited numerical models for MRE materials. In this study, the Bouc-wen model is used to represent the behaviors of MREs as shown in Fig. 2. The model consists of two parts: the linear stiffness associated with damping that represents the viscoelastic properties and the Bouc-Wen component that describes the hysteresis behavior of the material. The response force of the model is expressed as,

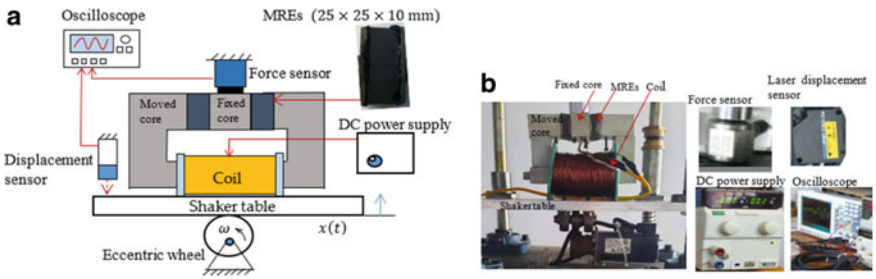

Fig. 2 Experiment set up to measure the properties of the MRE in the shear state: **a** schematic **b** photo of devices

$$F_{\mathrm{MRE}} = \alpha k_0 x + c_0 \dot{x} + (1 - \alpha) k_0 h, \tag{1}$$

$$\dot{h} = A\dot{x} - \beta |\dot{x}||h|^{n-1} z - \gamma \dot{x} |h|^n, \tag{2}$$

where the linear stiffness force and a purely hysteretic force are $\alpha k_0 x$ and $(1 - \alpha) k_0 h$, respectively. The coefficient, $\alpha \in (0, 1)$, represents the linearity level of the loop. The parameters A, n, β, and γ represent the shape and size of the hysteresis loop as shown in the Eq. (2). Where A is related to the amplitude of the hysteresis loop, β and γ represent the shape of the delay, and n is the nonlinear order of the hysteresis.

The variables model are approximated under input current as follow,

$$\begin{aligned} k_0 &= k_{0a} + k_{0b} I,\ c_0 = c_{0a} + c_{0b} I, \\ \alpha &= \alpha_a + a_b I,\ A = A_a + A_b I, \\ \beta &= \beta_a + \beta_b I,\ \text{and}\, \gamma = \gamma_a + \gamma_b I. \end{aligned}$$

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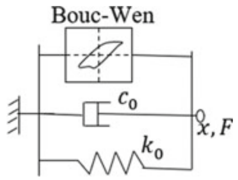
The least squares method is used to determine the parameters of the model. A data set is used to update the parameter so that the least mean square error is within the allowed range. This method is easy to use and highly effective in determining the parameters of nonlinear models. The parameter values of the model are listed in Table 1 (Fig. 3).

Comparison of force–displacement response between model and experimental results under different levels of applied current with excitation amplitude $x_0 = 0.75$ mm: (a) $f = 1$ Hz, (b) 15 Hz, as shown in Fig. 4. When performed at a low

Table 1 Parameter values of MRE-based obsorber using Bouc–Wen model

k_{0a}	c_{0a}	α_a	A_a	β_a	γ_a	k_{0b}	c_{0b}	a_b	A_a	β_a	γ_a
25	0.06	0.6	2	3.8	-1	12	0.01	0.05	0.2	0.2	0.3

Fig. 3 Bouc-Wen model



frequency (1 Hz), the viscosity of the material is negligible; we see that the amplitude of the force response increases significantly with increasing current. However, the loop width increases significantly with increasing current. This demonstrates that the magnetic field affects the hysteresis properties of the material. When the amplitude of oscillation changes, the angle of inclination of the loop also changes. As the oscillation frequency increases to 15 Hz, the loop becomes more elliptical due to the influence of viscous. Figure 5 shows the change in the stiffness under the applied current (magnetic field) levels. In this experiment, the stiffness is defined as $k = F_0 \big/ x_0$, where k is the stiffness, F_0 is the amplitude force of the shear force, and x_0 is the amplitude displacement of the shear strain. The stiffness increases significantly when the material is placed in the magnetic field. From the figures, we see that the model represents the properties of the MRE well. This model can be used for the design of vibration systems.

