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Abstract

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Keywords

Experimental, investigation, vibration, characteristics, magnetorheological, elastomer, sandwich, beam, under, non, homogeneous, small, magnetic, fields

Disciplines

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Experimental investigation on vibration characteristics of a magnetorheological elastomer sandwich beam under non-homogeneous small magnetic fields

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Abstract

In this study, the magnetorheological elastomer (MRE) was manufactured and tested, and the MRE sandwich beam was also fabricated by treating with MRE between two thin aluminum layers. The experiment test rig was set up to investigate the vibration response of the MRE sandwich beam under non-homogeneous magnetic field. The experimental results show that the first natural frequency of the MRE sandwich beam decreased as the magnetic field that applied on the beam was moved from the clamped end of the beam to the free end of the beam. It is also noted that the MRE sandwich beam had the capabilities of left shifting first natural frequency when the magnetic field was increased in the activated regions.

Keywords: MR elastomer, sandwich beam, vibration, non-homogeneous magnetic field

1. Introduction

Magnetorheological (MR) materials exhibit rapid variations in their rheological properties such as viscosity and shear modulus when subjected to different magnetic field intensities. Since their discovery by Rabinow in 1948, MR materials have developed into a family with MR fluid, MR foam and MR elastomer [1]. The most common MR material is MR fluid (MRF). The general criterion to estimate the MR effect of MRF is the variation capability of dynamic yield stresses within a post-yield regime under external applied magnetic field. A lot of applications based on MRF benefit from the properties that the dynamic yield stress can be continuously, rapidly and reversibly controlled by the applied magnetic field.

MR elastomer (MRE), the structural solid analogs of MRF, is composed of polarizable particles dispersed in a polymer medium. Typically, magnetic fields are applied to the polymer composite during crosslinking so that particles form chainlike or columnar structures, which are fixed in the matrix after curing [2-4]. The difference between MRE and MRF is that MRE has the effects of field dependent modulus within the pre-yield regime. Such properties show that MRE is promising for many applications, such as adaptive tuned vibration absorbers (ATVAs), stiffness tunable mounts and suspensions, and variable impedance surfaces [5-11]. Deng et al [5-6] developed an adaptive tuned vibration absorber (ATVA) based on the unique characteristics of MRE. Xu et al [7] described the principle, design and testing of a novel active-damping-compensated MRE ATVA. The principle and the vibration attenuation effect of the active-damping-compensated ATVA were also compared with theoretical approaches. Zhang and Li [8] also developed an adaptive tuned

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MRE vibration absorber, whose natural frequency can be tuned from 75 Hz to 150 Hz. Albanese et al [9] used MREs as field-dependent springs within three vibration absorber configurations, and their vibration absorption characteristics were also determined. Kallio et al [10] also investigated the possibility of using MREs as tunable spring elements. The innovative ideas and methods for development of MRE devices were reviewed by Li and Zhang [11].

MR material has been used to carry out vibration analysis to observe vibration responses in real time and vibration suppression capabilities of three layered MR adaptive sandwich beams [12-13]. It was shown that the vibration minimization capabilities of MR adaptive structures are significant.

