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Development of a Vibration Isolator on the Basis of a Magneto-Rheological Elastomer

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ABSTRACT

Magnetorheological elastomers (MREs) are smart materials. Their rheological properties can be controlled by applying an external magnetic field. MRE is a solid rubbery material that can change its modulus through the application of a magnetic field. This article presents the research on the simulation, manufacturing, and testing of vibration insulators. The first step in MRE vibration isolator design. A sufficient magnetic field for the stiffness change is considered in the material selection of the vibration isolator. The effectiveness of electromagnetic circuits in generating magnetic fields to minimize vibration is demonstrated using finite element method magnetics software. A vibration isolator test rig is installed as a second step. Lastly, different effects of current input on MRE isolators have been examined. The higher current input is more effective in eliminating vibration using the MRE isolation system.

Keywords: vibration, isolator, damper, magnetorheological elastomer.

INTRODUCTION

Reducing vibration is crucial in various industrial and engineering contexts to improve product quality, reduce noise emissions, and enhance safety [1, 2]. High vibration amplitudes can be particularly problematic near resonance frequencies or during start-up and run-down processes. Several methods for vibration reduction have been studied, including variable frequency excitation for single and multi-degree-freedom systems [1], wave barriers between external sources and receivers, and soil stabilization underneath concrete slabs. These techniques have shown significant reductions in vibration levels, ranging from 30% to 80% depending on the method and application. Additionally, modifying support positions in water-pipe systems can reduce transmitted vibrations by over 60% [3]. The development of new vibration reduction systems based on existing theories and practical applications continues to be an active area of research [4, 5].

Research has shown that rubber materials can effectively reduce vibration in various applications. In aerospace, rubber shock absorbers have been successfully used to mitigate vibration in UAV LiDAR systems, with numerical simulations closely matching experimental results [6]. In railway engineering, mixing rubber particles from scrap tires with sub-ballast materials has demonstrated significant vibration attenuation, with a 5% rubber addition reducing mean acceleration peaks by 50% [7, 8]. For excavators, attaching rubber and other materials to buckets has shown promise in reducing vibration amplitudes across different modes [9]. Rubber inertial dampers with metal spheres show promise for electric vehicle suspensions, offering a simpler and more cost-effective solution than traditional dampers [10, 11]. Elastomeric isolators are widely used in various automotive applications, including powertrain mounts, suspension bushings, and body mounts, to reduce noise and vibration while meeting multiple design criteria [12]. Natural fibers like hemp, jute, and cotton have also been investigated for their damping properties, with experimental results showing a 30% improvement in door vibration damping when applied strategically to low-damping areas [13]. These advancements offer sustainable and effective solutions for enhancing passenger comfort and vehicle performance. Recent trends in vibration reduction include advanced measurement techniques, engineering controls, and smart technologies, with a focus on interdisciplinary research and global approaches to address this occupational health risk in agriculture [14].

Previous research demonstrated that rubber's vibration isolation properties depend on factors such as shape, load area ratio, and temperature, with the dynamic modulus and internal friction showing specific relationships to these variables. Rubber has a constant stiffness value. Innovations in rubber materials, such as Magnetorheological Elastomers (MREs), are needed to change their stiffness values to dampen varying vibrations. MREs are smart composite materials consisting of magnetic particles embedded in an elastomeric matrix [8, 15–17]. Their mechanical and viscoelastic properties can be rapidly and reversibly tuned by applying an external magnetic field. MREs are typically fabricated using conventional rubber-mixing techniques, with carbonyl iron particles commonly used as the magnetic component. The properties of these materials depend on factors such as particle type and size, matrix composition, and additives [18]. Crosslinking the elastomer in a magnetic field can promote the formation of aligned particle chains, resulting in anisotropic structures. Soft MREs can exhibit significant increases in storage modulus, exceeding one order of magnitude, when exposed to a magnetic field. These tunable characteristics make MREs suitable for various applications, including vibration absorption, isolation, and automotive components [19].

