

# Effect of the Magnetic Field on Magnetic Particles in Magnetorheological Elastomer Layers



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**Abstract** A Magnetorheological Elastomer (MRE) can be categorized as a smart material as it can respond when it is subjected to a magnetic field against itself. Shrinking and changing shape in MRE is due to the displacement of magnetic particle in the MRE matrix. However, the lack of understanding of the magnetic flow through magnetic particle in the elastomer matrix causes difficulties to improve the best MRE matrix type and a magnetic circuit for use in MRE devices. In this paper, a finite element magnetic method (FEMM) software has been used to investigate and to study the effect of the magnetic flow when the angle of the magnetic particle in the MRE changed. The analysis was conducted in two-dimensional cross-section (axisymmetric type) with two magnetic particles in the elastomer matrix and the magnetic core. The result shows by changing the angle of the magnetic particle, the value of the magnetic flow and magnetic flux density also change. As a conclusion, the magnetic particle arrangement in the elastomer matrix plays a vital role in designing the MRE matrix layer and MRE device. By understanding the magnetic flow through the magnetic particle, one can improve the method in the preparation of MRE matrix and MRE magnetics circuit.

**Keywords** Magnetorheological elastomer · FEMM analysis · Magnetic particle

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## 1 Introduction

Any material that gives a response when an external energy is applied, is considered a smart material. The various smart materials exist nowadays, which is, piezoelectric material, that provides reactions when a voltage is applied, shape memory alloy (SMA) with magnetic and thermal sensitivity that responds during applied magnetism or heat and magnetorheological (MR) material that responds during applied magnetic field [1]. A Magnetorheological elastomer (MRE) is a viscoelastic material and considered as a smart material due to repeatability and fast response when a magnetic field is applied to it. There are various methods and types of elements in the preparation of MRE. Different magnetic particles are used in the development of MRE layers such as nickel, carbon, and carbonyl iron [2]. The most popular materials that is selected nowadays for MRE is carbonyl iron [3]. The size of the particles ranges from 5 to 100  $\mu\text{m}$ . Furthermore, the matrix selection process also has variety and difference matrix, for example, natural rubber, silicon rubber and so on. In MRE, there are two different types of MRE, according to the used curing method. The first type is isotropic, which is the particle in the matrix are randomly arranged. The second type is anisotropic, which means that during the curing process a magnetic field was applied to it. As a result, the particles in the MRE will form a chain according to the applied magnetic field over it [4].

Due to its changing and controllable properties, it has high potential to be used in various applications in the industry such as a vibration isolator, base isolator, sensing device, and capacitor and so on. It was suggested in Ref. [5] to use MRE to develop a tunable vibration absorber (TVA). MRE and MRF were suggested in [6] for designing vibration insulators. MRE with multi-layer insulation was suggested in [7] for suppression of building vibration under seismic event. A tunable absorption system based on magnetorheological elastomer and Halbach array for energy absorption and mitigation of vibratory motions from an impact excitation was designed in [8]. Furthermore, MRE was used in [9] as a dielectric in an electric capacitor and a MRE capacitor was designed as a hybrid MRE with graphene Nano particles. However, to optimize the device performance, there is a need for understanding the behavior of MRE under the influence of an magnetic field, for preparing the MRE layer.

To understanding the behavior and magnetic distribution of the MRE layer, many researchers involved the computational investigation of the MRE behavior during the action of the magnetic field. A computer simulation and analysis of the shape effect in the experimental characteristic magnetorheological elastomer by using a multiscale simulation of typical experimental scenario in a two-dimensional setting was conducted in [10]. The magnetic flux distribution in the laminated MRE isolator with various iron particles filling by using a FEMM analysis software was investigated in [11]. From the literature, many researchers investigated the magnetic distribution in the system of the MRE device. However, understanding the effect of the magnetic field on the iron particle in the MRE layers is of great importance due to the main working in MRE layer is iron particle displacement. The effect of

magnetic field on the damping ratio was studied in [2] by investigating the amplification region of the transmissibility curve, viscoelastic dynamic damping natural by the force-displacement hysteresis graph and the effect of the magnetic field to the ion particle in the MRE layer at the various distances. The investigation shows that the distance and percentage of the magnetic particle influence of the performance of the MRE layer on the energy loss between the particles and also influence the stiffness when the iron particle filling is increased.

