J. Cent. South Univ. (2014) 21: 2612−2619
DOI: 10.1007/s11771-015-2791-4

Springer

A novel approach to investigate effect of magnetic field on dynamic properties of natural rubber based isotropic thick magnetorheological elastomers in shear mode

Sriharsha Hegde, Katari Kiran, K V Gangadharan

Department of Mechanical Engineering, National Institute of Technology, Surathkal, Mangalore 575025, India

Abstract: The preparation of natural rubber based isotropic thick magnetorheological elastomers (MRE) was focused on by varying the percentage volume concentration of carbonyl iron powder and developing a test set up to test the dynamic properties. Effect of magnetic field on the damping ratio was studied on the amplification region of the transmissibility curve. The viscoelastic dynamic damping nature of the elastomer was also studied by analyzing the force-displacement hysteresis graphs. The results show that MR effect increases with the increase in magnetic field as well as carbonyl iron powder particle concentration. It is observed that softer matrix material produces more MR effect. A maximum of 125% improvement in the loss factor is observed for the MRE with 25% carbonyl iron volume concentration. FEMM simulation shows that as carbonyl iron particle distribution becomes denser, MR effect is improved. FEMM analysis also reveals that if the distance between the adjacent iron particles are reduced from 20 μm to 10 μm, a 40% increase in stored energy is observed.

Key words: magnetorheological elastomer; natural rubber; carbonyl iron powder (CIP); dynamic analysis

1 Introduction

Materials which can respond to the changes in the environment in a predictable manner are called smart materials. Smart materials have played an important role in improving the efficiency of real-time systems. Examples of smart materials include piezoelectric materials, shape memory alloys, thermo chromic materials, photo chromic materials and magnetorheological (MR) fluids/elastomers. Magnetorheological elastomers (MRE) are smart materials in which magnetically- polarizable particles are distributed in a non-magnetic medium [1] and their rheological properties can be controlled rapidly and reversibly by an externally applied magnetic field [2]. In recent years, magnetorheological elastomers have created lot of interests because of the advantages it has over MR fluids for instance, the polarizable particles does not settle down and it is easy to store [3]. There are many options when it comes to choose materials for preparations of MRE. Particles used for the preparation of MREs are magnetically polarizable powders of iron, nickel or cobalt of size ranging from 5 to 100 μm in diameter. One of the most popular materials is carbonyl iron powder in the range of 1 to 10 μm size. There are many different matrix materials like natural rubber, silicone rubber, thermosetting rubber, synthetic rubber and so on [2]. Basically there are two types of MR elastomers based on the way it is cured. If the curing is done without the presence of magnetic field, the ferromagnetic powders are distributed randomly in the matrix resulting in isotropic MRE, which is also referred to as elastomer ferromagnetic composite. When the curing is done under a magnetic field, the polarizable particles form a chain like structure along the direction of flux path and these may be referred to as structured or anisotropic MREs. SUN et al [4] investigated the damping properties of isotropic as well as anisotropic MRE prepared by cis-polybutadiene rubber. They documented that for the same percentage of iron content, the loss factors of anisotropic MRE is lower than isotropic. GONG et al [5] investigated the mechanism of damping behavior of MRE by considering them as special particle reinforced components. They found that the damping property of MRE is due to intrinsic damping, interface damping and the magneto-mechanical damping. They also conducted experiments and concluded that the overall performance of the MRE is related to the particle content and the strain amplitude. FAN et al [6] studied the process of interfacial friction damping properties in MRE by conducting experiments on samples prepared by two different sized carbonyl iron particles. The smaller

Received date: 2014−01−13; **Accepted date:** 2014−06−05
Corresponding author: Sriharsha Hegde; Tel: +91−8147756715; E-mail: Sriharsha.mangalore@gmail.com

size particles showed more agglomeration resulting in fluctuation of loss factor values in comparison with other samples. They concluded that interfacial frictional damping was mainly due to the sliding between the rubber matrix and the carbonyl iron particles. TIAN et al [7] added graphite and prepared isotropic and anisotropic MREs and conducted steady state and dynamic experiments. This new type of MRE led to improvement of zero-field mechanical properties, but MR effect was found to reduce. EEM et al [8] modelled MR elastomers in shear mode of deformation by combining Ramberg-Osgood model and the Maxwell model. Compared with experimental results, the effective nature of the proposed model was proved. GORDANINEJAD et al [9] conducted experiments on thick MR elastomers of thickness varying from 6.35 mm to 25.4 mm. They found that field induced modulus change is independent of the thickness of the MRE. POSSINGER et al [10] investigated the interfacial adhesion between elastomer matrix and carbonyl iron powder at high strain rate. A silane primer was applied to carbonyl iron powder which resulted in better adhesion bonding. The MRE samples with silane coated particles showed better performance than normal MREs up to a strain of 150%. Various mathematical modeling approaches like Kelvin model, Voigt model, and Maxwell model, can be applied to predict the behavior of MREs. JOLLY et al [11] developed a quasi-static one dimensional model to predict the mechanical and magnetic properties of MRE. The model is semi-empirical, i.e., to fit in the experimental data, an unmodelled parameter data should be adjusted to account for magnetic non-literalities. KALETA et al [12] tested the magneto-mechanical properties of both isotropic and anisotropic thermoplastic elastomer based MREs under cyclic loading of constant frequency of 1 Hz. They observed that the anisotropic samples showed better magnetorheological effect. In the current work, four samples were prepared by varying the percentages of carbonyl iron powder and transmissibility ratio was plotted against input frequency at different magnetic fields. Hysteresis plot of force vs displacement is a measure of energy dissipated which is used as a good measure of characteristics of the system. By making use of laser pick-up from micro epsilon, displacement was measured and force versus displacement graphs were plotted at different magnetic fields.