MREs are emerging as promising materials for developing adaptive engine mounts to reduce vibration in vehicles. These smart materials allow for adjustable stiffness and damping properties through the application of magnetic fields [20]. MR engine mounts have shown effectiveness in attenuating unwanted vibrations, as demonstrated through hardware-in-the-loop simulations and experimental studies [12, 21]. While simple one-degree-of-freedom models can provide insights, including vehicle chassis dynamics in two-degree-of-freedom models offers more accurate predictions of displacement response and force transmission [22, 23]. Overall, MR-based engine mounts show potential for improving vibration control in passenger vehicles.

The objective of this research is the development of a vibration isolator using the material of MRE and the optimization of variables such as material selection. Objectives include characterization of MRE, development of MRE motor mount which requires careful consideration of housing materials, and optimization of magnetic field generation and vibration isolation performance. Finite Element Method Magnetics (FEMM) software was used for simulating the system and finding the optimal design. To demonstrate the system's effectiveness in reducing vibration, a vibration isolator was fabricated.

MATERIAL AND METHODS

MREs have garnered significant attention in recent years due to their unique and versatile properties, making them a crucial component in numerous applications ranging from vibration control to adaptive structures. These materials possess the ability to reversibly change their mechanical properties, such as stiffness and damping, in response to an applied magnetic field. The materials for the manufacture of MREs are silicone rubber silicone oil, and carbonyl iron powder (CIP) [24–26]. The conventional process for the development of MREs consists of three steps, as shown in Figures 1 and 2. Choosing the right materials is the first step in developing MREs. The materials selected are Carbonyl Iron Powder (CIPs), a compound with low levels of magnesium and manganese, supplied by Sigma-Aldrich. Silica oil Dow Coring Corporation 200® liquid, viscosity 60,000 cSt (25 ^{o}C) was provided from Sigma-Aldrich. Permatex supplied clear RTV Silicone (100% silicone rubber). At room temperature, a mixture of silicone rubber, silicone oil, and microsized CIP is prepared. The second step is the mixing of the polymer matrix with the dispersed CIP. The air bubbles must be removed

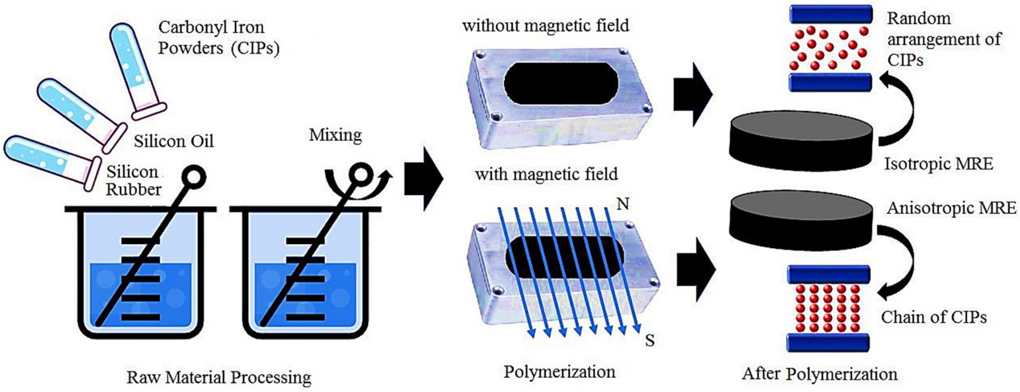

Figure 1. MR Elastomers manufacturing sequence

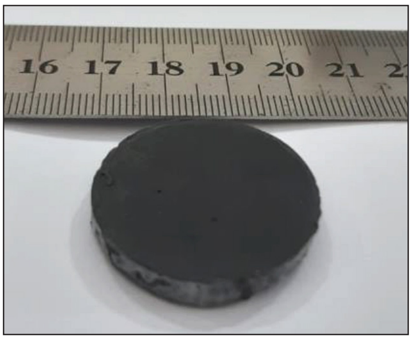

Figure 2. MRE after the curing process

from the sample. Depending on the curing time of the polymer, this may take minutes or hours. At room temperature, polymerization occurs for two to three hours. During the final cure, the ferrite particles are continuously processed into a chain by a magnetic field applied to the composite matrix. MREs, depending on their particle distribution after polymerization, have two types of structure, isotropic (random arrangement of CIPs) and anisotropic (chain of CIPs).