In this study, the geometry was prepared to investigate the effect of the magnetic field to a magnetic particle with various angles of the particle. The magnetic flux density and the rate of change of the magnetic density between two magnetic particles is also discussed. The geometry of the ion particle in the MRE layer with the magnetic core was prepared in a two-dimensional cross-section (axisymmetric type). The iron particle was made by various angles of the a particle with an increase of  $15^\circ$  from  $0^\circ$  to  $90^\circ$  with a constant current and distance of 0.5 A and 2  $\mu\text{m}$ .

## 2 Methodology

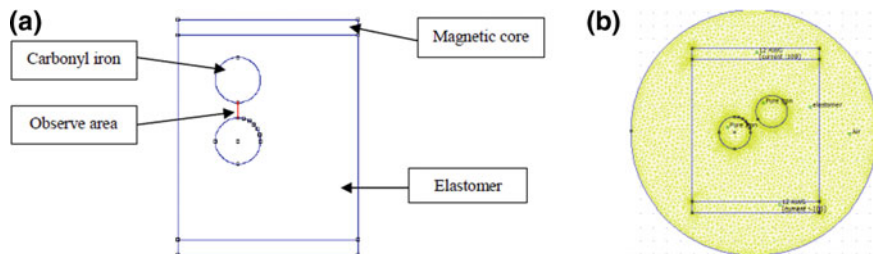
### 2.1 Finite Element Method Magnetic Analysis

The effect of the magnetic flow to carbonyl iron particle is great importance in the magnetorheological elastomer layer design. Therefore, in this work, the finite element method magnetic (FEMM) software package was used to analyse the distribution of the magnetic flux in the MRE layer. FEMM is an open source software that validated to the simple and accurate result. In the FEMM, the Maxwell equation was used to solve the magnetic problem in the system. The equation for this problem solved by:

$$\nabla \times \left( \frac{1}{\mu_{eff}(\mathbf{B})} \nabla \times a \right)^n = -j\omega\sigma\alpha + \hat{J}_{src} - \sigma\nabla V \quad (1)$$

where  $\hat{J}_{src}$  is the phasor transform of the applied current sources,  $\mu_{eff}$  is the effective magnetic permeability,  $V$  is the electric scalar potential,  $\sigma$  the medium of conductivity,  $\omega$  the fixed frequency,  $\rho$  is the change in density and  $\alpha$  is the complex amplitude of the phasor transformation. [12].

In this investigation, the model of the magnetic particle in MRE is divided into three sections, the magnetic core, the magnetic particles and the elastomer. The first section corresponds to the top and bottom of the magnetic core. The magnetic core section consists of wire copper AWG 12 with 100 turns. The second section referred to the magnetic particle and magnetic particle region, where magnetic particles with a diameter of 6  $\mu\text{m}$  and the gap between the particle of 2  $\mu\text{m}$  was set up. The third section referred to the elastomer matrix (natural silicon rubber).



**Fig. 1** Magnetorheological 2D Geometry (a) and meshing (b)

Details of each part are shown in Fig. 1a. In the FEMM software, the type of materials used for each part in this study can be found in the library of the software. In the first section, the type of copper coil (AWG 12), with 100 turns for magnetic core and the electric current supplied to the coils were then assigned. The second section, the magnetic particle was assumed as pure iron and the third section, an elastomer material is assigned to the non-magnetic material. After applying the boundary conditions and adding all material properties, the two-dimensional geometry of the magnetic particle in MRE layer is ultimately meshed with a fine triangular mesh at the critical region of the magnetic particle and the coarse triangular mesh at the outside region as shown in Fig. 1b. Various angles of the magnetic particle from  $0^\circ$  to  $90^\circ$  were decided to identify the effect of the magnetic flow in MRE layer.

### 3 Result and Discussion

The simulation of an iron particle in the MRE layer was finally archived. Figure 2 shows the observed area of the iron particle and the magnetic field distribution in the polymer matrix. Figure 2, show that the magnetic flux passes through the carbonyl iron and elastomer. Let's us look on region "A" in Fig. 2a referred; the magnetic flux flows smoothly to complete a circle of the magnetic flux region. These phenomena happen because in the elastomer matrix on that area there is no magnetic particle that deflects or attracts the magnetic flux flow. From the contour and magnetic flux on the whole of Fig. 2a, we can see that the magnetic flux densities on the magnetic particle area are higher because the magnetic flux was focusing to flow through both particles with the same magnetic flux and flow by their axis.

Region "A" and "B" in Fig. 2b show the magnetic flow in the elastomer matrix; magnetic flux density on the region "A" is higher than in region "B". The magnetic flux on region "A" shows a deflection of the magnetic flux by the presence of the magnetic particle; the magnetic particle was attracting the magnetic flux through it. Because of that, the contour of the magnetic density on that area is higher.