2 Material processing

For the preparation of MRE, latex obtained from rubber trees was selected as matrix material and carbonyl iron powder (BASF (Germany), CC grade of average diameter 5 μm) was selected as particle ingredient. Natural rubber is a high temperature vulcanizing rubber which requires several additives to be added to attain the required properties. The ingredients for the preparation of natural rubber based MRE are listed in Table 1. Mixing of the ingredients and molding has been done using the facilities at S.K Rubber industries at Baikampady Industrial Estate, Mangalore, India, The vulcanization process of natural rubber involves mastication which is the process of continuously passing the natural rubber between two hot rollers rotating in opposite direction. The fluidity of rubber increases and as a result it reaches a mushy state. Then after, the above mentioned ingredients were thoroughly mixed and the sample was cured for about 24 h and again made to pass through the hot rollers to bring back to mushy state. Iron powder was mixed with the mushy state rubber using proportional amount of silicone oil and the mixture was molded and cured at about 120 °C under the pressure of 10 MPa for 15 min. No magnetic field was applied while curing, which makes the MRE isotropic. Four different samples of MRE with dimensions 34 mm×34 mm×16 mm were prepared by varying the volume concentrations of carbonyl iron powder. The prepared samples were 0%, 15%, 20% and 25% (volume fraction) Fe. The shore-A hardness values of all the four samples are listed in Table 2.

Table 1 Additives for vulcanization

Ingredient	Amount/g
Rubber	1000
ZnO	50
Stearic acid	20
MBTS (Dibenzothiazole disulphide)	5
Sulfur	20
TMT (Dibenzothiazole disulphide)	2
Aromatic oil	50
TDQ (Trimethyl-1,2-Dihydroquioline)	5

Table 2 Shore-A hardness of MRE sample

Sample	Hardness (Shore-A)
Natural rubber (NR)	30
15% MRE	32
20% MRE	35
25% MRE	38

The microstructure of all the samples taken from digital microscope is shown in Fig. 2.

The photographs show the fairly uniform distribution of carbonyl iron powders in the matrix which proves that the prepared MRE indeed is isotropic in nature.