FEMM software has been integrated for magnetic circuit design using magnetic field simulations under various conditions and parameters. Figure 3 shows a sectional drawing of a vibration isolator. To ascertain the effect of material selection on component stiffness, the influence of both ample and uniform magnetic fields was taken into account. The housing and platform blocks are made of A1020 steel, while the bobbin part is made of aluminium-6061. The innovative magnetic circuit design allows for the determination of the optimal wire type, wire size, coil turn number, and coil current, thereby facilitating the generation of superior magnetic fields and the subsequent elimination of vibration. A comparative analysis of American Wire Gauge (AWG) 18 wire types was conducted to identify the optimal coil configuration for magnetic field (B) generation as shown in Figure 4. Once the wire type has been identified, the coil is then subjected to a series of turns. The software initiates the magnetic circuit simulation used to develop the design once the block properties and materials for each component have been defined.

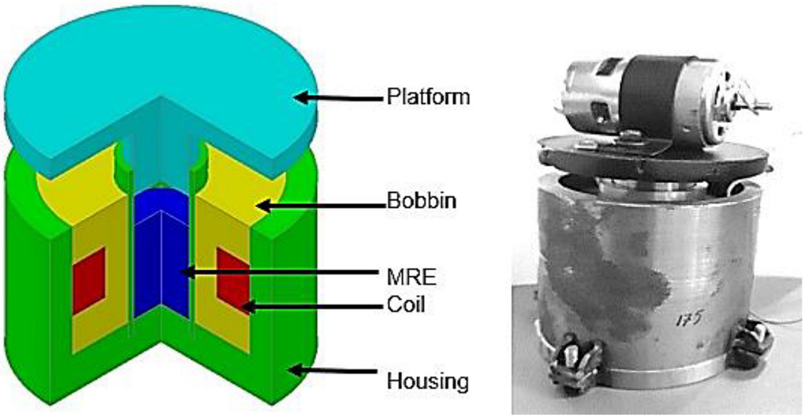

Figure 3. Design and fabrication of vibration isolator

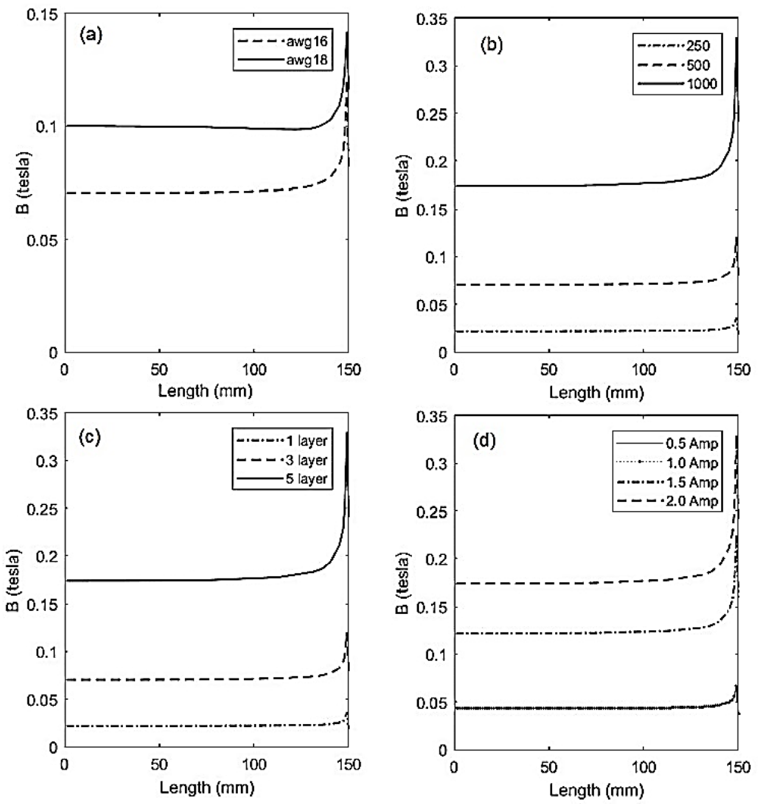

Figure 4. a) American Wire Gauge (AWG) 16 and 18 used on one winding, b) Windings of 250, 500, and 1000 are used on one winding, c) 1 layer (no steel inserted), 3 layers (1 steel inserted), and 5 layers (2 steel inserted) between MRE, d. 0.5 Amps to 2.0 Amps of current applied to winding power.