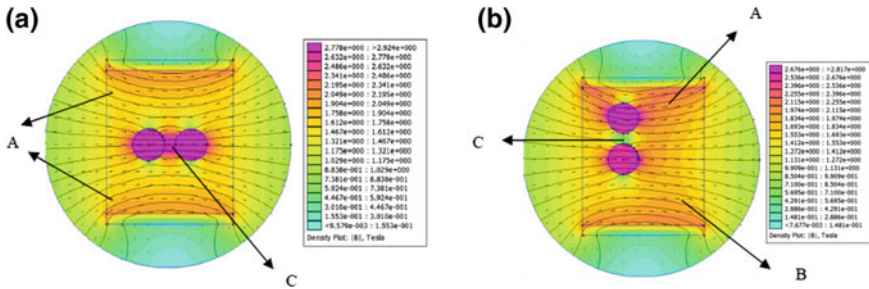


Fig. 2 Carbonyl iron particle in angle a 0° and b 90°

Furthermore, another reason is the iron particle neared with the magnetic core. The Magnetic flux on region “B” shows that the magnetic flux flow was smoothly to complete the circle of the magnetic field, because no magnetic particle crosses the magnetic flux.

By changing the angle of the magnetic particle, the magnetic flux density shows a different value. This statement can prove in Fig. 2a, b. The density of the magnetic flux changes because of the deflection of the magnetic flux in the magnetic field by the presence of a magnetic particle. Region “C” clearly shows the difference of the contour color at the area of observation. The Contour colour is presenting the density of the magnetic flux. Figure 2a shows that the magnetic density is higher with a value of 2.7 T for the magnetic flux density. This is because the magnetic flux was through the both of particle in the same magnetic field direction, deflection of magnetic field direction will lose the density of magnetic flux. Figure 2b shows that the magnetic density on observed area 90° is less than the angle of a particle in Fig. 2a with 0°. The magnetic flux shows that the magnetic flux flows through the particle with different magnetic flux, in the region C, no magnetic flux was through it. The figure also shows that the magnetic flux flows through each of the particle because the magnetic flux flows by their flux line.

Figure 3 shows the graph of a different angle of the magnetic particle and the difference of the magnetic flux density as observed in the area has shown in Fig. 1. The y-axis is the value of magnetic flux density in Tesla (T). The x-axis is representing the distance between two magnetic particles, legend show the color that represent the magntic flux density for every angle variable. The graph shows that, the angle on 0° are in concave shape and become convex when the angle of the particle changed until 90°. From the graph, one can observed that the magnetic flux density value between particle decreases when the angle of particle increases. The decrease in the magnetic flux density is because of the deflection of the magnetic flux, through the magnetic particle. From an angle of 0°, a high magnetic density was gained because the magnetic flux flowed through the both of magnetic particles, the magnetic flux flown without deflection, i.e. if there is no deflection of the magnetic flux, there is no loss.

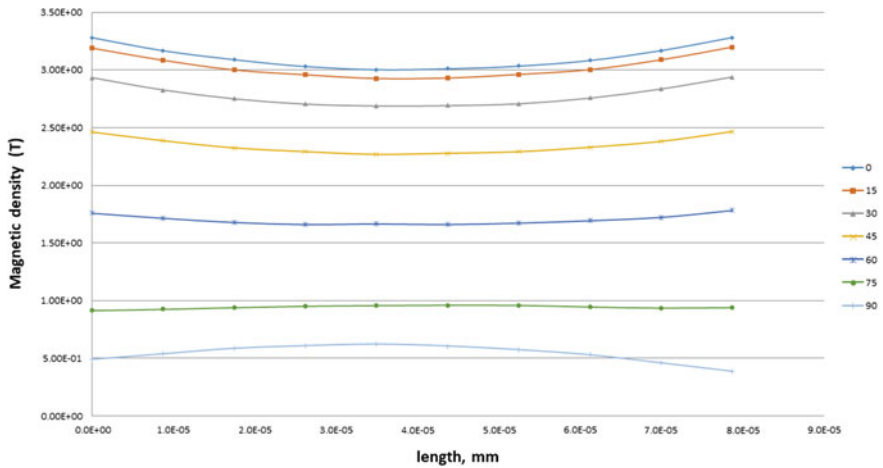


Fig. 3 Magnetic flux density

The magnetic flux density started to decrease when the magnetic particle was increased to 15° this is because the magnetic flux deflected from the existing flux. The angle of 60° and 90° show the difference of the curves, from concave change to a convex curve, the 60° and the 90° angle is the stage where the magnetic flux line breaks of still connected from the magnetic particle. The angle of 75° shows that the line of the graph is linear, the magnetic flux line in the stage is the end of broken linkage magnetic flux from particle a and b.