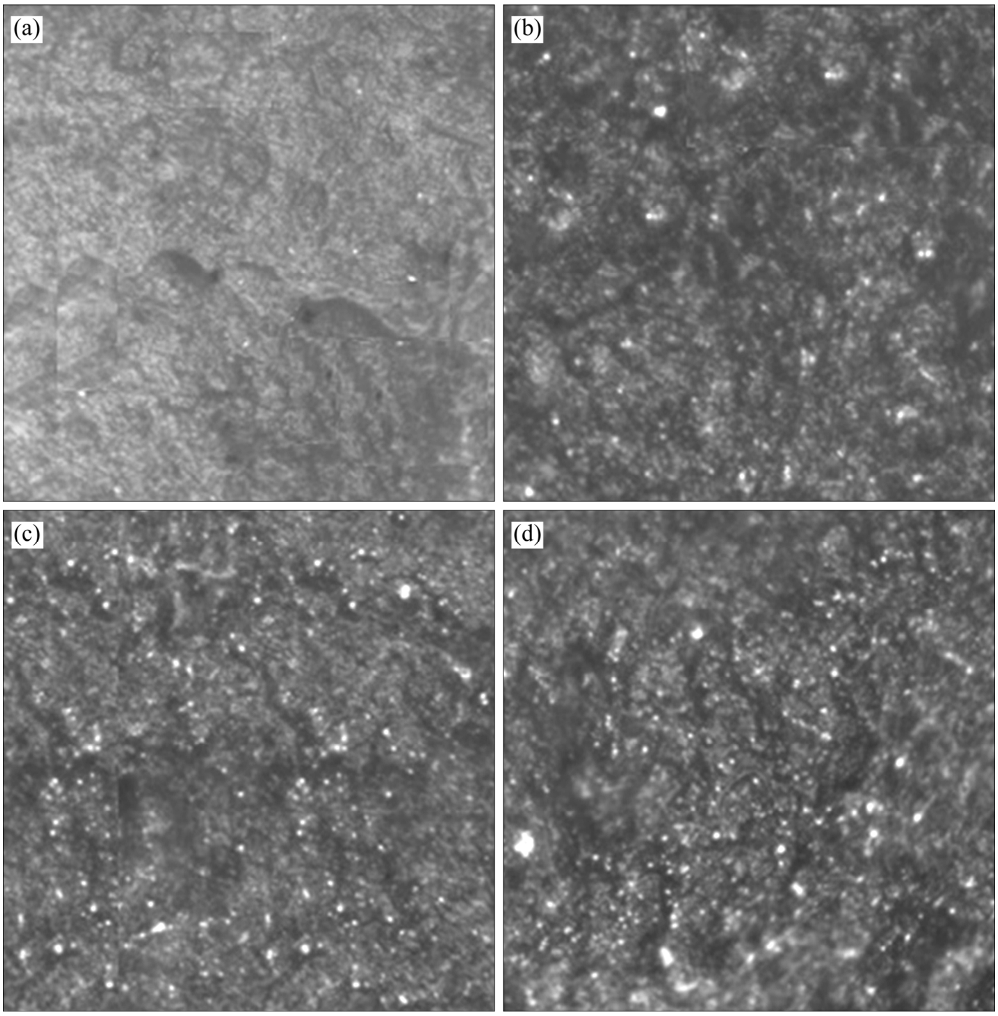

Fig. 1 Microstructure of samples: (a) Natural rubber; (b) 15% MRE; (c) 20% MRE; (d) 25% MRE

3 Experimental approach

The schematic representation of experimental set up is shown in Fig. 2. The experimental samples were prepared by sandwiching the sample between 3 mm thick aluminum strip which is 34 mm in width and bent in the form of an “L”. Cyanoacrylate based adhesive was used to stick the samples to the aluminum strips (Fig. 3).

The MRE was fixed to the structure and two force transducers (1100 N Kistler, of sensitivity 21.96 mV/g) were fixed at the top and bottom of elastomer to measure the input and the transmitted force respectively. A sinusoidal signal generated by NI PXI-5401 was amplified and fed to the electrodynamic shaker to generate the input force. Keeping the acceleration constant at 1 g throughout the experiment, the signal frequency was varied from 40 Hz to 400 Hz. The frequency sweep adapted was manual sweep over automated sweep, because automated sweep causes errors in acquired signal and manual sweep will allow for the system to stabilize before acquiring data [13]. Data acquisition was made using LabVIEW 2010. The ratio of output force (F_{tr}) and input force (F_o), i.e., force transmissibility against the input frequency graph, was plotted to analyze the system characteristics. The same experiments were conducted using Neodymium rare-earth permanent magnets (Grade 32) as a source of magnetic field. The magnetic field was increased up to 0.3 T. The magnetic field intensity was measured using Lakeshore Gauss meter. The magnetic field intensity variation across the elastomer was achieved by varying the distance or air gap between the magnets and elastomer using a modified self-centering vice.

4 Results and discussion

4.1 Transmissibility ratio plots

In order to investigate the change in loss factor with the magnetic field, transmissibility ratio vs input frequency was plotted for all four samples. The plots are shown in the Fig. 4.

The profile shapes are similar for all the samples. For the sake of highlighting the magnetic field induced

