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Analysis and Verification on the Chain-like Model with Normal Distribution of Magnetorheological Elastomer

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Magnetorheological elastomer (MRE) is a new kind of smart materials, the rheological properties can be controlled rapidly by the external magnetic field. It is mainly composed of rubber and micron-sized ferromagnetic particles, which forms a chain-like structure. Therefore its mechanical, electric, and magnetic properties can be changed by the applied magnetic field, which is called as the magneto-induced effect. But this effect is not remarkable enough currently for the engineering application. So it is important for material preparation to optimize parameters to enhance the magneto-induced effect. In this work, based on chain-like model, some factors influencing the magneto-induced effect of MRE were analyzed theoretically by using dipole method with the normal distribution of chain's angle introduced. The factors included the oblique angle of particles chains, magnetic field intensity, and shear strain, etc. Some experiments were also carried out.

Key words: Magnetorheological elastomer, Dipole, Magneto-induced effect, Normal distribution

I. INTRODUCTION

Magnetorheological (MR) materials are a group of smart materials, the rheological properties can be controlled rapidly by the external magnetic field. 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 fluid (MRF), 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 [2–8].

Magnetorheological elastomer (MRE) is the solid-state analogue of MRF, and a new branch of MR materials [9–15]. MREs are a new member of MR materials which consists of natural or synthetic rubber and micron-sized magnetizable particles solidified under the external magnetic field [15] and its shear modulus can be significantly changed. It has a very broad prospect in adjustable stiffness of small amplitude vibration systems because its application devices do not need sealing, and have stable performance and quick response [5,6,9]. MRE was introduced by Shiga *et al.* [9] and Jolly *et al.* [5] almost a decade ago when many research efforts were still made on MRF and MRF-based damping devices.

By curing the polymer in the magnetic field, the field-induced interactions between particles can result in the formation of anisotropic ordered preconfiguration such as chains or more complex three dimensional structures. After the mixture is cured or cross-linked, these structures are locked into place. When such prepared MREs are exposed to an applied magnetic field, the field-induced dipole magnetic forces between the particles result in the field dependence performance.

One of the most important factors describing the magnetorheological effect of MREs is shear modulus change caused by magnetic field. Currently, MREs can not be used cosmically because of the limited range of shear modulus caused by magnetic field. So it is very important to study the MRE shear modulus, the factors influencing shear modulus change of MREs should be analyzed theoretically. Firstly the internal structure of the MRE should be understood clearly.

When the MRE is prepared, the particles form an ordered chain structure in the matrix [15]. Because of the chain-like structure of particles in the rubber, its mechanical-electrical and magnetic properties can be controlled by the applied magnetic field.

MRE has attracted increasing attention and obtained broad application prospects recently. Jolly *et al.* assumed that the iron particles in the rubber form chain-like structure under the external magnetic field, particles are aligned in perfect chains (albeit with gaps between particles), quasistatic shear strains and associated stresses are uniformly distributed over the length of each particle chain. They also calculated the shear modulus [15]. Bellan *et al.* studied the shear stress-strain

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relationship under applied magnetic fields [16]. Ginder *et al.* investigated the magnetostriction performance [17]. And Bossis *et al.* researched on the conductivity and optical properties [18]. Shen *et al.* considered the interactions between adjacent particles in a chain, and he also thought that the particles chain was completely parallel with the external magnetic field [19]. Dang *et al.* analyzed the effect of distributed chains and got the relationship of chains which was parallel with external magnetic field and chains that was not parallel with external magnetic field, however the specific result was not be calculated [21].

MRE can be applied potentially in the wide field of vibration isolation and impact buffering, and helps to greatly simplify the mechanical structures. But its magneto-induced effect is not remarkable enough currently for the engineering application. So it is important for material preparation to optimize parameters to enhance the magneto-induced effect.

However, there exist many unsolved problems in the magnetorheological effect and the shear modulus of MRE. In this work, on the basis of chain-like model, some factors including the oblique angle of particles chains, magnetic field intensity and shear strain etc. which influence the magneto-induced effect of MRE are analyzed theoretically by using dipole method. Furthermore the normal distribution of chain's angle is introduced to optimize the result, and some experiments were carried out.

