Magnetorheological Elastomer Based Flexible Metamaterials Coupler for Broadband Longitudinal Vibration Isolation: Modeling and Experimental Verification

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\textbf{ABSTRACT} Longitudinal vibrations due to different external excitations are omnipresent in almost every machine, eventually leading to unplanned downtime, and in some cases, catastrophic failures. The passive approach to isolate such vibration has some limitations. Magnetorheological elastomers (MREs) typically consist of micron-sized magnetic particles dispersed in an elastomeric matrix. Their mechanical and rheological properties can be altered under the influence of magnetic field. Thus, the distinctive behavior of magnetorheological elastomers paved the way for successful employment in vibration isolation. In this study, an MRE-based metamaterial coupler is designed for broadband vibration attenuation with distinctive characteristics unattainable by conventional couplers in longitudinal vibration. The vibration control performance of the proposed model is investigated in terms of its transmissibility factor. Sweep vibration test is conducted to examine the transmissibility factor for single, double, and triple-layer MRE metamaterial couplers accompanied by different activation scenarios. The results reveal that the stiffness of the MRE layers increases with the strength of the applied magnetic field. Utilizing more than one layer of MRE increases the ability to isolate longitudinal vibration at different frequency bands. The maximum reduction curves achieved by single, double, and triple-layer MREs are approximately 84.5\%, 97\%, and 99.6\%, respectively. The findings of this study demonstrate that the proposed MRE-based metamaterial couplers can attenuate vibrations at broadband frequencies.

\textbf{INDEX TERMS} Metamaterials, multi-layered magnetorheological elastomer, vibration isolation, transmissibility factor.

\section{I. INTRODUCTION}

Mechanical systems in various engineering applications are prone to vibrations. Such vibrations are due to different external excitations and are omnipresent in almost every type of machinery. Vibrations are undesired as they can accelerate machine wear, consume excessive power, result in severe deformations, and ultimately lead to catastrophic failures and unplanned downtime. Therefore, vibration isolation techniques have become an essential part of the research field [1], [2]. The main objective is the reduction of the interconnections between the source of vibration and the equipment. There are three main techniques to reduce the dynamic effect of vibrations: passive, active, and semi-active systems. Passive isolation systems use the natural properties of a spring and a damper to reduce vibrations and are efficient at mitigating high-frequency vibrations. However, they have limitations in low-frequency due to their natural resonance. Active isolation systems use integrated control systems to improve low-frequency performance. Semi-active isolation systems are intermediate between active and passive and combine the advantages of both methods [3]–[5].
Exploring the system transmissibility ratio is one way to quantify the vibration imparted to the system. The transmissibility of a system is defined as the ratio of the output to the input, and it is self-evident that the transmissibility must be less than one to reduce the system vibration effectively. From Figure 1, two regions can be depicted. The first region is identified as the amplification area where the frequency ratio is less than $\sqrt{2}$. The second region is the reduction area, where the frequency ratio is more than $\sqrt{2}$ and the transmissibility amplitude drops significantly [7].

One of the methods to implement semi-active vibration isolation is by using smart materials in which their properties can be altered by external stimuli such as temperature, pressure, and magnetic field. Magnetorheological elastomer (MRE) is a class of smart composite materials consisting of a non-magnetic polymer matrix (silicone rubber) embedded with micron-sized ferromagnetic particles. MREs have emerged as one of the most efficient materials with the ability to tune their stiffness and viscoelastic properties using an input of magnetic field [8], [9]. Due to the sensitive response of the micron-sized particle to the magnetic field, MREs exhibit a magnetorheological effect in the presence of the magnetic field, offering a field-dependent physical or mechanical property, such as a controlled stiffness. MREs can restore their original, natural property while removing the magnetic field [10]. MREs have been widely employed in the research applications of semi-active vibration isolation systems due to their ease of controllability and adaptability to the magnetic field [11], [12]. Zhang et al. [13] presented a novel adaptive tuned vibration absorber using MRE for powertrain vibration reduction. Li et al. [14] developed an adaptive seismic isolator using MRE for potential application in structural control. Xing et al. [15] designed an adaptive MRE bearing for seismic mitigation of bridge superstructures. Sun et al. [16] reported developing a compact squeeze MRE absorber in a shear working mode and its subsequent performance at various magnetic fields. Likewise, Leng et al. [17] designed a tunable vibration absorber based on MRE in the coupling of shear-squeeze mode to provide a new insight for using MRE in vibration reduction applications. Sethi et al. [18] demonstrated the effectiveness of an MRE based vibration absorber in vibration reduction of powertrain during the transient stage.