Recently, the development of MRE based sandwich structure was initiated. The sandwich structures apply metal skins to enhance their bulk zero-field flexural rigidity and utilize MRE cores to alter their bulk flexural rigidity magnetically due to the field dependent transverse shear modulus of the cores. This attempt may lead to stiffness-controllable structures with high initial stiffness and wide field-controllable ranges of stiffness. Zhou, et al. [14] investigated the effect of structural parameters on the field-dependent rigidities of single-layer sandwich beams with MRE cores through finite element analysis, the dynamic stiffness of such sandwich beams could be well modeled by spring-mass model in the low frequency range. Furthermore, a multilayer sandwich configuration was introduced to provide structures with higher bulk field-dependent rigidities. The structural design rules for multilayer sandwich beams for achieving the desired zero-field rigidities and desired relative change ranges of the field-dependent rigidities were also presented. Zhou and Wang [15-17] also carried out theoretical study on MRE embedded smart sandwich beams with non-conductive skins and conductive skins based on higher order sandwich beam theory respectively. Wei and coworkers [18] did a preliminary experiment on vibration characteristics of MRE sandwich beam, the results showed that the natural frequencies increased and the vibration amplitude of each mode decreased when the magnetic field was applied to the MR elastomers beam. Dwivedy, et al. [19] derived the governing equations of motion of a soft-cored symmetric sandwich beam with magnetorheological elastormer subjected to periodic axial load using higher order theory. The parametric instability regions for simple and combination resonances was also investigated for simply supported, clamped-pinned, clamped-guided, and clamped-free end conditions by modified Hsu's method. The instability regions of the system with and without MRE patch, with different magnetic field strengths and permeability of skin materials had been studied also. Navak, et al. [20] investigated the dynamic analysis of a three-layered symmetric sandwich beam with MRE embedded viscoelastic core and conductive skins subjected to a periodic axial load. The governing equation of motion was derived using extended Hamilton's principle along with generalized Galarkin's method. The effects of magnetic field, length of MRE patch, core thickness, percentage of iron particles and carbon blacks on the regions of parametric instability for first three modes of vibration had been studied. Ying and Ni [21] studied the micro-vibration response of a clamped–free sandwich beam with an MR elastomer core and a supplemental mass under stochastic support micro-motion excitation. The dynamic behavior of MR elastomer was described and the sixth-order partial differential equation of motion was also derived. Numerical results illustrated the influences of the MR elastomer core parameters on the root-mean-square velocity response and the high response reduction capacity of the sandwich beam. Choi et al. [22] investigated the dynamic behaviours of MRE cored sandwich beams with steel skins. Modelling of the dynamic behaviour was carried out by adopting a higher order sandwich beam theory. The experimental responses were generated from a specially designed test rig to study dynamic behaviour, damping effects, localized magnetic field effects and energy dissipation with varying topology.

However, these research works for MRE sandwich beam in the current literature are mostly only carried out under homogeneous magnetic fields, not considering the non-homogenous magnetic field effects on the beam. The aim of this study therefore is to address this limitation and to investigate the vibration response of the MRE sandwich beam under non-homogeneous magnetic field.

In this paper, the vibration characteristics of MRE sandwich beam were presented and discussed experimentally. A MRE sandwich beam, which is treated with MRE between two separate aluminum layers, was constructed and applied. The vibration responses of the test beam under non-homogeneous magnetic field were investigated and discussed.

2. Fabrication of MRE sandwich beam

2.1 Fabrication of MRE material

MRE is a composite material, whose mechanical properties are changed when external magnetic field is applied. It is made of two main components: matrix and dispersed particles. In this paper silicone sealant (SELLEYS PTY.LIMITED, Australia) and the Poly (dimethylsiloxane) fluid (SIGMA-ALDRICH Company, USA) are chosen as matrix and the dispersed particles are carbonyl iron, which has the diameter of 4.5-5.2 μm (SIGMA Company, USA). The mass fraction ratio of iron, silicone oil and silicone rubber in the mixture is 7:1:2. First put the carbonyl iron particles in a container and then pour Poly fluid into it, mix them with silicone sealant. At last stir them until all the materials mixed thoroughly. The mixture was poured into a mould after the air bubbles that inside it are removed. After 24 hours curing under room temperature, MRE sample are fabricated with iron particles mass fraction 70%.

2.2 MRE material rheological properties

In the three-layered MRE sandwich beam configuration, the MRE materials experience shear stress and shear strain that is confined in the pre-yield regime. The stress-strain relationship based on linear viscoelastic theory is given by the following equation:

$$\tau = G^{*}\gamma \tag{1}$$

In equation (1), τ is shear stress, γ is shear strain, and G^* is the complex shear modulus represented in the form

$$G^{*} = G' + G''i \tag{2}$$

where G' is the storage modulus, and G'' is the loss modulus. The storage modulus is proportional to the average energy stored during a cycle of deformation per unit volume of the MRE material. The loss modulus is proportional to the energy dissipated per unit volume of the MRE material over a cycle.

