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ARTICLE

Damping of Magnetorheological Elastomers

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The damping property of magnetorheological (MR) elastomers is characterized by a modified dynamic mechanical-magnetic coupled analyzer. The influences of the external magnetic flux density, damping of the matrix, content of iron particles, dynamic strain, and driving frequency on the damping properties of MR elastomers were investigated experimentally. The experimental results indicate that the damping properties of MR elastomers greatly depend on the interfacial slipping between the inner particles and the matrix. Different from general composite materials, the interfacial slipping in MR elastomers is affected by the external applied magnetic field.

Key words: Magnetorheological elastomers, Damping property, Interfacial slipping

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I. INTRODUCTION

Magnetorheological (MR) materials belong to a class of function materials with smart behavior, due to their rheological properties that can be changed continuously, rapidly and reversibly by applied magnetic fields. Recently, MR materials have been playing important roles in the domain of the automotive vehicles, architecture, vibration controls, etc. [1].

The most common MR materials are MR suspensions, comprising micro-sized or sub-micro-sized magnetizable particles dispersed in liquid-state materials. Changes of two or three orders of magnitude may occur in the yield stress and apparent viscosity, as well, the suspension system changes from Newtonian liquid to non-Newtonian liquid when a magnetic field was applied on MR suspensions [2-8].

MR elastomer is the solid-state analogue of MR fluid, and a new branch of MR materials [9-15]. The problems existing in MR suspensions such as particle sediment are well overcome via replacing the fluid matrix by a solid matrix such as a polymer. By curing the polymer in the magnetic field, the field-induced interactions between particles can result in the formation of anisotropic ordered pre-configuration such as chains or more complex three-dimensional structures. After the mixture is cured or crosslinked, these structures are locked into place. When such prepared MR elastomers are exposed to an applied magnetic field, the field-induced dipole magnetic forces between the particles result in the field dependence performance. MR elastomers have attracted increasing attention and obtained broad application prospects recently. Bellan *et al.* studied the shear stress-strain relationship under applied magnetic fields [16], Ginder *et al.* investigated the magnetostriction performance [17], and Bossis *et al.* researched the conductivity and optical properties [18]. Ginder [19], Lerner [20] and Deng [21] developed adaptive tuned vibration absorbers based on MR elastomers. It is noted that the absorber effect of those devices greatly depends on the MR elastomers' damping property. Theoretical results have shown that a low damping ratio leads to a high vibration reduction effect while high damping ratio results in bad vibration suppression [22]. However, little work has focused on the damping property of the MR elastomer so far. There are many unsolved problems existing in the damping property of this new novel particle/polymer composite.

In this work, the damping properties of MR elastomer was investigated. The influence of the matrix type, dynamic strain amplitude, driving frequency, and content of iron particles are characterized by using a modified dynamic mechanical-magnetic coupled analyzer system.

II. EXPERIMENTS

A. Preparation of MR elastomer materials

Two groups of MR elastomer samples were prepared. The first group of samples were fabricated on different types of matrix, including silicon rubber (SiR), natural rubber (NR), and chloroprene rubber (CIIR). These samples had the same ingredient proportions by weight (30% of rubber matrix, 10% of plasticizers, and 60% of iron particles). The iron particles were provided by BASF (German, model of SM) and had an average diameter of 2.5 μm.

When preparing the MR elastomer samples based on SiR, the iron particles, dimethyl-silicon oil (acting as plasticizer, with a viscosity of 0.3 Pa·s, provided by Shanghai Resin Factory, China), and RTV SiR (Xida Adhesives Factory, China, Model 704) were mixed together. Then the mixture was put into the mold un-

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der the magnetic flux density of 0.4 T for curing up to 24 h at room temperature. When preparing the MR elastomer samples based on NR and CIIR, the fabrication progress consisted of three major steps: mixing, forming pre-configuration and sulfuration. During fabrication, each composition was firstly mixed homogeneously, then the magnetic particles formed ordered structures, and finally the sample became an elastomer. The illumination of the mechanical-magnetic coupling fabrication system was detailed in Ref.[23]. With this method, MR elastomer samples based on NR and CIIR were prepared under the external magnetic flux densities of 0.4 T. The NR, CIIR, and other additives were provided by Hefei Wangyou Rubber Company of China.

The second group of samples were based on NR, with different proportions of iron particles (60%, 70%, 80%, and 90% by weight). In each sample, the content of the rubber matrix and plasticizers was the same, and the pre-configuration magnetic flux density was set as 1 T.

