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Experimental study on the dynamic properties of magneto-rheological materials

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Abstract. Magneto-rheological elastomer (MRE), is considered to be a smart material, which transFigure their rheological properties with the external applied magnetic field. Due to this novel property, MREs are extensively employed to control the vibration of a system at resonant frequency. Presently, MREs are integrated in a structure through a layer by layer technique and the bigger drawback of this technology is that, in the presence of high transverse shear stresses, de-lamination occurs which may result in failure of the system. To overcome the aforementioned problem, a novel method is proposed to merge the MREs with Fused Deposition Method (FDM). FDM is used to develop the primary structure with cavities using a FDM compatible material and MRE i.e. secondary material is filled in the cavities. It is postulated that the proposed methodology has the capability of reducing the possibility of de-lamination. Now, to investigate the dynamic performance of the developed structure, an experimental test setup was developed by fixing one end of the beam and supplying the desired magnetic field to the beam using an electromagnet. From the test results, It was concluded that, with the increase in the applied magnetic field, the isolation effect of the structure enhanced and it reduced with the shift of electromagnet from the free end to fixed end of the beam. Further, in the case of MRE, high magnetic field is required for achieving satisfactory performance, which results in increase of the electromagnet weight, in turn making the system bulkier. Therefore, the present work endeavours to replace the MRE with MR Fluid (MRF) in the same primary structure and perform a comparison study between MRE and MRF, for the same applied magnetic field. From the experimental results it was envisaged that the MRF depicted better isolation capability than MRE.

Keywords: MRE, MRF, Vibration, Additive Manufacturing.

1. Introduction

Smart materials such as MRE(Magneto-rheological elastomer) and MRF (Magneto-rheological fluid), are being considered for controlling the vibration of a system, due to their capability of changing their dynamic properties such as stiffness and damping, under the influence of external stimuli [1]. These materials are composed of nano carbonyl iron particles and a carrier matrix (e.g. oil [2,3], honey [4], silicone rubber[5] etc). Additional supplements such as surfactants, adhesives etc are added into the MR materials to improve their performance. Both, MRF and MRE show's magnetic field dependent property, i.e. the dynamic properties can be varied with the help of external magnetic field. However the difference between the two lies that, under the influence of external magnetic field, MRE doesn't allow iron particles to move from its actual position whereas MRF gives freedom to align the iron particles in the direction of magnetic. Therefore the variation in the rheological properties for MRF is high (changes from liquid to solid), which results in more variation in dynamic properties. Another important difference between the two is that MRE works at pre yield region while MRF works at post yield region. The most common method used by various researchers, is to embed the MRE in the required location of the primary material with the help of adhesive, which binds the surface of elastomer with the structure [6]. The wide applications of MR materials include MR breaks[7], suspension system i.e. vibration isolators and dampers etc[8,9].
Li et al. [8] reviewed the research and development carried out so far in MRE and critical issues are addressed such as operation modes of MR elastomer, placement of coils in electromagnet and preparation of MR Elastomer. Li et al. [8] also presented, a comprehensive review on the vibration absorbers and vibration isolators, which explains the wide application of MR elastomer to bring the change in the technological revolution in the field of vibration. Zhou et al. [1,10] pointed out an interesting effect of MRE by using point dipole model, he found that the young's modulus of MRE for induced magnetic field was negative, which signifies that the stiffness of MRE decreases by applying external magnetic field. Hu et al. [6] used MRE to reduce the vibration by applying external magnetic field and it was found that the resonant frequency of the beam shifted leftwards when the external magnetic field is applied to it. Poojary et al. [11] performed experimental study on MRE and found that the force transmissibility of MRE depends not only on the magnetic field but strain rate is also an important factor to change the MR effect. The isolation effect was found to be higher at large magnetic field while the isolation effect was reduced at higher strain rate. Zhou and Zhang [12] developed a semi active double barreled damper with MRF as an lubricant. Hegde et al.[13] investigated the effect of size of iron particles used in MRE and it was shown that the smaller particle resulted in increase in MR effect due to higher dipole moment observed between smaller iron particles. Poojary et al. [14] investigated variation of dynamic stiffness in MRE by varying the strain rate under discretized magnetic field.
This paper presents a novel methodology to combine the MRE and MRF using FDM. MR effect is investigated by performing forced vibration analysis and the frequency response is presented to understand the change in dynamic stiffness. Comparison study of MRE and MRF is carried out to check their variation change in MR effect. The technique discussed in this article can be carried further to use with other conventional manufacturing methods as well.