In this study, the relationship between the storage modulus, loss modulus and the applied magnetic field is expressed by experiment done on a parallel-plate rheometer (Physica MCR 301, the Anton Paar Company, Germany). The MRE sample is about Φ20 mm×1.15 mm. At a constant angular frequency ω=5 rad/s, get the relationship under current intensity of 0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2A, respectively. The magnetic field is applied through tuning current. Figure 1 shows the relationships between the storage modulus of MRE and the strain under different magnetic field (current intensity), and figure 2 shows the relationships between the loss modulus of MRE and the strain under different magnetic field (current intensity). From the two figures, it can be seen that the storage modulus and the loss modulus increased as magnetic field strength (current intensity) increased. However, the storage modulus and loss modulus increased very slowly when the magnetic field intensity bellows 100 mT.

Figure 3 display the storage modulus and the loss modulus as a function of the magnetic field when the shear strain is below 0.01%. From the figure, it is noted that the storage modulus and the loss modulus increased as the magnetic field strength increased, and both of them increased dramatically when the magnetic field strength exceeds 100 mT.

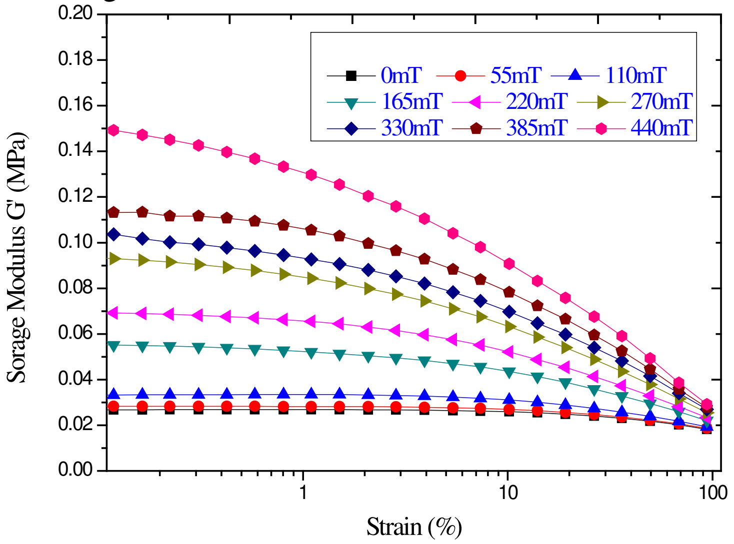


Figure 1. The storage modulus of MRE under different magnetic field

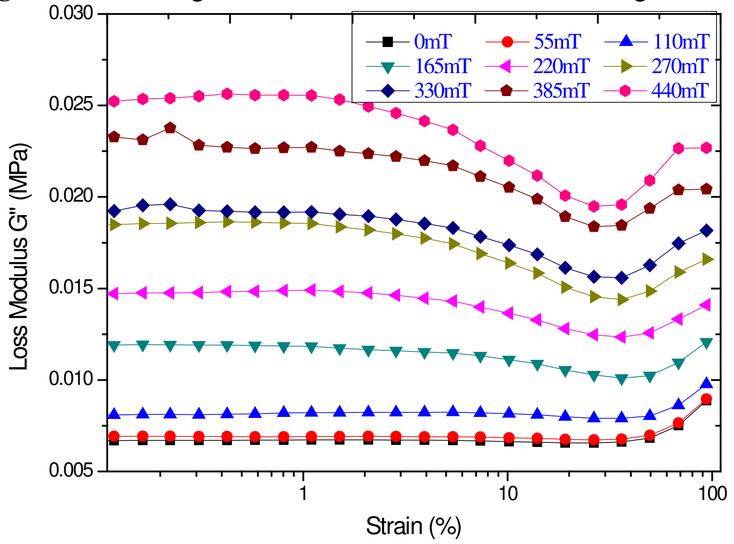


Figure 2. The loss modulus of MRE under different magnetic field

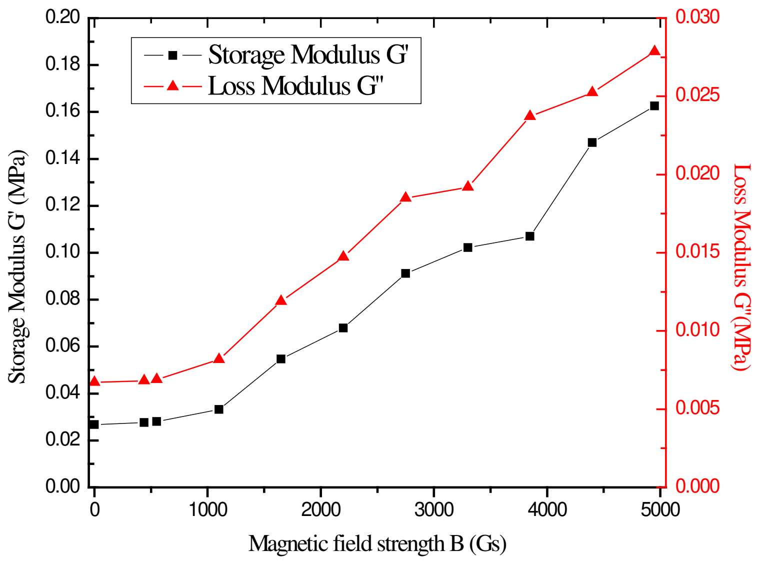
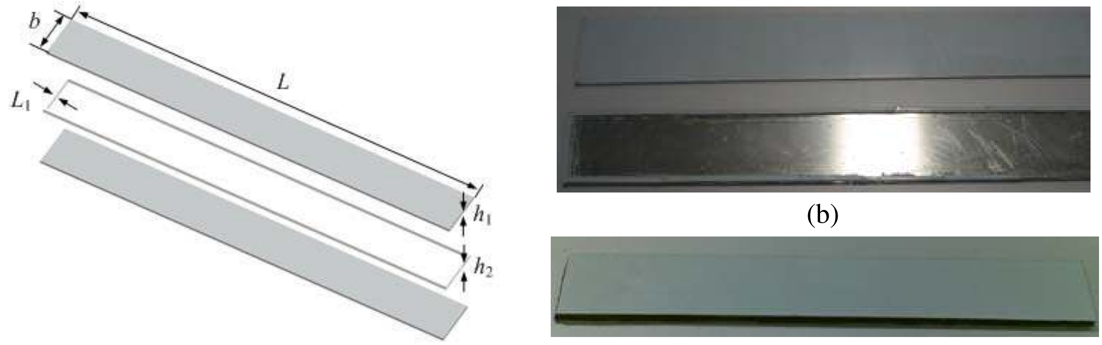


Figure 3. Storage modulus and loss modulus as a function of the magnetic field