B. Dynamic testing system of MR elastomer performance

A Dynamic Mechanical Analyzer (DMA) is common equipment for dynamic testing on viscoelastic materials [24]. In this work, the DMA (Triton Technology Ltd.UK, Model Tritec 2000B) system was modified to characterize MR elastomer performances by introducing a self-made electromagnet which can generate a variable magnetic flux density up to 1 T (see the details in Ref.[23]). This system applies a fixed oscillatory strain on the specimen and measures the amplitude and phase of the output force, from which the resultant stress, the modulus (shear storage modulus G' and loss modulus G'' included), and the loss tangent ($\tan\delta=G''/G'$) can be calculated. Then the damping ratio of MR elastomer samples can be calculated. Testing involved recording the modulus and the damping ratio of various specimens at various frequencies, strains and applied magnetic fields.

The experiment was conducted at room temperature, and the temperature variation of the electromagnet was less than 3 °C during the whole experiment.

C. Observation of microstructure

The microstructure of the MR elastomer sample was observed by using an environmental scanning electronic microscope (SEM, Philip of Holland, model of XT30 ESEM-MP). The sample was firstly cut into pieces with surface area of 3 mm×3 mm, each surface of which was coated with a thin layer of gold and then placed into the SEM. The microstructures of samples were observed at an accelerating voltage of 15 kV. Through the microstructural observation, the interactions between rubber and magnetic particle were caught.

III. RESULTS

The damping ratio of the first group of MR elastomer samples, based on the NR, SiR, and CIIR, was measured at a dynamic strain of 0.3%, driving frequency of 5 Hz, and under various magnetic flux densities (B) from 0 up to 800 mT. The results are shown in Fig.1. It can be seen from this figure that the damping ratio of the MR elastomer based on NR is lower than that of MR elastomer based on SiR and CIIR. Figure 1 also shows that with the increment of magnetic field, the damping ratios of the MR elastomer samples follow an increasing trend until a maximum value (at about B=300 mT), then they follow a decreasing trend. This phenomenon has not been reported by others so far.

The damping ratio of the MR elastomer sample based on NR prepared in the first group was measured at a driving frequency of 5 Hz, under various magnetic fields from 0 up to 800 mT, and at dynamic strain amplitude of 0.03%, 0.16%, 0.3%, and 0.5%. The results are shown in Fig.2. It can be seen from this figure that the damping ratio has great dependence on the dynamic strain amplitude. When the strain amplitude is 0.03%, the average damping ratio is 0.04, and when the strain amplitude is 0.5%, the average damping ratio reaches 0.11. It is noticeable in Fig.2 that the damping ratio of MR elastomer with the strain amplitude of 0.03% fluctuates around 0.04 and does not obey the up-down trend seen in the other data.

The damping ratio of the MR elastomer sample based on NR fabricated in the first group was measured at dynamic strain amplitude of 0.3%, under various magnetic fields from 0 up to 800 mT, and at driving frequency of 5, 10, 15, and 20 Hz. Results are shown in Fig.3. In the figure, the damping ratio measured at 5 Hz is lower than those measured at other frequencies when the magnetic flux density is zero, higher than others when the magnetic flux density is 300 mT, and lower than others when the magnetic flux density is 800 mT. Therefore, the change of damping ratio at 5 Hz is higher than others in that applied field. The damping ratio is

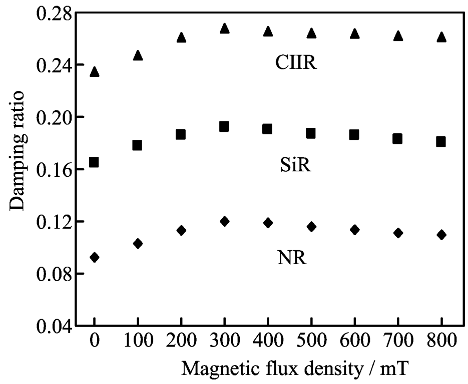

FIG. 1 Damping ratio of MR elastomers based on different types of matrix.

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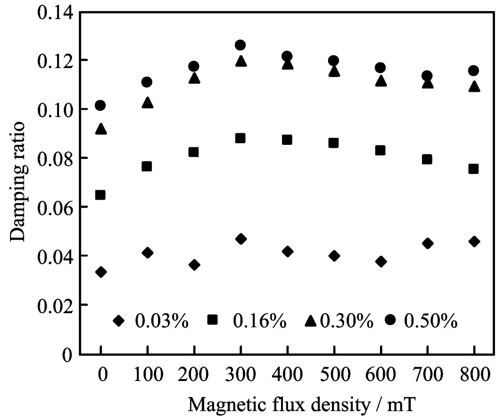

FIG. 2 Damping ratio of MR elastomers measured under different dynamic strain amplitudes.

