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Synthesis and Experimental Investigation of Magneto-rheological (MR) Fluid for Damper

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Abstract. Magneto-rheological (MR) fluids have been an attractive field of study since the invention of the smart fluid. This paper presents the characterization and development of MR fluid prepared by immersing ferromagnetic elements in carrier oil. Micron-sized atomized iron and carbonyl iron surfaces are coated with guar and xanthan gum to counter issues with sedimentation, cluster formation, and cake formation of the MR fluid (MRF). A variety of MR fluid mixtures are organized by means of amalgamation of base fluids (Paraffin oil and silicone oil), ferromagnetic particles, and additives. The morphology of carbonyl iron has a flake-like structure and atomized iron dust forms a smooth granular configuration. MR fluid comprising Xanthan gum coated iron particles demonstrated enhancement in sedimentation. Additionally, by providing power, the magnetism of the magnetic piston is investigated, and discovered that magnetic flux density rises with the applied current in Ampere. The sedimentation results demonstrate that MR Fluid-4 and MR Fluid-3 enhanced the sedimentation rate substantially more than the others. Paraffin oil-based MR (MR Fluid- 4) presented better viscosity than any other fluids. The fluid's high viscosity property contributes to increasing the resisting force of the MR damper system. Lastly, the performance of the MR damper is investigated by applying currents of 1A and 1.5A at various excitation velocities. MR damper enhances dampening force by 15% and decreases overall vibration acceleration by 30% when operating at 1.5A current.

Keywords—Damper, Magneto-rheological (MR) fluid, Shear stress, Sedimentation, Synthesis.

INTRODUCTION

An intelligent fluid known as a magneto-rheological (MR) fluid instantly modifies its rheological characteristics when subjected to an external magnetic field. This reversible, regulated transition occurs rapidly with minimal energy input. Ferromagnetic particles smaller than a micron are dispersed at random in the carrier oil. [1,2].

Ferromagnetic particles, carrier fluids, additives are the three basic components of MR solution. Carbonyl iron concentrate with a high magnetic permeability and saturation magnetization are frequently utilized for mixing in oil. As the base (carrier) fluid, low viscosity lubricants like mineral, silicone, and synthetic oils are used. Surfactants are frequently used as additives to reduce the aggregation of ferromagnetic ingredients or to slow down the rate at

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which they settle [3]. Due to the particle's high density and tendency to settle or silt, the use of additives is an important consideration that, if ignored, could cause the device to become unusable. When a magnetic field is provided, the particles line together in a pattern to form chain links, and the MR fluid acts like a viscoelastic solid.. Lacking magnetism, the fluid functions exactly like regular hydraulic fluid. This aligned chain-like structure offers great resistance to the oil layer thus increasing the viscosity within a short time. Such fluids have received increasing interest recently for applications like suspension systems, brakes, and clutches [3].

The MR damper has a significant amount of potential for semi-actively controlled variable damping with little power. Figure 1(a) shows the magnetic piston developed for the MR damper (Magneto-rheological damper) and Figure 1(b) shows the assembly of the retrofit MR damper. Only the damper part is replaced in a conventional shock absorber.

(a) (b)

FIGURE 1. (a) Magnetic Piston (b) Assembled MR Damper

In this article, four different MR fluids are developed by using different material combinations. With the help of a literature review, magnetic particles, coating gums, and carrier fluids are identified. The presented MR fluids are visually investigated for sedimentation analysis in the sedimentation analysis section. Composition of MR fluid is discussed in a methodology section. In the results and discussions, the change in viscosity of all fluids and its impact on damping force is evaluated. Finally concluding comments are drawn in the final section