2.3 Fabrication of sandwich beam with MRE core

The structural profile of the MRE sandwich beam is shown in Figure 4. It is made of three layers: the top and bottom layers are aluminum and the core is MRE material. Thin aluminum plates were chosen for elastic surface plates due to its low damping properties and relatively high stiffness properties compared to those of MREs. Additionally, aluminum’s relatively magnetic permeability equal to zero, which indicates that it does mot affect the distribution and strength of the magnetic field. The beam is L=360 mm in length and b=40 mm in width, the upper aluminum layer and the bottom aluminum layer thickness is h_1=1.61 mm, and the MREs layer thickness is h_2=2.98 mm.

Firstly, 133g iron, 38g Silicone sealant and 19g Poly fluid were put in a container, and an aluminum stick was used to stir them to blend until all the materials in the container mixed thoroughly. Then a bottom aluminum layer was put in a steel plate slot of 500 mm×40 mm×3 mm, and the MRE mixture was packed into the bottom aluminum layer surface evenly. In order to prevent the dissipation of the MRE under the magnetic field, an aluminum rectangle boundary of L_1=2 mm width and h_2=2.98 mm thickness was manufactured to bond on the bottom aluminum layer. Next, the upper aluminum layer was placed on the MRE. Then force was applied on the upper aluminum layer to make sure that the upper surfaces of aluminum layer and the steel plate are parallel. At last, a heavy steel plate was placed on the MRE sandwich beam, and the sandwich beam was cured for about 24 hours under room temperature, which lead to the MREs layer to be an analog solid structure.