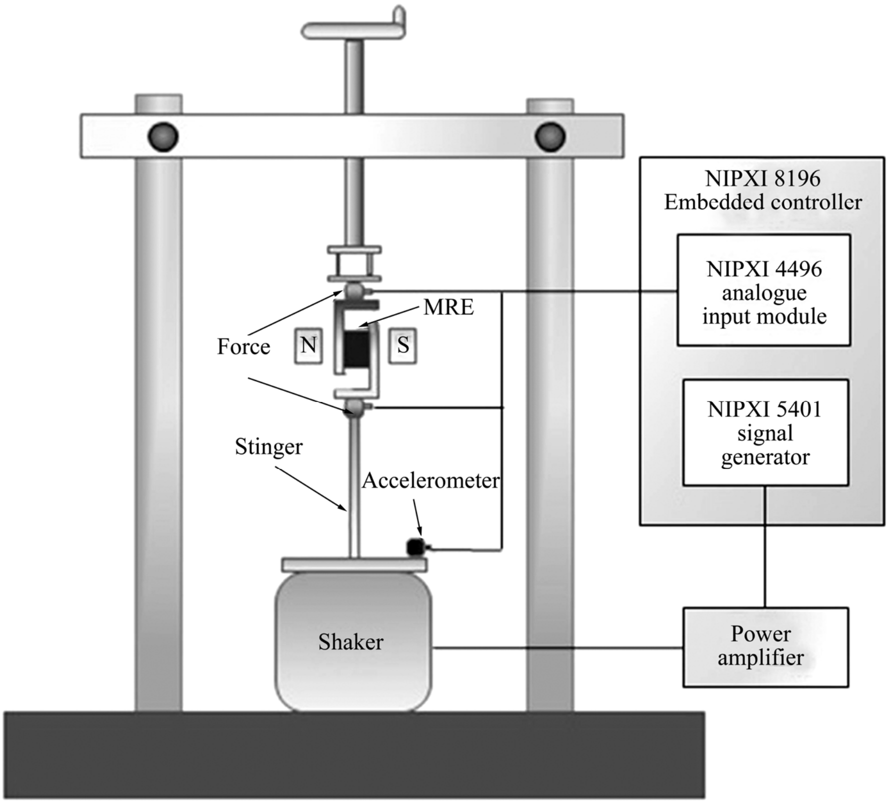

Fig. 2 Schematic representation of experimental set up

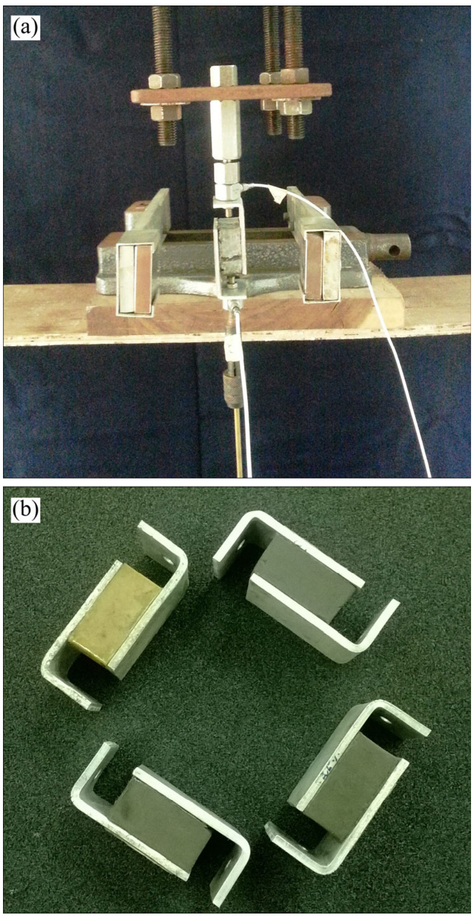

Fig. 3 Actual photograph of set-up: (a) Photograph of setup with NdFeB magnets; (b) Test samples

changes of the samples, only natural rubber graph is shown fully and for other samples only the amplification region of the curves are highlighted. The system damping properties can be deduced from the transmissibility curve from basic mechanical vibrations theory.

Transmissibility ratio in case of forced vibration is given by

$$R_{\mathrm{T}}=\frac{F_{\mathrm{Tr}}}{F_{\mathrm{o}}}=\sqrt{\frac{1+(2\zeta\lambda^2)^2}{(1-\lambda^2)^2+(2\zeta\lambda^2)^2}} \tag{1}$$

where F_{Tr} and F_{o} are respectively the transmitted force and the input force (N); ζ is the damping ratio and λ is the frequency ratio $\omega/\omega_{\mathrm{n}}$, where ω is the operating frequency and ω_{n} is the natural frequency of the system configuration (rad/s). At resonance, operating frequency ω equals natural frequency ω_{n}. By making this change, loss factor can be expressed in terms of transmissibility ratio as

$$\zeta=\frac{1}{2}\sqrt{\frac{1}{(R_{\mathrm{T}}^2-1)}} \tag{2}$$

For materials with relatively small damping ratios, loss factor η can be approximated to be twice that of damping ratio, i.e.,