2. Methodology

In the present section, an overview of the parameters taken in account while conducting experimental analysis is discussed. This section is further subdivided into 3 sections, in which explanation of (i) preparation of MR material, (ii) preparation of sample using fused deposition technique and (iii) finally the sensors and actuators used for the experimental study are discussed to conduct the experimental analysis.

2.1. *Manufacturing of smart material*.

In this study, MRF and MRE is Prepared by mixing carbon iron particles (BASF, Type CN, Germany) of diameter 5µm of an average with room temperature vulcanizing (RTV) silicone (Link Composites, LLP, Karnataka, India). 73% by mass of silicone rubber, 27% by mass of iron particles were used to prepare the mixture of isotropic MRE and MRF[11]. The mixture is assorted for 15 minutes by mixing silicone oil into it to relieve the stresses. Air bubbles present in the mixture were then removed by keeping the mixture in vacuum chamber for 15 minutes. Finally half the mixture was separated and it was mixed with curing agent to lock the iron particles to use in one of the specimen. The material without curing agent was used in another specimen so that the dynamic properties can be checked without locking the iron particles.

2.2. *Manufacturing of specimen*

Manufacturing of specimen is done using 3D printer which uses fused deposition technique to lay the filament layer by layer [15,16]. Figure 1 shows a 3D printer used in this study. Simplify 3D software was used to control the machine using a high speed A/B cable connected from the USB port of the system to the hardware interfaced with the 3d printer. Acrylonitrile butadiene styrene polymer was used to manufacture the specimen with 250mmX25mmX6mm in overall dimension. 1.75mm diameter filament was fed to the nozzle which was heated at the melting temperature i.e. 2400C through a ceramic cartridge heater, and it was extruded by pushing the filaments into the heater by passing it into the spur gears. Extruded filament was maintained at Ø 0.5 mm size as the diameter of nozzle was 0.5 mm. Infill percentage of the beam was kept 25% to make the cavities inside the specimen so that the smart material can be filled into it. To reduce the warpage in the specimen the bed temperature was kept at 1000C [17]. Layer thickness was chosen by hit and trial method to keep it as minimum as possible to improve the bonding between each layer and to avoid the nozzle blockage. Each layer of the specimen was printed at 0.3 mm layer thickness to ensure that the bonding between the layers is strong [17,18]. 2 bottom solid layers were printed and then 16 layers were printed at 25% infill density, machine was stopped just before starting the top solid layers. MRE and MRF were filled in each specimen in equal quantity to maintain the same mass. After 24 hours, the machine was started again and the starting point of the printing was kept at 4.8 mm. 2 Top solid layers were printed again in each of the specimen to cover the MR material. Fig. 2 depicts the printed specimen with and without smart materials. It is to be noted that one beam is filled with MRE and other with MRF to compare the dynamic properties.

2.3. *Experimental setup*.

Specimens manufactured using FDM embedded with MRF and MRE were tested using forced vibration testing. Figure 3(a, b) shows the schematic and experimental setup to test the MR sandwich beam. In this study, cantilever beam condition was chosen to study the dynamic behavior of MR materials i.e. the beam was fixed rigidly from one end and it was made free from the other [6]. An amplified piezo actuator(APA) was used in this study to excite the system harmonically at the required amplitude(voltage) and frequency (Hz)[19]. The upper end of the specimen was attached rigidly to APA using a allen bolt as shown in the Fig.3(b). Sinusoidal excitation of 10V was given to the APA using NI ELVIS. The excitation frequency was varied from 9 Hz to 20Hz in frequency steps of 0.5 mm. The signals obtained from NI ELVIS were fed to an amplifier to amplify the voltage from 10 V to 200V. The response of the system was obtained using a non contact type sensor laser pickup to avoid the additional mass of the sensor which is caused due to contact type sensors such as accelerometers. NI 9203 current input module was used in this study to capture the signals obtained from laser pick. The aforementioned module was interfaced using NI 9174 C-Daq chassis and it was further connected to the NI LabVIEW software to view the response. Sampling rate of the acquisition was maintained at 12800 samples per second and the samples were read in every 2 seconds i.e. 25600 samples were fetched using NI 9203 data acquisition device which gave the resolution of measurement to be 0.5 Hz. The peak amplitude of the excitation frequency was captured for every 0.5Hz increment in the frequency from the range of measurement i.e., 9Hz to 20Hz. Discretized magnetic field was supplied to the system by using an electromagnet. A variable DC power source was used to control the magnetic field of the electromagnet by changing the value of current manually. Lake Shore (Model 410) Hall sensor module was used in this study to measure the magnetic field generated by the electromagnet.

