Dynamic behavior of sandwich beams with different compositions of magnetorheological fluid core

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ABSTRACT
Magnetorheological fluid (MRF) sandwich beams belong to a class of adaptive beams that consists of MRF sandwiched between two or more face layers and have a great prospective for use in semi-active control of beam vibrations due to their superior vibration suppression capabilities. The composition of MRF has a strong influence on the MRF properties and hence affects the vibration characteristics of the beam. In this work, six MRF samples (MRFs) composed of combination of two particle sizes and three weight fractions of carbonyl iron powder (CIP) were prepared and their viscoelastic properties were measured. The MRFs were used to fabricate different MRF core sandwich beams. Additionally, a sandwich beam with commercially available MRF 132DG fluid as core was fabricated. The modal parameters of the cantilever MRF sandwich beams were determined at different magnetic fields. Further, sinusoidal sweep excitation tests were performed on these beams at different magnetic fields to investigate their vibration suppression behavior. MRF having larger particle size and higher weight fraction of CIP resulted in higher damping ratio and vibration suppression. Finally, optimal particle size and weight fraction of CIP were determined based on the maximization of damping ratio and minimization of weight of MRF.
1. Introduction

Magnetorheological fluids belong to a class of smart materials and consists of micron-sized (preferably less than 10 microns) magnetizable particles (mainly iron particles) suspended in carrier fluid such as silicone oil, polyalphaolefin oil, etc with small amounts of suitable additives. The properties of MRF can be enhanced by application of magnetic field and its original properties can be restored when field is removed. This is due to dipole moment induced in the iron particles and leads to orientation of these particles along the magnetic field. This property change occurs in a fraction of a second [1]. This smart property has been used and investigated in several applications by many researchers [2–5] although it has been successfully implemented in few applications such as MR dampers for suspensions, seats, mounts, prosthetics, MR brakes, tactile feedback device, MR dampers for buildings and bridges [6,7].

An MRF core beam consists of MRF sandwiched between elastic base and constraining face layers, sealed using adhesive. Its vibration behavior can be altered by the application of magnetic field due to controllability in the properties of MRF. Several research works have been performed on MRF sandwich beams due to their vibration suppression capabilities and have potential applications in flexible structures such as aircraft wing, automobile hood, appendage of space robot, and other structural applications [8]. When used in structural beam applications, the MRF functions in the pre-yield regime and shows a viscoelastic behavior with complex shear modulus relating to shear stress and shear strain [9]. The vibration characteristics of a beam depends on the stiffness, mass, and damping. With the usage of magnetorheological fluid sandwiched between elastic face layers and varying the magnetic field, the modal and dynamic behavior of the beam can be altered.

The vibration controllability of MRF sandwich beams has been investigated theoretically and experimentally in many research works. Sun et al. [10] performed oscillatory tests to determine the viscoelastic properties of MRF and forced excitation tests of MRF sandwich beam at different magnetic fields. It was found that as magnetic field is incremented, the complex shear modulus increased, the natural frequencies shifted to higher frequencies and the amplitude of vibration under forced excitation decreased. Yalcintas and Dai [11,12] compared the theoretical and experimental vibration behavior of MR sandwich beams and found that there is positive shift in natural frequencies, loss factor variation and vibration amplitude reduction. Lara-Prieto et al. [13] performed free vibration tests on MRF sandwich beams and concluded that the sandwich beam vibration response can be controlled in the form of variations in vibration peak response and shifts in natural frequency. Hu et al. [14] analytically studied vibration behavior of a MRF sandwich beam under changing magnetic field strength and they found out that with increase in magnetic field strength, there is an increase in the natural frequencies and the loss factors of the MRF beam while the vibration response got reduced. Fadee [15] studied the effects of boundary conditions, MRF layer thickness and properties of material and the magnetic field on vibration characteristics of functionally graded MRF sandwich beams through analytical approach and concluded that the effect of magnetic field on loss factor is more than that on natural frequency. Rajamohan et al. [16]
investigated the influence of MR layer thickness on natural frequency and loss factor; effect of magnetic field intensity on natural frequency, loss factors, and vibration amplitude of simply supported, cantilever, and clamped-clamped MRF sandwich beams. It was determined that the natural frequencies shifted to higher frequencies and the loss factor of the MRF sandwich beams increased with increase in the magnitude of magnetic field. Kolekar and Venkatesh [17] determined the dynamic behavior of MRF sandwich beam under different-localized magnetic fields. It was concluded that there is a shift in the natural frequency and decrease in vibration amplitude, while there is a decrease in loss factor. Allien et al. [18,19] fabricated MRF sandwich beams with face layers having different percentages of Silicon carbide (SiC) reinforced aluminum metal matrix composites (MMC). It was found that at 600 Gauss magnetic field, 20% SiC reinforced aluminum MMC MRF sandwich beam yielded maximum reduction in vibration response. Allien et al. [20,21] prepared different thickness of polymer matrix composite (PMC) as face layer for MRF sandwich beams and determined their vibration suppression behavior. It was found that at 600 Gauss magnetic field, 2 mm thick MRF core enclosed between 2 mm thick top and bottom face layers of PMC resulted in maximum percentage reduction in vibration amplitude. Srinivasa et al. [22] performed free and forced vibration experiments of fully filled MRF sandwich beams of different core thicknesses of 2, 4, and 6 mm and concluded that 2 mm core MRF sandwich beam yielded highest damping ratio and vibration suppression. Further, free and forced vibration studies of partially filled MRF sandwich beams of different core lengths were performed. Based on the literature review, it is evident that the MRF sandwich beams can be successfully used in the control of beam vibrations.