The effective region where the MREs were located was identified as the area exhibiting the highest magnetic flux density concentration, which was the primary objective of this design. Modifications to the vibration isolator are required to achieve larger magnetic fields in the effective MRE area. The simulation was used to model the effects of one, two, and no steel plates positioned between the MREs in the effective area to generate the most intense magnetic fields. The simulation outcomes indicate that the configuration comprising five layers exhibits optimal performance in comparison to the other alternatives. The final simulation involved the application of a distinct current to the

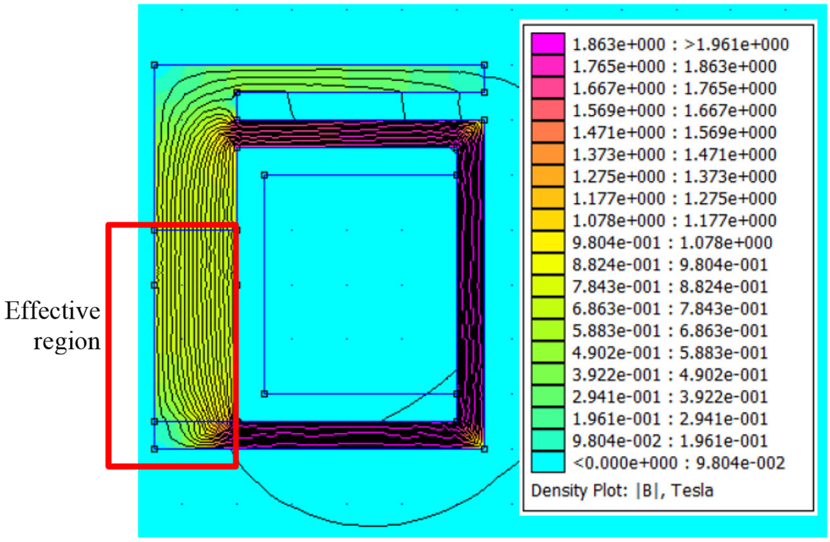

Figure 5. The magnetic flux density

vibration isolator. Figure 5 below shows the magnetic flux density results of the FEMM simulation.

RESULTS AND DISCUSSION

APEX™ EDS is EDAX's flagship software program for the acquisition and analysis of energy-dispersive x-ray spectroscopic (EDS/EDX) data and for characterizing the composition of materials. The microstructures of the isotropic and anisotropic samples were examined. The MRE samples were sliced to a thickness that would accommodate the SEM holder because the chain-like features of the anisotropic samples run parallel to the thickness direction. SEM micrographs of the MREs structure of anisotropic specimens samples are shown in Figure 6. It is noteworthy that the placement of the sample in the SEM holder during the scanning process is responsible for the change in orientation of the chain structure. The orientation of the chains is parallel to the thickness of the specimen. The EDX results presented in Figure 7 that some points were selected for the determination of the composition of MREs. They include Si, Fe, O, C, Ca, and Ti (34.35, 29.71, 20.64 and 15.31%, respectively). The weights and atomic percentages are tabulated in Table 1. The existence of element Ca is one of the binding elements in Silicone Rubber RTV with a very small intensity. The Ti element is one of the impurities formed in the MRE manufacturing process.

