Design of magnetic Circuit Simulation for Curing Device of Anisotropic MRE

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Abstract. The strength of magnetic field during fabrication of magnetorheological elastomer (MRE) plays a crucial role in order to form a pre-structured MRE. So far, gaussmeter were used to determine the magnetic intensity subjected to the MRE during curing. However, the magnetic flux reading through that measurement considered less accurate. Therefore, a simulation should be done to figure out the magnetic flux concentration around the sample. This paper investigates the simulation of magnetic field distribution in a curing device used during curing stage of anisotropic magnetorheological elastomer (MRE). The target in designing the magnetic circuit is to ensure a sufficient and uniform magnetic field to all the MRE surfaces during the curing process. The magnetic circuit design for the curing device was performed using Finite Element Method Magnetic (FEMM) to examine the magnetic flux density distribution in the device. The material selection was first done instantaneously during a magnetic simulation process. Then, the experimental validation of simulation was performed by measuring and comparing the actual flux generated within the specimen type and the one from the FEMM simulation. It apparent that the data from FEMM simulation shows an agreement with the actual measurement. Furthermore, the FEMM results showed that the magnetic design is able to provide sufficient and uniform magnetic field all over the surfaces of the MRE.

1 Introduction
Magnetorheological elastomer (MRE) is one of the smart materials in which their mechanical and rheological properties can be quick, persistently and reversibly changed by controlling the external magnetic field. MRE comprises carbonyl iron particles (CIP) implanted in a rubber-like matrix. Generally, MRE can be classified into two types which isotropic and anisotropic MRE fabricated with and without external magnetic field [1]. Curing the MRE with an external magnetic field can prompt the formation of a chain-like structure that trapped inside the rubber matrix [2]. These chain-like structures are beneficial to improve the MR effect of MRE [3]. Because of these special properties, anisotropic MRE received increasing attention and gained wide application prospects mainly in applications that employ variable stiffness such as vibration absorbers [4,5].
The formation of chain-like structures exceptionally reliant on the strength of magnetic field during curing process [6]. The formation of chains can be fluctuated by the strength of magnetic field. It can be a single chain-like, three-dimensional structures or even more complex structure [7]. The variability of magnetic field strength during curing will result in the formation of anisotropic MRE with different magnetorheological effect. For instance, Li et al [6] have fabricated MRE with different magnetic field strengths from 0 to 350 mT and the results revealed the differences of MR effect for each of the sample. Wu et al. [3] cured polyurethane MRE under a magnetic field strength of 900 mT, the relative MR effect achieved was only 21%. Ju et al. [8] fabricated anisotropic polyurethane based MREs with a constant magnetic field strength of 700 mT. The result revealed that the MR effect of the anisotropic MRE was 33.7%.

In order to fabricate the MRE with anisotropic configuration, curing device with an attachment of the external magnetic field device or a couple of permanent magnets could be considered to be utilized. Previous researchers have built up their own curing device to fabricate the anisotropic MRE. Lu et al [9] developed the curing system with the attachment of magnetic field and temperature control to fabricate the styrene-b-ethylene-co-butylene-b-styrene (SEBS) based MRE. The MRE was cured using the homemade magnet-heat coupled device and the actual intensity was measured with a Tesla meter. In the mean time, Kaleta et al [1] had used a couple of permanent magnets to cure the MRE samples. The strength of the magnetic field applied during curing was tested in between the gap of the mold and the value is equal to 0.5 T. However, a noteworthy issue with this sort of technique is the correct estimation of the magnetic field intensity subjected to the MRE sample can't be resolved. Furthermore, most of the researchers have focused on studying the rheological properties of anisotropic MRE itself, such as its dynamic stiffness, damping factor and MR effect. A little report has been noticed discussing on the magnetic intensity distribution inside the curing device to ensure the uniform distribution to the MRE samples. Therefore, this paper focuses on the study of magnetic field distribution in curing device using FEMM. This FEMM analysis is used to illustrate the efficiency of the design. Finally, an actual measurement was measured in the chamber of the device and the result was compared with the simulation result. It was done to verify the distribution of the magnetic flux within the MRE samples as the real magnetic intensity within the MRE sample cannot be measured with the gauss meter probe.