The effect of constituents of MRF such as particle size, weight fraction of carbonyl iron powder (CIP), base oil viscosity, additives on the performance of MR devices were investigated, such as MR dampers [23,24] MR brakes [25], MR rotary brakes [26] and the optimal composition of MRF which yielded best performance for those MR devices were determined. Romaszko et al. [27] determined the vibration characteristics of MR beam filled with two types of commercial MRFS and concluded that weight fraction of iron particles in the fluid has a major effect on the natural frequency and damping coefficient of the beam. However, magnetic field was applied by means of electromagnet for small portion of the beam and variation in vibration parameters with change in location of electromagnet was studied. The study on the vibration behavior of MRF sandwich beams involving prepared MRFs having different proportions of iron particle weight fractions and particle sizes are scarce in literature. In this work, the effect of particle size and weight fraction of iron powder in the MRF on the vibration behavior of MRF sandwich beams were studied. Six different MRFs having combination of two different particle size and three weight fractions of CIP were used to fabricate different MRF sandwich beams. The free vibration tests of MRF sandwich beams at different magnetic fields were performed to compare their natural frequencies and damping ratio. Further, sinusoidal sweep excitation tests were performed on these beams to determine the reduction in the amplitude of vibration for MRFs with different particle weight fractions, particle sizes at different magnetic fields. Finally, optimal CIP particle size and its weight fraction in MRF was determined using multi-objective genetic algorithm (MOGA)
optimization method based on maximization of damping ratio and minimization of weight of MRF as objectives.

2. Characterization of carbonyl iron powder

The viscoelastic properties of MRF depend on the magnetic properties of iron particles, their size and distribution. CIP of different sizes were used as dispersed phase for the preparation of MRF and they are products of BASF (CN grade) and Sigma Aldrich (C3518).

The particle size distribution of different powders were obtained using Cilas 1064 Particle Size Analyzer which has particle size measuring range from 0.04 to 500 microns. (Figures 1(a,b)) shows the volume basis particle size distribution of smaller and larger sized CIP denoted as SCIP and LCIP, respectively. The nomenclature is based on the mean particle diameter of the powders. Mean diameter of SCIP and LCIP were found to be 2.9 microns and 9.68 microns, respectively.

(Figures 2(a,b)) depicts the scanning electron microscope images of SCIP and LCIP obtained using Field Emission Scanning Electron Microscope at a magnification of 25,000 X (FESEM, Make: ZEISS SIGMA). Both the SCIP and LCIP have particles of nearly spherical shape.

![Figure 1. Particle size distribution of (a) SCIP and (b) LCIP.](image1)

![Figure 2. FESEM images of (a) SCIP and (b) LCIP.](image2)
Vibrating Sample Magnetometer (Lakeshore Model 7410) was used to obtain the magnetization curves of the SCIP and LCIP and are shown in (Figure 3). The testing was performed on 20 mg of samples at a temperature of 25°C. 151 data points were acquired from 15,000 Gauss to −15,000 Gauss with a field increment of 500 Gauss.

The saturation magnetization of SCIP and LCIP are 184.2 emu/g and 224.6 emu/g, respectively. LCIP has higher saturation magnetization compared to SCIP which means the LCIP get magnetized up to higher magnetic field than SCIP which is beneficial for MR effect. The coercivity and retentivity of SCIP are 0.59 Gauss and 0.045 emu/g, respectively, while those for LCIP are 18.8 Gauss and 0.84 emu/g, respectively. The coercivity and retentivity of SCIP are lower than those of LCIP which are essential magnetic properties for an MRF [28].