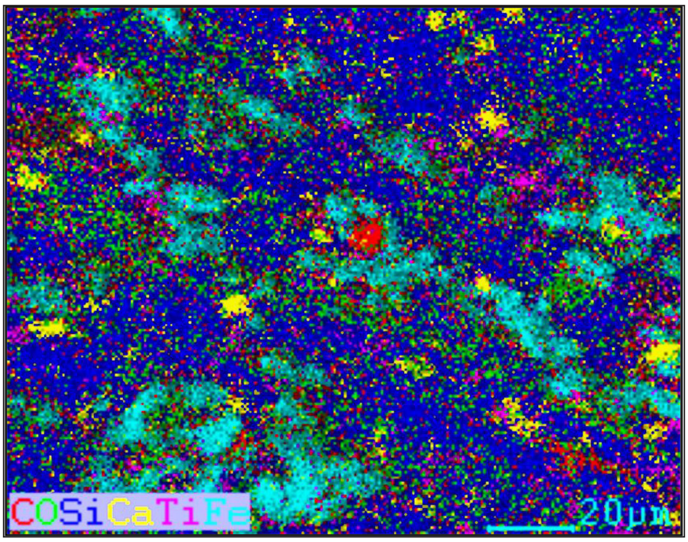

Figure 6. The MRE structure of anisotropic specimen samples

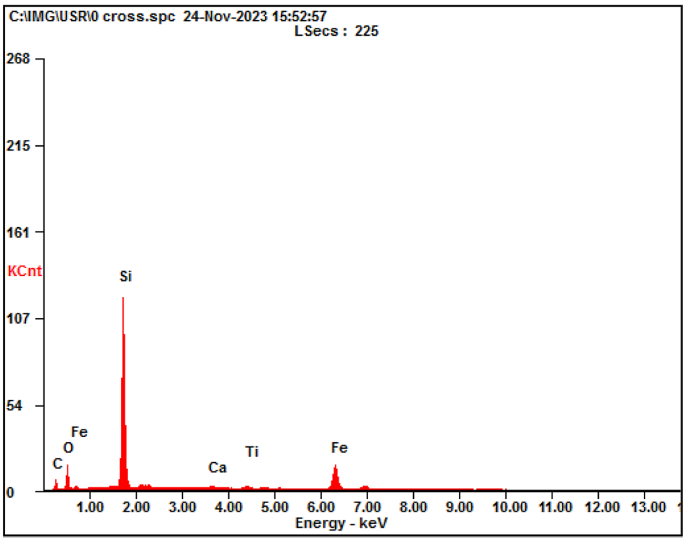

Figure 7. Si has the highest peak

Table 1. The composition of the MRE

Element	Results	
	Weigt %	Atomic %
Si	42.15	36.39
Fe	26.06	11.32
O	14.87	22.54
C	13.90	28.07
Ca	01.54	00.93
Ti	01.47	00.75

MRE preparation and manufacturing methods are based on the published work of [18] and follow the methodology described therein. For this investigation, the rubber matrix employed is natural rubber. The magnetic particle filler is a CIP, which has an average diameter of 10 µm. The fabricated sample of magnetic elastomer materials had a diameter of 30 mm and a thickness of 2 mm. Oscillatory tests were performed on the sample using a rotational rheometer (Physica MCR 302, Anton Paar, Germany) to investigate the rheological properties of the MR elastomer. To observe any changes in the behavior of the elastomer, the current varying applied from 0 Amps to 5 Amps. In addition, a sweep strain test was performed to determine the linear viscoelastic range by analyzing the shear strain at 30 points. The sweep strain was varied at a frequency of 0.1–100 Hz.

Dynamic mechanical analysis (DMA) is a methodology employed to quantify the dissipation of energy in a given material subjected to oscillatory forces. In DMA, the application of a sinusoidal force at varying frequencies, strain amplitudes, and temperatures allows for the measurement of the displacement of the materials, thus enabling the