2 Experimental

2.1 Design Consideration

The important consideration in designing the curing device is to make sure that all the magnetic lines must pass through the area inside the magnetic coil. Therefore, the strongest and uniform magnetic field distribution can be guaranteed at the MRE sample areas. The magnetic field is uniformly concentrated in the center of the coil, while at the outside region of the coil, the strength of the field is weak and divergent. Figure 1 shows the proposed idea of the mold and curing device that would be developed. The curing device mainly consists of a magnetic coil, bobbin, steel cover customized mold. The details of the components include the raw materials are listed in Table 1.
Table 1. Detail of material selections for each part.

| No. | Part list    | Material                        |
|-----|--------------|---------------------------------|
| 1   | Mold         | Low carbon steel, AISI 1117      |
| 2   | Steel cover  | Low carbon steel, AISI 1117      |
| 3   | Coil         | Copper wire (0.9mm)              |
| 4   | Bobin        | Plastic                          |
| 5   | MRE sample   | -                                |

The space between the coil and the bobbin are separated by the ambient air to allow heat release generated during magnetization [10]. Due to the magnetic principle, all the magnetic lines that enter any region must also leave that region without any remanence [11]. The customized mold was made from low carbon steel and will be placed in the center of the coil. The region of the MRE sample is about 1 x 50 mm in thickness and diameter respectively. The steel from the same types of mold was used to cover the bobbin of the coil. It is necessary to create an enclosed path for magnetic flux so that the flux is passed and went to the inside core through the mold. The magnetic coil then connected to an external direct current (DC) power source to generate the magnetic field throughout the coil. When the current is “ON”, thus the charges will move around the coil and produce the magnetic field which is called as electromagnetism. This phenomenon can be explained by Faraday’s Law where it explained that a changing magnetic field produces an electric field. For example, if a loop of wire is placed in a magnetic field so that the field passes through the loop, a change in the magnetic field will induce a current in the loop of wire.

2.2 Simulation
The magnetic flux distribution around the curing device was simulated first using FEMM 4.2 software. FEMM is one of the useful software to analyze the magnetic behavior around the magnetization area. In order to validate the result from the FEMM software, the actual measurement from the curing device was measured using Hirst Magnetic Instrument GM08 Gaussmeter. Figure 2 shows a step by step of the magnetic circuit simulation using FEMM software.
Figure 2. Model of curing device for anisotropic MRE in FEMM simulation (a) designing stage, (b) meshing area of the model, (c) magnetic flux density distribution, and (d) close up at MRE samples space.

The simulation was performed in a 2D axis-symmetric plane. The sketch map of the curing device includes the mold are illustrated in Fig. 2 (a). The simulation was conducted in 2D axis symmetric were the cross section of the desired design was drawn to represent the magnetic flux distribution around the design. Then, the type of materials was chosen at the FEMM built in library of block property definitions. The selection of material was based on the availability of the material on the market. Thus, low carbon steel, AISI 117 was chosen as the main material for the mold and the steel cover due to the abundant source in the market. The coil was firmly wounded on the plastic bobbin and the total winding number of a coil is 1500 turns with the diameter of 0.9 mm. After all the block were labeled by the selected materials, the mesh was created by 5545 nodes as shown in Fig. 2 (b) before the flux line plotting as illustrated in Fig. 2 (c). The magnetostatic simulation plotted in Fig. 2 (c) has resulted from 0.5 A of applied current in each coil. From the figure, the flux lines pass through the steel cover right into the mold by forming a closed loop magnetic circuit. Fig. 2 (d) shows the close up of the MRE region at the center of the mold. From the magnetic simulation, the region for MRE samples shows the highest strength and uniform magnetic flux concentration.
3 Results and Discussion
The verification of the FEMM simulation then was performed by comparing the result from the simulation results with the actual measurement at the test chamber of curing device. The measurement was made in the region between the top of the steel cover and the mold. The currents were controlled by external DC power supply and varied from 0 to 1 Tesla by an interval of 0.1 A. Fig. 3 presents the comparison between the simulation and the actual measurement. The differences between these two are still considered acceptable.

![Figure 3. Validation result between actual measurement and FEMM simulation.](image)

Next, the simulation was made in the MRE region to evaluate the flux density that passes through the MRE sample. This is because, in real measurement, the gaussmeter cannot be placed nearby the sample. Therefore, by doing this simulation, the magnetic flux density passes through the MRE sample can be predicted. Table 2 presents the simulation measurement for the MRE region. As shown in Table 2, the value of the magnetic field strength can be achieved when the regulated current supply is 1T was about 681 mT approximately.

| Current, A | Magnetic field strength, mT (MRE region) |
|-----------|-----------------------------------------|
| 0.1       | 70                                      |
| 0.3       | 209                                     |
| 0.5       | 345                                     |
| 0.7       | 482                                     |
| 1.0       | 681                                     |
4 Conclusions

Through the finite element analysis, this paper presents a thorough investigation of the magnetic flux intensity distribution inside the curing device. The curing device for anisotropic MRE was developed based on the rough simulation through FEMM software. The magnetic flux density distribution has been successfully stimulated by the software in order to identify the uniform distribution to all over the MRE sample. Experimental testing was conducted to obtain the actual magnetic field passes through the MRE region. The result of the actual measurement was then compared with the simulation analysis and it is found that the result shows a correlation with the measurement result. Furthermore, through the simulation, it is observed that the middle of the mold possessing the strongest and uniform magnetic field distribution. Therefore, it is suggested the MRE samples should be placed in the middle of the mold.

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