$$\eta=2\zeta=\sqrt{\frac{1}{(R_{\mathrm{T}}^2-1)}} \tag{3}$$

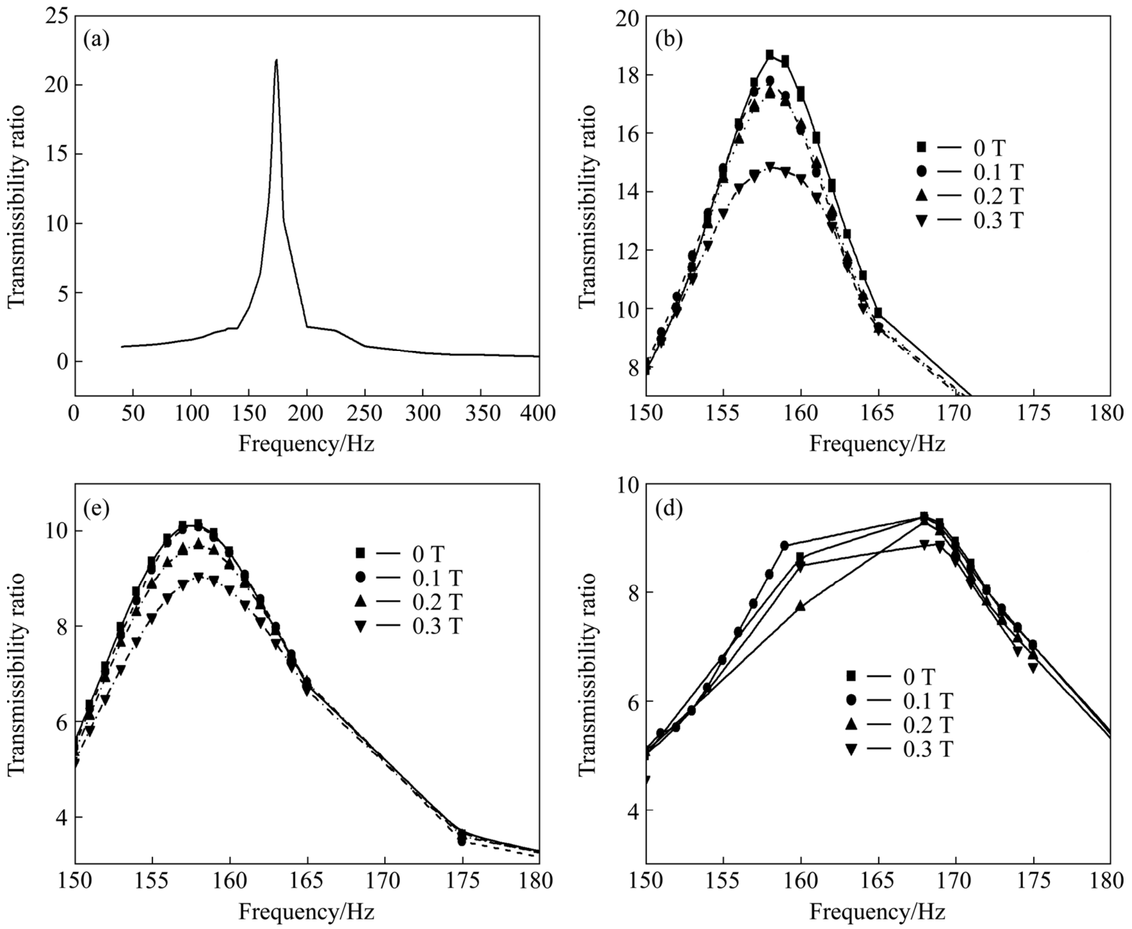

Fig. 4 Transmissibility ratio versus frequency: (a) Nature rubber; (b) 15% MRE; (c) 20% MRE; (d) 25% MRE

Figure 4 indicates that the natural rubber sample has the highest transmissibility ratio of 21.9039 at resonant frequency. From Eq. (3), the loss factor of natural rubber without any iron powders was found to be 0.0457. As the content of carbonyl iron powders increased, there was not only on absolute increase in loss factor, but also a relative increase in loss factor with magnetic field. When carbonyl iron powder is added to the natural rubber matrix, there is an improvement in the zero field properties when compared with pure rubber. This is because any addition of iron powder makes it like composite materials where iron powders can be thought of as fiber materials which enhance the zero field properties. This is evident from the plots which shows the reduction of transmissibility ratio as the content of iron powder increased. The variation of loss factor with the magnetic field for all the samples are shown in Fig. 4. The absolute change in loss factor is the highest (135% increase) for 25% MRE sample. But the relative change of loss factor (a 21% increase from 0.0551 at 0 T to 0.06379 at 0.3 T) of 15% MRE sample was more than other samples. Under the application of magnetic field, there is a force of attraction between the adjacent iron particles which results in relative motion between the particles and the matrix resulting in energy dissipation which is responsible for the improvement of damping properties of MRE. At higher magnetic fields, the force of attraction increases, resulting in field induced damping enhancement. Also, when the magnetic field is applied, the iron particles get aligned in the direction of flux lines. If the iron percentage is lower, the matrix is softer which makes the alignment of particles in the direction of magnetic field easier. At higher contents of iron particles, the matrix becomes harder thereby reducing the MR effect. Even though the loss factor of