II. THEORETICAL CALCULATION

In fact, particle chain is not strictly along the direction of the preparation magnetic field, but has a certain angle with the direction of the magnetic field. When MRE is sheared, particle chain also has a certain angle with the direction of the external magnetic field, because the external magnetic field and the preparation magnetic field are of the same direction. So analyzing the magneto-induced shear modulus, the angle between the particle chain and the direction of the magnetic field should be considered.

A. The relation of the angle and the shear strain (θ out of γ')

Each of the magnetic particles in the MREs is regarded as a magnetic dipole under the applied magnetic field.

Based on the dipole theory, under the external magnetic field, two adjacent particles' magnetic energy can be expressed as Eq.(1).

$$E_{12} = \frac{1}{4\pi\mu_0\mu_1}\left[\frac{\mathbf{m}_1\cdot\mathbf{m}_2 - 3(\mathbf{m}_1\cdot\mathbf{e}_r)(\mathbf{m}_2\cdot\mathbf{e}_r)}{|r|^3}\right] \quad (1)$$

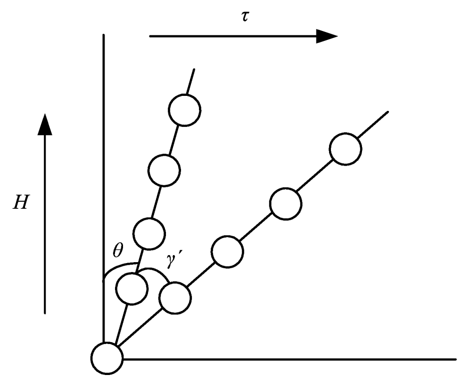

FIG. 1 Shear deformation of oblique chain.

where μ_1 is particle magnetic conductivity, μ_0 is vacuum magnetic conductivity, m is dipole moment, r is the particle spacing.

It is assumed that the dipole moment keeps constant in the shear strain, and is aligned in the direction of the applied magnetic field.

Denoting shear angle of the chains by θ, when the dipole moments are of identical strength m and are aligned in the same direction as applied field before deformation, Eq.(1) becomes:

$$E_{12} = \frac{1}{4\pi\mu_0\mu_1}\cdot\frac{m^2(1-3\cos^2\beta)}{|r|^3} \quad (2)$$

where β=θ+γ', θ is the angle between the initial state chain and the direction of magnetic field, γ' is the strain of chain (Fig.1). For a particle, the dipole moment is determined by:

$$m = \frac{4}{3}\pi a^3\mu_0\mu_1\chi H \quad (3)$$

where a is particle radius, χ is particle magnetization coefficient, H is magnetic field intensity.

Considering the interaction among particles in the same chain after being magnetized, the magnetic field intensity in the particle i can be expressed as:

$$\begin{aligned} H_i &= H_0 + \sum_{j\neq i} H_j \\ &= H_0 + 2\cos\theta\cdot\sum_{j=1}^{n}\frac{3r_j(r_j\cdot m_j) - m_j}{4\pi\mu_0\mu_1 {r_j}^3} \\ &= H_0 + 2\cos\theta\cdot\sum_{j=1}^{n}\frac{m(3\cos^2\theta-1)}{4\pi\mu_0\mu_1 {r_j}^3} \end{aligned} \quad (4)$$

It is assumed that the distance among particles are equal, when the distance between two particles is r

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(r_j=$j\cdot r$), the dipole moment of the particle i:

$$m_i=\frac{4}{3}\pi a^3\mu_0\mu_1\chi H_i =\frac{4}{3}\pi a^3\mu_0\mu_1\chi\left[H_0+2\cos\theta\cdot\sum_{j=1}^{n}\frac{m(3\cos^2\theta-1)}{4\pi\mu_0\mu_1(j\cdot r)^3}\right] \quad (5)$$

Eq.(5) can be written as:

$$m_i=\frac{4}{3}\pi a^3\mu_0\mu_1\chi\left[H_0+C\frac{m\cos\theta(3\cos^2\theta-1)}{2\pi\mu_0\mu_1 r^3}\right] \quad (6)$$

$$C=\sum_{j=1}^{n}\frac{1}{j^3}$$

Under the external magnetic field, the magnetic energy of particle i can be expressed as Eq.(7).