LITERATURE REVIEW

The authors are motivated to employ their knowledge of magneto-rheological fluids, which Rabinow discovered in 1948, in a variety of applications [1]. A MR fluid with variable viscosity as a function of current can effectively replace a conventional viscosity-based hydraulic system. It responds quickly, consumes minimal electrical power, and offers controlled mechanical power output. [2]. Micro sized iron particles that aren't properly dissolved in the base fluid cause sedimentation problems and it is very important for the synthesis of MR fluid [3]. The particle structure in the presence of magnetic field provides shear stress to the MRF. When particle sizes increase, MRF shear stress rises. However, due to a problem with sedimentation, the use of larger sized particles is restricted. [4]. Natural gum is utilized as a surface coating to prevent the MR fluid from adhering, corroding, and sedimenting. Carrier fluids are blended with grease and other thixotropic additives. Iron particles settle down at the bottom when MR fluid is not in use for several days and additives will help in solving this [5]. A MR damper is a simple, semi-active device containing MR fluid and having the capacity to change damping force within milliseconds. It provides better ride comfort than conventional suspension systems [6]. Applications for MR dampers can be found in a variety of civil constructions, including buildings and bridges, as well as in vehicles and railway systems. According to displacement and frequency of vibrations, damping force can be generated by supplying required voltage [7]. The MR damper system is operated for all types of input excitations by controlling the current supplied to MR damper RD-8040-1 and can be used to design a seat suspension for fatigue-free rides [8]. To develop an organic oil blend, silicone oil is blended with environmentally safe natural organic oils like sunflower and cottonseed. Considering viscosity, the cottonseed oil blend-based MR fluid outperforms the sunflower-based fluid [9].

A unique electronically controlled power steering system that makes use of MR fluid was proposed by Park and Jung. They conducted trial investigation to prove the feasibility of the proposed system [10]. Umit Dogruer investigated an off-highway, high mobility vehicle's semi-active MR fluid damper. He built a quarter-car model with two degrees of freedom and employed variety of control algorithms to manage the MR fluid damper. The Bingham Plastic model is used to mimic the behaviour of the MR fluid, and a magnetic finite element analysis is used to determine the magnetic field circulation [11]. Lin et al. assessed the effectiveness of a retrofitted MR damper under dynamic loading conditions. Modified Bouc-model is developed to check functionality of the MR model. Moreover, they used an experimental structure with MR damper [12].

On a Stryker vehicle, authors tested the MR semi-active suspension system. An algorithm was used to test the full model, which included eight dampers and controls [13]. Nabaglo conducted both experimental and numerical research on MR damper control system with low energy requirements. The goal was to significantly lessen vertical acceleration in the presence of moments and forces operating on the vehicle under various riding circumstances [14]. The theoretical characterization of a lightweight MR damper is explored by Aydar et al. They discovered that the MR damper's controllability enables them to alter the damping necessary for various frequencies and lowers noise at resonance [15]. PID control algorithms are used to study the impact of road disruptions. Inputs from step and impulse road disturbances perform very well with PID controllers. It cannot, however, adapt as the circumstance does. A fuzzy-based PID controller produced better outcomes [16]. Skyhook, fuzzy logic, LQG, and sliding mode controllers are some of the controllers that can be implemented with MR dampers. Dong et al. claimed that the best suspension performance is provided by sliding mode-controlled MR dampers [17]. For variable displacement engines, an engine mount utilizing an MR damper is developed and offered the best control over vibration minimization [18]. By modulating the magnetic field, author demonstrated that MR dampers have good damping characteristics [19]. Artificial neural network MR damper models were investigated by the authors. They came to the conclusion that the proposed ANN could model MR dampers more effectively than existing parametric models. [20]. Fuzzy logic controller was tested in a car suspension system and proved that fuzzy logic controller offers appreciably superior ride comfort [21].

Avinash et al. compare the damper's performance by varying the fluid environment, namely, MR fluid damping, viscous damping, and air damping and reported that MR fluid dampers provide better-damping presentation [22]. When properly adjusted, the Skyhook algorithm outperforms the passive suspension in terms of ride comfort and vehicle handling by managing the MR damper with a range of current values [23]. Authors proved that the developed hybrid MR damper could absorb shocks in severe road conditions also [24–25]. An electromagnetic field study of the constructed damper was performed using the ANSYS programme, and it was found that a damping force of 6517 N was achieved at 1.5 A. It was validated experimentally and found that the maximum damping force reaches 6838N at a damping coefficient of 300 kN-s/m [26]. In the quarter car concept, the active seat suspension is modeled with the equivalent damping model and the Bingham model. Initially a bump input with varying degrees of road roughness is applied. The Equivalent Damping Model is found to perform better than the damper behaviour of the Bingham model in both circumstances, i.e., bump input and random road input [27]. Neural network based model method has an improved capacity to forecast the damper force for a more complex excitation [28]. H. Zambare et al. compared the analytical design of the passive suspension and semi-active suspension using the Bouc-Wen, Dahl, and Bingham hysteresis models. The observations show that the Bouc-Wen model is the most practical and suitable model for developing a semi-active suspension system. [29].

