SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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SIMULATION OF MAGNETORHEOLOGICAL ELASTOMER (MRE) DAMPING MECHANISM

By

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled "**Simulation of Magnetorheological Elastomer (MRE) Damping Mechanism**". I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title for any other examining body or University.

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TABLE OF CONTENTS

CONTENTS **Page**

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

FEA	Finite element analysis
FEM	Finite element method
MR	Magnetorheological
MRE	Magnetorheological elastomer
MRF	Magnetorheological fluid
NR	Natural rubber

LIST OF SYMBOLS

σ	Stress
E	Elastic modulus
ε	Strain
γ	Shear strain
S	Shear deformation
l	Length
u	Strain energy
V	Volume of the body
ω	Driving frequency
ϕ	Phase angle
ψ_I^s	Strongly bonded interfacial damping
ϑ	Poisson ratio
V_p	Volume fraction of the particles
C	Correction factor
ρ	Density
G'	Storage modulus
G''	Loss modulus

SIMULASI MEKANISME REDAMAN TERHADAP ELASTOMER MAGNETORHEOLOGICAL (MRE)

ABSTRAK

Getaran adalah subjek asas dalam kejuruteraan. Masalah yang serius mungkin berpunca daripada getaran apabila bahan tidak dipilih dengan teliti untuk integriti dinamik. Tujuan utama projek ini adalah untuk meningkatkan pemahaman yang lebih baik mengenai redaman. Terdapat tiga kes yang dikaji dalam projek ini iaitu pengaruh bahan pada mekanisme redaman, pengaruh frekuensi pada mekanisme redaman dan pengaruh daya dikenakan pada mekanisme redaman. Kesan tan δ dianalisis untuk kesemua kes. Untuk kes pertama, getah asli (NR), MRE #1 dan MRE #2 telah dipilih untuk dikaji pengaruh bahan pada mekanisme redaman. Keputusan yang diperolehi menunjukkan MRE #2 mempunyai tan δ lebih baik berbanding NR dan MRE #1. Untuk kes kedua, lima frekuensi yang berbeza iaitu 20 Hz, 40 Hz, 60 Hz, 80 Hz dan 100 Hz telah dipilih untuk dikaji pengaruh frekuensi pada mekanisme redaman. Data yang diperolehi menunjukkan selepas 61 Hz, terdapat penurunan mendadak terhadap tan δ. Untuk kes ketiga, lima daya yang berbeza iaitu 0.5 N, 1.5 N, 2.5 N, 3.5 N dan 4.5 N telah dipilih untuk dikaji pengaruh daya terhadap mekanisme redaman. Keputusan menunjukkan bahawa hubungan antara tan δ dan daya adalah linear dengan nilai tan δ meningkat sehingga 0.2910. Di samping itu, terdapat sedikit perbezaan pada nilai simulasi tan δ dengan eksperimen tan δ apabila dibandingkan. Nilai yang diperoleh daripada simulasi tan δ untuk NR, MRE #1 dan MRE #2 adalah 0.1225, 0.1473 dan 0.1586 manakala untuk eksperimen tan δ adalah 0.1202, 0.1472 dan 0.1584. Perbezaan untuk simulasi tan δ dengan eksperimen tan δ apabila dibandingkan adalah tidak melebihi 2% dan di dalam keadaan yang dipersetujui.

SIMULATION OF MAGNETORHEOLOGICAL ELASTOMER (MRE) DAMPING MECHANISM

ABSTRACT

Vibration is fundamental subjects in engineering. Severe problems may arise from vibration when material is not carefully selected for its dynamic integrity. The main aim of this project is to develop a better understanding about damping. There are three cases studied in this project which were the influence of material on damping mechanism, the influence of frequency on damping mechanism and the influence of force on damping mechanism. The effect of tan δ was analyzed for all cases. For the first case, natural rubber (NR), MRE #1 and MRE #2 were selected to investigate the influence of material on damping mechanism. Result obtained shows MRE #2 had excellent tan δ compared to NR and MRE #1. For the second case, five different frequencies, 20 Hz, 40 Hz, 60 Hz, 80 Hz and 100 Hz were selected in order to study the influence of frequency on damping mechanism. The data obtained shows that after 61 Hz, a rapid decrease of tan δ was observed. For the third case, five different forces of 0.5 N, 1.5 N, 2.5 N, 3.5 N and 4.5 N were selected to observe the influence of force on damping mechanism. The result shows the relationship between tan δ and force is approximately linear with the value of tan δ increase up to 0.2910. In addition, there is slight difference in values of simulation tan δ with experimental tan δ when compared. The value that was obtained from simulation tan δ for NR, MRE #1 and MRE #2 were 0.1225, 0.1473 and 0.1586 while for experimental tan δ were 0.1202, 0.1472 and 0.1584. The difference for the simulation tan δ compared with experimental tan δ was not exceed than 2% and in a good agreement.

CHAPTER 1

INTRODUCTION

1.0 Overview

Magnetorheological elastomer (MRE) are a specific class of smart materials named magnetorheological (MR) materials, whose rheological or mechanical properties can be regulate by external magnetic field. MRE materials promote damping mainly by the viscous flow of the rubber matrix, but inclusion of magnetic particles in rubber enables additional damping through magnetic particle interaction and interfacial damping. Furthermore, the usage of damping material is a significant measure for vibration and acoustics control in engineering. However, severe problems may arise from vibration when structure is not carefully designed for its dynamic integrity. In this project, several case studies are involved to explain the difference of various consideration methods of damping effects.

1.1 Magnetorheological Elastomer (MRE)

Materials which react to changes in the surrounding conditions in an ingenious manner can be categorized as smart materials. A few of famous smart materials are magneto sensitive materials, piezoelectric materials, thermos chromic, photo chromic materials and shape memory alloys. Magnetorheological elastomer (MRE), foams and fluid belong to such family of smart materials. This smart material whose mechanical or rheological properties can be reversibly and accelerated controlled by an external magnetic field of certain intensity (Weihua Li et. Al, 2008).

MRE are a specific class of smart materials named magnetorheological (MR) materials, whose rheological or mechanical properties can be regulate by external magnetic field. Due to their broad applications in shock absorption, noise reduction and other areas, MRE have captivate great attention and have been used in many devices such as the adaptive tuned vibration absorbers, mass dampers, sensors, actuators, base isolation (Ge et al. 2013).