$$E_i=\sum_{j\neq i}E_{ij}=2\sum_{j=1}^{n}E_{ij} = 2\sum_{j=1}^{n}\frac{1}{4\pi\mu_0\mu_1}\frac{m^2[1-3\cos^2(\theta+\gamma')]}{|jr|^3} = 2C\frac{m^2[1-3\cos^2(\theta+\gamma')]}{4\pi\mu_0\mu_1 r^3} \quad (7)$$

For a MRE in which particle volume percentage is ϕ, and total volume is V, the number of the particle is $n=\frac{V\phi}{4/3\pi a^3}=\frac{3V\phi}{4\pi a^3}$, and the total magnetic energy can be shown in Eq.(8).

$$E=nE_i=\frac{3V\phi}{4\pi a^3}\cdot E_i \quad (8)$$

The total magnetic energy density can be shown in Eq.(9).

$$U=\frac{E}{V}=\frac{3\phi}{4\pi a^3}\cdot E_i = \frac{3\phi}{4\pi a^3}\cdot 2C\cdot\frac{m^2\left[1-3\cos^2(\theta+\gamma')\right]}{4\pi\mu_0\mu_1 r^3} = \frac{3\phi}{2\pi a^3}\cdot C\cdot\frac{1-3\cos^2(\theta+\gamma')}{4\pi\mu_0\mu_1 r^3}\cdot m^2 \quad (9)$$

Substituting Eq.(6) into Eq.(9), the total magnetic energy density can be formulated.

$$U=\frac{3\phi C\left[1-3\cos^2(\theta+\gamma')\right]}{8\pi\mu_0\mu_1(ar)^3}\cdot\left\{\frac{4}{3}\pi a^3\mu_0\mu_1\chi H_0\cdot\left[\frac{1}{1-2/3\,(a/r)^3\chi C\cos\theta\,(3\cos^2\theta-1)}\right]\right\}^2 = \frac{2a^3\mu_0\mu_1\chi^2{H_0}^2}{3r^3}\cdot\frac{\phi C\cdot\left[1-3\cos^2(\theta+\gamma')\right]}{\left[1-2/3\,(a/r)^3\chi C\cos\theta\,(3\cos^2\theta-1)\right]^2} \quad (10)$$

The relation between oblique chain's shear strain and the MRE' shear strain [22] can be expressed as $\gamma'=\gamma\cos^2\theta$.

So the shear stress can be calculated by taking the derivative of the magnetic energy density with respect to the overall strain.

$$\sigma=\frac{\partial U}{\partial\gamma} = \frac{2\mu_0\mu_1\chi^2{H_0}^2a^3\cdot\phi C\cdot\cos^2\theta\cdot\sin(2\theta+2\gamma')}{r^3\left[1-2/3(a/r)^3\chi C\cos\theta\,(3\cos^2\theta-1)\right]^2} \quad (11)$$

MRE magnetic shear modulus can be calculated by taking the derivative of the shear stress with respect to the overall strain.

$$\Delta G=\frac{\partial\sigma}{\partial\gamma} = \frac{4\mu_0\mu_1\chi^2{H_0}^2a^3\cdot\phi C\cdot\cos^4\theta\cdot\cos(2\theta+2\gamma')}{r^3\left[1-2/3(a/r)^3\chi C\cos\theta\,(3\cos^2\theta-1)\right]^2} \quad (12)$$

B. The relation between the angle and the shear strain ($\theta>\gamma'$)

Following the calculation method mentioned above, for $\theta>\gamma'$, shown in Fig.2, the MRE magnetic shear modulus can be also calculated:

$$\Delta G=\frac{4\mu_0\mu_1\chi^2{H_0}^2a^3\cdot\phi C\cdot\cos^4\theta\cdot\cos(2\theta-2\gamma')}{r^3[1-2/3(a/r)^3\chi C\cos\theta(3\cos^2\theta-1)]^2} \quad (13)$$

C. The relation between the angle and the shear strain ($\theta<\gamma'$)

For $\theta<\gamma'$, shown in Fig.3, the MRE magnetic shear modulus can be also calculated:

$$\Delta G=\frac{4\mu_0\mu_1\chi^2{H_0}^2a^3\cdot\phi C\cdot\cos^4\theta\cdot\cos(2\gamma'-2\theta)}{r^3[1-2/3(a/r)^3\chi C\cos\theta(3\cos^2\theta-1)]^2} \quad (14)$$