3. Preparation of MRFs

Six MRFs were prepared composed of SCIP (2.9 microns) and LCIP (9.68 microns) and having three different particle weight fractions namely 60, 70, and 80%. Polyalphaolefin (PAO) oil (Exxon Mobil) was used as the carrier fluid. It has 32 cSt kinematic viscosity (@ 40°C) and specific gravity of 0.824.

![Figure 3. Magnetization curves of SCIP and LCIP.](image)

| Sl. No. | MRF sample | SCIP Weight fraction (%) | PAO oil Weight fraction (%) |
|--------|------------|--------------------------|----------------------------|
| 1.     | MF60L      | 60                       | 40                         |
| 2.     | MF60S      | 60                       | 40                         |
| 3.     | MF70L      | 70                       | 30                         |
| 4.     | MF70S      | 70                       | 30                         |
| 5.     | MF80L      | 80                       | 20                         |
| 6.     | MF80S      | 80                       | 20                         |
Initially, electronic weighing balance was used to weigh desired weight of PAO oil and CIP. Using a mechanical stirrer, CIP was mixed in PAO oil at 500 rpm for 8 h to properly mix the powder in the oil. The constituents of the prepared MRFs is listed in Table 1. The prepared MRFs are named on the basis of particle weight fraction and particle size. MF60L and MF60S are composed of 60% weight fraction of LCIP and SCIP, respectively.

4. Viscoelastic properties of MRFs

The viscoelastic properties are measures of the material’s ability to store and dissipate energy. The MRF exhibits viscoelastic nature within the pre-yield region under external magnetic field [29]. The storage modulus is a measure of the elastic property and the loss modulus is a measure of the viscous property of MRF. These two quantities are combined and expressed as complex shear modulus. The viscoelastic properties of the six MRFs and MRF 132DG were measured by performing oscillatory rheology tests using Modular Compact Parallel Plate Rheometer (MCR-702 Anton Paar) as shown in (Figure 4).

The Rheometer is connected to RheoCompass software through which the user can specify the test conditions and store the acquired data. A magnetorheological device (MRD) cell is DC power supply device, which is used to provide required magnetic field on the MRF sample poured on the stationary plate of Rheometer. During the tests, a small amount of MRF was poured on the bottom stationary parallel plate, the gap between 20 mm parallel plates was set to 1 mm and temperature was set to 25°C. Prior to measuring the viscoelastic properties, the MRF was pre-sheared at shear rate of 10 s\(^{-1}\) for 10 seconds followed by 5 seconds waiting time to ensure uniform distribution of iron powder in the sample. The tests were performed at strain amplitude of 0.1% and frequency logarithmically increasing from 0.1 Hz to 100 Hz [30]. Strain amplitude was chosen as 0.1% (0.001) to ensure that the MRF operates in pre-yield regime [29].

![Figure 4. Rheometer (Courtesy: Central Research Facility, NITK Surathkal).](image-url)
storage, loss and complex moduli were measured at 16 distinct frequency values. The viscoelastic properties were measured in the absence of current (Off-state condition), that is, 0 A (0 Gauss) and with the application of currents (On-state condition), namely 0.38 A and 0.75 A which produce magnetic fields of 745 Gauss and 1,475 Gauss, respectively.

The variation of storage modulus with frequency for prepared and MRF 132DG fluids at 0 Gauss, 745 Gauss and 1475 Gauss are shown in (Figures 5(a-c)), respectively. The variations of loss modulus with frequency for different MRFs at 0, 745, and 1475 Gauss are shown in (Figures 5(d-f)) respectively. The variation of complex shear modulus with frequency for different MRFs at 0 Gauss, 745 Gauss and 1475 Gauss are shown in (Figures 5 (g-i)) respectively. It can be seen that in off-state condition (0A), the storage, loss and complex shear moduli increase with frequency. The loss modulus is considerably higher than storage modulus in the off-state condition indicating that the MRF has more viscous behavior than elastic one. An opposite behavior is observed in the on-state condition, as MRF changes to semi-solid which in turn increases the storage modulus more compared to the loss modulus. Viscoelastic properties increase with weight fraction of CIP in MRF in both on-state and off-state conditions. Also, MRFs having LCIP have higher viscoelastic properties compared to those containing SCIP due to higher saturation magnetization of LCIP. The viscoelastic properties are enhanced when magnetic field is applied [29,31,32]. In the off-state condition, the viscoelastic properties of MRF 132DG fluid are lower than MF80S and MF80L among the prepared MRFs. Though, these MRFs have same weight fractions of iron powder, MRF 132DG fluid has a very low apparent viscosity of 0.114 Pa-s at 40°C (LORD Corporation Technical Data Sheet, 2003) [33]. MRF 132DG fluid has 80.98 weight percentage of magnetic particle phase in the MRF. Nevertheless, the viscoelastic properties of MRF 132DG fluid in the on-state condition are higher compared to those of the prepared MRFs which indicates that it is more responsive to the magnetic field.

