Fabrication and Testing of Modified Magnetorheological Damper Fitted with External Permanent Magnet Assembly

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Abstract—**Many vehicle systems and industrial equipment face the issue of vibrations. As such, vibration control devices like classical hydraulic dampers are utilized to minimize vibrations. In this context, magenetorheological fluid is introduced as a damper fluid to improve the damper's vibration reduction capability. This damper is known as the MR damper in which the magnetic field required to activate MR fluid is produced by using an electromagnet over the piston inside the damper cylinder. However, some severe problems are observed due to internal electromagnetic piston configuration in the conventional MR damper. Therefore, modification is suggested in the damper in the form of an external permanent magnet assembly's fitment.The proposed model consists of a damper cylinder filled with MR fluid and an external assembly of permanent magnets positioned near the cylinder. The conventional and modified MR dampers have been tested on a test rig by changing the MR fluid configuration, excitation frequency of exciter, and excitation current. The MR effect on velocity and damping force in conventional and modified dampers has been recorded and compared. The results convincingly indicate that the modified MR damper delivers good performance by generating sufficient damping capacity that can be utilized for necessary applications. Importantly, it resolves the problems associated with conventional MR dampers like electric current unavailability at field, clumping, hard cake formation, remanence phenomenon, and excessive heat formation.**

Index Terms—**Magnetorheological Damper (MR damper); Magnetorheological Fluid (MR fluid/MRF), force-velocity characteristics, external permanent magnet, excitation current and frequency**

I. Introduction

Vibration control technology has remained a challenging area of study for many engineers and researchers. Civil structures, vehicle systems, industrial equipment, etc., have been facing the problem of excessive vibrations. In the last several years, different kinds of vibration control devices have been developed to minimize vibrations. Magnetorheological dampers (famous as MR dampers) are introduced to reduce the excessive vibrations at various fronts. MR damper is an improved version of a classical hydraulic damper. Smart fluid named Magnetorheological fluid (MR fluid) is used instead of simple damper oil in it. This MR fluid has the right combination of carrier liquid and freely suspended iron particles. MR fluid works as ordinary damper oil when no magnetic field (OFF state condition) is applied [1]. As soon as the electric power is supplied to the electromagnetic piston of the conventional MR damper, it generates a magnetic field. This activity is known as the ON state condition, here freely suspended iron particles form a chain-like structure due to the magnetic field generated. The damping capacity is tremendously improved due to this behavior of MR fluid particles that is illustrated in Fig. 1.

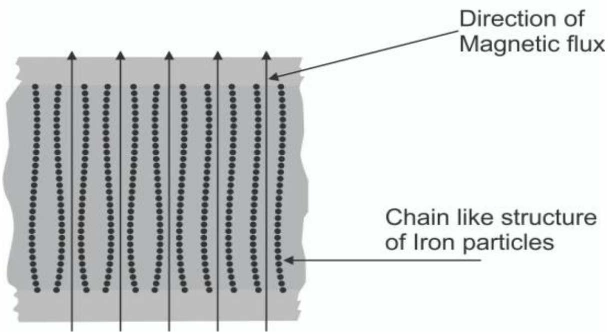

Figure 1. MR Fluid in presence of magnetic field

The Electromagnet contains multiple numbers of copper coil windings. Electric current is circulated through these windings to produce the electromagnetic effect [2]. The existing damping system is mainly classified into three main types, namely active, passive, and semi-active damping systems [3]. The MR damper is an excellent example of a semi-active damper. The MR

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fluid's viscosity changes in few milliseconds after the application of the magnetic field.