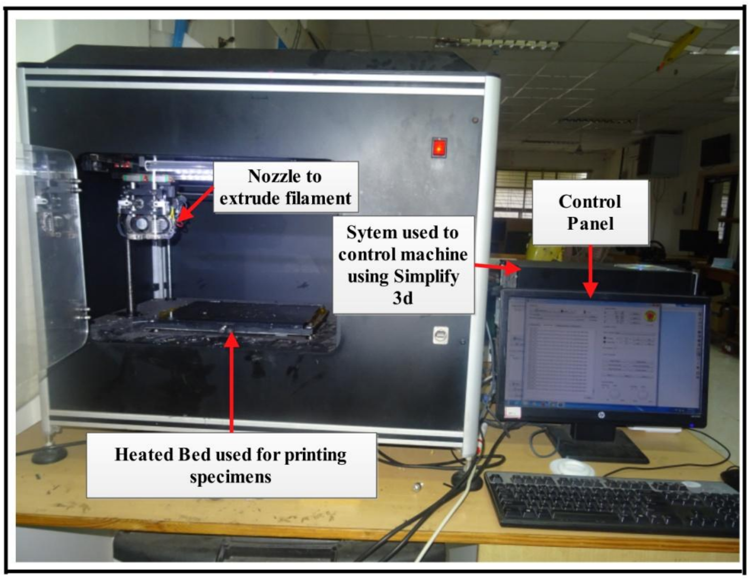
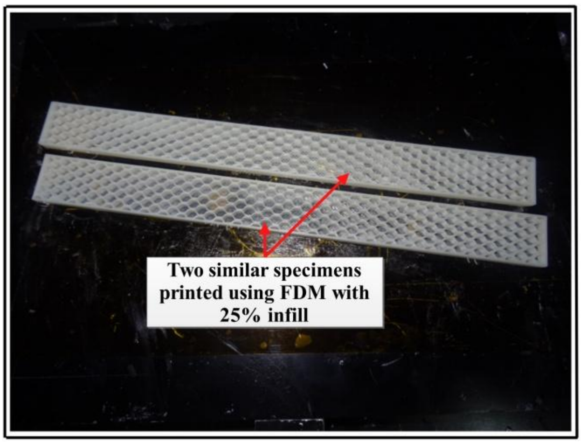
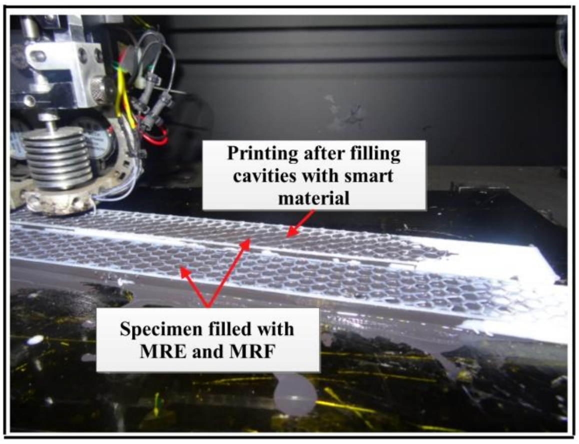


Figure 1. Shows 3d printer used in this study to print MR sandwich beam



(a)



(b)

Figure 2. (a) Beam printed using fused deposition technique (b) Beam embedded with smart material i.e. MRE & MRF

3. Results & Discussion

In this section, the results obtained from the forced vibration study are presented. Results shown in this section are further subdivided into two sections wherein first section studies the change in dynamic behavior obtained when MRE is embedded to the primary material and the second section deals with the comparison of the MR effect between the MRE and MRF embedded in two similar beams [20]. Each beam is divided into 3 zones and the electromagnet is aligned to each of the zone to conduct forced vibration analysis to understand the change in dynamic property (i.e. resonant frequency) at various magnetic field. It is to be noted that, the comparison study is carried out only at the region where MR effect is found to be maximum. The distance between the poles of electromagnet is maintained to be equal while supplying the magnetic field. System was excited from 9Hz to 20Hz frequency in the frequency steps of 0.5Hz increment from the starting frequency. After incrementing the frequency, the steady state peak amplitude was stored into an array in LabVIEW. Similarly all the peak amplitudes were captured by exciting the system harmonically. A sample of steady state vibration of the system is shown in Figure 4. It can be seen from the Figure 4 that the data is captured in every 2 sec.