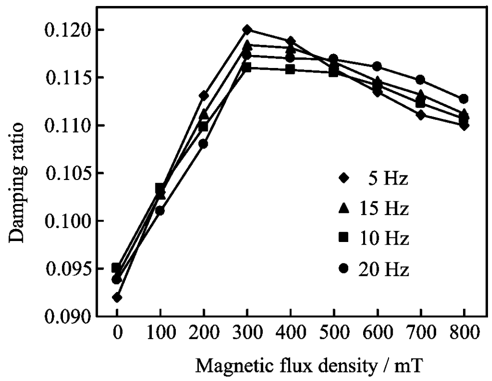

FIG. 3 Damping ratio of MR elastomers measured at different driving frequencies.

more affected by the magnetic field when the MR elastomer sample is driven at lower frequency.

The damping ratios of the second group of MR elastomer samples with iron particle contents of 60%, 70%, 80%, and 90%, were measured at dynamic strain of 0.3%, driving frequency of 5 Hz, and under various magnetic fields from 0 up to 800 mT. The results are shown in Fig.4. It can be seen from this figure that the damping ratio of the MR elastomer is markedly increased with the increment of the iron particle content.

IV. DISCUSSION

The damping ratio of composites usually comes from the total of each component. In addition, when components are combined with each other weakly, there is still some energy dissipation on the interfacial slipping. In this condition, the damping ratio of the composite consists of the damping ratio of the each component and the energy dissipation on the interface between each component [25]. Figure 5 is the microstructure of the MR elastomer based on natural rubber fabricated in the first group. The white spheres are the magnetic

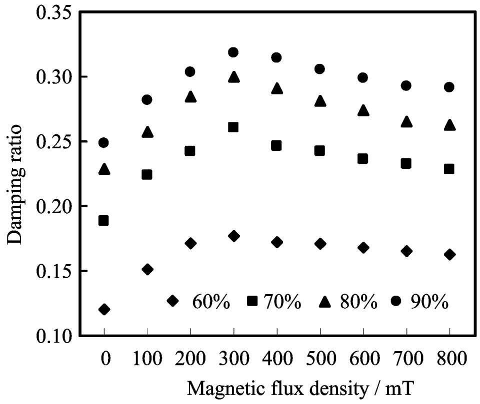

FIG. 4 Damping ratio of MR elastomers with different iron particle proportions.

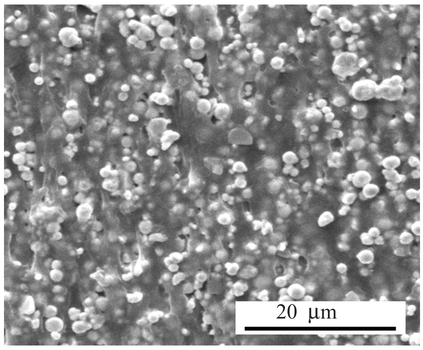

FIG. 5 The microstructure of the MR elastomer sample observed by an environmental scanning electronic microscope.

iron particles and the dark background is the rubber matrix. It is seen from Fig.5 that the iron particles are not all embedded in the rubber matrix and they are poorly combined with each other.

Since MR elastomer is a kind of weak inter-combined composite, its damping ratio can be expressed as

$$D = \phi_m D_m + \phi_p D_p + D_s \tag{1}$$

where ϕ_m and ϕ_p are the percentage in volume of the matrix and the particle respectively, D_m and D_p are the damping ratio of the matrix and the particle respectively, and D_s denotes the energy dissipation coming from the interfacial slipping between the inner particles and the matrix in unit volume. The damping ratio of particle D_p can be ignored compared with that of the polymer matrix, so Eq.(1) can be simplified into

$$D = \phi_m D_m + D_s \tag{2}$$

here D_s can be written as

$$D_s = nfS \tag{3}$$

where n is the number of particles in the unit volume of MR elastomers, f is the sliding frictional force between

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the particle and matrix, and S is the displacement of interfacial slipping.

When an external field is applied, a magnetic force is applied on the particle and is transferred to the rubber matrix. The rubber matrix is a kind of soft material whose shape is easily to changed by an external force, so the direction of static interaction force between particles and rubber is basically vertical to their contact interface. This means the average friction force $f=\mu(F_0+F_m)$, where μ is the friction factor between the iron particle and the matrix, and F_0 and F_m is interaction between particle and matrix without and with a magnetic field, respectively. Therefore, the damping ratio of MR elastomers can be written as

$$D = \phi_m D_m + \mu n(F_0 + F_m)S \tag{4}$$

From Eq.(4), it is known when MR elastomers are embedded with the same content of particles and then tested in the same condition, the damping ratio of the matrix plays an important role in the damping property of the MR elastomers. It has been proved in the rubber technology that the damping ratio of NR is lower than most rubbers, such as SiR and CIIR [26], so the natural rubber has a lower damping ratio than others. This result indicates that it is advisable to use natural rubber as the matrix to fabricate MR elastomers and is helpful to MR elastomer based adaptive tuned vibration absorbers whose vibration reduction effect can be enhanced by the low damping ratio.