Figure 4 shows the rate of change of the magnetic flux density from 0° to 90°. The x-axis represents the magnetic particles angle, whereas the y-axis is the value of the magnetic flux density. This graph is relevant for the understanding of the rate of change in the magnetic flux density. This investigation is for identifying whether with every 15° angle, the magnetic flux density changes in a certain pattern or randomly. From the observations in Fig. 4, the rate of change of magnetic flux density in this study shown that, the paten of changing is not linear, the magnetic flux density was drop at angle 75° to 90°. The changing is because of the magnetic flux density slightly deflects from the origin. The largest is for transition from 60° to 75° with value 0.8 T.

Figure 5a, b show the contour and magnetic flux differences occurring for the angle of 60° and 75°. One can observe that the rate of change for 60 and 75 is experiencing a higher change than others. The region “A” in Fig. 4b is referred to; the contour indicates that the magnetic flow is passing through the area between the two particles and still produces a high magnetic flux density which produces a polar magnetic flux density in the concave state as shown in Fig. 3. This is the case because the magnetic flux distances through both particles have a close distance even though the magnetic flux between the two particles is not shared.

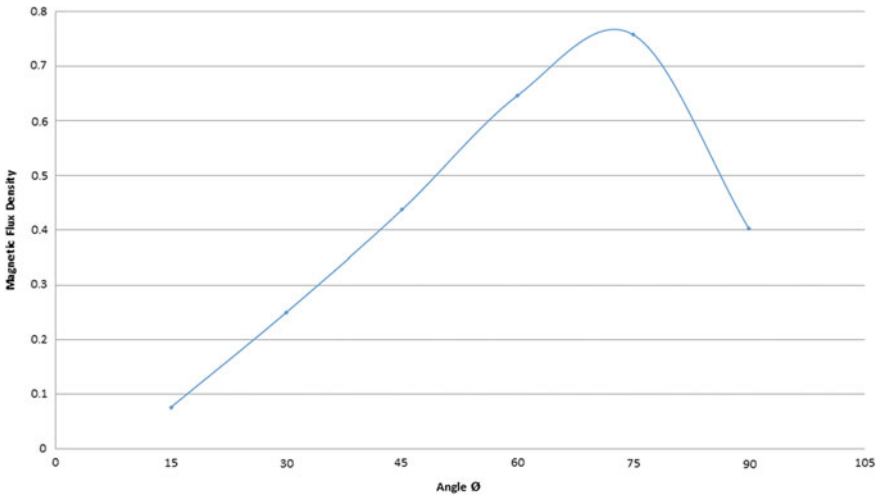


Fig. 4 Rate of change of magnetic flux density

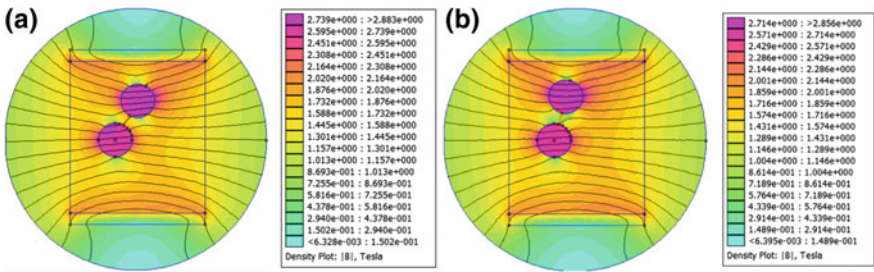


Fig. 5 Carbonyl iron angle 60° (a), 75° (b)

Figure 4c shows, the magnetic flux passing through magnetic particles to discuss the pattern at 70° in Fig. 3. The pattern produced at angle 70° is as if such as a straight line, and at this angle, we can see, it is the middle of the change of polar magnetic flux density of 60° and 90°. This situation occurs because at this angle began to break off the magnetic flux line on particles A and B. When there is no magnetic flux correlation between the particles as shown in Fig. 4b, c, the magnetic density prevailing at the observation area will decrease.

To answer the question of large rate of change at angle 60 and 70, we can compare region A to both Figs. 4b, c. A significant change occurred in the magnetic flux passing through particle "A", an observation made, the magnetic flux through particle "A" 60° is more than through particle "A" at 75°. Furthermore, at the angle of 70°, no magnetic flux linkage connected between particles A and B. The strength of the magnetic flux density occurs when the magnetic flux flows straight to its axis without any magnetic field deflection and magnetic flux sharing between particle A and B becomes a critical factor increasing the magnetic flux density.