The main contribution of this work is the development of an MRE-based metamaterial coupler for broadband longitudinal vibration isolation. The metamaterial coupler is composed of multiple MRE layers in which their viscoelastic properties can be changed under the influence of a magnetic field. The metamaterial coupler’s holders act as electromagnetic coils that induce the magnetic field to the MRE layers. Hence, the metamaterial coupler is artificially designed to have distinctive mechanical properties that result from its multilayer geometry and the characteristics of unconventional elastomers. The main advantage of this model is its versatility in tuning the stiffness of each MRE layer individually. An experiment was conducted to evaluate and characterize the behaviour of the MRE metamaterial coupler using a vibration testing facility. The MRE coupler was subjected to base motion excitation under harmonic cyclic load, and the performance was investigated in terms of the linear transmissibility factor. Additionally, a compression test was performed to outline the change in stiffness of MRE layers to the applied magnetic field.

This paper is organized as follows. Section 2 presents the mathematical modelling of the MRE coupler. Section 3 discusses the fabrication of the MRE and the experimental setup adopted to conduct the investigation. Section 4 compiles the results obtained from the experiments and presents the analysis performed to investigate the response behaviour. The paper ends with a conclusion that summarizes the work completed throughout the study and presents the research findings.

II. MATHEMATICAL MODEL

A single-layer MRE metamaterial coupler that consists of upper and lower coupler hubs, electromagnetic coils and a single MRE layer, as shown in Figure 2(a), is used to derive the mathematical model. The MRE layer is fixed between the coupler’s hubs, where the coils are embedded. The coils’ polarities are oriented such that the magnetic flux is directed through the MRE layer for more efficient
performance, as shown in Figure 2(a). The direction of the magnetic field, \( B \) depends on the polarities of the current supply, which is either adjusted in series or parallel.

The coupler’s equation of motion is developed using Newton’s law of motion as follows:

\[
m\ddot{x} + c\dot{x} + k_x + k_{mre} (x - y) = c\dot{y} + ky
\]  

In Eq. (1), the coupler’s dynamics are modeled input base displacement, \( y \), as shown in Figure 3(b), stiffness, \( k \), damping, \( c \), and mass displacement, \( x \). The magnetic field has a minor effect on the MRE’s damping properties and hence neglected. By Laplace transform to Eq. (1) and substituting \( s = j\omega \), the transfer function of the system is obtained as follows:

\[
\frac{Output(\omega)}{Input(\omega)} = \frac{X(\omega)}{Y(\omega)} = \frac{c\omega + k_{sys}}{m(\omega^2 + c\omega + k_{sys})} 
\]  

The vibrations transmitted to the mass due to a base excitation displacement, \( \omega \), is quantified through the transmissibility factor, \( T \), as:

\[
T = \frac{|X(\omega)|}{|Y(\omega)|} = \frac{(\omega^2 + k_{sys})^2}{(\omega^2 + (k_{sys} - m\omega^2))^2}
\]  

where, \( \omega \), is the excitation frequency in rad/s, and \( k_{sys} = k + k_{mre} \). In the absence of a magnetic field, the MRE is identified as passive, and its elasticity is described as [17]:

\[
E_{passive} = E_o(1 + 2.5\phi + 14.1\phi^2) 
\]  

where, \( E_o \) and \( \phi \) are the unfilled elastomer stiffness and volume fraction of ferromagnetic particles, respectively. The field-dependent shear modulus for conventional MRE is extended to investigate the MRE’s behavior for longitudinal vibration mode as the following [19]:

\[
E_{active} = 6\phi\mu_o\mu_m H_o^2 
\]  

where \( \mu_o = 4\pi \times 10^{-7} \), and \( \mu_m \approx 1 \) are the vacuum and matrix relative permeability, respectively. The magnetic field \( (H_o) \) is directly proportional to the current (I) by the number of turns per meter (\( \alpha \)) and is expressed as \( H_o = \alpha I \). The overall elasticity of the MRE is expressed as:

\[
E_{mre} = E_o(1 + 2.5\phi + 14.1\phi^2) + 6\phi\mu_o\mu_m\alpha^2 I^2 
\]  