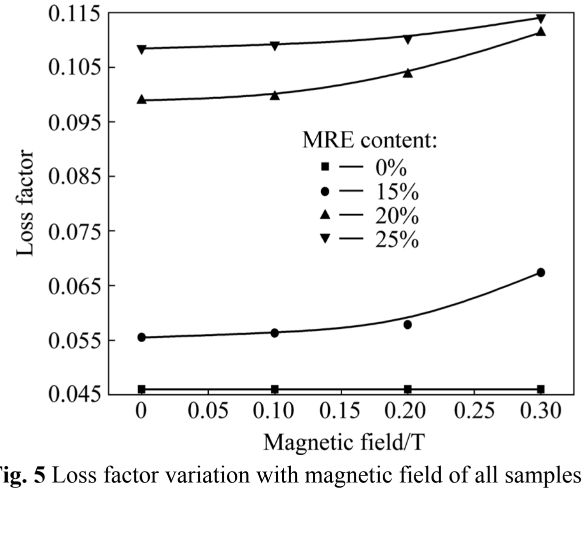

Fig. 5 Loss factor variation with magnetic field of all samples

25% MRE sample is more than the other samples, the magnetic field induced increase is lower than those of 15% and 20% MRE samples.

Graphs reveal that the magnetic field increase has improved the damping property which is evident from the reduction in transmissibility.

4.2 Dynamic damping analysis

Polymers in general are made of cross linked chains of molecules and there are molecular interactions happening during deformation of polymers which gives rise to its inherent properties like stiffness and energy dissipation in response to a cyclic deformation which is nothing but damping [14]. In case of homogeneous and isotropic polymers like the samples in the current work, the stiffness and damping characteristics vary with the temperature and to a lesser degree with operating frequency.

When a sinusoidal input force is applied to a viscoelastic material, the resulting displacement is also sinusoidal with a phase difference or lag. The plots of input force versus measured displacement are elliptical in nature. This can serves as a means to compute the inherent dynamic properties of the material. The slope of the major axis gives the stiffness of the material and the ratio of minor axis to major axis (aspect ratio) is a measure of damping. The following figure shows the force versus displacement plots of all the samples under different magnetic fields at an operating frequency of 8 Hz. This is because the operating frequency of automobiles usually varies from 0.1 to 10 Hz.

It was observed from plots that the area of the graph which is the energy dissipated per cycle per unit volume increased with the magnetic field and also when the content of iron powders was increased. The shape of the curve in all the cases is elliptical indicating the viscoelastic nature of damping.

The absolute change of 40% increase energy dissipated was observed for 25% MRE sample, which is more than all other samples. But the relative change was more for the 15% MRE sample (about 19.5%) which is more than other samples. The inter-particle magnetic force is responsible for the magnetic field induced property enhancement of magnetorheological elastomers. Under the influence of magnetic field, the particles are magnetized in the direction of flux lines. The force between two magnetic poles is given by

$$F = \frac{\mu q_1 q_2}{4\pi r^2} \tag{4}$$

where F is the force (N); q_1 and q_2 are the intensities of poles 1 and 2, respectively (A·m); m is the permeability