## 4 Conclusion

In this study, a two-dimensional geometry in a FEMM software was created to investigate the effect of the magnetic field flow in a Magnetorheological elastomer. The simulation consists of two particle magnetic particles that declare as pure iron and around of the magnetic particle is an elastomer polymer matrix. The objective of these studies is to study the effect of the magnetic flow in the MRE layer through the magnetic particle inside MRE layer. The result showed the different response if we change the angle of the magnetic particle. From these studies, we can conclude that the magnetic particles are a significant element in the working principle of the MRE. An elastomer matrix with no magnetic particles does not give any deflection of the magnetic flux, if there is no magnetic flux deflection, then the shrinkage of the matrix elastomer does not occur. With the presence of magnetic particles in the elastomer matrix, the magnetic flux generated from the magnetic core will decelerate and go towards the magnetic particles, by attracting magnetic flux to a magnetic particle which causes the elastomer matrix to shrink when the magnetic field is applied to it and is known as a magnetorheological elastomer. Angles for the arrangement of magnetic particles have been varied to study whether the change of angle on the magnetic particle arrangement affects the magnetic field changes in the MRE layer. From the observation and discussion, it was found that by the changing of magnetic particles angle also affects the magnetic flux density changes in the MRE Layer. With the changing of magnetic particle angle, we can see that the rate of change for each different angle. From the observation, the rate of the change of magnetic flux density changes in a random state because the magnetic flux affects the density of magnetic density. For the overall conclusion, we have understood that the arrangement of an iron particle in the MRE plays the vital issue to design the MRE matrix. Proper selection of the correct MRE type, either isotropic or anisotropic will increase the efficiency of the MRE layer in any application that uses MRE layer.

**Acknowledgements** All the experiment and analysis conducted under System Engineering and Energy Laboratory, Universiti Kuala Lumpur, Malaysian Spanish Institute, Kulim Kedah, Malaysia.

## References

1. Rakotondrabe, M.: Smart Materials-Based Actuators at the Micro/Nano-Scale (2013)
2. Hegde, S., Kiran, K., Gangadharan, K.V.: A novel approach to investigate effect of magnetic field on dynamic properties of natural rubber based isotropic thick magnetorheological elastomers in shear mode. *J. Cent. South Univ.* **22**(7), 2612–2619 (2015)
3. Koo, J.H., Dawson, A., Jung, H.J.: Characterization of actuation properties of magnetorheological elastomers with embedded hard magnetic particles. *J. Intell. Mater. Syst. Struct.* **23**(9), 1049–1054 (2012)



4. Li, Y., Li, J., Li, W., Du, H.: A state-of-the-art review on magnetorheological elastomer devices. *Smart Mater. Struct.* **23**(12), 123001 (2014)
5. Ginder, J.M.: Magnetorheological elastomers in tunable vibration absorbers. *Proc. SPIE* **4331**, 103–110 (2001)
6. Sun, S.S., et al.: Development of an isolator working with magnetorheological elastomers and fluids. *Mech. Syst. Signal Process.* **83**, 371–384 (2017)
7. Yang, J., et al.: Development of a novel multi-layer MRE isolator for suppression of building vibrations under seismic events. *Mech. Syst. Signal Process.* **70–71**, 811–820 (2016)
8. Bocian, M., Kaleta, J., Lewandowski, D., Przybylski, M.: Tunable absorption system based on magnetorheological elastomers and Halbach array: design and testing. *J. Magn. Magn. Mater.* **435**, 46–57 (2017)
9. Bica, I., Anitas, E.M., Chirigiu, L.: Magnetic field intensity effect on plane capacitors based on hybrid magnetorheological elastomers with graphene nanoparticles. *J. Ind. Eng. Chem* **56**, 407–412 (2017)
10. Keip, M.A., Rambašek, M.: Computational and analytical investigations of shape effects in the experimental characterization of magnetorheological elastomers. *Int. J. Solids Struct.* **121**, 1–20 (2017)
11. Wahab, N.A.A., et al.: Fabrication and investigation on field-dependent properties of natural rubber based magneto-rheological elastomer isolator. *Smart Mater. Struct.* **25**(10), 107002 (2016)
12. Baltzis, K.B.: The finite element method magnetics (FEMM) freeware package: may it serve as an educational tool in teaching electromagnetics? *Educ. Inf. Technol.* **15**(1), 19–36 (2010)