Authors have illustrated MR fluid properties or studied MR damper responses to excitation using software models. MR fluid developed by authors is not experimentally examined for developed MR damper. The selection criteria for the MR fluid in the MR damper of the suspension system are the subject of an experimental investigation in the current paper.

METHODOLOGY

Composition of MR Fluid

This chapter focuses on the process of developing trustworthy MR Fluid capable of working with MR damper. Magnetic material with high purity such as carbonyl iron powder and iron dust appears to be the main magnetic practical composition. Material composition and steps required for MR fluid preparation are shown in Figure

2. The enduring component of MR fluid is made up of the base (carrier) liquid, which could consist of silicone oils, mineral oils, or paraffin oils.

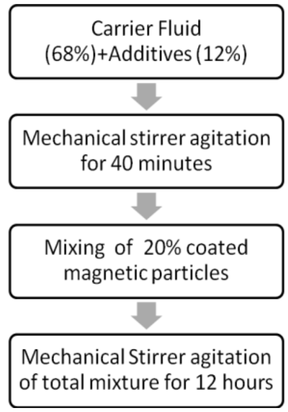


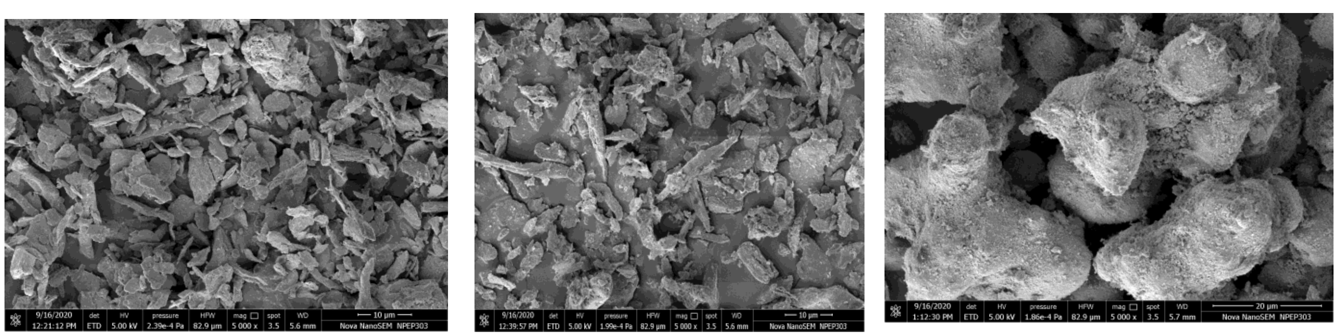
FIGURE 2. Structural outline for preparation ofMR Fluid

For the fluid combinations stated in Table 1, carbonyl and atomized iron powder typically in the range of 0.1 to 10µm have been employed in the current study. Guar gum and xanthan gum powder are employed to coat the iron particle surfaces, enhancing the fluid's performance. The carbonyl iron is donated by Industrial Metal Powders India Pvt. Ltd. in India, and the atomized iron dust is donated by Höganäs AB in Sweden. According to Table 1, the density of atomized iron dust coated with guar gum is larger than that of samples 1 and 2. Sedimentation of fluid increases with an increase in density. Hence only carbonyl iron samples are used further for fluid combinations.

TABLE 1. Surface coating of ferromagnetic material

Sample No.	Magnetic particles with coating	Density (gm/cm^3)
Sample 1	Xanthan Gum coated Carbonyl Iron	1.48
Sample 2	Guar Gum coated Carbonyl Iron	1.40
Sample 3	Guar Gum coated Atomized Iron	2.82

Field Emission Scanning Electron Microscopy (FESEM), which is available at Savitribai Phule Pune University, is employed to observe the particle outlines and dimensions. Size and shape of all ferromagnetic constituents is observed at magnification of 5000x as shown in Figure 3. Particle dimensions of guar gum and xanthan coated carbonyl iron powder vary from 1 to 10 microns, whereas those of guar-coated atomized iron dust vary from 5 to 20 microns. Larger iron particles have stronger magnetic fields than smaller iron particles, but they have tendency to go down at the bottom of fluid resulting in sedimentation.