The magnetorheological fluid is prepared with a proper combination of the carrier liquid, ferromagnetic particles, and additives [4]. The information about particle size distribution is the main criterion and requirement in comparing MR materials [5]. Sedimentation stability is one of the important factors that need to be taken into consideration. The basic reasons for sedimentation stability are the gravity effect, force's direction, and Brownian motion. The additives operate as anti-settling agents on MR fluids [6]. The sedimentation ratio is affected by the percentage of additives like grease, nanoparticles, and graphene. The sedimentation ratio can be improved from 20 to 81% by adding novel grapheme and is one of the important criteria to decide whether the prepared MR fluid component combination is acceptable or not. MR fluids have great potential for research [7]. The concept of magnetorheology was used to prepare MR fluid (MRF), MR elastomer (MRE), MR grease (MRG), MR polymer gels (MRPG), and MR plastomers (MRPs). MRF has been used worldwide because it is a smart material. It is easy to prepare, very sensitive to change in the magnetic field, and unresponsive to contamination. Due to these properties, MRF is very famous as the smart material used for vibration control. MRF viscosity reduces during long-time operations [8]. This long cyclic process affects the orientation of ferromagnetic particles in MRF. Increment in the damping force was recorded as 44% and 90% in ON state and OFF state conditions than initial force. This was due to the effect of increment in viscosity. MRF has wide applications [9] like in automotive (car and seat suspension), protection to civil structures from seismic action, household appliances, robot fabrication, MR brake, MR clutch, MR beams, heavy vehicles especially defense automotive parts, MR damper bumper to minimize accident effect, etc. Some defects of MRF in working conditions have been found [10]. These defects are hard cake formation, clumping, oxidation of iron particles, and MR fluid particles settlement (known by the name of magnetic saturation). The remedies for such defects are the use of proper additives and the application of an optimal magnetic field. Design and analysis of low force MR damper (where current variation was 0.1 A to 1 A) has been explained [11]. The damper design and geometry calculation process, magnetic circuit design process, and material selection are mentioned in this work. The model design has been analysed with ANSYS software. It has been stated that total damping force is the algebraic sum of damping force due to shear stress and viscous damping force. This conclusion satisfied the low force damper design requirement.

Volume fractions and magnetic induction are also responsible for influence on microstructure evolution of MR fluids [12]. The remanence phenomenon has been observed in the case of conventional MR dampers. The current flows through the coil of the electromagnetic piston results generation of magnetic flux. Due to such magnetic flux acting in the electromagnetic piston, the electromagnetic piston remains considerably magnetized although no current flows through it. The ferromagnetic particles of MR fluid are attracted by electromagnetic piston even in OFF state conditions after the experimentation. It affects the performance of the MR damper. Magnetorheological (MR) gels have been widely utilized as smart material in the vibration reduction of engineering structures [13]. Existing models for MR materials are based on the magnetic dipole theory for MR fluid, but particle size is not taken into consideration in it. This theory cannot be applied to MR gels as MR gels contain a higher volume fraction of particles. So a new micromechanical model was fabricated and it was experimentally verified by using the planar current loop model. The basic performance characteristics of MR gels including magnetization effect and sedimentation stability are carried out in the process. The magnetic energy of particles was calculated by using the magnetic dipole model and the planar current loop model. The results obtained by both methods are compared.MR dampers are also used to reduce the resonance of a structure [14]. The current at which MR fluid regions get saturated is known as the maximum allowable current. The simulation of MR damper has been done by using simulation software like ANSYS, COMSOL, etc., to know the effect of various parameters on the application of magnetic fields. A designer can forecast the range of various parameters, for example, MR fluid gap, magnetic field required to activate MR fluid, damping force range, copper coil stages, shape and size of the piston through it. The MR damper has been used in earthquake vibration mitigation too. The MR dampers with multiple coils are used to improve the damping force and performance in seismic conditions. A three-coil MR damper is the best example of it [15]. The experimentation shows dynamic characteristics and magnetic saturation properties of the three-coil MR damper when different excitation currents and loading conditions. The Bingham model of MR damper with the formula relating the yielding shear stress and the MR damper control current is derived [16]. The formula put before matches with experimental results. To control the semi-active structure, the online real-time control method is suggested. The distortion of structure response can be solved by considering the time-delay problem of semi-active control. In the end, the comparison between controlled and uncontrolled structures is performed by an example of a three-storey reinforced concrete structure. Seismic distortion can be reduced effectively by using this approach. To reduce dynamic responses of a platform under the wide frequency range excitation, a new vibration isolation and reduction device is designed and manufactured [17]. Tests are conducted on such devices to understand the effect of the frequency as well as excitation amplitude on the properties of this device. The dynamic responses of such a platform are calculated under various excitations. It can be noted that such a device helps to reduce dynamic responses significantly.