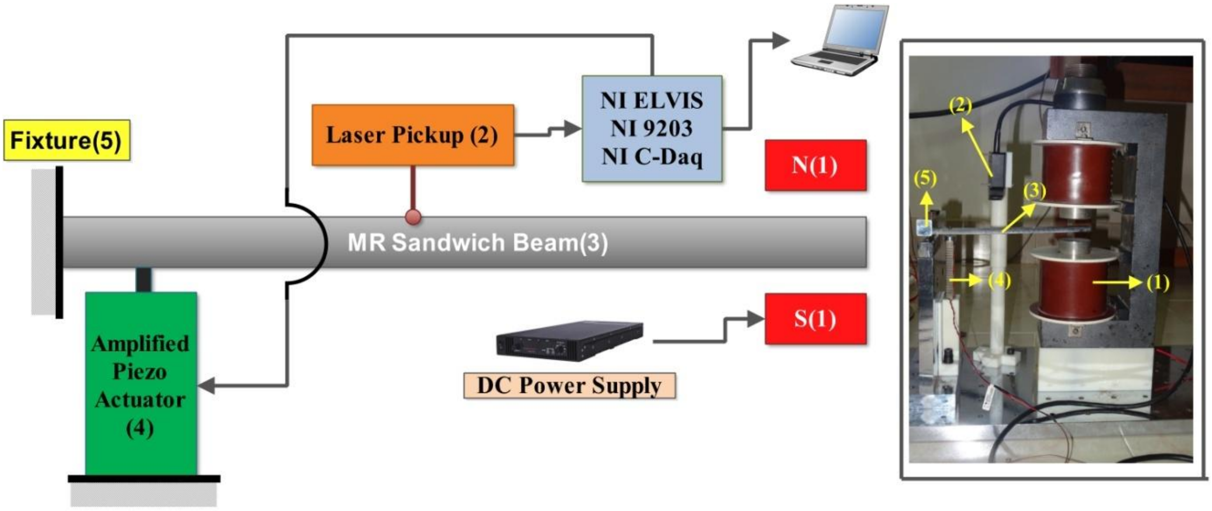


Figure 3. (a) Schematic depicting the experimental setup with the hardware used in this study (b) Experimental Setup (1): Electromagnet, (2): Laser Pickup, (3): Sandwich beam, (4): Amplified piezo actuator (APA), (5): Fixture

The time domain data acquired from the sensor was fed to the FFT analyzer to obtain the steady state amplitude of the excited frequency, furthermore amplitude and level measurement toolkit of NI LabVIEW was used to capture the peak amplitude of the MR sandwich beam. The MR effect of the system was calculated by checking the reduction in the amplitude of the vibration at the excitation frequency when the external magnetic field is applied to it. A mathematical expression used to compute the change in MR effect in terms of amplitude and frequency is shown in Eq. (1) & (2).In this study the comparison of amplitudes are done at the resonance state by applying discretized magnetic field to compute the reduction in the amplitude of vibration.

$$Reduction\ in\ amplitude(\%) = \left(\frac{A_{nm}-A_m}{A_{nm}}\right) X100 \quad \text{...(1)}$$

$$Reduction\ in\ frequency(\%) = \left(\frac{f_{nm}-f_m}{f_{nm}}\right) X100 \quad \text{..(2)}$$

3.1 *Results obtained from the sandwich beam embedded with MRE.*

In this section, the dynamic behavior of MRE is studied at discretized magnetic field. Figure 5 depicts the response obtained from the system when the electromagnet is aligned in the first zone, It can be seen from the graph that the resonance frequency at various magnetic field is found to be different which shows that the MR materials are capable of changing the resonant frequency of the system dynamically which in turn reduces the vibration of the system [6,8]. 15.6 % of reduction in frequency and 87.5% reduction in amplitude is achieved by applying the magnetic field of 0.15T. It can also be noticed from the Figure 5, that the amplitude of vibration increases as the resonant frequency is shifted in leftward direction, which is due to that fact that when the beam reaches to its maximum and minimum amplitudes, the beam experiences force of attraction with each pole of the magnet and as a result of that the amplitude of vibration increases at the resonant region. The second order differential equation of a spring mass system can be represented as:

$$M\ddot{x} + C\dot{x} + Kx = A\sin\omega t \quad \text{..(3)}$$

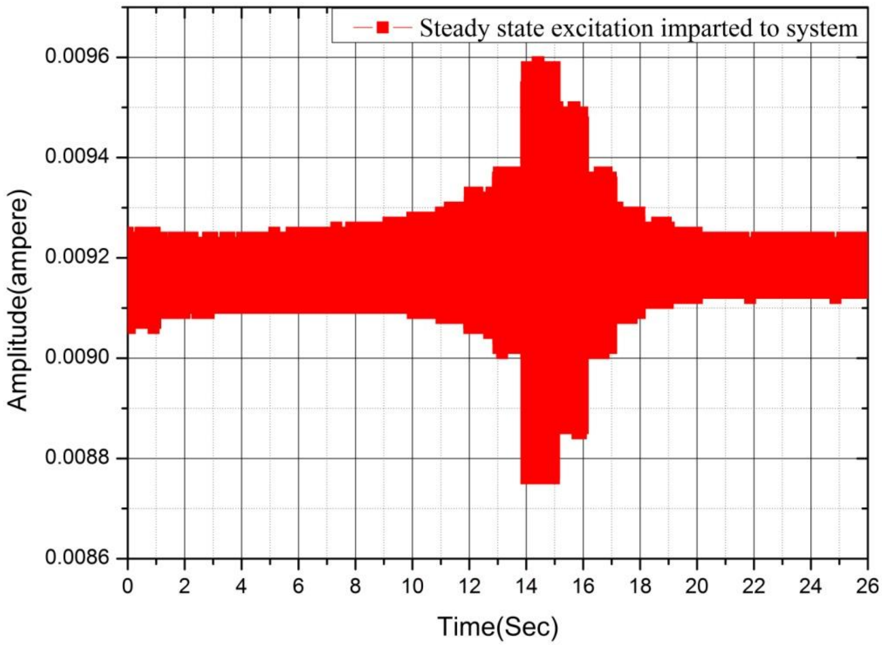


Figure 4.Depicting the sample response obtained using the excitation given to the MR sandwich beam

Here, M, C & K are the mass, damping and stiffness of the system. A & ω represents the amplitude and operating/forcing frequency of the system. In this study, amplitude (A) and the frequency (ω) are obtained by the voltage given to the APA and the sinusoidal frequency supplied to it using NI ELVIS. As discussed, when magnetic field is applied in the system, an extra force of attraction pulls the beam and hence the amplitude of vibration becomes

$$\mathrm{A_{total}} = \mathrm{A(due\ to\ APA)} + \mathrm{A'(due\ to\ additional\ force/pull\ obtained\ from\ magnet)}$$

Figure 3(b) shows the position of electromagnet. It can be seen from the Figure that the magnetic field is supplied along the direction of actuation. It was observed that the static deflection of the beam increases with proportional to the magnetic field. The same can also be inferred from the Figure 5. Due to increase in static deflection, the resonant frequency of the system has shown a clear leftward shift as seen in Figure 6. The formulation of the same is shown in eq. 4.