According to Boczkowska (2010) magnetorheological elastomers (MRE) are solid shape analogues of magnetorheological fluids. The MRE consist of ferromagnetic carbonyl iron particles and a soft elastomer matrix. Their mechanical properties change because of the influence of an external magnetic field. According to the literature, the elasticity modulus of MRE can undergo a change by about 30-40%, and even 60% due to the presence of the magnetic field.

Iron particles and suitable matrix materials include natural rubber, polyurethane rubber, silicone rubber, polybutadiene and polyisobutylene are the common magnetic particles used in MRE. The magnetic particles can be added and subsequently processed into a final solid form as these materials are nonmagnetic viscoelastic materials. Moreover, these materials can be processed into a final solid form through plastic processing or conventional rubber (Rendek & Lion, 2010).

Besides, there are a few factors which can influence the behavior in which an MRE will react, for example, the elastomer matrix will have its own material properties of elastic modulus. Therefore, material selection for the elastomer matrix is very consequential for the viscoelastic behavior of the MRE. Similarly, the material selected for the micron sized magnetisable particles also may have its own effect on the overall

MRE manner. Besides, as if the particles are small enough, it is believed that the ferromagnetic particles will uniformly magnetized (Ruddy et al. 2007).

MRE however, they are distinguished by their field dependent modulus and maneuver within the pre yield regime. Because of the capability to change modulus with the field, MRE materials are very useful in structures as to attune the natural frequency, which is susceptible on the equivalent stiffness of the structure. With increasing shear modulus, the natural frequency shifts to higher frequencies. By customize the natural frequency, one can obviate the system from attaining the resonance or other few phenomena (Ginder et.al., 2001).

A typical magnetorheological elastomer consists of viscous liquids, viscoelastic material and powdery metals. All these have either a bounded mutual solubility or compatibility, even if they can be thoroughly dispersed in each other. The interaction between the filler particles and the matrix can be either invigorated or impotent and it will affect the mechanical and rheological properties of the composite. Rheological experiments expose that the linear viscoelastic region vanish with increment of filler content, which is a general characteristic of most practical rubber compounds. The linear behavior is irretrievable and the composites exhibit a modulus decline similar to the Payne effect, above definite filler content. Besides, Payne effect can be explained as the decrease of the in phase or storage of shear modulus with increasing amplitude of oscillation. The Payne effect will accelerate with increasing concentration of filler material in the composite (Payne & Whittaker, 1971).

The most consequential single parameter affect the composite behavior is the average particle size of the filler. With sizes smaller than 100 nm the structure reinforcement is readily achieved but, the particle geometry become to be more serious factor in the mechanical behavior of the composite. Moreover, particle distribution and wetting are also important elements. As the free agglomerates are potential failure initiation sites, particles should be homogeneously distributed. Thereby, for forming a continuous composite structure, good wetting of particles by polymer chains is a must (Leblanc, 2002).

When compared with basic rubbers, MRE offer several distinct benefits. MRE may promote damping mainly by the viscous flow of the rubber matrix. But inclusion of magnetic particles in rubber enables interfacial damping and additional damping through magnetic particle interaction thus, stiffness may increase. Furthermore, stiffness and damping can be varied by application of an applied magnetic field during in service or fabrication. Moreover, MRE are often referred to as the solid analogue of previously developed magnetorheological fluids (MRF). MRF basically used in damping of automotive suspensions and the magnetic particles are contained within oil. Either within a composite structure or alone, MRE can be utilized for damping. The main advantage of MRE over MRF is that particle sedimentation is overcome. In addition, MRE do not need seals or containers to prevent leakage or hold the fluid (Lakes RS, 2001).

1.2 Damping in MRE

Oscillation amplitudes that are decrease through irreversible removal of vibratory energy in a component or a mechanical system are the term that usually used to describe what is damping. Apart from that, damping is also digests as a macro scale manifestation of atomic scale dissipation. Furthermore, the mechanism by which irreversible energy will transfer which is from vibratory to thermal is usually refers to dissipation.

In certain precision instrumentation and also sensor, low damping basically is used to increased sensitivity. While for high damping is usually used to acquire vibration and low noise levels. Furthermore, at resonance where the inertia force and stiffness become equal, damping will become more apparent. As a conclusion, damping always is a greatest factor in predicting vibration response of structures.

To reduce vibration in structural systems and mechanical, damping materials are used for energy absorption. Furthermore, viscoelastic character may contribute greatly to damping. The damping performance achieved by particular viscoelastic materials. Viscoelastic material is the ability of the material to dissipate the energy within it and the product of the fraction of vibration energy that gets into the damping materials. Moreover, the fundamental parameter to assess energy dissipation capability in a viscoelastic material is generally known as the loss tangent, or called tan δ (Deng & Gong, 2008).

In the case of MRE, the basic material damping can be considered to be of viscous character. Studying the free vibration response of the system or subjecting the system to forced oscillations, the vibration damping can be studied if the damping is on a subcritical level. Moreover, the critical level of damping is defined as the smallest amount of damping for which no oscillation happen in free vibration response of the system to an external impulse (Kallio, 2005).

Damping in MRE is considered to be predominantly by the viscous flow of the rubber matrix. The inclusion of magnetic particles allows additional damping through interfacial damping at the interface. The interface is between the magnetic particles and the matrix and magnetism induced damping. Therefore, it requires identification for modeling of total damping capacity of MRE. Identification requirement of the individual components in the material and a determination of their contributions to the total damping also needed (Shuib & Pickering, 2016).

Viscous damping of MRE is generally provided by the rubber matrix. Rubber is a viscoelastic material which display both elastic and viscous manner. The elastic stress follows Hooke's law where stress is directly proportional to strain. While the viscous stress follows Newton's law of viscosity which states that, viscous stress is proportional to strain rate. For a viscoelastic material, the stress strain relationship is defined by a linear differential equation with respect to time. A general employed relationship is based on the Kelvin Voight model. Furthermore, this model can be represented by spring and dashport elements.

Interfacial damping is the interface between matrix and the magnetic particles. The interfacial damping is also consequential in determining the damping of MRE. Interfacial damping can be attributed to damping through strongly bonded interfaces and weakly bonded interfaces. Weakly bonded interfaces are formed due to weak interactions between particles and the matrix. For weakly bonded interfaces, the damping is basically due to interfacial friction between the matrix and the surfaces of particles during deformation. The effect of weakly bonded interfaces on the overall damping of the composites can be describing using Lavernia analysis. In this analysis, the damping is determined by the normal stress and the friction coefficient between two constituents. Furthermore, the normal stress is at the interface where the relative moment is probably to occur (Lavernia et al., 1995).