(b)

(a) (c)

Figure 4. The schematic of MRE sandwich beam: (a) Schematic of three layers; (b) Photograph of top and bottom aluminum layer; and (c) Photograph of the MRE sandwich beam

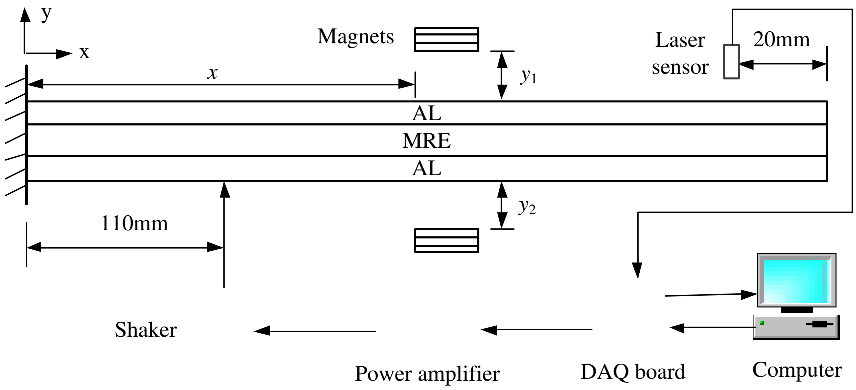
3. Experimental set-up

In this experimental test, MRE sandwich beam was clamped at a fixed platform using a cantilever configuration. Figure 5 presents a schematic configuration and photograph of the experimental set-up, which is integrated with magnets, sensor, shaker and signal analysis equipment. The instruments used in the experiment include LabVIEW programming, PCI multifunction Data Acquisition (DAQ) board, laser sensor, shaker and power amplifier.

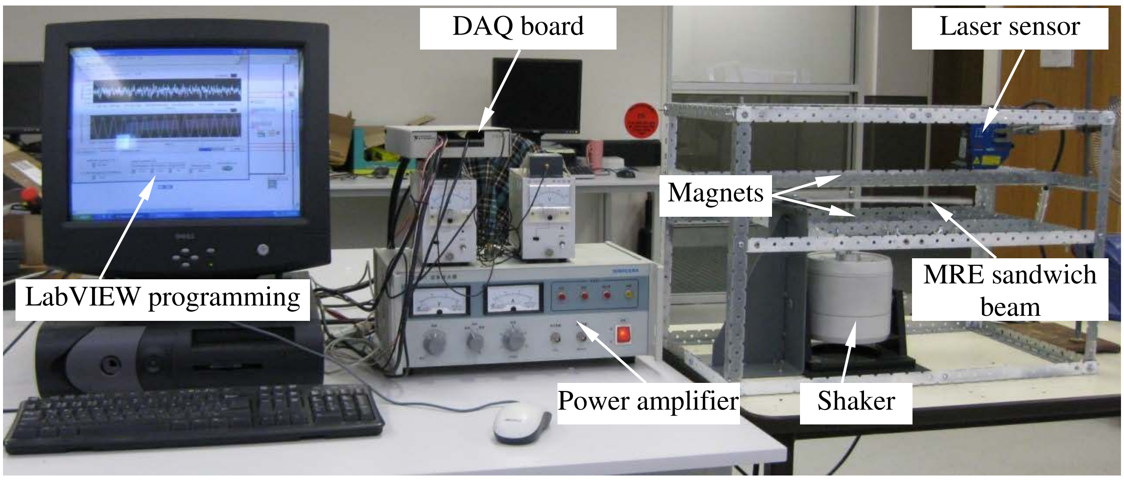
The DAQ board produced by National Instruments Inc. with model of PCI 6221 is connected to a Connector Block produced by National Instruments Inc. with model of SCB-68, both of them are used to generate and acquire the signals. The laser sensor produced by MICRO-EPSILON Company with model of opto NCDT 1700 is used to measure the vibration displacement at a single location, and this sensor could sense the displacements from 0 to 20 mm. The shaker produced by Sinocera Piezotronics Inc. with model of JZK-5 is driven by the voltage signal from the power amplifier with model of YE5871A, which is also produced by Sinocera Piezotronics Inc., this voltage signal is generated by DAQ output through LabVIEW programming. The shaker could generate a nominal force up to 50 N with a displacement of 7.5 mm and a bandwidth from 0 to 5 kHz. The LabVIEW programming is used for obtaining and analyzing the acquired analogue signals from the laser sensor.