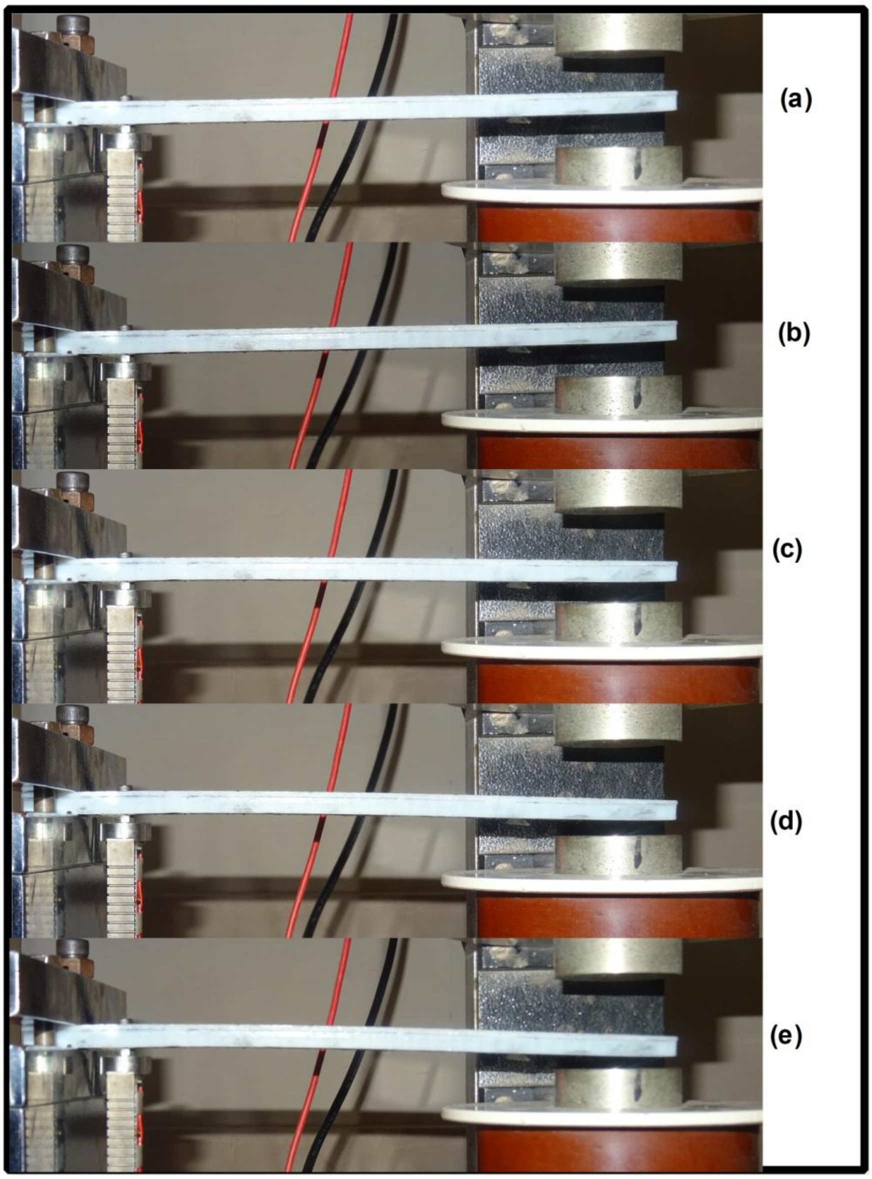


Figure 5. Depicting the increase in static deflection at various current (a) 0 amp (b) 1 amp (c) 2amp (d) 3amp, (e) 4amp.

Using the second order differential equation for a single degree of freedom system, we know that:

$$\omega_n = \sqrt{\frac{g}{\delta}} \qquad (4)$$

where, g, δ and ω_n represents the acceleration due to gravity, static deflection and natural frequency of the system respectively.

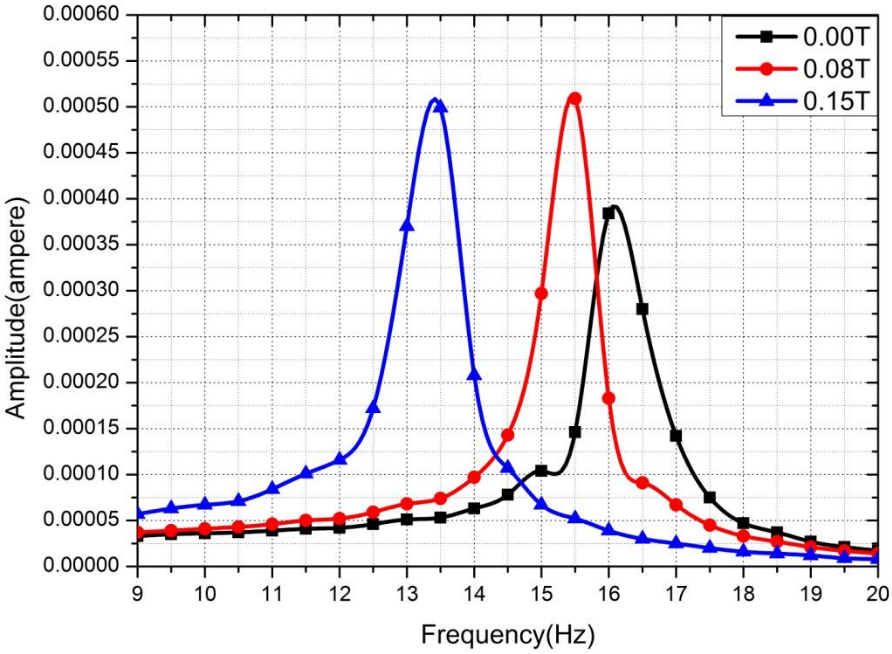


Figure 6. Depicting the response obtained when the magnet is aligned at position 1 i.e. at the free end of the beam

Now, the electromagnet was shifted to second and third zone to understand the behavior of the system and the results are shown in Figure 7 & Figure 8. The resonant frequency has shown a clear shift in leftward direction but the change in the MR effect is found to be reducing as the magnet is taken from free end of the beam to the fixed end. Hence, it can be said that the magnetic field should be supplied in the region where the vibration of the system is higher i.e. to a lesser stiffer region. An interesting effect is noticed when the electromagnet was aligned in the third zone, Fig.7 shows that when the magnet is taken more closer to the fixed end, the change in amplitude has the same trend but the change in the frequency is found to be zero. This position is specifically shown to understand that in the worst cases there’s is a chance that MR effect may lead to a dangerous situation wherein magnetic field will aid to increase the vibration but this can be avoided by proper placement of electromagnet or by controlling the magnetic field properly.