One of the modified MR damper designs [18] consists of a permanent magnet. This design has been used to resolve the fail-safe problem of MR dampers. A permanent magnet and magnetic valve have been utilized [19]. This model is based on electromagnetism theory and the Bingham model. Permanent magnet and self-sensing compact devices have been developed further. A tunable MR damper is another device operated by permanent magnets [20]. There is no use of electromagnetic piston to produce magnetic fields in it. 2 DoF quarter car model with a hybrid magnet MR damper has been developed [21]. This experiment is quite successful for improvement in tire deflection, ride comfort, and suspension control. Magnetic shields (and sandwiched shields) are also used in some cases for twin-tube MR dampers with a single-coil in them [22]. Deviation in the flux lines has been observed due to the effect of such shields.

This study reveals that most of the work reported on MR dampers is with the use of electromagnets located on pistons inside the damper cylinders [23]. But from the application point of view, there may be chances of unavailability of electric current or battery provision on the actual field. Moreover, some of the common defects like hard cake formation, clumping, oxidation, and settlement of MR fluid particles are found in conventional MR dampers. As MR fluid is a good conductor of heat, the heat generated also affects fluid viscosity adversely [24]. So, permanent/hybrid magnets have been tried out in some of the recent designs to find the solutions for existing conventional damper problems. Although an internal permanent/hybrid magnet at piston of MR damper has undoubtedly addressed the heat and short circuit problems, it promotes continuous ON state condition. Moreover, the conventional MR damper has to be dismantled during maintenance that can be quite cumbersome due to internal magnet arrangement. As the result, there will be some limitations of conventional MR damper application due to the need for repair and maintenance on the actual site Such issues open up the scope for modification of conventional MR damper by using an external permanent magnet assembly. There shall be fewer chances of failure in magnetic circuits when one fits such external permanent magnet assembly to the damper cylinder. The modified MR damper becomes more effective as far as the application is concerned.

The present paper is an effort in this direction. The performance of the modified MR damper is investigated and its results are compared and validated vis-à-vis conventional MR damper in the paper.

II. Materials and Methodology

Fig. 2 represents the flowchart of the methodology adopted for the experiments with a modified MR damper. The same methodology has been adopted for conventional MR dampers also.

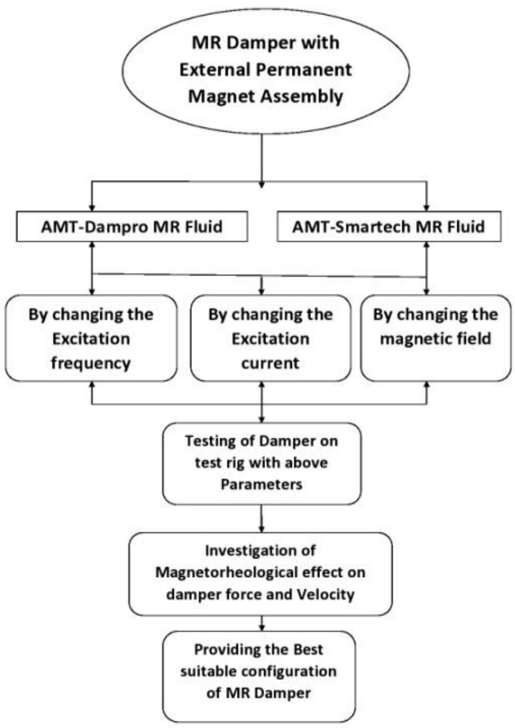


Figure 2. The methodology adopted for experimentation

The modified MR damper is tested. The effect of magnetorheology on velocity and damping force is recorded. The MR fluids can be prepared with 20 to 40 % volume fractions of ferromagnetic particles and are commercially available. They contain different volume fractions of ferromagnetic particles. These volume fractions can affect damper performance. The presented experimental work can be performed with only one type of MR fluid. However, it is better to test modified MR damper performance against more types of MR fluids to understand damper performance when particle fractions of MR fluids are varied. So that, two types of MR fluids AMT-Dampro and AMT-Smartech are used in experimentations. The excitation current is responsible for the change in excitations provided to the damper by the exciter. These excitations provided can be considered as input excitations. The magnetic field (which is externally applied to the modified MR damper) is responsible for the change in the behavior of MR fluid. It effects on output provided by the MR damper. So that, the modified MR damper is tested on a test rig by changing the MR fluid configuration, excitation frequency of exciter, magnetic field, and excitation current. The conventional MR damper is also tested on the same experimental test rig by varying the same parameters for comparison. The best suitable configuration of modified MR damper with used MR fluid and applied magnetic field is suggested from the results obtained from the experimental data.