Permanent magnets were used to generate magnetic field over the test beam. The magnetic field was applied in the vertical direction of the beam surface. As shown in Fig. 5, the permanent magnets were activated on a particular region of the sandwich beam because of its size limitation. The magnetic field in the whole beam is non-homogeneous. In our experiments, the magnetic field intensity generated by the permanent magnets is less than 100 mT, which is quite small compared with other MRE testing. In addition, the variations of the magnetic field intensity were obtained by changing the distance y_1 and y_2 between the permanent magnets.

An external rod of the shaker was connected to the beam at the actuation location of 110 mm from the fixed end of the beam. The laser point was located at the position of 20 mm from the free end of the beam. The experimental procedure is carried out as follows: the signal output from the DAQ is sent to the shaker through the amplifier. The shaker provides the external vibration over the test beam. The vibration data of the test beam is acquired by the laser sensor and sends to the computer through DAQ. The LabVIEW programming in the computer processes the input signal. Then, the vibration response in frequency domain, natural frequencies and amplitudes of the vibration are presented in the output of the analysis results.



(a)



(b)

Figure 5. Experiment set-up for MRE sandwich beam: (a) Schematic; (b) Photograph

4. Results and discussion

In the test, the LabVIEW program was set using a swept sine actuation at a range of 0-30 Hz with

0.1 Hz increment, and the excitation electric signal was set v=200 mV. The magnetic field was provided by a single group magnet, which including three magnets in each group.

Figure 6 shows the vibration response of MRE sandwich beam at different activated regions. In the test, the distance between the magnetic poles is 70 mm (y_1=20 mm, y_2=50 mm), and the magnetic field intensity in the centre of the activated region is 95 mT. The magnets was moved from the clamped end of the beam to the free end of the beam along x direction that shown in Figure 5. Fig. 7 displays the experimental first natural frequency at different activated magnetic field region. From the two figures, the first natural frequency of the MRE sandwich beam is decreased quickly as the magnets moves towards the free end. Compared with the frequency under zero magnetic fields, the first natural frequency decreased 13.9%. Stiffening the MRE in the regions away from the clamps of the beam results in a decrease in the natural frequency of the beam compared with the natural frequency in the absence of the field. This behaviour agrees with the experimental results carried out by Lara-Prieto and his coworkers [23], where the first natural frequency of a cantilever PET MR beam decreased when the magnet moved towards the free end. And it is also similar to the theoretical prediction of Yalcintas and Coulter [24], where the natural frequency of a simply supported ER beam decreased when the beam was activated only in the central regions, away from the clamped ends.

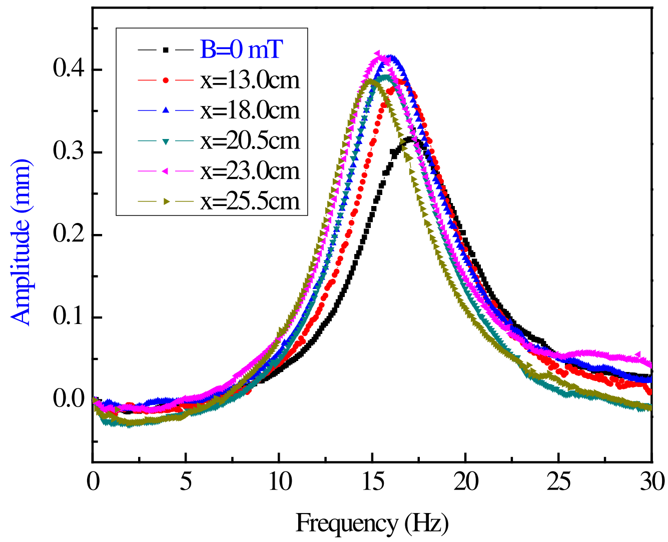


Figure 6. Vibration response of MRE sandwich beam at different magnetic field region