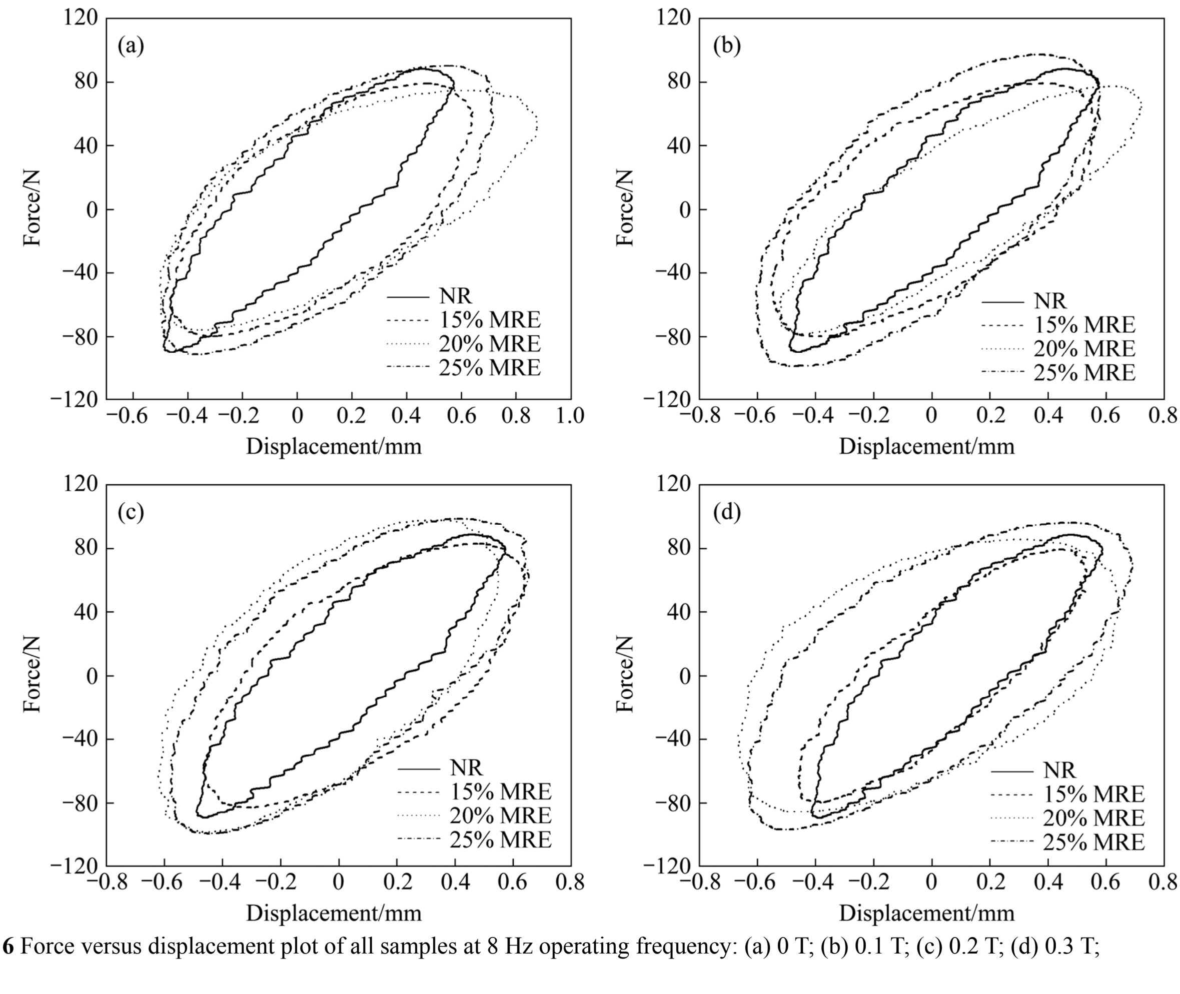

Fig. 6 Force versus displacement plot of all samples at 8 Hz operating frequency: (a) 0 T; (b) 0.1 T; (c) 0.2 T; (d) 0.3 T;

of the medium in (H/m) and r is the distance of separation of poles (m). This force between dipoles is responsible for magnetic field induced changes in properties of MRE. At lower MRE contents, assuming uniform distributions of iron particles, the distance between the particles is more than that of higher MRE content. The energy dissipation is due to the friction produced because of the relative motion between the particles and the elastomer matrix when the magnetic field is applied. At lower MRE contents, the energy dissipation is less. But the stiffness change of the matrix because of addition of iron powders is not much thereby making the relative movement of iron particles easier at lower MRE contents. With the increase in MRE contents, the matrix becomes stiffer. Hence, the relative increase in energy dissipation is less for higher MRE content samples.

This can be proved by doing a simulation of carbonyl iron powder particle in the rubber matrix using FEMM software. In the current work, it is assumed that the distribution is uniform and the diameter of the powder is 5 μm. For the ease of simulation, only two volumes of carbonyl iron powders are considered at 2 different distances apart in the rubber matrix, assuming that the distance between particles reduce as the MRE content increases. The simulation results are shown in Figs. 7 and 8.

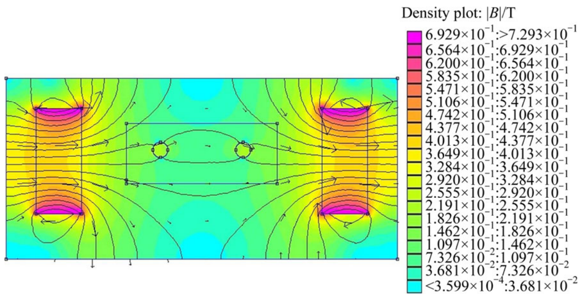

Fig. 7 Simulation at distance of 20 μm

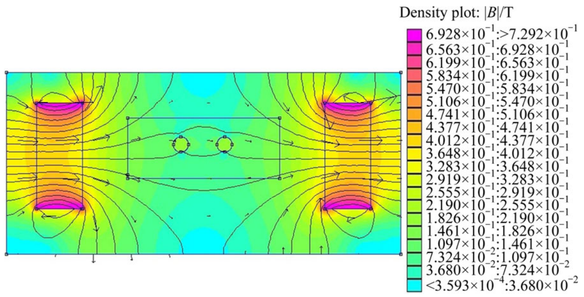

Fig. 8 Simulation at distance of 10 μm

FEMM analysis package allows computing magnetic field energy stored in the selected areas by making use of the following relation [15].

$$W=\int\left(\int_0^B H(B')\mathrm{d}B'\right)\mathrm{d}V \tag{5}$$

where H is the field intensity (A·t/m) and B is the flux density (T). V is the volume under consideration. From electromagnetic field theory, H and B are connected by the relation

$$H(B')=\frac{B}{\mu_0\mu_r}=\frac{B}{\mu}$$

where μ_0=4π×10^{-7} H/m is the permeability of free space, μ_r is the relative permeability of the material. The Eq. (5) can be written as

$$W=\int\frac{B^2}{2\mu}\mathrm{d}V \tag{6}$$

From Eq. (6), it can be deduced that energy stored in a field is a function of the volume or in turn the surface area. As the content of iron increases, the surface area increases thereby increasing the stored energy which in turn improves the MR effect. The simulation results show that when the distance between the particles was reduced from 20 μm to 10 μm, the energy increased from 2.75216×10^{-6} J to 3.85775×10^{-6} J, a 40% increase in stored energy.