Hence, the MRE axial stiffness is determined, \( k_{mre} = A E_{mre}/L \), where \( A \) and \( L \) are the area and the length of MRE, respectively. Increasing the magnetic field intensity increases the stiffness, which shifts the system’s natural frequency, ultimately achieving lower transmissibility. The natural frequency is expressed as:

\[
\omega_n = \sqrt{\frac{k_{mre}}{m}}
\]  

III. EXPERIMENTAL SETUP

A. FABRICATION OF MREs

The manufacturing procedure of MREs is similar to that of ordinary rubbers. MREs typically consist of two main parts: the elastomer and the soft-magnetic particles. A schematic of the manufacturing steps of MREs is shown in Figure 3. The elastomer used in this study is the silicone rubber from Zhermack (Elite Double 32-fast), which has two parts a base and a catalyst. Carbonyl iron particles (CIPs) from BASF are used as magnetic particles. The CIPs type used in this study is SQ-I, which is easy to magnetize and has high saturation and demagnetization characteristics. The fabrication process of MREs includes three steps: Mixing, Curing, and magnetic particles alignment under input magnetic field. The silicone rubber base is mixed with the CIPs with a 10% volume fraction. This specific ratio is an intermediate between sufficient magnetization and passive stiffness. After the base and CIPs mixture is adequately mixed, the silicone catalyst is added with a 1:1 ratio with the base. The mixture is then stirred for a while before pouring it into the casting mold. The mold is then covered, and the MREs are left to cure for about 15 minutes. It must be outlined that the fabricated MREs are an isotropic type, hence, the curing process occurred in the absence of an input magnetic field. In isotropic MREs, the polarized particles are uniformly suspended, and the MRE exhibits a homogeneous physical characteristic in all directions.

![FIGURE 3. Schematic of manufacturing steps of magnetorheological elastomers (MREs).](image-url)
FIGURE 4. MRE-based metamaterial coupler components and dimensions.

FIGURE 5. Schematic of the experimental setup.
Contrary to isotropic MREs, the anisotropic class is cured under the presence of a magnetic field. In anisotropic MREs, the polarized particles are scattered along the input direction of the magnetic field during the curing process, resulting in a flat MRE specimen with a perpendicular direction \([20]\). In terms of the MR effect, it was stated that the anisotropic MREs possess a higher MR effect than the isotropic MREs that also have a slower response time \([21]\). The overall MRE coupler dimensions are summarized in Table 1, whereas a summary of the material properties are given in Table 2.

### TABLE 1. Dimensions of the MRE coupler components in mm.

|                  | Coupling hubs | MRE coupler lengths | MRE (Elastomer) |
|------------------|---------------|---------------------|-----------------|
|                  |               | d                   | h               |
|                  | D             | 40                  | 15              |
|                  | d             | 30                  |                 |
|                  | S             | (End – Middle) 23 – 36 |               |
|                  | s             | (End – Middle) 10 – 20 |               |
|                  | H             | Single-MRE coupler | 61              |
|                  |               | Double-MRE coupler | 112             |
|                  |               | Triple-MRE coupler | 163             |

### TABLE 2. Material properties.

|                  | Coupling hubs | Elastomer | CIPs |
|------------------|---------------|-----------|------|
|                  |               | Material  |      |
|                  |               | Silicone rubber (Zhermack - Elite Double 32- fast), |      |
|                  |               | Thickness [mm] 15 |      |
|                  |               | Mixing Ratio 1:1 |      |
|                  |               | Type | BASF, SQ-1 |      |
|                  |               | Volume fraction ratio, \(\phi\) [\%] 10 |      |

B. VIBRATION TEST SETUP

Figure 5 represents a schematic of the experimental setup designed to perform the vibration test. This setup consists of a vibration table with soft vibration absorbing mounts. This table was constructed to ensure the stability of the structure while performing the test, particularly when the system is subjected to low-frequency excitations where the amplitude is high. A SmartShaker\textsuperscript{TM} by The Modal Shop with an integrated power amplifier is mounted at the centre of the
vibration table. An Impedance sensor is mounted at the excitation port of the vibration shaker. This sensor can measure the input force and acceleration exerted on the model. The model is then installed on the impedance sensor mount, and an accelerometer is placed on its top surface to measure the output acceleration. Dewesoft Sirius DAQ is used to perform a sine sweep test for a frequency range from 0–500 Hz. The MRE coils are supplied with electric current ranging from 1 – 3A.