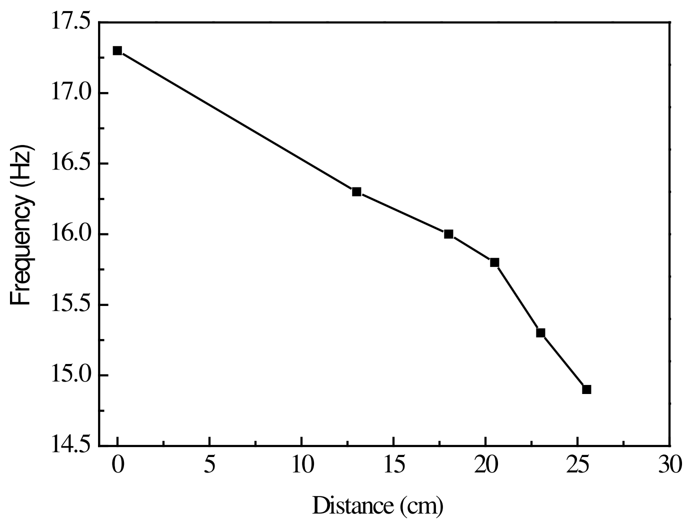


Figure 7. Experimental natural frequency at different activated magnetic field region

Figure 8 shows the vibration response of MRE sandwich beam under different magnetic field intensity. During the experiments, the magnetic field intensity was changed by adjusting y_1, and y_2 was set to be 50 mm, as shown in table 1. The magnetic field was applied on a specific region of x=23 cm. The first natural frequency of MRE sandwich beam under different magnetic field intensity is shown on Figure 9. It is also noted that the first natural frequency of the MRE sandwich beam decreased as the magnetic field increased. So, it showed the frequency left shift trend. Compared with the frequency under zero magnetic fields, the first natural frequency decreased 11.5%.

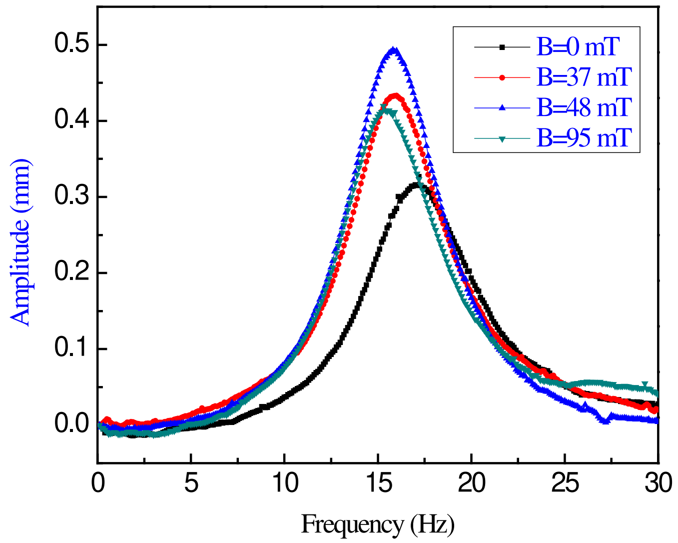


Figure 8. Vibration response of MRE sandwich beam under different magnetic field intensity

Table 1. The relationships of magnetic field intensity B and distance y_1 and y_2.

	y_1 (mm)	y_2 (mm)	B (mT)
1	70	50	37
2	45	50	48
3	20	50	95

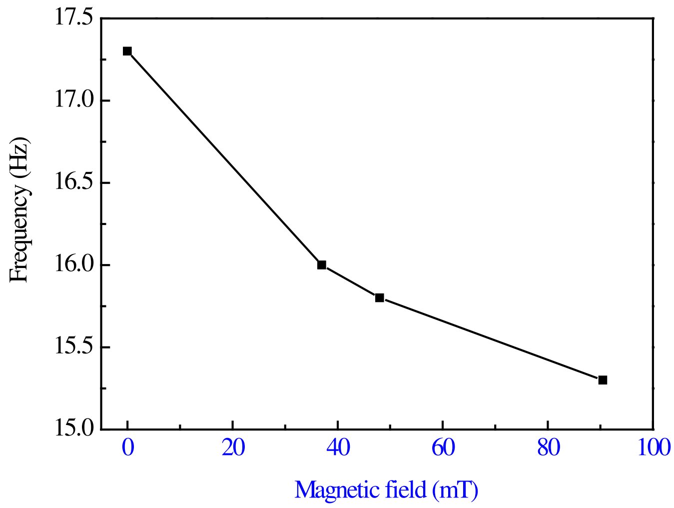


Figure 9. Experimental first natural frequency under different magnetic field intensity