Magnetism induced damping in MRE is happen due to energy absorbed to annihilate magnetic interaction between neighboring particles. This process will convert elastic energy into magnetic energy and subsequently dissipates by magnetic hysteresis. Other mechanism incorporate in this damping is magneto mechanical damping. The process for energy absorption by the magneto mechanical damping is due to change of magnetic domain structure induced by application of stress.

1.3 Objective

A complete review of vibration analysis is presented. The usage of damping material is a significant measure for vibration and acoustics control in engineering. The simulation based results on vibration analysis is very keen to the input methods and description of damping properties. In this project, the consideration of vibration damping using software ANSYS Workbench 15.0 for transient structural analysis is addressed.

i. To study the effect of damping mechanism with usage of different materials.
ii. To investigate the effect of damping mechanism on different force in Magnetorheological Elastomer (MRE).
iii. To analyze the effect of damping mechanism on different frequency in Magnetorheological Elastomer (MRE).

1.4 Problem Statement

Vibration and dynamics are fundamental subjects in engineering. Severe problems may arise from vibration when structure is not carefully designed for its dynamic integrity. Vibration may cause break down or malfunction of machines that exhibit misalignment or unbalance. It can also lead to massive engineering failures such as the collapse of a bridge, building collapse, collapse oil platform and dam failure (Lokander & Stenberg, 2003).

It is firstly desirable and often necessary to understand its whole nature, such as transmission path and frequency content, its originating source, the nature and direction of the vibration and acoustics at the problem location when an acoustics problem and unacceptable vibration needs to be controlled. Then, it must be decided whether the problem would be best solved by passive, active or semi active control methods (Cai et al. 2002).

Passive control is known as the mechanism that may operate without using any external energy supply. It will use the potential energy generated by the structure's response to supply the control forces. To provide added damping to the system to reduce the response to controllable limits, the control forces will distributed through the structure. Meanwhile, active control may be operated by using an external energy supply. This type of control is more efficient than passive control because it can control displacement, velocity and acceleration of the structure to any extent. Besides, it also included computer controlled actuators which provide seismic resistance by imposing forces on the structure. This force function is to counter balance the ground motion induced forces.

Furthermore, if the supplied control energy were stopped, most of the active control mechanisms can operate as passive control too. However, the advantages involved in using active control for control of large structure outweigh by far is the economical reason. The cost of an active control is much more expensive than passive control. Besides, other than active and passive control, there is semi active control or also known as hybrid control. Semi active control is a combination of active and passive control which includes a combination of isolators and dampers.

Furthermore, the resistance offered by the fluid to the moving body will causes the energy to be dissipated when mechanical systems vibrate in a fluid medium such as gas, air, water and oil. The amount of dissipated energy may depends on many factors, such as the viscosity of the fluid, size and shape of the vibrating body, the frequency of vibration, and the velocity of the vibrating body. In viscous damping, the damping force is proportional to the velocity of the vibrating body.

1.5 Scope of Study

This study is concerned only with the damping modification in passive control methods. If the acoustics and undesirable vibration is conquering by one or more resonance of the structure, it basically can be controlled by boost the damping of the system. Many acoustics and non-resonant vibration problems cannot be solved by the damping treatment. Moreover, the increased damping must be larger than the initial damping for an added damping system to be effective. Besides, the most usually used method of increasing the damping is to include highly damped polymeric material at strategic locations onto the structure. The polymer and structure must interact with each other in such a way as to cause the polymer to dissipate as much energy as possible.

The categories of common damping in engineering are investigated. It is explained how ANSYS Workbench 15.0 considers the damping properties for engineering purpose. Several case studies are involved to explain the difference of various consideration methods of material damping effects. Finally, some key points are drawn for correct application of damping effects for transient structural analysis in ANSYS Workbench 15.0.

1.6 Thesis Outline

This project is about simulation of MRE damping mechanism. In Chapter one of this project, it presents the background and introduction to the topic, defines research problem, states the aims and objectives and outlines the method of investigation used in this project. Chapter two will provides an overview survey of literature on the material, effect of damping, type of damping and fabrication simulation. Chapter three outline the general methodology adopted in the research project. Discussion on the research flow chart and methods, step by step numerical experimental procedure employed in the study are given in detail.

Chapter four aims at presenting and discussing the results and findings of the experimental works done and synthesizing the information on the usefulness of simulation of MRE damping mechanism in this study. It will discuss the influence of the material to the damping mechanism, the effect of force and also effect of frequency on damping mechanism. Chapter five will highlights the conclusion and recommendations pertaining on the advantages and disadvantages of the magnerorheological elastomer (MRE) damping mechanism and suggestion for future work and further developments as optimum process of this research.

CHAPTER 2

LITERATURE REVIEW

2.0 Overview

MRE consist of soft elastomer matrix and ferromagnetic carbonyl iron particles. There are two category of MRE which are anisotropic and isotropic. The fabrication of anisotropic and isotropic of MRE depends on whether an external magnetic field is applied or not. Furthermore, through steady state and dynamic properties the effect of magnetorheological can be evaluated. Besides, there are a few models that have been developed as to investigate the dynamic mechanical properties of MRE. Moreover, the combination of ”mesh free” method and finite element method (FEM) will make possible creation of a discrete model.

2.1 Magnetorheological Elastomer

Solid phase analogue of magnetorheological fluids is also known as MRE. MRE consist of soft elastomer matrix and ferromagnetic carbonyl iron particles. Besides, their mechanical properties may change because of the influence of an external magnetic field. According to Dorfmann and Brigadnov (2003) due to the presence of the magnetic field, the elasticity modulus of MRE may undergo a change by about 30 - 40% and even to 60%.

MRE generally consist of a synthetic or natural rubber matrix interlace with micron sized typically 3 to 5 microns ferromagnetic particles. Elastomers such as rubber are usually used because they are generally deformable at room temperature and also soft. Depending on the specific material used, the elastomers can have the ability to reversibly extend from 5 - 700%. Besides, the solid matrix for the particles will avoids some common problems such as settling of particles normally associated with MR gels and fluids. For the micron sized particles in the rubber matrix, pure iron is usually used but some alloys of cobalt and iron can also be used too for good effect. The ferromagnetic particles may be added to the elastomer before it is cured. Factors including the distribution of the applied magnetics and also strength may be considered for the configuration and rigidity of the chain structures (Jolly et al. ,1996).