From the Fig.1-Fig.4, it is seen that with the increase of the external magnetic field, the damping ratio of MR elastomers goes up steadily with a maximum at the flux density of 300 mT, and then gradually drops to a low value. This phenomenon has not been observed in other composite materials, and has not been reported by other magnetorheological materials research groups. The reason can be explained from the energy dissipation on the interface between the particles and matrix. When a low magnetic field is applied to the MR elastomer sample, the magnetic force between magnetic particles occurs and increases as the magnetic field increases. Therefore, the magnetic interaction (F_m) between particle and matrix is accordingly increased with the increase of the magnetic field. The larger F_m will lead to more energy dissipated on the interface slipping and the higher damping ratio of the MR elastomers. This relationship is also shown in Eq.(4). In these conditions, the damping ratio increases with the increase of the magnetic field. On the other hand, S is not a constant but a function of the F_m. It is easy to understand that if large normal force is applied, the slipping will become difficult, and the displacement of interfacial slipping will be reduced. So, as the increase of the magnetic field and the magnetic force, S is reduced. At this time, the energy dissipation on the interface goes down, and damping ratio of MR elastomers declines accordingly. For this reason, the damping ratio increase in the low field and decrease in the high field. This result indicates that the vibration reduction effect of the MR elastomer based vibration absorber can be increased by increasing the applied magnetic field after reaching the critical value of 300 mT.

The above results indicate that MR elastomer is a new kind of smart material whose damping ratio can be controlled by the magnetic field. Therefore it is hopeful to design a novel kind of the adaptive damper based on MR elastomer. Compared to the MR fluid damper, there will be neither airproof problem nor wall effects in the MR elastomer damper.

The result that damping ratio is affected by the amplitude of dynamic strains (see Fig.2) can also be explained by the energy dissipation method. As the dynamic strain amplitude increases, the slipping displacement on the interface S is increased. Then more energy will be dissipated, and the damping ratio is increased accordingly. The fact that the damping ratio of MR elastomer with the strain amplitude of 0.03% fluctuates around 0.04 suggests that there is little slipping between the particle and the matrix under such a low strain of 0.03%. The magnetic field has little impact on the energy dissipation and the damping ratio. Figure 2 also shows that little change happens to the damping ratio by increasing the strain amplitude when it reaches 0.3%. This indicates that the slipping displacement on the interface almost reaches the maximum when the dynamic strain amplitude is 0.3%.

An interesting phenomenon is shown in Fig.3 that the magnetic field has more influence on the damping ratio when the MR elastomer sample is driven at lower frequency. It can be explained from the viscoelastic behavior of rubber matrix. For the viscoelastic materials, there is always a phase difference between the input force and the output displacement. In other words, the displacement only occurs for some period of time after the force is applied. So when the driving frequency is too high, there is not enough time for the magnetic force to show its effects on the interfacial slipping and the energy dissipation. The result indicates the influence of the magnetic field on the MR elastomers' damping ratio will disappear when a high enough driving frequency is applied.

In Fig.4, as the particle content increases, the damping ratio of MR elastomer dramatically increases. From Eq.(4), it is known that when number of particles in the MR elastomers is increased, more energy is dissipated from the slipping on the interface, and the damping ratio is increased accordingly. It is noticeable that with the increase of the particle content, the percentage of matrix ϕ_m is decreased. This will decrease the damping ratio of MR elastomers to some extent. The fact of the increase in the damping ratio by particle content suggests that the energy dissipation on the interface damping ratio of the MR elastomers play a more role in than the damping ratio of each component.

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V. CONCLUSION

The damping property of MR elastomer samples was experimentally explored in this work. With an increasing magnetic field, the damping ratios first increases, then decreases after reaching a critical value. The critical magnetic flux density for MR elastomer damping ratio is 300 mT. The damping ratio of MR elastomer is affected by the matrix properties. Low damping ratio matrix leads to low damping ratio MR elastomer. The dynamic strain amplitude plays an important role in the damping ratio of the MR elastomer. As the dynamic strain amplitude increases, the slipping displacement on the interface is increased. Then the damping ratio increases accordingly. At lower driving frequency, the damping ratio of the MR elastomer sample has more dependence on the magnetic flux density. As the iron particle content increases, the number of contact points between particles and the matrix increases. Then more energy is dissipated from the slipping on the interface, and the damping ratio increases accordingly.

VI. ACKNOWLEDGMENTS

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