5. Geometry of MRF sandwich beam

MRF sandwich cantilever beam having dimensions shown in (Figure 6(a)) was used in this study. Aluminum was used as beam material, as it has a relative permeability equal to one and has no effect on the response of the beam when subjected to magnetic field. The aluminum beam is 260 mm long, 25 mm wide and 6 mm thick. MRF layer of 2 mm was chosen based on the study performed by Srinivasa et al. [22]. Using wire electro discharge machining (EDM), central cavity of 2 mm height and length of 220 mm was created in solid aluminum material, leaving 2 mm each top and bottom face layers of aluminum material.

Seven aluminum beams with cavity for filling MRF were manufactured using wire EDM machining. The periphery of cavity was sealed with silicone sealant to avoid MRF leaks. A small portion (hole) was not sealed at each end of the beam so as to fill the MRF. The MRF was poured into the cavity through one of the holes while the beam is held vertical. The other hole helps in pushing out the trapped air present in the cavity of the beam when MRF is poured. After filling the beam with MRF, the small holes were properly sealed with silicone sealant. (Figure 6 (b)) shows six beams filled with prepared MRFs and one beam filled with MRF 132DG fluid. The MRF sandwich beams are named as MRB60S, MRB70S, MRB80S, MRB60L, MRB70L, and MRB80L based on the weight fraction of iron
Figure 5. (a)-(c) Storage modulus of MRFs, (d)-(f) Loss modulus of MRFs, (g)-(i) Complex shear modulus of MRFs.
powder and particle size in the MRF. The beam filled with MRF 132DG is named as MRB 132DG.

6. Modal parameters of the MRF sandwich beams

Free vibration tests of MRF beams at different magnetic fields were performed as per ASTM E756-05 standards [34] using the set up shown in (Figure 7). It consists of stainless steel rigid base with provisions to hold the beam and the permanent magnet fixtures. Beam fixture is used for mounting the beams whereas permanent magnet fixtures are used to mount the permanent magnets. The permanent magnet fixtures are screwed to a vertical plate and can be moved to vary the distance between the permanent magnets so as to obtain desired magnetic field induced on the beam. Miniature accelerometer
(Make: Kistler) was used to acquire acceleration signals and sent to LabVIEW software through NI 9234 data acquisition device (DAQ, Make: National Instruments). An instrumented impact hammer (Make: Kistler) was utilized to apply impact excitation to the beam.

One end of the MRF beam was fixed to the fixture such that 38 mm of the beam was fixed and remaining beam length containing MRF was free and could be exposed to magnetic field. The distance between the permanent magnets which are mounted the top and bottom fixtures was adjusted such that it produced a desired of magnetic fields of 250 Gauss, 500 Gauss and 750 Gauss. The beam was given impact excitation to the beam at 20 mm from its clamped end and acceleration signals were acquired using accelerometer mounted 25 mm from the beam’s free end. This procedure was repeated for different magnetic fields by varying the distance between the permanent magnets and also for all different fabricated MRF beams.

Free vibration tests using instrumented Impact hammer were performed on the MRF sandwich beams to determine the first three natural frequencies and their corresponding damping ratios. The first three natural frequencies of the beams were identified from peaks in the free vibration test results. Using half power bandwidth technique, the damping ratio at the first three natural frequencies of the beam were calculated [12,35]. In this method, the peak amplitude at a particular natural frequency ($\omega_n$) is noted. The peak amplitude is divided by $\sqrt{2}$ and the frequencies ($\omega_1$, $\omega_2$) at this amplitude are identified. The ratio of the difference between these frequencies to the twice the natural frequency is termed as damping ratio and is given by Equation (1).