2.1.1 Natural Rubber

Dyke et al. (1996) stated that natural rubber has good damping performance and ease of processing, and then it was chosen and used as a matrix. Besides, because of low cost, have high saturation and permeability, that why iron sand also was chosen as magnetic particles. To provide coupling between natural rubber and iron sand, the surface modification of iron sand using silane coupling agent was introduce. It has also been reported that the silane modified particles also may decrease the interfacial tension around the particles. The results in improved the degree of magnetic particle alignment in anisotropic of MRE and also may improve the dispersion of magnetic particles in isotropic MRE (Shuib & Pickering 2015).

2.1.2 Silicone Rubber

Magnetization orientation of each particle and on their spatial relationship will be a factor for magnetic interactions between particles in these composites. The number of interesting magneto mechanical phenomena will accelerate when coupling the magnetic and strain fields in the materials. Shiga et al (1995) had prepared a kind of composite gel with magnetic properties and then, Jolly et al. (1996) tested and analysis the mechanical properties of silicon rubber based magnetorheological elastomer. The shear modulus ratio rise about 40% of the initial value when the magnetic field was 0.8T. There are number of groups studied about the effect of volume fraction on the magnetorheological effect and concluded the optimal volume fraction is around 27%.

2.2 Fabrication of Isotropic and Anisotropic Magnetorhoelogical Elastomers

There are two main category of MRE which are anisotropic and isotropic. The fabrication of anisotropic and isotropic of MRE depends on whether an external magnetic field is applied or not. Figure 2.1 shown a schematic of the fabrication methods of MRE that have been studied by Tian et al. (2011).

The main investigated in MRE is anisotropic type which is a kind of restructured magnetic elastomer. An external magnetic field is applied to the mixture of magnetic particles and elastomer matrix during the curing process. The magnetic particles also able to align in the direction of magnetic field to form a column structure or chain-like (see Figure 2.2a). After curing, these structures were locked in the matrix and this type of MRE is known as anisotropic MRE. The kind of unstructured magnetic elastomers is known as isotropic MRE. The particles do not form chains or columnar structure because no external magnetic field was applied on the mixture during curing process (see Figure 2.2b).

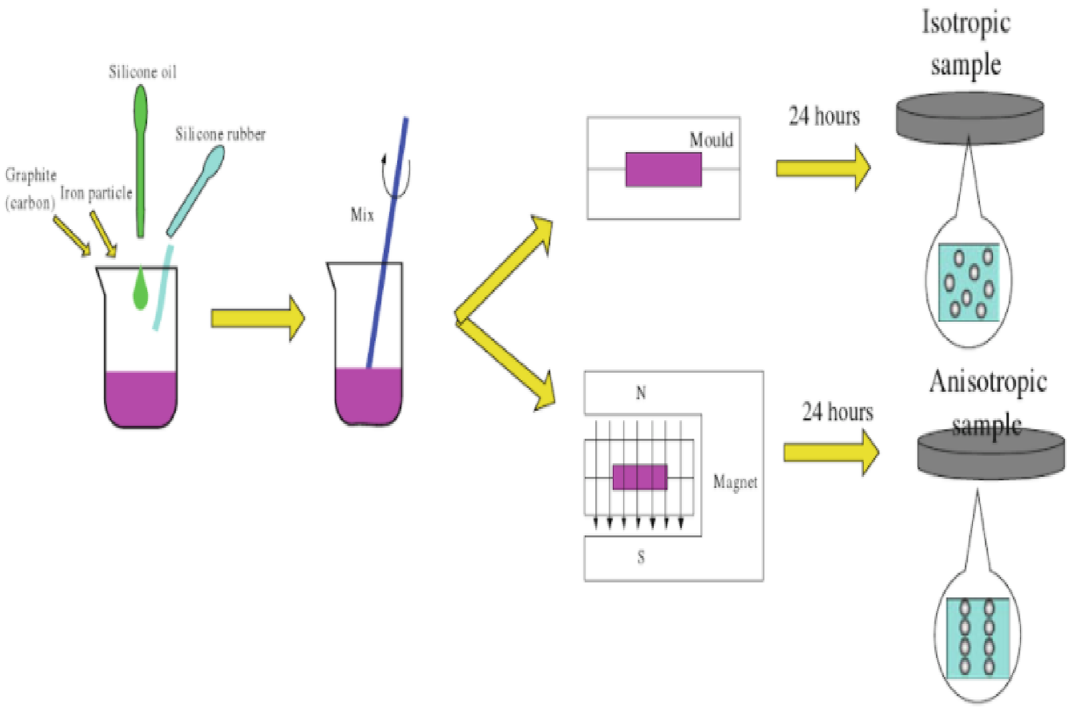
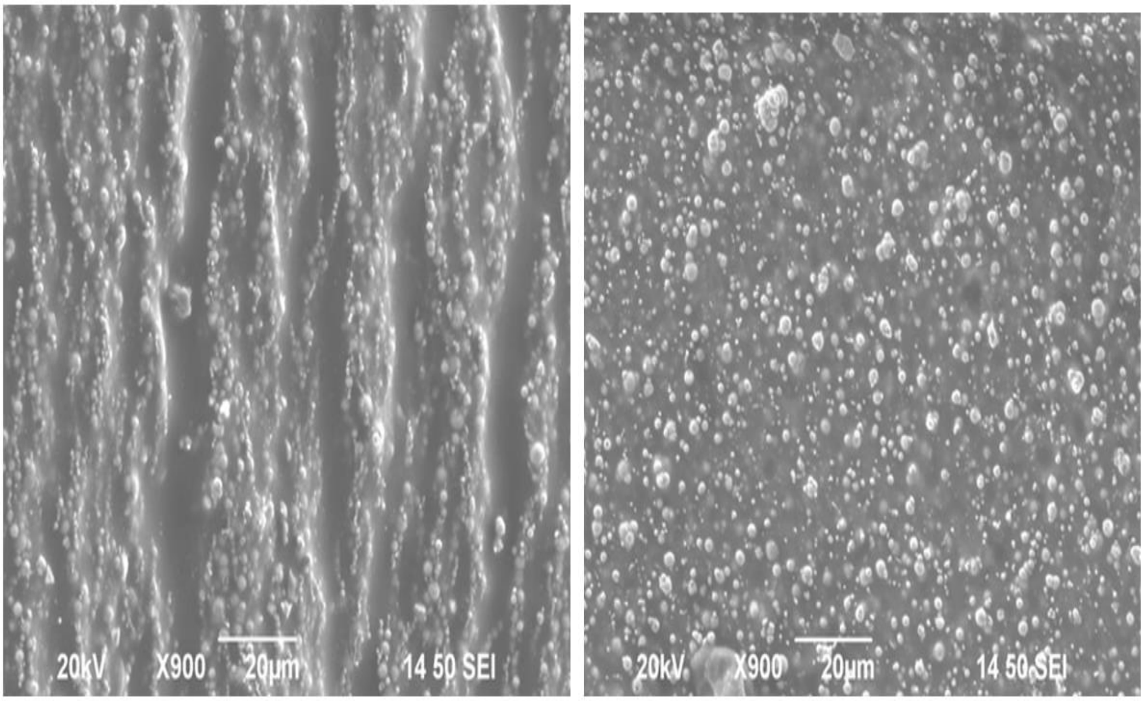