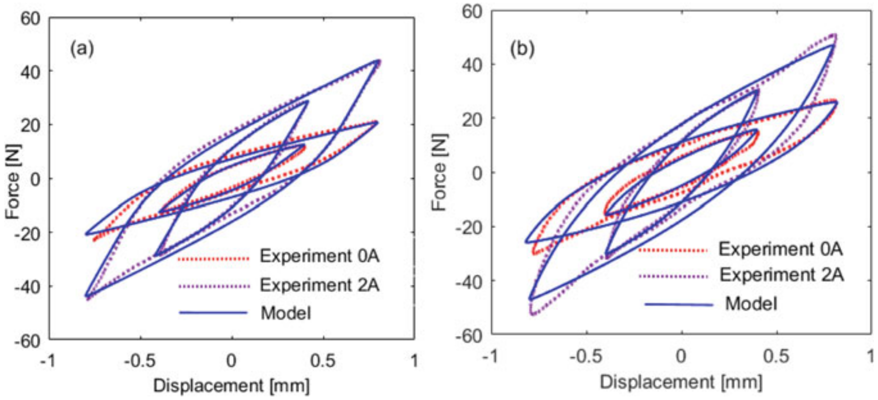


Fig. 4 Comparison between model and experimental

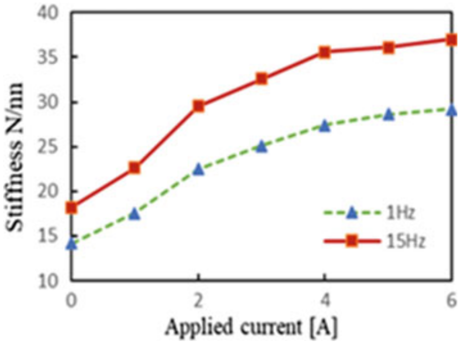


Fig. 5 Stiffness response of MRE

3 Application of Magnetorheological Elastomer (MRE) in Vibration Systems

The one-degree-of-freedom oscillation system is investigated, as shown in Fig. 6, to analyze the damping effect using MRE. The MRE is the system's elastomer, where the stiffness is adjustable. Assuming the system uses the material sample as investigated above, the minimum stiffness (no current applied) is $k_1 = 13\,\mathrm{N}\big/\mathrm{mm}$,, the maximum stiffness (4 A) is = 30 N/mm, mass $m = 1.5$ kg, and the damping coefficient $c = 1\,\mathrm{Ns}\big/\mathrm{mm}$. The dynamic equation of the system is described in the time domain as,

$$m\ddot{y} + c\dot{y} + ky = c\dot{z} + kz. \tag{3}$$

Equation (3), m is the mass, z the displacement of the ground base, c the MRE damping coefficient, y the displacement of mass, k is the variable stiffness parameter of the MRE, k stiffness value is adjustable from k_1 to k_2.

Use the Laplace transform for Eq. (3) and the ratio of the output to the input is determined

$$L(s) = \frac{Y(s)}{Z(s)} = \frac{\frac{c}{k}s + 1}{\frac{m}{k}s^2 + \frac{c}{k}s + 1}, \tag{4}$$

where $Z(s)$ is the Laplace transform function of $z(t)$, and $Y(s)$ the transform of $y(t)$.

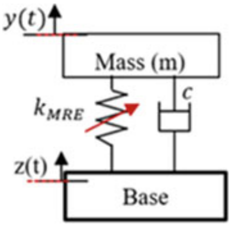


Fig. 6 1DOF vibration system using MRE

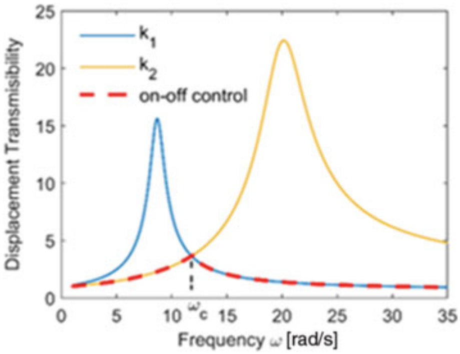


Fig. 7 The transmissibility of mass response in frequency domain

By replacing s with $j\omega$ in function $L(s)$, displacement transmissibility $T_R(\omega)$ of the system $L(j\omega)$ is further defined in frequency domain as

$$T_R(\omega) = |L(j\omega)| = \sqrt{\frac{1 + (\omega\eta)^2}{\left(1 - \omega/\omega_0\right)^2 + \eta^2}} \tag{5}$$

where $\omega_0 = \sqrt{k/m}$ is the tunable natural frequency of the system

The switching control algorithm was used to optimize the response in the frequency domain,

$$k = \begin{cases} k = k_1(k_{\min}, I = 0\,A), \text{ if}\omega \le \omega_c \\ k = k_2(k_{\max}, I = 4\,A), \text{ if}\omega > \omega_c \end{cases}, \tag{6}$$

where ω is the base excitation frequency, I is the applied current to the coil, ω_c is the switching frequency value that is the characteristic frequency of the system and determined as shown in Fig. 7.

The response of the system is shown in Fig. 7. The figure shows that the system's natural frequency can be adjusted from 8 to 22 rad/s. The transmissibility of the system is greatly reduced when using the on–off algorithm. From the investigation of the 1-DOF system using MRE, it is found that the system is efficient and avoids resonance for the vibration system.

4 Conclusion

This study introduces magnetorheological elastomer (MRE) in the field of vibration, including fabrication methods, mechanical properties, models, and applications. The MRE properties are non-linear functions of the magnetic field density, displacement amplitude, and excitation frequency. A dynamic elastic model of an isolator based on the MRE has been presented. Models are also introduced to represent the MRE properties, in which the Bouc-Wen model has described the MRE's dynamic properties well. Vibration systems using the MRE were also introduced. One-degree-of-freedom vibration system has been investigated; the results show that the response is significantly reduced when the system is combined with a control algorithm.

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