3.2 *Comparison study on MR Materials*

In this section, comparison study of MR effect obtained by magneto-rheological elastomer and magneto-rheological fluid is carried out. Since it was found that the MR effect obtained by the MRE was maximum at the free end of the beam, hence the test was conducted only at the free end region using MRF sandwich beam, the change in the resonant frequency is compared to study the MR effect of both the beams under the same magnetic field. Fig. 8 represents the result obtained by conducting the forced vibration study of the beam filled with MRF. It can be seen that that the similar effect is obtained as it was obtained in case of beams filled with MRE i.e., the resonant frequency shifts in leftward direction. Also, there's increase in amplitude is found when the magnetic field is supplied to the system. 25 % of reduction in frequency and 91.6 % reduction in amplitude are found by maintaining the same magnetic field which shows that beams filled with MRF has better isolation capability than the beams filled with MRE. Hence to achieve the same MR effect as from MRE, MRF beams will require lesser magnetic field which will help in reducing the weight of electromagnet effectively.

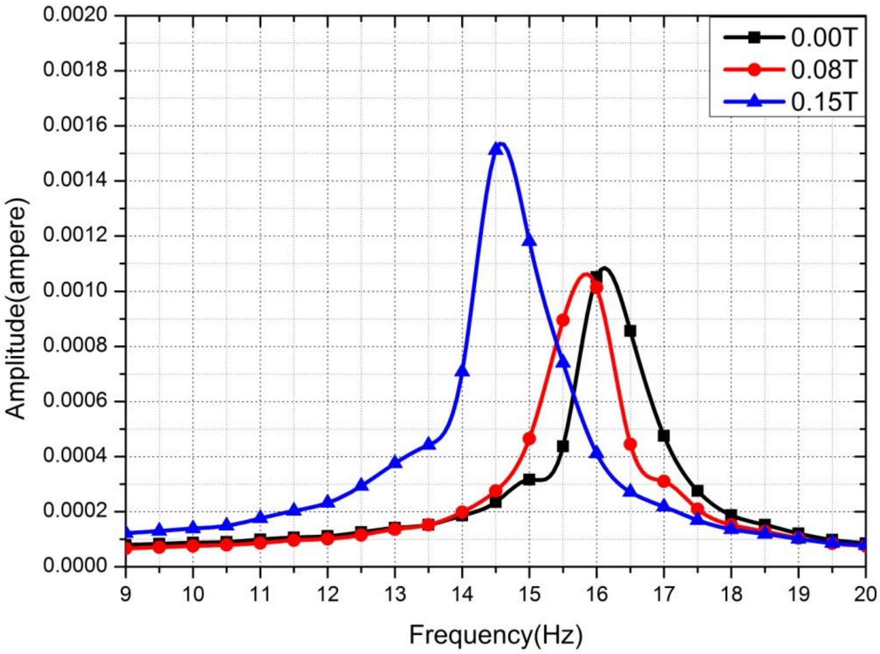


Figure 7. Depicting the response obtained when the magnet is aligned at position 2 i.e. at the mid span of the beam