MRE belongs to the family of viscoelastic materials. The constitutive equation of this kind of material is significantly nonlinear and it is often described in terms of the principle extension ratios through the Ogden strain potential. This means that the shear modulus of the MRE is dominated by the stress condition, or strain energy. When a magnetic field applied, the MRE will deform along the direction of the magnetic field. If we adopt a single chain model, similar to that used in [25-26] to analyze the shear stress induced by interparticle magnetic forces, the total magnetic energy density (energy per unit volume) is given by [27]

$$U = \frac{\phi(\gamma^2 - 2)M^2 d_p^3 \mu_0}{24 r_0^3 (1+\varepsilon)^3 (1+\gamma^2)^{5/2}} \tag{3}$$

where M is the magnetization of the particles, d_p is the diameter of the particles, μ_0 is the permeability of free space, φ is the volume fraction of the MRE and r_0, $\gamma = tg\theta$, $\varepsilon = \frac{r - r_0}{r_0}$ represent the relative position of two adjacent particles in a chain after deformation, respectively (see figure 10).

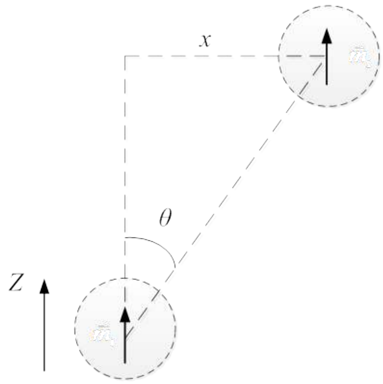


Figure 10. Magnetic interaction between two dipoles

The complex shear modulus G^* is assumed as the sum of the shear modulus G_0 with no field applied and the shear modulus ΔG(B) induced by interparticle magnetic forces. Let $\varepsilon = 0$ (no normal strain occurs); the shear stress induced by the application of a magnetic field can be deduced by taking the derivative of the total magnetic energy density in equation (3) with respect to γ:

$$\tau_B = \frac{\partial U}{\partial \gamma} = \frac{\phi\gamma(4-\gamma^2)M^2 d_p^3 \mu_0}{8 r_0^3 (1+\gamma^2)^{7/2}} \tag{4}$$

For the small deform of γ, equation (4) can be expressed as

$$\Delta G(B) = \frac{\phi \mu_0 M^2 d_p^3}{2 r_0^3} \tag{5}$$

When the magnetic field is applied along the z direction, let γ =0 (no shear strain occurs); the stress induced by the application of a magnetic field can also be computed by taking the derivative of the total magnetic energy density with respect to ε:

$$\sigma_B = \frac{\phi M^2 d_p^3 \mu_0}{4 r_0^3} - \frac{\phi M^2 d_p^3 \mu_0}{r_0^3}\varepsilon \tag{6}$$

So, the Yong's modulus induced by interparticle magnetic forces can be given as

$$\Delta E(B) = -\frac{\phi M^2 d_p^3 \mu_0}{r_0^3} \tag{7}$$

Equation (7) reveals a negative field induced modulus which is caused by exchange between the magnetic energy and the strain energy.

The complex shear modulus G* and the equivalent Yong's modulus E* can be expressed as

$$G^{*}=G_0+\Delta G(\mathrm{B}) \tag{8}$$

$$E^{*}=E_0+\Delta E(\mathrm{B}) \tag{9}$$

As show in equation (4), (7)-(9), the complex shear modulus G* is increased, while the equivalent Yong's modulus E* will become smaller when the applied magnetic field increases. Furthermore, the decreased ΔE(B) is twice of the increased ΔG(B). At the same time, as shown in figures 1 to 3, the storage modulus G' and loss modulus G'' changed very slowly when the magnetic field intensity bellows 100 mT, which means the complex shear modulus G* changes very slowly. On the influence of the slowly increased G* and the more quickly decreased E*, the first natural frequency decreased as the magnetic field increased, just shown in figure 8 and figure 9.

5. Conclusion

This study revealed the possibility of shift the natural frequency to lower frequency through applying non-homogenous small magnetic field, which was achieved by partially activated region of the sandwich beam. It has been observed that the first natural frequency of the MRE sandwich beam decreases 13.9% when the single group magnet moves from the clamped end to the free end, and the first natural frequency decreases 11.5% when the applied magnetic field increases from 0 mT to 95 mT in the particular location of x=23 cm.

Acknowledgements

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