Figure 6 presents the experimental setup used to conduct the vibration test. Three different MRE metamaterial couplers are tested: single, double and triple-layer MRE couplers. The primary objective of this experimental work is to investigate the multilayer MRE coupler’s performance in mitigating longitudinal vibration. Transmissibility curves are obtained from the DAQ for each coupler set at different current values.
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FIGURE 12. Double layer MRE linear displacement transmissibility factor curves.

C. COMPRESSION TEST SETUP

A compression test is conducted to determine the MREs behaviour under applied compressive loads. The MRE materials have been tested by applying compressive loading using INSTRON 5585H universal testing machine (UTM). The wooden plates, shown in Figure 7, were designed and attached to the UTM fixtures instead of the metal compression platens. This ensures that the magnetic flux is directed only to the MRE and eliminates any metal surface interference. Load against displacement plots are retrieved from this experiment and used to acquire the stiffness of the MRE materials. The single-layer MRE coupler was exposed to a continuously increasing compression load at a rate of 2\text{mm/min} for a maximum of 4\text{mm} compressions. The intensity of the magnetic field crossing the sample is varied, and the MR effect on the material characteristics was evaluated in terms of stiffness. The test was performed on MREs of 10% and 5% CIPs volume fractions.

IV. RESULTS AND ANALYSIS

A. FORCE-DISPLACEMENT CURVES

The stiffness is defined as the slope of the force-displacement curve; however, elastomers do not exhibit linear elastic deformation. The force-displacement curve across a range of electric currents from 0 – 3A was observed, as shown in Figure 8. Borin et al. [22] performed a tensile test on elastomers with magnetic powder and found that the modulus can be divided into two deformation ranges: small and large deformation ranges. The stiffness behaviour of the MRE metamaterial coupler has shown a similar behaviour as depicted in Figure 8. The stiffness characteristics were examined for MRE layers with 10% and 5% CIPs volume fractions. It was observed that as the intensity of the magnetic field increases, the MRE layer becomes stiffer. This is due to the increased inter-particle interaction between the CIPs in the elastomeric matrix.

The stiffening of the MRE layer was noted in the small deformation region. The magnetic field affected the inter-particle interaction when the particles were close to each other, i.e., in the small deformation region. On the contrary, the particle interactions required to generate a change in the stiffness in the large deformation region did not occur. Figure 9 compares the stiffnesses of MREs with 10% and 5% CIPs volume fractions. It is depicted that an increase in CIPs volume ratio enhances the MR effect in terms of stiffness.

B. LINEAR TRANSMISSIBILITY CURVES

The vibration test was conducted for different activation scenarios for double and triple-layer MRE that are summarized in Table 3. For example, the combination \(C_1\) in double-layer, MRE is (0 – 1), which means only the upper MRE layer is subjected to input magnetic field. On the other hand, the combination \(C_2\) is (1 – 0) indicates that the bottom MRE layer is subjected to a magnetic field while the upper MRE is not. By default, single layer MRE has only one combination to be tested.

Figure 10 is a graphical illustration of the different activation scenarios. The activation of the MRE layers is achieved by controlling the current supply to the electromagnet coils. For the triple-layer MRE coupler, the 1 – 0 – 1 combination is practically analogous to 1 – 1 – 1. The three coils are supplied with current in both combinations, which activates the intermediate MRE layer. The results of single, double, and triple-layer MRE isolators show a consistent pattern for all scenarios. The obtained transmissibility curves illustrate the performance of MREs in longitudinal vibration attenuation and reveal the stiffness variations.

1) SINGLE-LAYER MRE

Figure 11 shows the linear transmissibility curve for a single-layer MRE coupler for different current values. It is observed that the transmissibility peaks shift to a higher frequency as

| Combination Number | Single | Double | Triple |
|--------------------|--------|--------|--------|
| \(C_1\)            | 1      | 0 – 1  | 0 – 0 – 1 |
| \(C_2\)            | –      | 1 – 0  | 0 – 1 – 0 |
| \(C_3\)            | –      | 1 – 1  | 1 – 0 – 0 |
| \(C_4\)            | –      | –      | 0 – 1 – 1 |
| \(C_5\)            | –      | –      | 1 – 1 – 0 |
| \(C_6\)            | –      | –      | 1 – 1 – 1 |

TABLE 3. Multilayer MRE Coupler Activation scenarios.
the magnetic field intensity increases. The resonant peaks have relatively similar amplitude; however, at some current excitation, the peak is slightly higher due to the decrease in the damping ratio of the MRE. When the system is not subjected to any magnetic field, its natural frequency is near 150 Hz with linear transmissibility of 5. The stiffness increases proportionally with the current excitation, and the incremental rate is within a range of 5-10 Hz. Due to the increase of MRE linear stiffness, the natural frequency, $\omega_n$, shifts right to a higher frequency. Hence, these findings indicate that the increase in the applied current shifts the system’s natural frequency. The minimum attainable transmissibility factor for a single layer MRE based isolator is displayed in Figure 11.