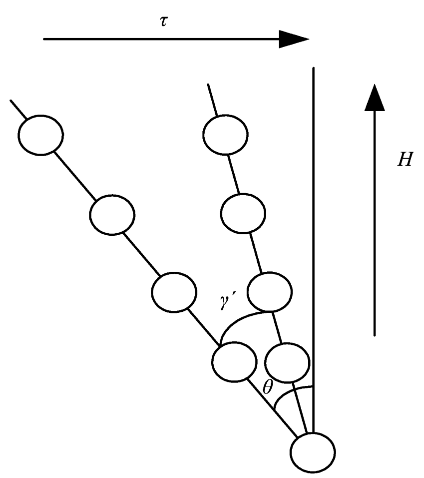

FIG. 2 Shear deformation of oblique chain ($\theta>\gamma'$).

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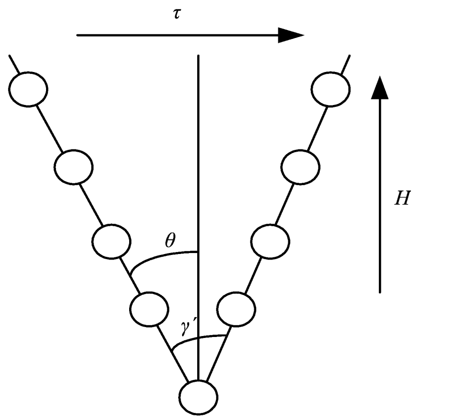

FIG. 3 Shear deformation of oblique chain ($\theta<\gamma'$).

In fact, there are many factors which affect the particle chains's formation. When the external magnetic field exist, the ferromagnetic particles can not arrange aline with the direction of the external magnetic field, even if some particles spread rulelessly in the magnetorheological elastomer. According to the characters of MRE's preparation, it is assumed that the distribution of the particles in the MRE matrix is the normal distribution.

$$D(\theta)=\frac{1}{\sqrt{2\pi}\sigma}\mathrm{e}^{-(\theta-\mu)^2/(2\sigma^2)} \tag{15}$$

where μ is the position of particle chain's distribution center, σ denotes the rate of divergence of the distance between the particle chain and the center. Hence, the distribution can be assumed as the standard normal distribution.

$$D(\theta)=\frac{1}{\sqrt{2\pi}}\mathrm{e}^{-\theta^2/2} \tag{16}$$

Considering the situation above, the MRE magnetic shear modulus can be expressed as following.

$$\begin{aligned}\Delta G=&\int_{-\pi/2}^{-\gamma'}\Delta G_1 D(\theta)\mathrm{d}\theta+\int_{-\gamma'}^{0}\Delta G_2 D(\theta)\mathrm{d}\theta+\\&\int_{0}^{\pi/2}\Delta G_3 D(\theta)\mathrm{d}\theta\\=&\int_{-\pi/2}^{0}\Delta G_1 D(\theta)\mathrm{d}\theta+\int_{0}^{\pi/2}\Delta G_3 D(\theta)\mathrm{d}\theta\end{aligned} \tag{17}$$

$$\Delta G_1=\frac{4\mu_0\mu_1\chi^2H_0^2a^3\cdot\phi C\cdot\cos^4\theta\cdot\cos(2\theta-2\gamma')}{r^3[1-2/3(a/r)^3\chi C\cos\theta(3\cos^2\theta-1)]^2}$$

$$\Delta G_2=\frac{4\mu_0\mu_1\chi^2H_0^2a^3\cdot\phi C\cdot\cos^4\theta\cdot\cos(2\gamma'-2\theta)}{r^3[1-2/3(a/r)^3\chi C\cos\theta(3\cos^2\theta-1)]^2}$$

$$\Delta G_3=\frac{4\mu_0\mu_1\chi^2H_0^2a^3\cdot\varphi C\cdot\cos^4\theta\cdot\cos(2\theta+2\gamma')}{r^3\left[1-2/3(a/r)^3\chi C\cos\theta\left(3\cos^2\theta-1\right)\right]^2}$$

Therefore, the MRE magnetic shear modulus can be considered as the weighted average of three kinds of different initial oblique angles of particles chains following the standard normal distribution.