(a) (b) (c)

FIGURE 3. Microscopic images at 5000x of ferromagnetic particles (a) Sample 1, (b) Sample 2, (c) Sample 3

The spherical, guar gum coated atomized iron dust (Sample 3) have a smooth surface and a big size of 20 microns. With guar gum and xanthan coated carbonyl iron powder (Sample 1 and 2), a flakes-like structure can be seen and a particle size of fewer than 10 microns is obtained. Flake structure helps to increase the strength of the bond under a magnetic field which further leads to increased fluid viscosity. It is observed from the experiments that, Xanthan gum coating is more effective than guar gum coating in minimizing the sedimentation of MR fluid. Furthermore, three potential non-magnetic oils are specified, as listed in Table 2, including silicone oil, synthetic oil, and paraffin oil. The density of paraffin oil is more than the density of silicone and synthetic oil.

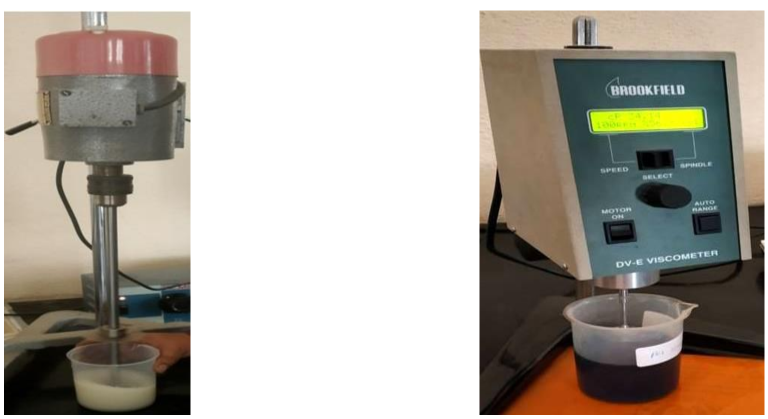
TABLE 2. Base fluid characteristics

Base fluid	Kinematic Viscosity (centistokes)	Density (gm/cm^3)
Silicone oil	11.2	0.771
Synthetic oil	36.2	0.794
Paraffin oil	171	0.823

TABLE 3. Combination of additive blends

Blended Base Fluid	Additives	Base fluid	Density (gm/cm^3)
Fluid A	Oleic acid+ Grease	Synthetic oil	0.822
Fluid B	Stearic acid+ Grease	Paraffin oil	0.871
Fluid C	Ethanol + Glycerine	Silicone oil	0.916

According to Figure 4 (a), base fluid and additives are properly combined using a mechanical stirrer. Figure 4 (b) illustrates how the Brookfield DV-E viscometer is used to determine the kinematic viscosity of these stirred fluids. All the ingredients are stirred for 12 hours to prepare the fluid, as shown in the flow structural diagram.



(a) **(b)**

FIGURE 4. (a) Mechanical Stirrer (b) DV-E Viscometer

To synthesize the MR fluid, quantities of paraffin, silicone, and synthetic oil are used as the base fluid. The kinematic viscosity of paraffin oil is the highest, measuring 171 cSt. These primary fluids are combined with additive mixtures, as shown in Table 3, to improve the rheological and sedimentation characteristics of MR fluid. Developed fluid mixtures are evaluated on a viscometer to see how shear stress increases as the shear rate changes. Figure 5 demonstrates that Fluid B has a higher shear stress level.It is observed that base fluid paraffin oil and synthetic oil perform better than the silicone oil mixed with glycerine and ethanol. Density of Fluid C is more but the required shear stress is less than the other two. Shear stress rises with fluid viscosity, which enhances the dampening properties of the damper, consequently Fluid A and Fluid B are chosen for MR Fluid experiments.

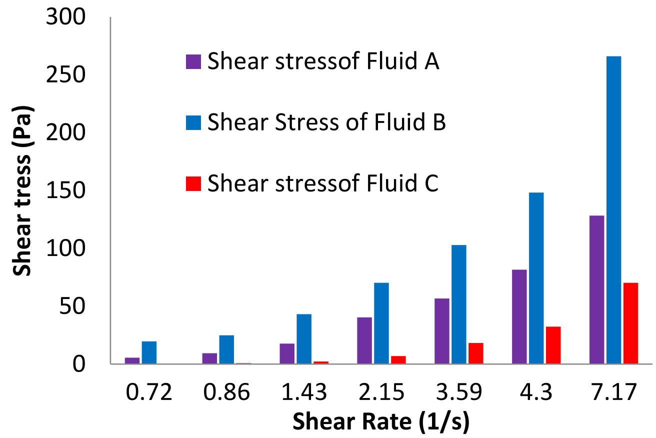


FIGURE 5. Shear stress Versus shear rate of blended base fluids

Synthesis and development of MR fluid

The essential components of fluid blended with additives are paraffin oil and synthetic oil. To develop MR fluid, guar and xanthan gum coated carbonyl iron are added to carrier fluid. Table 4 provides an overview of the four prepared MR fluid types. Since larger particles will ultimately settle down, the size of guar gum surface coated atomized iron dust, which ranges from 5 microns to 20 microns, is not taken into consideration. Fluids are uniformly prepared by stirring various MR fluid combinations at 900 rpm continuously for 12 hours.