6 Conclusions

1) The loss factors of all the MRE samples increase not only with the addition of iron powders but also with the magnetic field. The 25% MRE sample shows better results owing to higher content of iron powders, but 15% MRE sample shows more increase with respect to magnetic field than other 20% and 25% MRE samples.

2) By analyzing force versus displacement plots of MRE samples, increase in area of the plots with the magnetic field proves the improvement in MR effects, i.e., energy dissipation capabilities of the MRE samples.

3) It is deduced that the relative change in damping properties is a result particle to particle force of attraction which results in iron particle and matrix material interaction when magnetic field is applied. This is evident from the results which indicates that softer matrix, i.e., lower content of iron powder resultes in higher relative change in magnetic field induced properties.

4) Absolute change of 135% increase in loss factor is observed for 25% MRE sample, indicating that natural rubber is a potential material for the preparation of dampers. FEMM simulation also proves that when the content of iron powders is higher, the distance between the particles is lower which leads in better particle to particle interaction which in turn improves MR effect.

Acknowledgements

The experimental facility for the current work is provided by Centre for System Design (CSD), NITK and

SOLVE, the Virtual Lab, Government of India.

References

[1] CARLSON J D, JOLLY M R. MR fluid, foam and elastomer devices [J]. Mechatronics, 2000, 10: 555−569.

[2] LI Wei-hua, ZHANG Xian-zhou. Recent patents on mechanical engineering [J]. 2008, 161−166.

[3] KALLIO M. The elastic and damping properties of magnetorheological elastomers [J]. Tampere, Finland: Tampere University of Technology, 2015: 1−149.

[4] SUN T L, GONG X L, JIANG W Q, LI J F, XU Z B, LI W H. Study on the damping properties of magnetorheological elastomers based on cis-polybutadiene rubber [J]. Polymer Testing, 2008, 27: 520−526.

[5] YANG Jie, GONG Xing-long, DENG Hua-xia, QIN Li-jun, XUAN Shou-hu. Investigation on the mechanism of damping behavior of magnetorheological elastomers [J]. Smart Mater Struct, 2012, 21: 1−11.

[6] FAN Yan-ceng, GONG Xing-long, XUAN Shou-hu, ZHANG Wei, ZHENG Jian, JIANG Wan-quan. Interfacial friction damping properties in magnetorheological elastomers [J]. Smart Mater Struct, 2011, 20: 1−8.

[7] TIAN T F, LI W H, ALICI G, DU H, DENG Y M. Microstructure and magnetorheology of graphite-based MR elastomers [J]. Rheol Acta, 2011, 50: 825−836.

[8] EEM Seung-hyun, JUNG Hyung-jo, KOO Jeong-hoi. Modeling of Magneto-Rheological Elastomers for Harmonic Shear Deformation [J]. IEEE Transactions on Magnetics, 2012, 48(11): 3080−3083.

[9] GORDANINEJAD F, WANG Xiao-jie, MYSORE P. Behavior of thick magnetorheological elastomers [J]. Journal of Intelligent Material Systems and Structures, 2012, 23(9): 1033–1039.

[10] POSSINGER T, BOLZMACHER C, BODELOT L, TRIANTAFYLLIDIS N. [C]// SPIE Micro technologies conference, Grenoble, France: SPIG, 2013: 1−13.

[11] JOLLY M R, CARLSON J D, MU˜NOZ BETH C. A model for the behaviour of magnetorheological materials [J]. Smart Mater Struct, 1996, 5: 607−614.

[12] KALETA J, KR´OLEWICZ M, LEWANDOWSKI D. Magnetomechanical properties of anisotropic and isotropic magnetorheological composites with thermoplastic elastomer matrices [J]. Smart Mater. Struct, 2011, 20: 1−12.

[13] ASTM standard E756-04, Standard Test Method for Measuring Vibration-Damping Properties of Materials. [S]. 2013.

[14] JONES D G. Handbook of viscoelastic vibration damping [M]. Wiley Publications, 2001.

[15] BRAUER J R. Magnetic actuators and sensors [M]. New York: John Wiley Publications, 2005.

(Edited by DENG Lü-xiang)