A. Details of Modified MR Damper Set Up

A Mono-tube MR damper is chosen for experimental work that consists of two cylinders and a piston arrangement. The outer cylinder and piston rod have an eye arrangement. The lower and upper eyes are fixed to the piston rod and closed end of the outer cylinder respectively. These eyes are helpful to fix the damper to the test rig or any equipment where the damper is to be used. The lower end is fixed with the hub of the exciter. As discussed earlier, the internal electromagnet arrangement is removed completely in the modified MR damper. The magnetic field in the modified MR damper is varied by changing the distance between the magnets and by adding or removing the magnets in the external magnet assembly. The entire modified MR damper unit can easily be fitted or installed on any structure or equipment just like the normal damper. The actual configuration of conventional and modified MR dampers are presented in Fig. 3 (a) and (b) respectively.

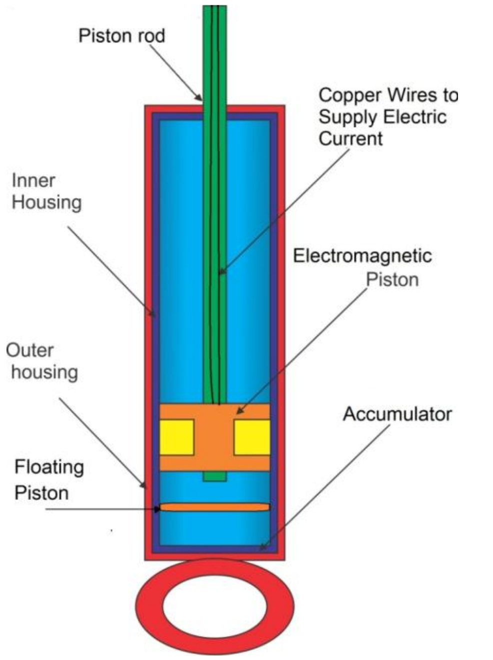


Figure 3 a). The actual configuration of conventional MR damper

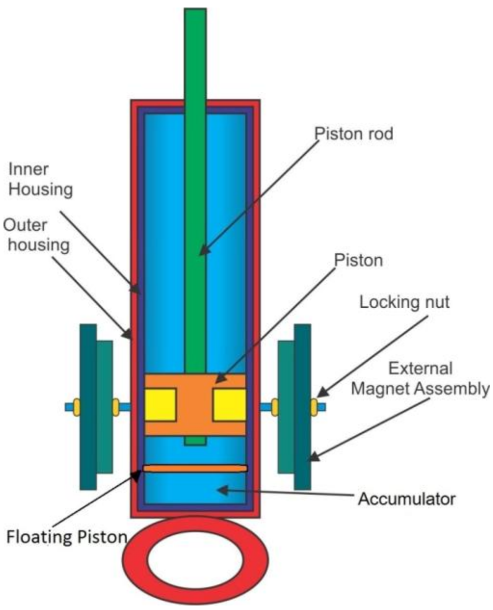


Figure 3 b). The actual configuration of modified MR damper

Two types of magnetorheological fluids, i.e. AMT-Dampro, and AMT-Smartech, are separately used for testing purposes. The properties of MR fluids are consolidated In Table I.

TABLE I. PROPERTIES OF MR FLUID USED

Properties of MR Fluid ↓	AMT-Dampro	AMT-Smartech
Density (gm/cm^3)	2.45	2.90
Zero field Viscosity (Pa s) @ 40ºC	0.29	0.37
Response time	<milliseconds	<milliseconds
Flash Point (in ºC)	>180	>180
Operating Temperature Range(in ºC)	-20 to +150	-20 to +150
Solid Content by weight %	73	81
Yield stress (kPa)	42	69

From the table, it can be seen that a wide range of yield stress is achieved in MR fluids at low intensity of the magnetic field. Excellent quality stabilizing agents have been added to the fluids due to which they have good settling resistant properties. The operating temperature of all fluids can be varied from -20° to +150° C and the fluids have improved properties like optimum viscosity, enhanced lubricity, and wear resistance.