TABLE 4. MR fluid types

MR Fluid	Blended Base Fluid with Additives	Magnetic particles
MR Fluid-1	Fluid A	Carbonyl Iron with Guar Gum coating
MR Fluid-2	Fluid A	Carbonyl Iron with Xanthan Gum coating
MR Fluid-3	Fluid B	Carbonyl Iron with Guar Gum coating
MR Fluid-4	Fluid B	Carbonyl Iron with Xanthan Gum coating

SEDIMENTATION ANALYSIS

Due to the difference in densities, the particles settle and leave relatively clear volume of carrier fluid behind. To measure the settling rate of iron particles, visual inspection is carried out to compare the heights of the dispersed phase (a) and the height of the settled phase (b) across different time frames. A illustrative experiment conducted for the sedimentation investigation is shown in Figure 6. Sedimentation ratio (SR) of settled particles is calculated with the help of Equation 1. Where value ‘a’ is dissolved phase and (a + b) represents total height of the MR fluid.

$$\% SR = \frac{a}{a+b} x\ 100 \qquad (1)$$

As shown in figure 6, a 50 ml cylinder had been filled with all the developed MR Fluids, and the mixture was let to stand for 120 hours. The volume of magnetic particles deposited at the bottom is depicted in Figure 6a.

FIGURE 6. (a) Sediment iron particles(b) Illustrativeimage of sedimentation

Figure 7 demonstrates how MRFluid-1 has a higher sedimentation ratio than other fluids. In MR Fluid-1, a synthetic oil-based fluid, iron particles settled quickly and reached 64%. In contrast to the other four fluids, the sedimentation ratio of carbonyl iron coated with xanthan gum powder in MR Fluid-4 slowed significantly. The elevated shear stress change caused by paraffin oil and grease (MR Fluid-4) and high density of Paraffin oil than Synthetic oil combination, particle settling speed of MR Fluid-4 is slower than Synthetic oil combination.

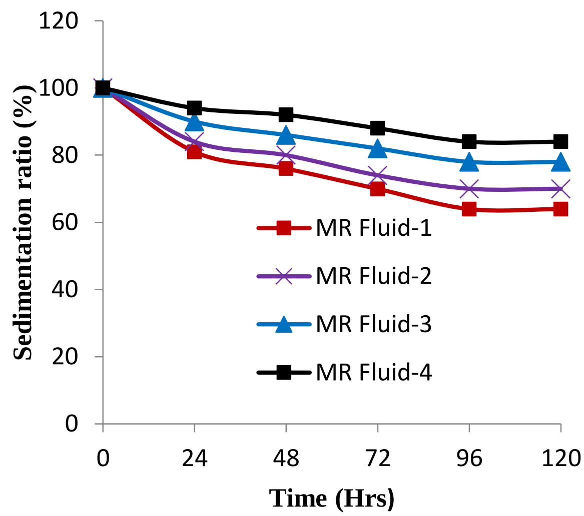


FIGURE 7. Sedimentation ratios of coated iron particles versus Time

MAGNETIC FLUX DENSITY OF ELECTROMAGNETIC PISTON

The magnetic field's flow is essential for an MR damper to perform well. The desired damping force of the MR damper is thus determined by the electromagnetic flux density of the magnetic piston. To improve the magnetic flux density and magnetic force of the MR damper, magnetic permeability is a crucial component. Equation 2 is used to compute the magnetic flux density. In the equation H is magnetic field intensity, "I" is current in Ampere, "*l" is* the length of the magnetic circuit on the piston, and "N" represents the number of turns. The length of copper wire winding on the magnetic piston is 26 mm and 320 numbers of turns are wound on the piston. The relative permeability of material is symbolized by "μ_r" which is 100 and permeability of free space is represented by "μ_0" which is $4\pi \times 10^{-7}$(Henries per meter).