$$\zeta = \frac{\omega_2 - \omega_1}{2\omega_n}$$

(Figures 8-10) show the variation of first three natural frequencies and damping ratios of beams filled with prepared MRFs and MRF 132DG. Damping ratio increases with increase
in applied magnetic field. Also, there is upward shift in the natural frequency with increase in magnetic field and is higher at second and third natural frequencies compared to that at first natural frequency. This is attributed to the increase in storage modulus with increase in magnetic field and subsequently the stiffness of the beam [15,31]. Natural frequencies of MRFs with higher weight fractions of CIP are lower especially at higher modes. This is due to the increase in mass of the beam with increase in weight fractions which would reduce the frequency. Further, with increase in weight fraction of CIP, there is significant increase in damping ratio due to more iron particles which cause higher MR effect. Damping ratio of beams with LCIP MRFs are higher compared to those with SCIP at all magnetic fields due to higher saturation magnetization of LCIP and subsequent higher complex shear modulus compared to SCIP MRFs. In the absence of magnetic field, beam with MRF 132DG fluid core has lower damping ratio compared to MF80S and MF80L MRFs, which is due to its lower loss modulus and complex shear modulus compared to them. However, with increase in applied magnetic field, the damping ratio increases at a higher rate compared to beams with MF80S and MF80L MRF cores and is higher than them at magnetic fields of 500 Gauss and 750 Gauss. Hence, beam with MRF 132DG fluid core
showed superior damping properties compared to all the fabricated MRF sandwich beams especially at higher magnetic fields.

7. Forced vibration response

(Figure 11) shows the experimental setup for performing forced vibration testing of MRF sandwich beams which consists of function generator (Make: Tektronix, AG 1022), power amplifier (Make: Saraswati Dynamics), electrodynamic shaker (Make: Saraswati Dynamics), data acquisition device (NI 9234, Make: National Instruments), accelerometer (Make: Kistler), load cell (Make: Kistler), structure for mounting the permanent magnets and stinger with fixture for holding the beam. A Labview program was interfaced with function generator and sensors by means of DAQ. The beam was subjected to sinusoidal sweep excitation from a start frequency to end frequency for desired duration of time. The start and end frequency, time duration for sweep excitation and number of iterations can be varied in the Labview program. The start and end frequencies were set to 1 Hz and
600 Hz, time duration as 20 seconds and the sweep excitation was repeated four times and average value was plotted. Based on input received from Labview program, the function generator produces sinusoidal excitation frequency ranging from 1 Hz to 600 Hz and sends it to amplifier. The amplifier output gain was set to 5% and it amplifies the voltage and sends it to electrodynamic shaker. This causes excitation of the beam which is held in the fixture mounted on a rod. Bottom end of the stinger rod is screwed tightly to the shaker while the other end holds the beam fixture. A load cell is screwed to the stinger rod near the fixture end. The load cell located in the stinger rod measures the input force acting on the beam while the accelerometer mounted on the beam acquires acceleration data and sends them to Labview program through DAQ device. The permanent magnets are moved away or toward each other equidistant from the beam to produce desirable magnetic field over the entire beam length. The frequency response function is obtained, which is the ratio of acceleration response (output) and the force (input), as a function of frequency.

The frequency response function for sandwich beams containing MF80S, MF80L and MRF 132 DG as core at different magnetic fields are depicted in (Figures 12(a-c)) respectively. It can be observed that there is significant reduction in vibration amplitude response of the beams at natural frequencies with increase in magnetic fields due to increase in damping ratio especially at first natural frequencies. Also, MRF beam

![Figure 12](image_url)

Figure 12. Frequency response functions of MRF Sandwich beams at different magnetic fields (a) MRB80S and (b) MRB80L and (c) MRB 132 DG.
consisting of LCIP (MRB80L) has higher vibration suppression capability compared to beam having SCIP (MRB80S) and this behavior is observed for other weight fractions too. This could be explained by their higher complex shear modulus obtained in oscillatory tests and also higher damping ratio as obtained from free vibration tests. However, the reduction in peak amplitude is lesser for sandwich beams with MRF having lower weight fractions of CIP as they possess lower damping ratio. MRF sandwich beam composed of MRF 132DG (MRB 132DG) produced highest speed reduction compared to all other beams due to their superior viscoelastic properties and damping ratio.