B. Experimental Set-Up and Testing

The experimental setup to obtain force-velocity characteristics is shown in Fig. 4. The exciter from Instrol devices, Bangalore, India has been utilized to provide excitations to the MR damper. The function generator attached to the exciter consists of a power amplifier and an oscillator. This setup generates sinusoidal signals. Load cell and dial gauge indicators are used to measure the parameters like force and displacement. Velocity and excitation frequency is measured with the help of four channels portable FFT analyzer.

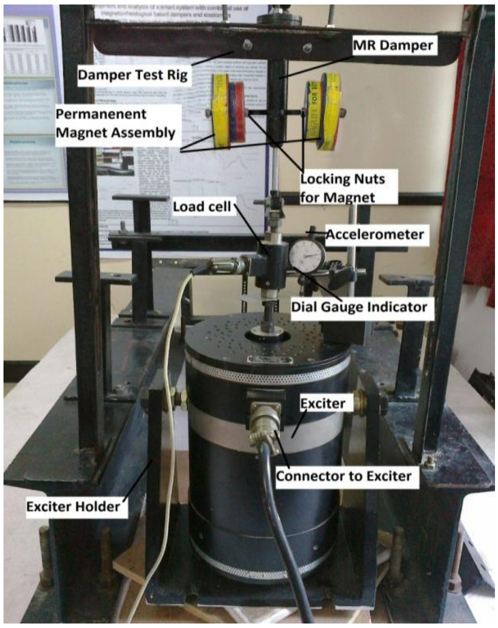


Figure 4. Experimental setup for modified MR damper testing

The damper is fixed at its lower end on the horizontal middle beam of the test rig. This horizontal beam is movable in a vertical direction to adjust the MR damper's position for its attachment with the exciter. A proper slot is provided on the middle horizontal beam. The external magnet assembly is connected to the modified damper. One can change the magnetic field in a modified MR damper either by adding or removing permanent magnets in it or by varying the distance between magnets and the cylinder of the damper. Permanent magnets are fixed at a certain distance away from the cylinder with a locking nut arrangement. When the assembly of permanent magnets is kept 15 cm away from the damper, it gives a very less magnetic field which is almost null This condition is the OFF state condition. Considerable magnetic field generation starts when permanent magnet assembly is brought near the cylinder. In other words, the magnetic flux density is increased when the distance between permanent magnet assemblies is reduced. This condition is the ON state condition. The specifications of the devices which are part of this setup are provided in Table II.

TABLE II. SPECIFICATIONS OF INSTRUMENTS USED IN THE EXPERIMENTAL SETUP

I. POWER AMPLIFIER	
MAXIMUM POWER OUTPUT	250 VA INTO 1.5 OHM
FREQUENCY RESPONSE	1 HZ-10 KHZ WITHIN +1DB
HARMONIC DISTORTION	LESS THAN 1 %
GAIN AT 1 KHZ	20 DB + 1DB
II. VIBRATION EXCITER MODEL ID-230	
PEAK SINE FORCE	200 N
MAXIMUM DISPLACEMENT	12 MM PEAK TO PEAK
MAXIMUM ALLOWABLE PAYLOAD	3 KG
III. OSCILLATOR	
WAVEFORM	SINUSOIDAL
FREQUENCY RANGE	1 HZ-10 KHZ
FREQUENCY RESPONSE	WITHIN + 1 DB WITH REF. AT 1 KHZ
TOTAL HARMONIC DISTORTION	LESS THAN 1 %
INDICATION ACCURACY	+0.2 % OF THE RANGE OR BETTER
IV. LOAD CELL	
TYPE	STRAIN GAUGE TYPE
RATED CAPACITY	20 KG
RESOLUTION	0.01 KG
ACCURACY	± 0.05 % OF THE RATED CAPACITY
V. DIAL GAUGE	
RATED CAPACITY	4 MM
RESOLUTION	0.01 MM
VI. FFT-ANALYZER	
MODULE	OR34
SOFTWARE	NVGATE®

The upper end of the damper is connected to the exciter hub. The range of excitation current is varied from 1.5 A to 6 A with an equal interval of 1.5 A. The excitation frequency of the exciter is set as 2 Hz, 4 Hz, 6 Hz, and 8 Hz. The magnetic flux generated with external permanent magnet assembly is set as 0 Gauss (G), (OFF state condition), 2000 G, 4000 G, and 7000 G.