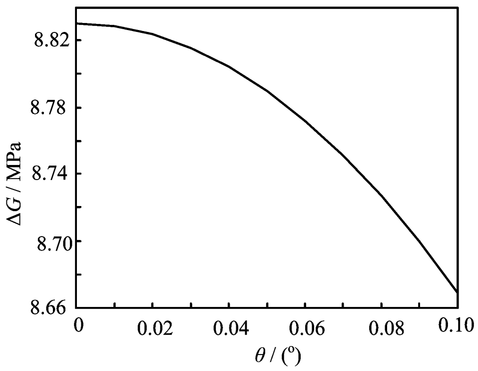

FIG. 4 The relationship between magneto-induced shear modulus ΔG and initial oblique angles θ.

III. ANALYSIS ON THE INFLUENCE FACTORS OF MRE MAGNETIC SHEAR MODULUS

A. The influence of the initial oblique angles of particles chains

According to Eq.(17), the relation between initial oblique angles θ and the magneto-induced shear modulus ΔG can be calculated, which is shown in Fig.4.

The other parameters are given: $C\approx1.4$, μ_1=500, H_0=400 A/m (B=0.25T), a=10^{-6} m, r=10a=10^{-5} m, ϕ=0.3, γ'=0.0027 [19,23,24].

According to the Fig.4, when the other parameters do not change, in the same magnetic field, the magneto-induced shear modulus will decrease as the initial oblique angles increase, which indicates that the rheological effect of the oblique chains is less than that of the chains with initial angle θ of 0. So the direction of the chains along the applied magnetic field should be taken into account.

B. The influence of the shear strain

The other parameters are given: $C\approx1.4$, μ_1=500, H_0=400 A/m, a=10^{-6}m, r=10a=10^{-5} m, ϕ=0.3, θ=0 [19,23,24].

When the other parameters are not be changed, the magneto-induced shear modulus will decrease as the shear strain's increase in the same magnetic field as shown in Fig.5. Because the distance among particles will increase as the shear strain's increase, resulting in the decrease of the interactive force among particles.

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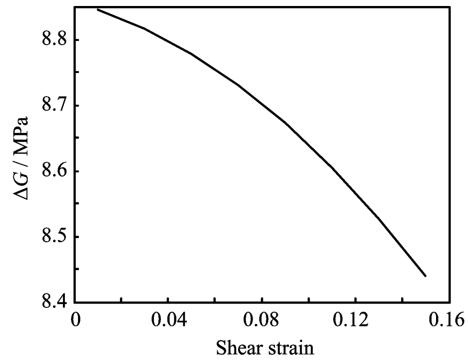

FIG. 5 The relationship between magneto-induced shear modulus and shear strain.

C. The influence of the external magnetic field intensity

The other parameters are given: ϕ=0.3, $C\approx1.4$, $a=10^{-6}$ m, $r=10a=10^{-5}$ m, $\gamma'=0.0027$, $\theta=0$ [5,19, 22,25].

When the external magnetic field intensity is small ($H<600$ A/m), the magneto-induced shear modulus change slightly. However, it change largely as the external magnetic field intensity's increase because of the external magnetic field intensity and the permeability of the ferromagnetic particles, as shown in Fig.6. According to the calculation and analysis as above, larger magnetic field intensity should be taken in order to get smaller initial angle of particles chains, which leads to increase the change of shear modulus of MRE. Furthermore, the factors including magnetic field intensity, particles distance, the volume fraction of particles and susceptibility will all affect the shear modulus change, certain measures to optimize these parameters should be taken to get better effect.

In addition, the magneto-induced shear modulus will decrease as the particles' space (r) increase in the same magnetic field. Because the particles' space increase will result in the decrease of the interaction energy among particles. The increase of magnetic coefficient (χ) is also helpful to improve the magneto-induced shear modulus, therefore the ferromagnetic particles with high magnetic coefficient should be chosen in the preparation process of MRE.