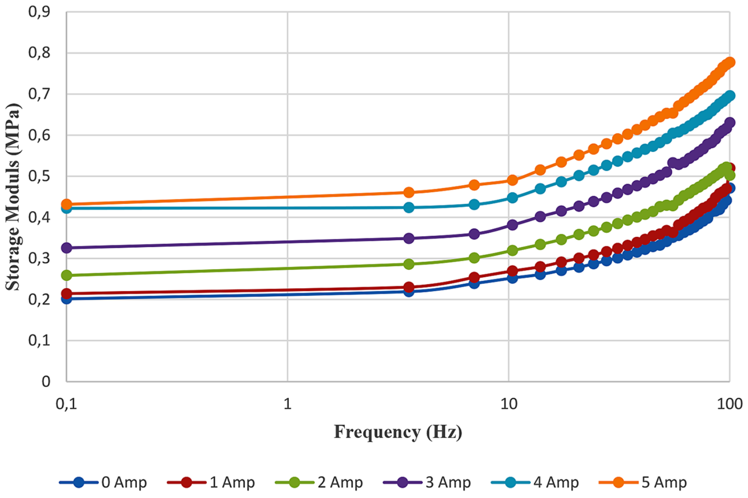

Figure 8. Storage modulus of the MREs

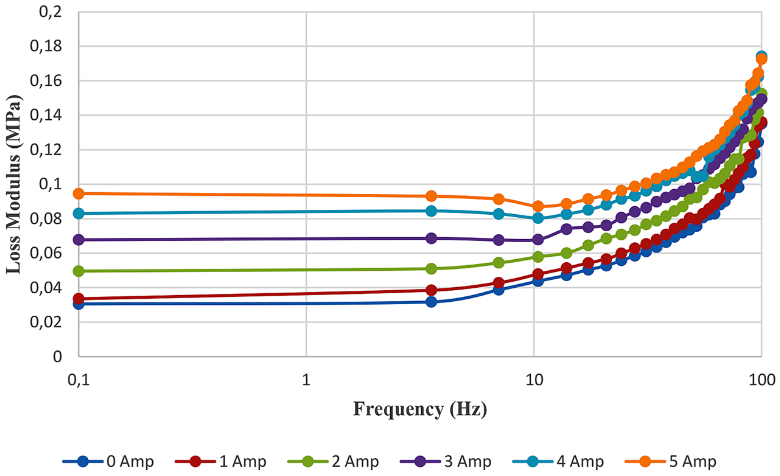

Figure 9. The loss modulus of the MREs

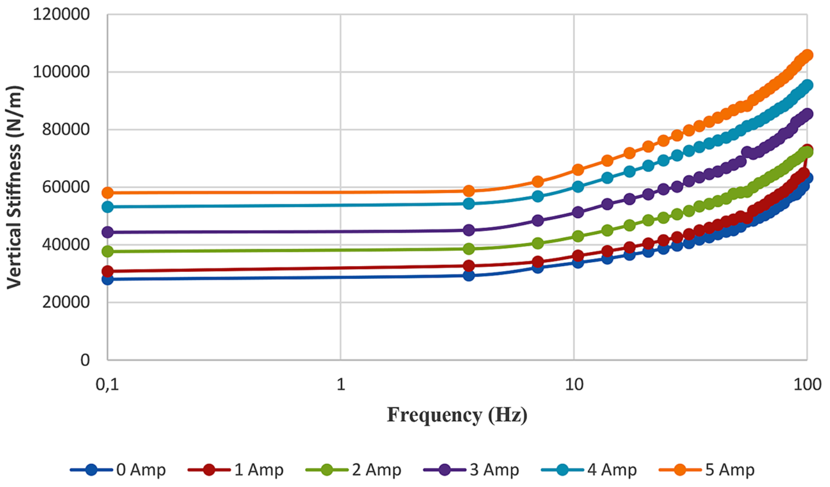

Figure 10. Vertical stiffness of the MREs

calculation of the storage modulus, loss modulus, and vertical stiffness. The experiments were conducted using a Perkin Elmer dynamic mechanical analyzer. As can be observed in Figures 8–10, there is a logarithmic linear relationship between the storage modulus, loss modulus, and vertical stiffness with frequency can be used to predict the storage modulus, loss modulus, and vertical stiffness at a given frequency. This indicates that the storage modulus, loss modulus, and vertical stiffness of the samples increase at higher frequencies.

The utilization of MRE materials in the vibration isolator schematic diagram of the test setup is shown in Figure 11, and experimental testing is presented in Figure 12, which depicts the apparatus employed in the experiment. The instrumentation used in this experiment included a Dewesoft measurement system, a piezoelectric