Magnetic flux density $B = \mu_r x \mu_o x H$ (Tesla) (2)

Where,

$\mu = \mu_r \times \mu_0$

$$H = \frac{NI}{l}$$

It is viewed from the Fig.8 that the magnetic flux density increases with increase in current of magnetic coil. Magnetic flux density increases linearly up to 1.2 A current and saturation point occurs at 1.8 A. Hence MR fluid is activated from current 0.1 A to 2 A.

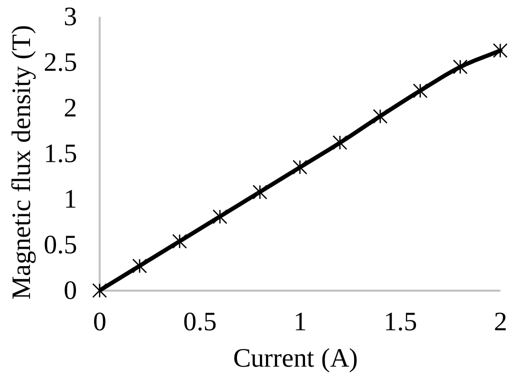


FIGURE 8. Magnetic flux density versus current

RESULTS AND DISCUSSION

Measurements of the rheological features of generated MR fluids are carried out by employing magnetism with the aid of current in the ampere. The rheology of MR fluids instantly changes from a free flowing low viscosity to high viscous liquid with controllable viscosity in centipoises when they are in close proximity to a magnetic field. Figure 9 demonstrates how fluids have high viscosity when a magnetic field is a present and low viscosity when one is not. The MR Fluid-4 with paraffin oil as the base oil and grease, stearic acid as additives mixed with xanthan gum coated carbonyl iron can create viscosity around 1800 centipoise, while viscosity of MR fluid-1 and MR fluid-2 with synthetic oil as base oil, mixed with additives grease, Oleic acid was limited to 1600 centipoise. After a value of 1.08 T magnetic flux density, MR Fluid-3 viscosity is lower than MR Fluid-4 but exhibits similar rheological characteristics. For MR damper testing, MR Fluid-4, which becomes highly viscous under magnetic fields, is added to the MR damper cylinder.

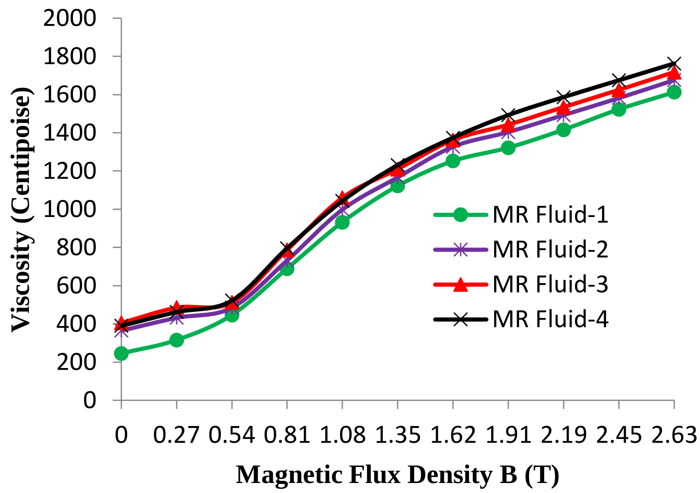


FIGURE 9. Viscosity versus Magnetic flux density for all four fluids

Magneto-rheological damper (MR damper) having an electromagnetic piston fitted in a cylinder filled with magneto-rheological (MR) fluid is used for testing the selected MR Fluid-4.MR damper is operated at current of 1.0A and 1.5A and compared with passive damper.