IV. EXPERIMENTAL VERIFICATION OF THE MODEL

A dynamic mechanical analyzer (DMA) is a common equipment for dynamic testing on viscoelastic materials [26]. In this work, the magnetic field generator was fixed on the Tritec2000DMA of British Triton Technology company, which has a adjustable magnetic field range from 0 to 1.1 T, and it can help to test the functions of the materials in the magnetic field [27]. The DMA testing system can adjust the parameters such as the shear strain, frequency etc. by the setting of the softwares.

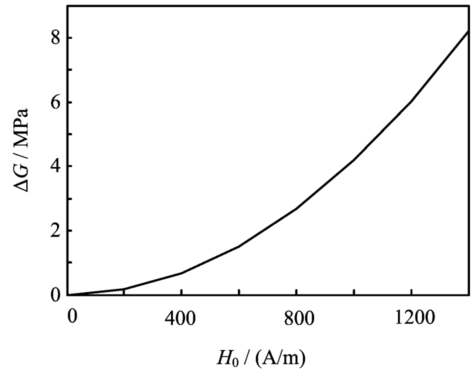

FIG. 6 The relationship between magneto-induced shear modulus and the external magnetic field intensity H_0.

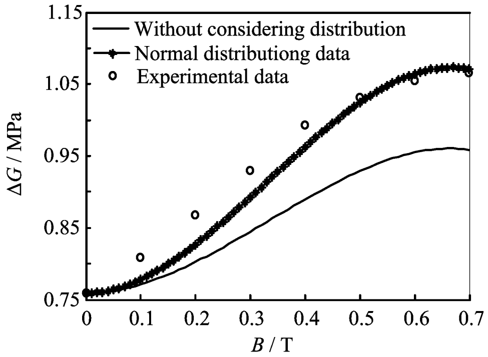

FIG. 7 The relationship between magneto-induced shear modulus ΔG and magnetic flux density B.

The change of magnetic field intensity can be realized by adjusting the intensity of the external magnetizing current. The experiment was conducted at room temperature, and the temperature variation of the electromagnet was less than 3 °C during the whole experiment. The group of MRE sample (10 mm×10 mm×2.5 mm) were prepared, and then the magneto-induced shear modulus of the MRE sample can be measured by the measurement system. This verification test involved recording the magneto-induced shear modulus at various applied magnetic field intensity, and then the relationship between magneto-induced shear modulus and magnetic flux density can be shown as Fig.7. In order to depict the experiment better, the magnetizing process of magnetic particles are considered as nonlinear process, the magnetic permeability is not considered as a constant. The optimized result can be seen from Fig.7.

Some parameters are given: $C\approx1.4$, $a=10^{-6}$ m, $r=10a=10^{-5}$ m, ϕ=0.3, $\theta=0$ [19,23,24].

According to the Fig.7, when the magnetic flux density is small, the magneto-induced shear modulus vary slightly, but then it change largely as the magnetic flux density's increase, and the change of the shear modulus will become slower when arriving a certain value because of the effect of the external magnetic field intensity and the permeability of the ferromagnetic par-

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ticles. The shear module will not increase any longer when iron particles get saturated.

From the Fig.7, the estimated magneto-induced shear modulus of the model by using dipole method with the normal distribution of chain's angle, can describe the experimental phenomena very well. By the way, the prediction magneto-induced shear modulus of the model is a little higher than the experimental datum, because the chain was considered in the MRE under the magnetic field as straight chain, neglected the branched chain and the free particles.

V. CONCLUSION

In this work, on the basis of chain-like model, some factors influencing the magneto-induced effect of MR elastomer are analyzed theoretically by using dipole method with the normal distribution of chain's angle, including the oblique angle of particles chains, magnetic field intensity and shear strain etc. The magneto-induced shear modulus of MR elastomer sample was experimentally explored in this work to verify the analyzed theoretically conclusions.

Through the theoretical analysis and the experimental verification, some conclusions can be obtained. (i) There are many factors which influence on the larger magneto-induced shear modulus, such as the external magnetic field intensity H_0, the shear strain γ', the particles' space r, magnetic coefficient χ, the solids volume concentration ϕ, and so on. The model proposed in this paper is useful to optimize these parameters effectively. (ii) According to the calculations and analysis above, a larger magneto-induced shear modulus can be obtained by the external magnetic field intensity increased and initial oblique angles minimized. The proposed model is capable to assist the design and development of high-performance MRE.

VI. ACKNOWLEDGMENTS

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