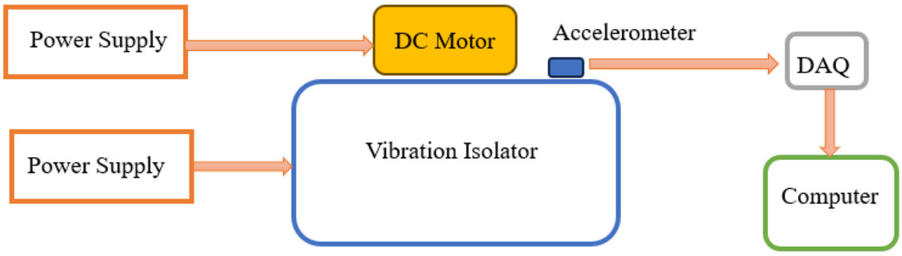

Figure 11. Schematic diagram of the test setup

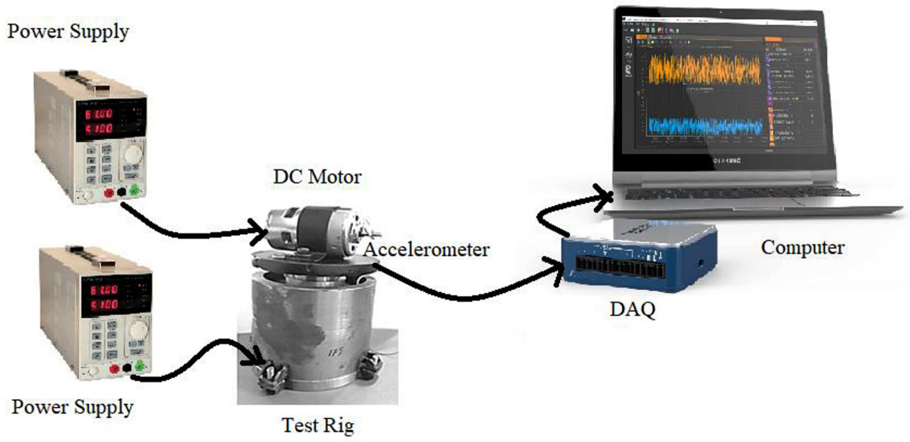

Figure 12. Vibration isolator test rig

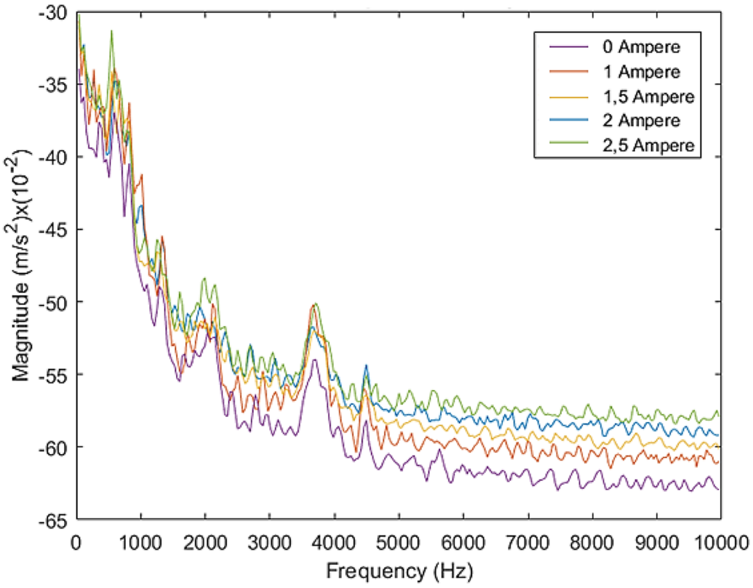

Figure 13. Power spectral density

acceleration PCB®, and a laptop computer. The laptop computer and the piezoelectric accelerometers act as the software and hardware interface for transmitting the vibration data to the digital analyzer. The electromagnetic coil located in a vibration isolator is powered by a DC power supply. In the experiment, a DC motor mounted on the insulator acts as a vibration source while a voltage is maintained at a constant level to generate oscillations. This experiment was conducted three times to obtain each data.

When currents are applied to the coil of the vibration isolator, the power spectral density for the vibration signal at the vibration isolator is shown in Figure 13. It can be seen that when the 0 A current is applied to the coil, the mean stiffness of the MRE has the lowest value compared to the others. When a 2.5 A current is applied to the isolator coil, the MREs have the highest acceleration magnitude value or high stiffness value. The graph shows that the vibration amplitude difference increases with each increment of the applied current.

CONCLUSIONS

The applicability of MR elastomers for isolating vibration has been investigated experimentally. The vibration isolator that has been made in this research uses a housing material made of steel and the number of coil turns is 1000 using AWG 18 wire type. The DC motor mounted on the top of the vibration isolator is used to generate disturbing noise. By adjusting the stiffness of the isolator through an external magnetic field created by applying an electric current to the isolator coil, the characteristics of the MRE can be changed. The results show that as the current applied to the isolator coil is increased, the magnetic field is increased and the stiffness of the MRE is increased.

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