Figure 2.1 Schematic fabrication of isotropic and anisotropic of MRE (Tian et al.,2011).



(a) (b)

Figure 2.2 SEM images of MREs: (a) anisotropic MR elastomer; and (b) isotropic MR elastomer (Tian et al., 2011).

The isotropic MRE only have about half field dependent modulus compared with anisotropic MRE. Curing with no magnetic field can massively clarify the fabrication process which is an advantage for manufacture in large quantities of industry (Gong et al., 2005).

2.3 Steady State and Dynamic Properties of MRE

2.3.1 Steady State Properties

Li et al. (2013) explained that by measuring the shear strain stress curve of sample with and without an applied magnetic field, the effect of magnetorheological can be evaluated. Basically to evaluate the shear modulus of MRE, the method used is quasi static shear method. Figure 2.3 shows the strain stress curve of a MRE sample at seven different magnetic field intensity ranging from 0 mT to 750 mT with a magnetic field step increase of 125 mT. The slope of the strain stress curve is the shear modulus of the material.

It proves that the MRE exhibited obvious magnetorheological effects when the shear modulus of material increased with increased of magnetic field. Furthermore, when the strain is within 10%, the shear strain shows a linear relationship with the shear stress. This also proves that when the strain is below 10%, the MRE will acts as linear viscoelastic properties. While for magnetorheological fluids, the linear viscoelastic region is only below 0.1% and this also prove that magnetorheological fluid only operates at the post yield region while MRE operate at the pre yield region. MRE reaches nonlinear viscoelastic regime when the strain is above 10% because the modulus reaches a maximum value and then steadily decreases.

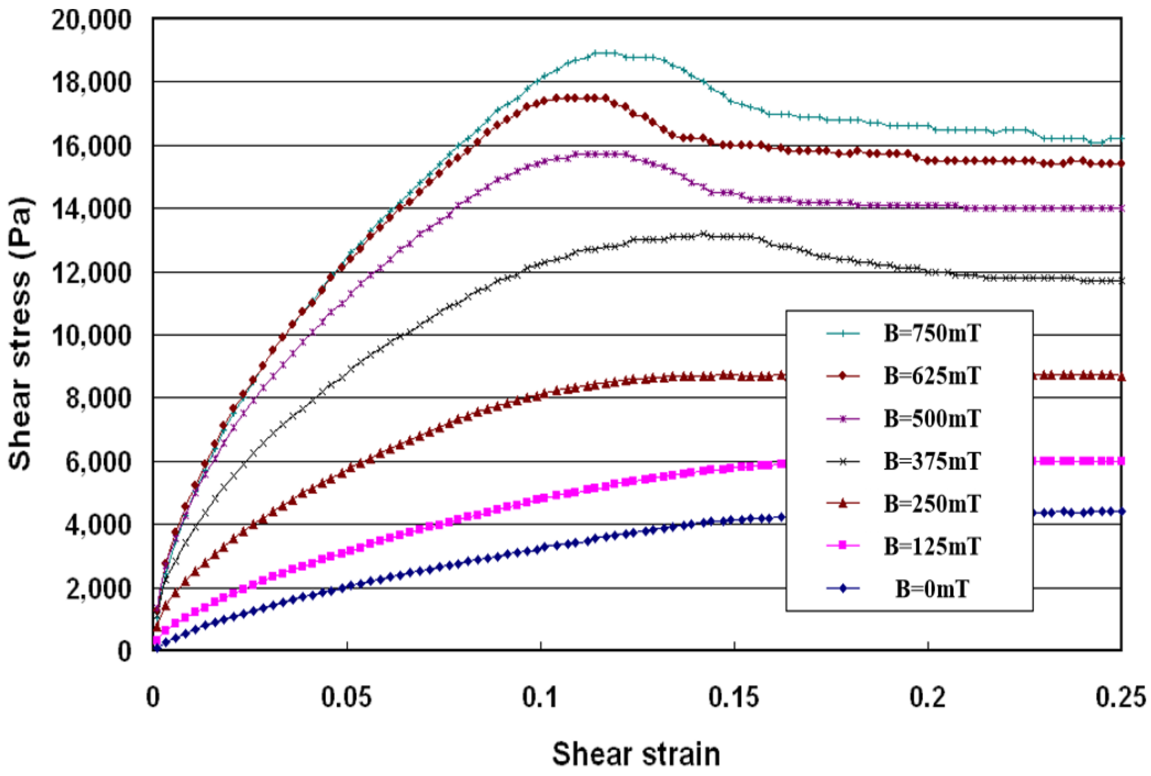


Figure 2.3 Shear stress strain curves of MRE sample under seven different magnetic fields (Li et al. 2013).

2.3.2 Dynamic Properties

Li et al. (2010) stated that MRE will exhibit viscoelastic properties under dynamic loading. Frequencies from 1 Hz to 10 Hz and various strain amplitudes ranging from 1% to 50% with harmonic loadings were used to study the dynamic properties of MRE samples. Figure 2.4 shows the stress strain relationships of the MRE sample at constant strain amplitude of 10% at various magnetic fields from 0mT to 440mT. It can be seen from this figure that all stresses and strains form nice elliptical shapes. With the increment of the magnetic fields, the areas also increase steadily.

These results prove that MRE materials have controllable mechanical properties. Generally, the modulus of MRE varies with magnetic field as the slope of the main axis of the elliptical loops varies with the magnetic field. The damping capacity of the MRE is a function of the applied magnetic field when the stress strain loops area with the magnetic field rise. These experimental results prove that not only the shape of the ellipse loops is different but the areas also dependent on the magnetic field. The magnetorheological fluids also prove that it only exhibit damping controllable properties while MRE exhibit variable damping properties and stiffness.