(Figure 13) shows the percentage amplitude reduction at the first natural frequency for the sandwich beams containing prepared MRFs and MRF 132 DG fluid as core at different magnetic fields. It can be observed that at 250 Gauss, 500 Gauss and 750 Gauss, the MRB80L sandwich beam yielded highest percentage peak amplitude reduction of 8.2, 18.2, and 26.6%, respectively, compared to all fabricated beams. This is attributed to its superior viscoelastic properties and highest damping ratios among fabricated beams containing prepared MRFs. Further, the sandwich beam consisting of MRF 132DG fluid has highest vibration suppression of 12.9, 22.8, and 30.3% at 250, 500, and 750 Gauss, respectively. Hence, the forced vibration analyses reveals the vibration control capability of sandwich beams with MRF core by application of appropriate magnetic field. In this study, permanent magnets were used to apply magnetic field. In real time application, electromagnets must be used and using suitable control strategy, the current supplied to the electromagnet should be varied to produce desired magnetic field on the beam. This in turn would alter the dynamic behavior of beam when it is subjected to excitation.

8.0 Selection of optimal particle size and weight fraction of CIP in MRF

The damping ratio for a sandwich beam should be high to achieve higher vibration suppression. Damping ratio is higher for higher weight fraction of CIP in MRF and vice versa. However, higher weight fraction of CIP results in higher weight of MRF and that of the sandwich beam. This also reduces the natural frequency of the beam especially in the higher modes. This conflicting criteria was solved using MOGA optimization technique. Maximization of damping ratio and minimization of weight of the MRF in the sandwich beam were specified as objectives of optimization to determine optimum particle size and weight fraction. The orthogonal array L6 (2 × 3) was used for conducting the experiments to analyze the effects on damping force and off-state viscosity of MRF and to determine the optimal particle size and weight fraction of iron powder.

Regression analysis were performed using MATLAB™ software to determine the relation between independent and response factors. The results of the damping ratios determined in accordance with L6 (2 × 3) orthogonal array and the weight of different prepared MRFs are tabulated in Table 2. Damping ratio (corresponding to 750 Gauss) and weight of MRF are considered as the response factors while particle size (S_p) and particle weight fraction (WF_p) are the independent parameters. The regression model for damping ratio (ζ) is given by Equation (2) and has R-square, adjusted R-square and root mean square error values of 0.9986, 0.993 and 0.001198, respectively.
\[
\zeta = -0.1119 + 0.002446 \times S_p + 0.003382 \times WF_p - 1.763e-5 \times S_p \times WF_p \\
- 1.258e-5 \times WF_p \times WF_p (2)
\]

The regression model for weight of MRF (W) is given by Equation (3) and has R-square, adjusted R-square and root mean square error values of 1, 1 and 2.487e-14, respectively.

\[
W = 9.064 - 2.502e-15 \times S_p + 0.3214 \times WF_p - 0.003245 \times S_p \times WF_p \\
+ 1.077e-16 \times WF_p \times WF_p (3)
\]

Pareto front solutions obtained from MOGA optimization using MATLAB™ software which satisfies the objectives of optimization is shown in (Figure 14). A set of solutions are obtained depending on more weightage given to each of the response factors. The selection of optimal result depends on higher weightage given to the magnitude of damping ratio. Also, the weight of MRF should be preferably lower. Pareto front solution with particle size of 9.65 microns and 74.92% particle weight fraction was selected as it yields damping ratio of 0.0817 and weight of MRF as 30.79 g.

9. Conclusions

Initially, shape, particle size distribution and magnetic properties of iron powders were determined. Combination of two iron particle sizes and three weight fractions of iron powder were used to prepare six MRFs. The viscoelastic properties of the prepared MRFs and MRF 132DG fluid were determined using oscillatory tests performed by means of a Rheometer. Seven MRF sandwich beams were fabricated filled with six prepared MRFs and MRF 132 DG fluid. Impact hammer tests of MRF sandwich beams were performed at different magnetic fields to evaluate the natural frequencies and damping ratio of the
canti-lever MRF sandwich beams. Further, response of the MRF sandwich beams under sinusoidal sweep excitations were also measured to investigate their vibration suppression capability. Following were the conclusions drawn from this study.

- The viscoelastic properties increase with increase in weight fraction of CIP in MRF, both in the presence and absence of magnetic field. Also, viscoelastic properties of MRFs having larger sized CIP (9.68 microns) are higher compared to those containing smaller sized CIP (2.9 microns) due to the higher saturation magnetization of LCIP compared to SCIP.
- The shift in the natural frequency with applied magnetic field is insignificant at first natural frequency. However, at second and third modes, the shift in frequency with magnetic field is significant for MRF sandwich beams with higher weight fraction of CIP. The shift in natural frequency is due to increase in storage modulus of MRF with magnetic field.
- There is a significant increase in damping ratio with increase in weight fraction of CIP compared to particle size in MRF.
- The damping ratio of beams with LCIP are higher compared to those with SCIP at all magnetic fields due to higher loss modulus and complex shear modulus of LCIP which is evident from oscillatory rheology tests.