III. CONFIGURATION OF MODIFIED MR DAMPER

The permanent magnets of 2000 G and 4000 G are initially used one by one in the external assembly of the modified MR damper to generate the magnetic field. However, deviation in the results, Fig. 5 and 6, has been found with these magnetic intensities as compared to conventional MR damper having fixed 7000 G magnetic field. So a combination of two magnets (3000 G and 4000 G) is used to generate 7000 G magnetic field. Modified MR damper gives results very near to conventional MR damper at 7000 G magnetic field. The optimum distance of magnets in the external assembly from the damper cylinder is found. Magnets are positioned at various distances from the outer cylinder and tested. The external permanent magnet assembly is connected to the outer housing and does not move with the piston. But the external magnet assembly can be moved and its position can be varied according to the piston stroke. Importantly due to the large size of the external permanent magnet, the magnet generates a sufficient magnetic field around it to activate MR fluid irrespective of any piston position. In the experiment, the recorded output was found to be stable like conventional/traditional MR damper. There are very small percentage differences in Force-Velocity characteristics of conventional and modified MR Damper. The average percentage difference in force and velocity characteristics of modified and conventional MR dampers is recorded in Table III. This table helps to decide the optimum distance between the outer cylinder of the modified MR damper and permanent magnets. From the results, a distance of 5 mm is desirable where the average percentage difference is minimum for both types of used MR fluids.

TABLE III. EFFECT OF DISTANCE BETWEEN OUTER CYLINDER AND MAGNETS

Distance between Magnets and Cylinder in mm	Average Velocity difference in %	Average Force difference in %	MR Fluid Used
5	4.51	5.85	AMT-Dampro
	4.85	6.11	AMT-Smartech
10	6.88	7.04	AMT-Dampro
	6.83	7.83	AMT-Smartech
20	8.65	8.34	AMT-Dampro
	8.09	8.89	AMT-Smartech
30	10.65	8.95	AMT-Dampro
	9.61	10.34	AMT-Smartech
40	11.35	11.4	AMT-Dampro
	11.17	10.71	AMT-Smartech
50	12.88	10.7	AMT-Dampro
	12.75	12.21	AMT-Smartech

It is therefore deduced that modified MR damper requires magnets of 7000 G that need to be arranged at a distance of 5 mm away from the outer cylinder. This configuration is selected for further experimental work.