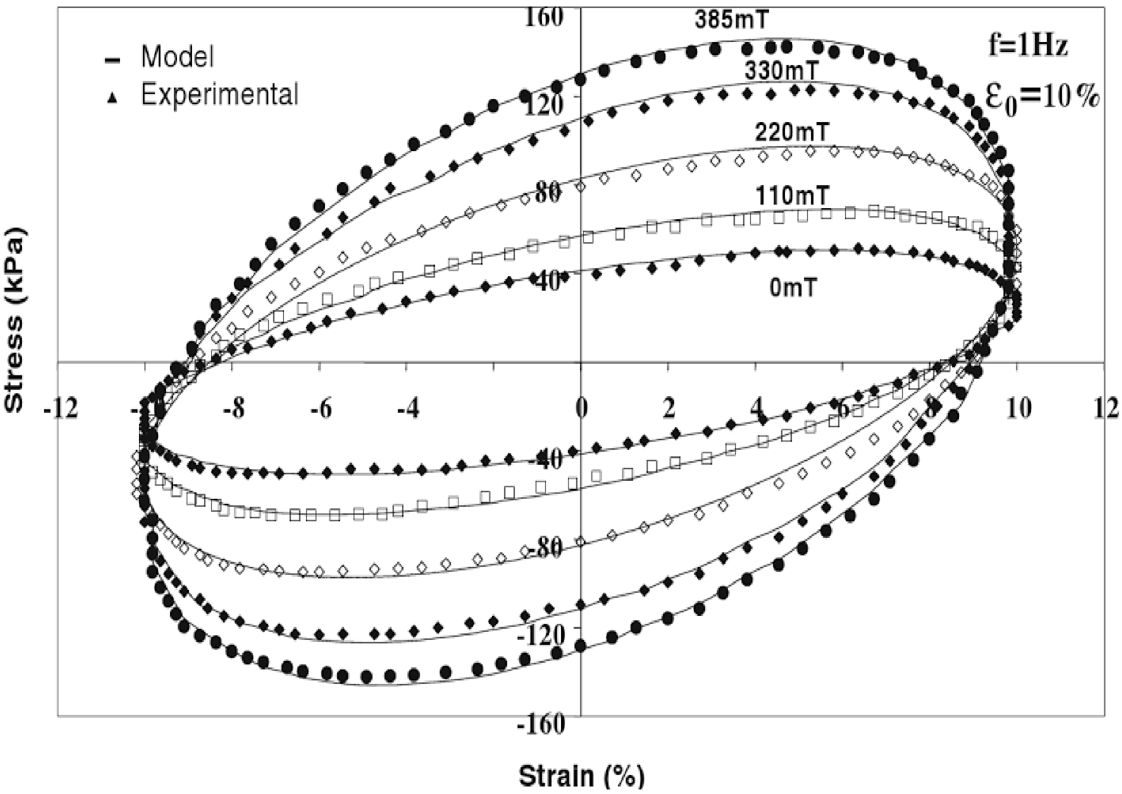


Figure 2.4 Stress Strain relationships with various magnetic fields at constant strain amplitude of 10% (Li et al., 2010).

Figure 2.5 shows the effects of shear strain frequency inputs on MRE performance. The slope of main axis of the ellipses is mainly influence by the shear strain frequency inputs. The slope of the main axis may increases steadily when the strain frequency inputs change from 1Hz to 5Hz. Furthermore, the slope of the main axis may increases slightly when the strain frequency inputs change from 5Hz to 10H.

With increasing shear strain frequency inputs, the slope of the main axis of the elliptical loops also increase while the maximum stress amplitudes of different strain frequency inputs changed steadily. This show that an increasing trend imply for the stiffness of the system with the frequency.

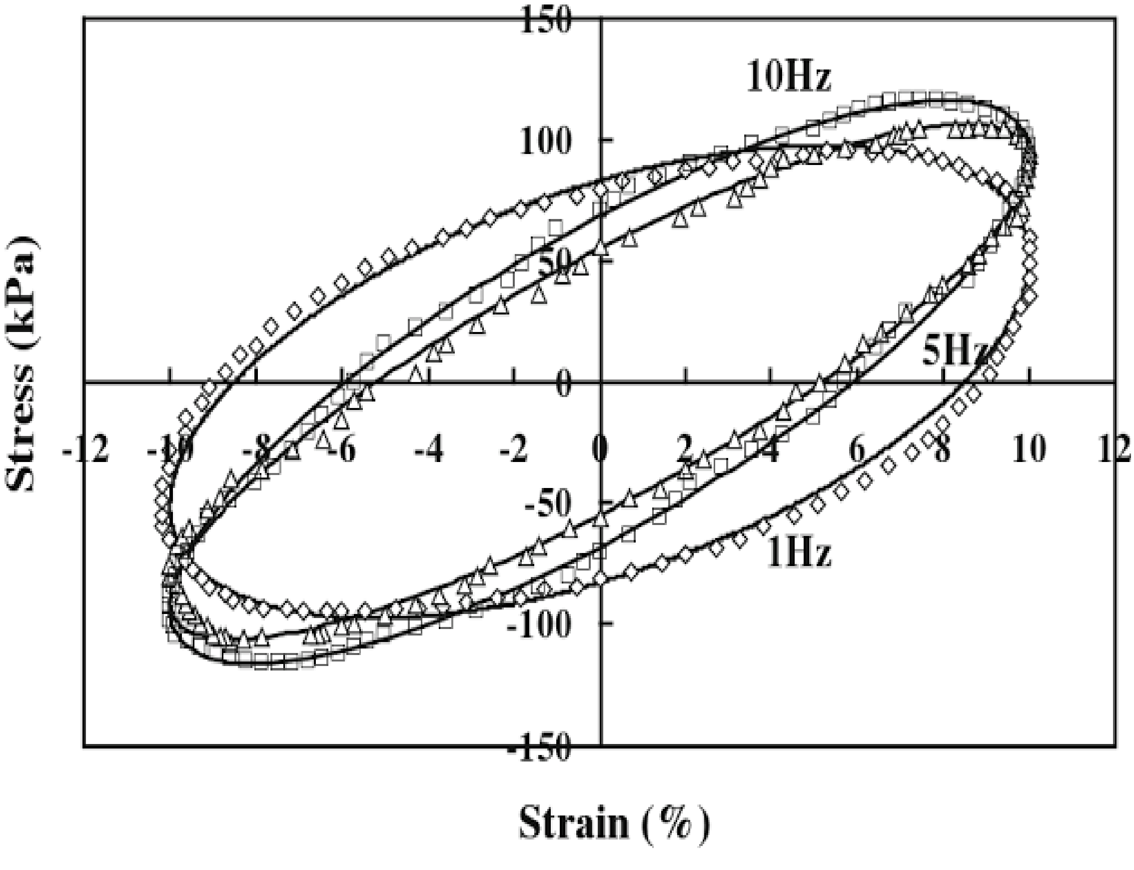


Figure 2.5: Stress strain relationships for different frequency inputs in 220 mT (Li et al., 2010).