| Sl. No. | MRF Sample | Damping ratio | Weight of MRF (grams) |
|---------|------------|---------------|-----------------------|
| 1       | MF60L      | 0.0588        | 26.46                 |
| 2       | MF60S      | 0.0501        | 27.78                 |
| 3       | MF70L      | 0.0756        | 29.36                 |
| 4       | MF70S      | 0.0660        | 30.90                 |
| 5       | MF80L      | 0.0878        | 32.26                 |
| 6       | MF80S      | 0.0815        | 34.02                 |

Figure 14. Optimal solutions from Pareto front.
• There is a significant reduction in forced vibration amplitude of the beams at the natural frequencies with increase in magnetic fields due to increase in damping ratio. Beams with higher weight fractions resulted in higher reduction in peak amplitude due to higher damping ratio, loss modulus, and complex shear modulus.
• Amongst the MRF sandwich beams composed of prepared MRF, beam with 80% weight fraction of LCIP in MRF yielded highest damping ratio and vibration suppression. At first natural frequency, for an applied magnetic field of 750 Gauss, the percentage reduction in the peak amplitude of 26.6% was observed.
• Sandwich beam with MRF 132DG fluid core showed superior damping properties and vibration suppression capability compared to all fabricated MRF core sandwich beams. At first natural frequency for an applied magnetic field of 750 Gauss, it yielded highest percentage reduction in the peak amplitude of 30.3%.
• MOGA optimization was used to obtain optimal particle weight fraction and particle size in MRF which maximizes damping ratio and minimizes weight of MRF. MRF with particle size of 9.65 microns and 74.92% particle weight fraction was selected as it produced damping ratio of 0.0817 and MRF weight of 30.79 g. This method would be predominantly useful for optimal selection of constituents of MRF for MRF sandwich beam considering different combinations of magnetic particles, carrier fluid, additives and their weight fractions.
• This controllability of stiffness and damping properties and hence the dynamic behavior of sandwich beams has prospective vibration control applications in aircraft and automobile structures.

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Disclosure statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