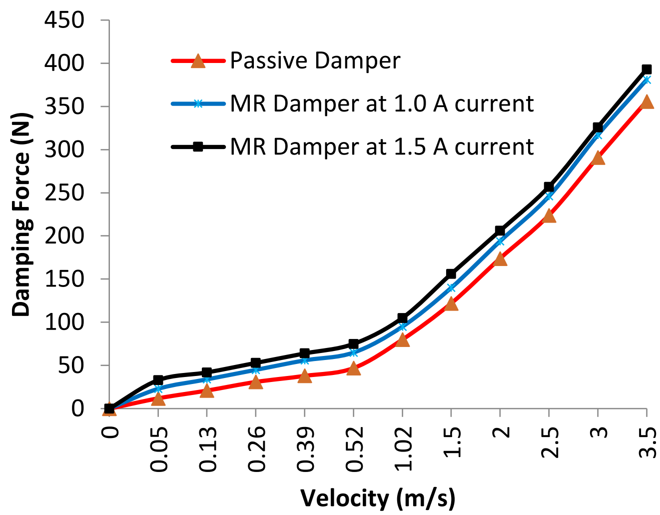


FIGURE 10. Damping force of Passive damper and MR damper versus Velocity

The damping performance of the MR damper is observed on the test rig under different excitation velocities, by supplying a current of 1A and 1.5A. Dampers reduce vibrations by dissipating the energy of vibrations. When a vehicle hit a bump on the road, the damper's piston advances to absorb the vibration and gets compressed. This compressed force experienced by the damper is compression force and the force that a shock absorber experiences as it decompresses and then expands back to its original state is known as rebound damping. Damping force as shown in Figure 10 is compression force required to reduce the vibration excitation. Rebound damping is not considered in the paper. It is observed that the MR damper outperforms the passive damper at all velocities of vibration. The damping force obtained at 1.5 A current is 15% more and at 1.0A is 11% more than the damping force obtained with a passive damper. Moreover, as demonstrated in Figure 11, the FFT Analyzer (Fast Fourier Transform spectrum analyzer) is employed to acquire the vibration acceleration. Initially, when the vehicle hit a bump, all dampers show an acceleration of about 1.4 m/s2, but after 10 Hz frequency amplitude of the MR damper at 1.5A current is much lower than the passive damper. The acceleration of the MR damper obtained at 1.0A current is slightly higher than that of 1.5 A.

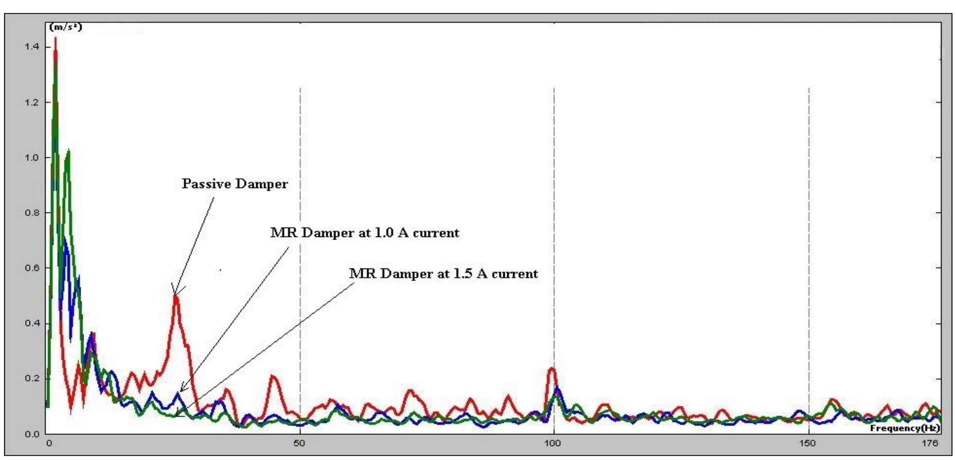


FIGURE 11. Acceleration of Passive damper and MR damper at different frequencies

CONCLUSION

In order to conduct an experimental examination on sedimentation, shear stress, viscosity, damping force, and vibration acceleration, this study includes four MR fluid samples. Samples are grouped using a combination of surface coated magnetic particles, carrier fluids, and additives. The statement is that the lowest sedimentation ratio is noticed in MR Fluids 4 and 3, that are using paraffin as the carrier fluid. When the current continuously increases, the magnetic flux density rises resulting increase in viscosity. It has been observed that all developed MR fluids became more viscous as magnetic flux density increased. Higher shear stress level above 250 Pa is observed in Paraffin based oil mixed with grease and stearic acid. Shear stress of less than 90 Pa is observed in Silicone based oil is not considered further for the fluid combination. Hence paraffin based MR Fuid-4 mixed with additives grease, stearic acid, and xanthan gum coated carbonyl iron illustrated a viscosity of more than 1800 centipoise. The fluid's high viscosity feature aids in boosting the MR damper's damping force. A damping force of about 400N is observed at 3.5 m/s velocity with the help of an MR damper. The damping force of the MR damper supplied with 1.5A current is 15% more than the damping force obtained by the passive damper. The acceleration amplitude of the MR damper with 1.5A current outperforms the passive damper by reducing acceleration by 30%.

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