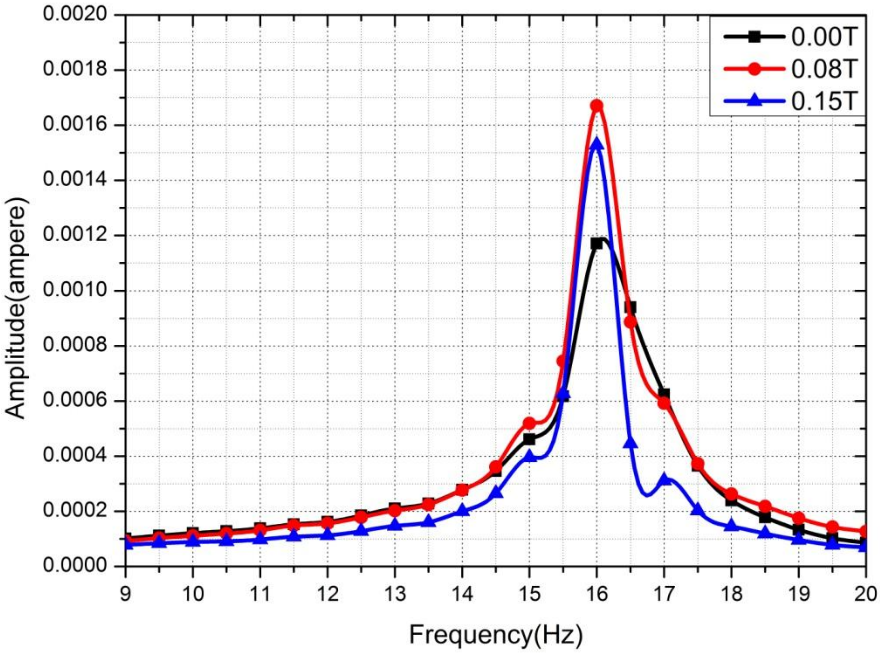


Figure 8. Depicting the response obtained when the magnet is aligned at position 3 i.e. close to the fixed end of the beam

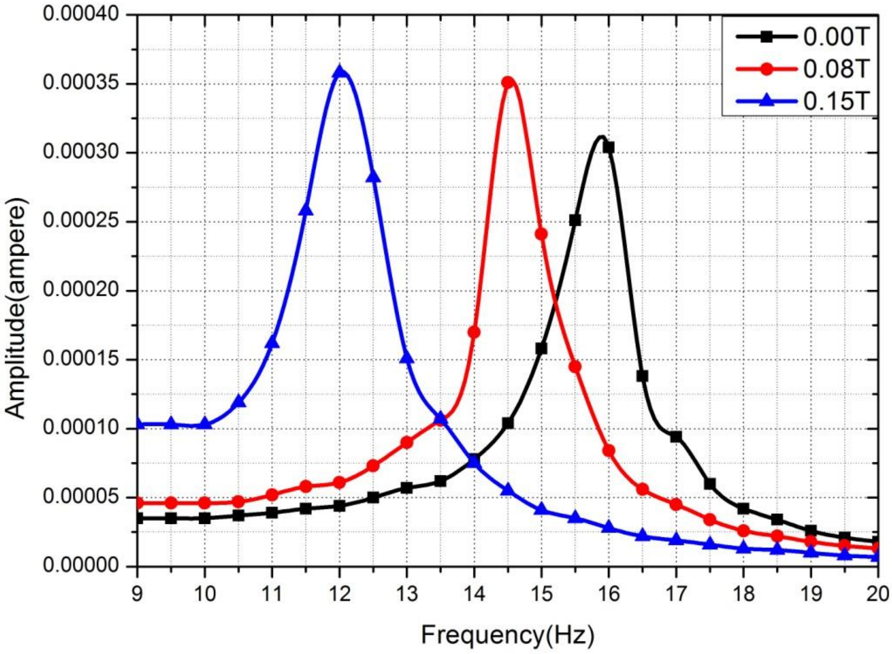


Figure 9. Depicting the response obtained when the beam embedded with MRF when the magnet was at the free end/position 1

Table 1.

Depicting the change in MR effect achieved by experimental study

S. No	Smart Material/Zone of electromagnet	Percentage reduction in frequency from resonant frequency at 0T to 0.15T	Percentage reduction in amplitude from resonant frequency at 0T to 0.15T
1	MRE/Zone 1	15.6	87.5
2	MRE/Zone 2	9.375	50
3	MRE/Zone 3	0	-33.34
4	MRF/Zone 1	25	91.6

4. Conclusion

In the present study, a novel methodology is presented to manufacture MR structure which can be used for reducing the vibration with the help of external magnetic field. ABS polymer was used as a primary material and MR material is used as a secondary material to change the dynamic properties of the system. Secondary material includes MRE and MRF, which were embedded with ABS beam printed using fused deposition technique. Forced vibration test were performed to excite the system harmonically for a predefined band of frequency range. A maximum of 15.6% shift in the resonant frequency was achieved in leftward direction and 87.5% reduction in amplitude was achieved by using MRE. Furthermore, MRF was used to compare the MR effect obtained using MRE at the zone 1. It was found that, under the same magnetic field and the position of electromagnet, MRF has more tendency to shift the frequency and reduce the amplitude of vibration dynamically, as a result of this MRF requires lesser weight of electromagnet to obtain the same amount of MR effect achieved by the beam embedded with MRE. Furthermore, instead of gluing the smart material with primary material, this work presents a novel technique to fill the smart material in the cavities of the beam and as a result of that de-lamination can be avoided. It was shown that the MR effect was maximum at the free end of the specimen, and this signifies that smart material is not required to be filled in entire beam, but only particular zones can be utilized to obtain the MR effect.

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