[1] Jacob R (1951) Magnetic fluid torque and force transmitting device. United States Patent 2,575,360, Nov.
[2] Muhammad A, Yao X, Deng Z. Review of magnetorheological (MR) fluids and its applications in vibration control. J Marine Sci Appl. 2006;5(3):17–29.
[3] Klingenberg DJ. Magnetorheology: applications and challenges. AIChE J. 2001;47(2):246–249.
[4] Wang J, Meng G. Magnetorheological fluid devices: principles, characteristics and applications in mechanical engineering. Proc Inst Mech Eng Part L. 2001;215(3):165–174.
[5] Leng J. Magnetorheology: advances and applications. In: Wereley NM, editor. International journal of smart and nano materials. Taylor & Francis, UK. Vol. 5, 1; 2014. p. 33.
[6] Spaggiari A, Castagnetti D, Golinelli N, et al. Smart materials: properties, design and mechatronic applications. Proc Inst Mech Eng L J Mat Des Appl. 2019;233(4):734–762.
[7] Ahamed R, Choi SB, Ferdaus MM. A state of art on magneto rheological materials and their potential applications. J Intell Mater Syst Struct. 2018;29(10):2051–2095.
[8] Kolekar S, Venkatesh K, Oh JS, et al. Vibration Controllability of sandwich structures with smart materials of electrorheological fluids and Magnetorheological materials: a review. J Vibration Eng Technol. 2019;7(4):359–377.
[9] Weiss KD, Carlson JD, Nixon DA. Viscoelastic properties of magneto-and electro-rheological fluids. J Intell Mater Syst Struct. 1994;5(6):772–775.
[10] Sun Q, Zhou JX, Zhang L. An adaptive beam model and dynamic characteristics of magnetorheological materials. J Sound Vib. 2003;261(3):465–481.
[11] Yalcintas M, Dai H. Magnetorheological and electrorheological materials in adaptive structures and their performance comparison. Smart Mater Struct. 1999;8(5):560.
[12] Yalcintas M, Dai H. Vibration suppression capabilities of magnetorheological materials based adaptive structures. Smart Mater Struct. 2003;13(1):1–11.
[13] Lara-Prieto V, Parkin R, Jackson M, et al. Vibration characteristics of MR cantilever sandwich beams: experimental study. Smart Mater Struct. 2009;19:1–9.
[14] Hu B, Wang D, Xia P, et al. Investigation on the vibration characteristics of a sandwich beam with smart composites-MRF. World J Modell Simul. 2006;2:201–206.
[15] Fadaee M. A new reformulation of vibration suppression equations of functionally graded magnetorheological fluid sandwich beam. Appl Math Modell. 2019;74:469–482.
[16] Rajamohan V, Sedaghati R, Rakheja S. Vibration analysis of a multi-layer beam containing magnetorheological fluid. Smart Mater Struct. 2009;19:1–12.
[17] Kolekar S, Venkatesh K. Experimental investigation of damping effect in semi-active Magnetorheological fluid sandwich beam under non-homogeneous magnetic field. J Vibration Eng Technol. 2019;7(2):107–116.
[18] Allien VJ, Kumar H, Desai V. Dynamic analysis and optimization of sic reinforced Al6082 and Al7075 MMCs. Mater Res Express. 2019;6(5):1–20.
[19] Allien VJ, Kumar H, Desai V. Semi-active vibration control of SiC reinforced Al6082 MMC sandwich beam with magnetorheological fluid core. Proc Inst Mech Eng L J Mat Des Appl. 2019;234:408–424.
[20] Allien V, Kumar H, Desai V. An investigation on characteristics and free vibration analysis of laminated chopped glass fiber reinforced polyester resin composite. ARPN J Eng Appl Sci. 2016;11:1016–11022.
[21] Allien VJ, Kumar H, Desai V. Semi-active vibration control of MRF core PMC cantilever sandwich beams: experimental study. Proc Inst Mech Eng L J Mat Des Appl. 2020;234(4):574–585.
[22] Srinivasa N, Gurubasavaraju TM, Kumar H. Vibration analysis of fully and partially filled sandwiched cantilever beam with Magnetorheological fluid. J Eng Sci Technol. 2020;15(5):3162–3177.
[23] Gurubasavaraju TM, Kumar H, Arun M. Evaluation of optimal parameters of MR fluids for damper application using particle swarm and response surface optimisation. J Braz Soc Mech Sci Eng. 2017;39(9):3683–3694.
[24] Acharya S, Saini TRS, Kumar H. Determination of optimal magnetorheological fluid particle loading and size for shear mode monotube damper. J Braz Soc Mech Sci Eng. 2019;41(10):392.
[25] Nguyen HQ, Choi SB, Hiep LD, et al. Material characterization of MR fluid on performance of mrf based brake. Front Mater. 2019;6:125.
[26] Gudmundsson KH, Jonsdottir F, Thorsteinsson F, et al. An experimental investigation of unimodal and bimodal magnetorheological fluids with an application in prosthetic devices. J Intell Mater Syst Struct. 2011;22(6):539–549.

[27] Romaszko M, Pakuła S, Sapiński B, et al. Vibration parameters of sandwich beams with two types of MR fluid. Mech Control. 2011;30:151–156.

[28] Genc S, Phulé PP. Rheological properties of magnetorheological fluids. Smart Mater Struct. 2002;11(1):140.

[29] Li WH, Chen G, Yeo SH. Viscoelastic properties of MR fluids. Smart Mater Struct. 1999;8(4):460.

[30] Hemmatian M, Sedaghati R, Rakheja S. Linear and nonlinear viscoelastic behavior of MR fluids: effect of temperature. Smart Mater Adaptive Struct Intell Syst. 2018. DOI:10.1115/SMASIS2018-8033

[31] Chooi WW, Oyadiji SO. Characterizing the effect of temperature and magnetic field strengths on the complex shear modulus properties of magnetorheological (MR) fluids. Int J Modern Phys B. 2005;19:1318–1324.

[32] Hemmatian M, Sedaghati R, Rakheja S. Temperature dependency of magnetorheological fluids’ properties under varying strain amplitude and rate. J Magn Magn Mater. 2020;498:166109.

[33] Lord Corporation (2003). MRF 132DG Technical data sheet. Cary, North Carolina, United States. http://www.lordmrstore.com/_literature_231215/Data_Sheet_-_MRF-132DG_MagnetoRheologicalFluid. (accessed 2020 08 12).

[34] ASTM E756-05. Standard test method for measuring vibration-damping properties of materials. United States: ASTM International; 2015.

[35] Eshaghi M, Rakheja S, Sedaghati R. An accurate technique for pre-yield characterization of MR fluids. Smart Mater Struct. 2015;24(6):065018.