2.4 Model

2.4.1 Rheological Model

To investigate the dynamic mechanical properties of MRE, there are a few models that have been developed. However, literature on the modeling of MRE damping mechanisms is limited. Davis (1999) and Jolly et al. (1996) have developed a few models describing the effect of inter particle magnetic interactions particularly on the shear modulus of MRE properties. Their work was based on finite element analyses (FEA) and theoretical of MRF.

Assumptions have been made when developing the models which are the particles are aligned in perfect chains and spherical in shape. Over the length of each particle chain, the quasi static shear strains and associated stresses are evenly distributed. These models are good in predicting shear modulus. However, there are some limitation in this model which are mechanisms other than interparticle magnetic interactions were not involve in this mechanism and prediction of damping also was neglected.

Lin (2008) and Yancheng et al. (2011) had described the contributions of the interface between rubber matrix and magnetic particles for the interfacial slip models. This model was about damping but not the damping mechanisms involve between the magnetic particle interactions and the matrix. The limitation of this model was the model not verified experimentally and also poor in describing total damping.

The first model that involves all damping mechanism was developed by Chen and Jerrams (2011). They proposed a model to predict overall shear modulus of MRE under cyclic deformation from separate shear moduli. The model also representing the different mechanisms that involve the matrix and inter particle magnetic interactions, viscoelasticity of the rubber matrix and interfacial slippage between magnetic particles. From the combined of shear modulus, the tan δ was then obtained. The model is suggested to be potentially reliable for prediction of the overall damping for MRE.

The effectiveness of the model was tested by numerical simulations. Furthermore, the model is more reliable because it involves weakly bonded interfaces between matrix and magnetic particles. Due to additional energy absorbed during viscous flow, the model become less accurate for MRE containing surface modified particles with strongly bonded interfaces. This is more constrained as due to the formation of interfacial bonding between particles and the matrix and the energy loss. The energy loss in this mechanism is due to stress released after debonding of particles from the matrix.

Jie et al. (2012) also developed a model to predict overall damping of MRE that aimed to take account of all possible damping mechanisms. This damping mechanism includes interparticle magnetic damping, intrinsic damping of component materials and also interfacial damping. In this model, to describe the intrinsic damping the rule of mixtures was used. This assuming that MREs as particle reinforced composites with magnetic particle chains of infinite length. For weakly bonded interfaces, it was proposed based on Coulomb's law of friction. Meanwhile, for strongly bonded interfaces, it was proposed by Eshelby inclusion theory.

Moreover, the model that has been developed by Jolly et al.(1996) may contribute to the interparticle magnetic damping that was described by using the interparticle magnetic interactions. Due to over implication in prediction of intrinsic damping by using the ROM, the differences between predicted damping values and experimental values were more than 40%. Furthermore, the dependence of frequency on material damping also was neglected.

2.5 Magnetic Field Effect

The magnetic field effects on both the damping modulus and dynamic stiffness are also investigated and explained by Ladipo et al. (2016). To show the effect of the magnetic field, the dynamic stiffness property is used. This is due to the damping modulus that has been shown to have little response to the magnetic field. Since the amplitude is usually higher thus by using various magnetic fields the response of the systems using the model is further simulated. Furthermore, the behavior of the MRE is assumed for simplicity to linear and governed by Equation 2.1 and Equation 2.2.

$$k(\beta) = a_k + b_k(\beta) \tag{2.1}$$

$$\varepsilon(\beta) = a_\varepsilon + b_\varepsilon(\beta) \tag{2.2}$$

By using this linearized model, the behavior of the MRE model can be understood. The following values were used in the simulation study: $a_k = 2000N/m$; $b_k = 4.55KNT/m$; $a_\varepsilon = 0.15$; B_ε 0.6364 and $B_s = 0.11T$. The system response is shown in Figure 2.6. Different values for the magnetic field (0<MRE<1.0) is used in the simulation.