2) MULTILAYER MRE
This section analyzes the performance of double and triple-layer MRE at different activation scenarios. The results indicate the overall pattern of double and triple-layer MRE is similar to single-layer MRE in terms of linear transmissibility factor. However, the difference is in the number of present peaks and the frequency range in which the linear transmissibility value is less than one. The vibration test is performed for double and triple layer MRE simultaneously with their combinations. The linear transmissibility factor accomplished by the lowest possible transmissibility values for the double and triple-layer MRE is given in Figures 12-13. The double and triple layer MRE results show the frequency shift with applied current, which displays the potential to isolate the unwanted longitudinal vibration at different frequency bands.

C. REDUCTION PERCENTAGE
The results of the lowest transmissibility curves have been recorded to calculate the reduction percentage for each case.

| Activation Scenario | 1st Mode | 2nd Mode |
|---------------------|----------|----------|
| Single-MRE          |          |          |
| 0 - 1               | 18       | 36       |
| 1 - 0               | 16       | 10       |
| 1 - 1               | 23       |          |
| 0-0-1               | 5        |          |
| 0-1-0               | 10       |          |
| 1-0-0               | 10       |          |
| 0-1-1               | 25       |          |
| 1-1-0               | 27       |          |
| 1-1-1               | 27       |          |
FIGURE 14. Maximum reduction percentage achieved for each isolator.

The maximum reduction curves for all the cases are highlighted and shown in Figure 14. The maximum possible reduction percentage for single, double and triple layer MRE is compared in Figure 15. Zero reduction means the response is amplified. It is observed that only using single-layer MRE might not be enough to isolate the vibrations due to its short frequency range. However, double or triple-layer MRE metamaterial couplers become more versatile to different frequency bands. For instance, a single-layer MRE can attenuate the vibration in a frequency span of approximately 175 – 500 Hz. However, if a double or triple-layer MRE is used, the vibration isolation range extends to 125 to 500 Hz, and 90 to 500 Hz, respectively. Using a triple-layer MRE presents the highest reduction condition, which is around 99.6% as compared to single or double layer MRE.

The magnetic field intensity is controlled by the current supply that ranges from 0 – 3 A. The maximum frequency shift that occurred due to the change in the magnetic field intensity is retrieved from the transmissibility curves. Table 4 displays the frequency shift property with the numerical values for all the cases.

FIGURE 15. Maximum reduction attained by the three isolators.
V. CONCLUSION

The performance of an MRE-based metamaterial coupler has been experimentally investigated in this study, for potential implementation in semi-active longitudinal vibration control. Isotropic MREs with 10% CIPs volume fraction were fabricated and used to develop the MRE-based vibration isolators. The relation between the MRE stiffness and the magnetic field intensity was established by performing a compression test on the single-layer MRE and plotting the force-displacement curves. An increase in the MRE stiffness was depicted across a range of increasing electric current. The results were compared with an MRE of 5% CIPs volume fraction. It was observed that an increase of the CIPs ratio in the elastomer matrix enhances the MR effect in the metamaterial coupler. Additionally, a longitudinal vibration test has examined the transmissibility factor of single, double, and triple-layer MRE. In all three cases, it was found that the increase in the magnetic field can shift the natural frequency of the MRE coupler. As a result, a minimum transmissibility factor can be achieved. Reduction percentage curves revealed that a broader frequency band of vibration isolation could be achieved using an MRE-based metamaterial coupler such as the double and triple-layer. For example, at 300 Hz and above, the triple-layer MRE grants better vibration attenuation with a reduction percentage of 99.6%. The MRE-based metamaterial couplers have demonstrated an enhancement in the vibration attenuation at different frequency bands. Overall, the findings reveal the promising potential of the multilayer MRE coupler in applying longitudinal vibration control.

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