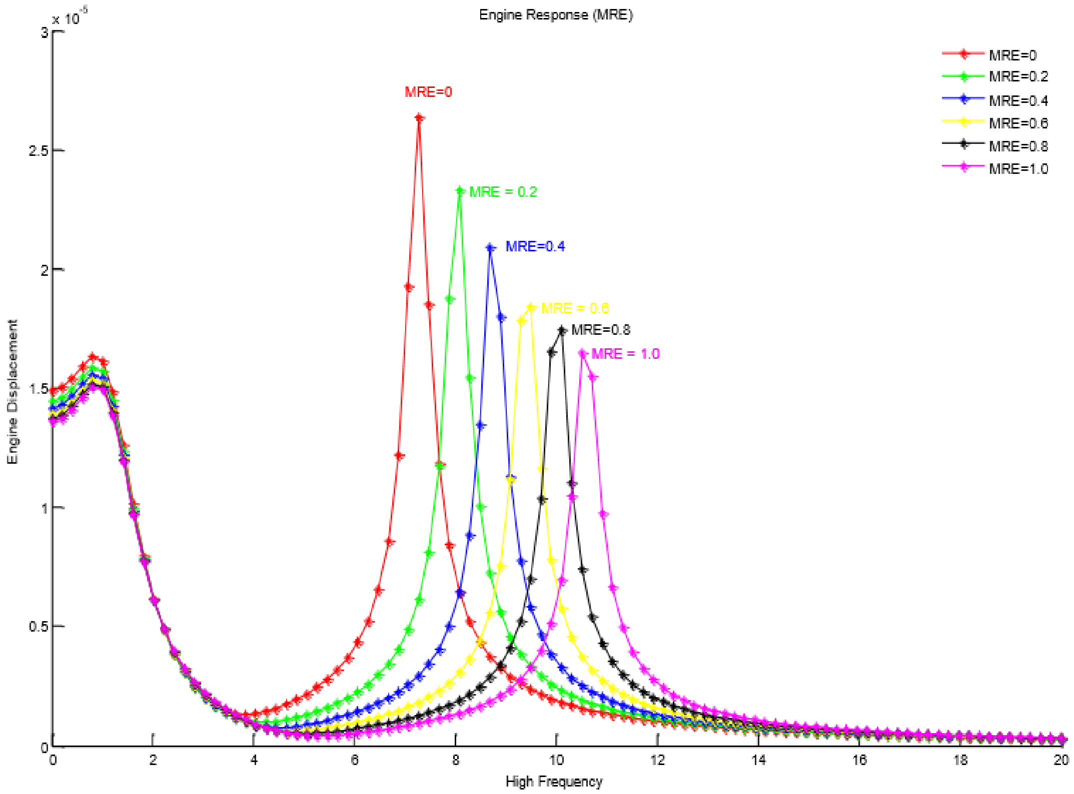


Figure 2.6 Effects of magnetic field on relative displacements (Ladipo et al. 2016).

High and low frequencies vibration problems may reduce due the tuning of the magnetic field as shown in Figure 2.6 and Figure 2.7. The influence of the alignment of the magnetic particles on the composite properties with and without applied of magnetic fields was studied by Kallio (2005). For both aligned and isotropic MRE, the stiffness and damping properties can be modified by applying external magnetic field. The damping and stiffness properties may increase in the magnetic field if the filler volume fraction exceeds 15% in isotropic MRE.

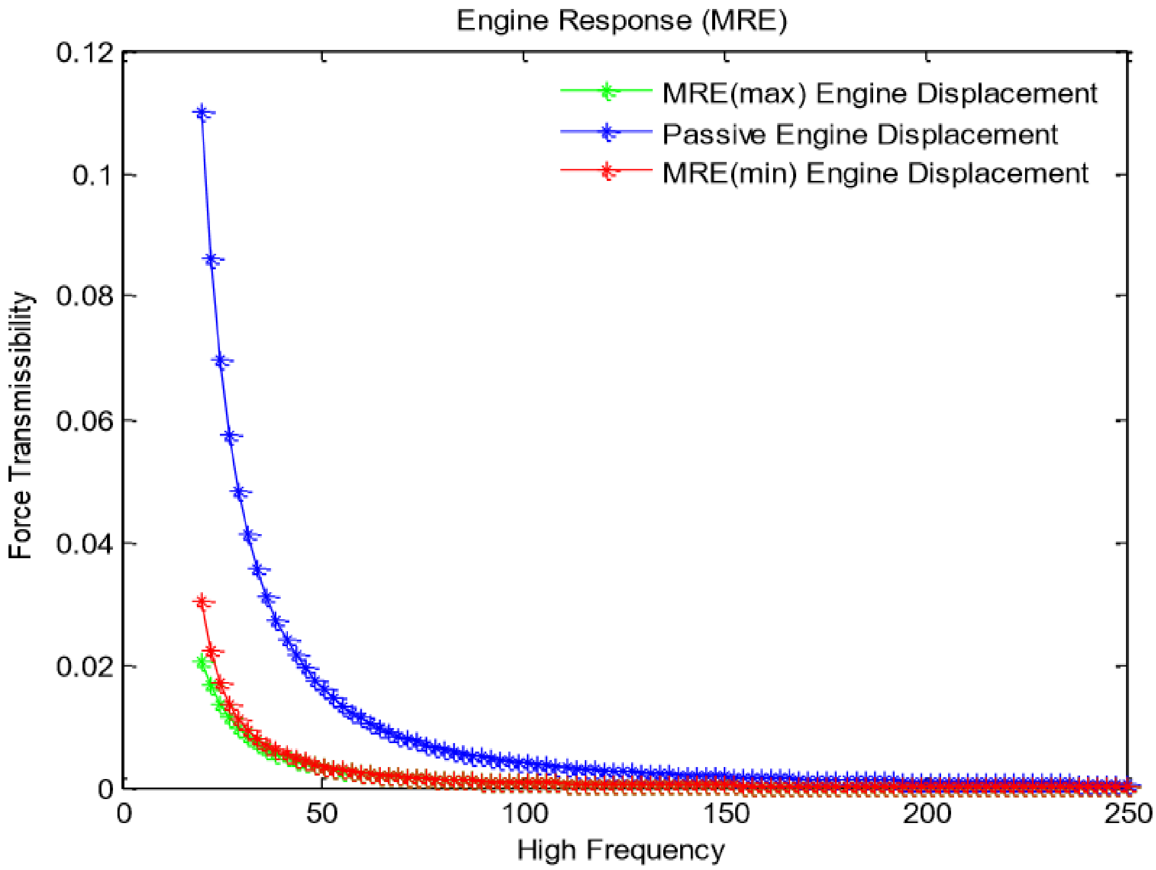


Figure 2.7 Effects of magnetic field on force transmissibility (Ladipo et al. 2016).

When measured with applied magnetic field, the damping may increases with the increasing volume fraction of iron and it has a maximum value at 27 vol. %. Moreover, magnetic field, mutual directions of load and the particle alignment in the composite may be a factor for stiffness and damping properties of aligned MRE. Besides, by applying the magnetic field and optimizing the particle alignment and density, the damping or stiffness of MRE can be increased.

Davis (1999) state that by using finite element analysis, it shows the increase in shear modulus for typical elastomers. The increase in shear modulus is because of interparticle magnetic forces at saturation is about 50% of the zero field modulus. During curing, the zero magnetic shear modulus of material with chains of particles that have been aligned along a magnetic field is no larger than the modulus for the same material with randomly rigid particles.

2.5.1 Influence on Vibration Damping in MRE

Lokander et al. (2003) have calculated the damping factor (tan δ) for a nitrile rubber (Perbunan 3445).They have studied the damping factor with and without the magnetic field with an iron content of about 37.8 vol.%. As a result of a large applied magnetic field (0.8 Tesla) in the frequency range of 1–20 Hz as shown in Figure 2.8, they have found that there is a small boost of about 0.01–0.02 in loss factor in isotropic MR elastomers. Furthermore, Jolly et al. (1996) have also noted an increase of 0.03 in tan δ values at higher peak strains (10%). That strains was tested in shear testing of aligned MR elastomers containing 30 vol. % of iron. Besides, the measurements were done with a magnetic field strength of 0.85 Tesla at 10 Hz. However, the measured increase in tan δ was too small to be of any practical importance.