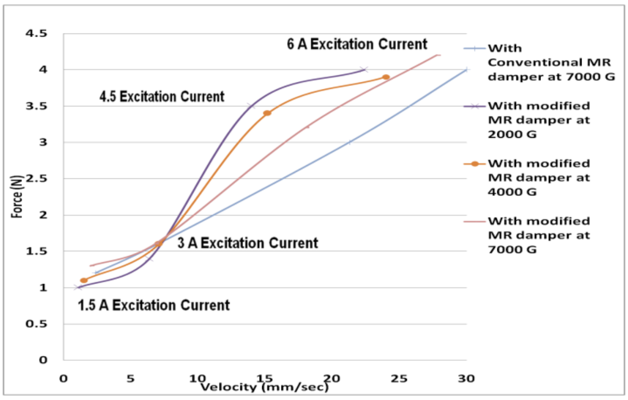


Figure 5. Force-velocity characteristics of MR damper with AMT-Dampro MR fluid

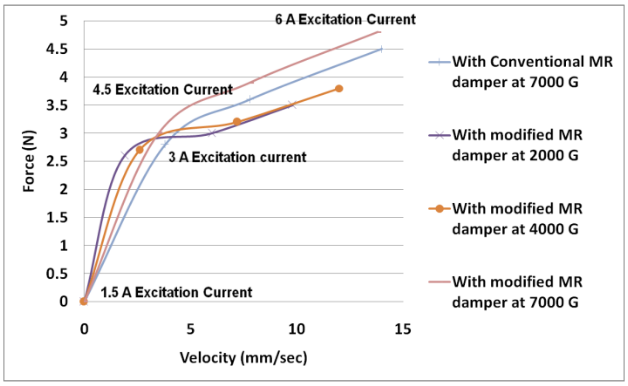


Figure 6. Force-velocity Characteristics of MR damper with AMT-Smartech MR fluid

IV. Results and Discussion

The exact velocity amplitude is recorded at various excitation frequencies by the FFT analyzer (with module OR34 and NVGate®Software). An accelerometer of FFT analyzer is useful to record the parameter like velocity. An integrated metallic plate connected to the damper on which an accelerometer with a magnetic base was mounted. For analysis, the velocity values obtained at a particular excitation frequency were recorded. There are two windows present; one is a recorder that records the reading as Time Vs Acceleration. After recording the reading, the second Analysis window is generated which can be Frequency Vs Acceleration, Frequency Vs Velocity, and Frequency Vs Displacement. The frequency Vs Velocity option is chosen out of these options here.

The force amplitude is recorded with the help of a digital strain gauge type load cell. The velocity amplitude *vs* excitation frequency plots of conventional and modified MR dampers at 7000 G are given in Figs. 7 to 9.

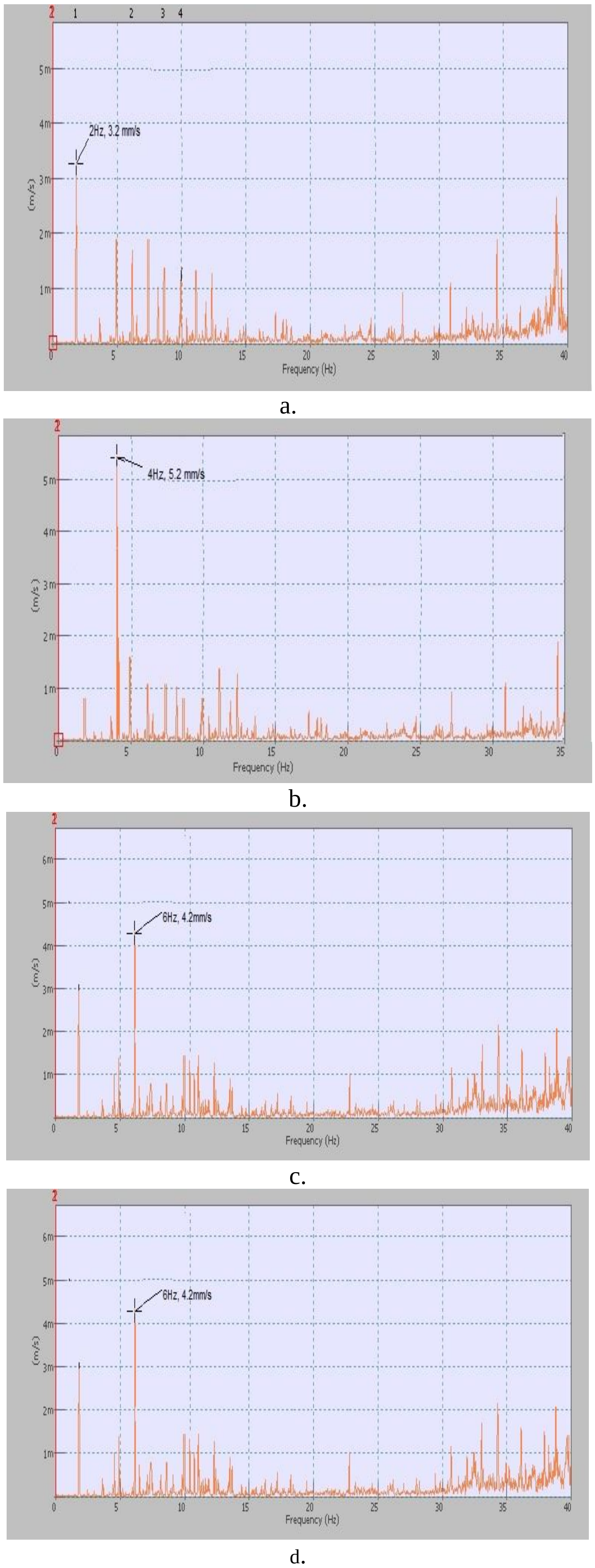


Figure 7. Velocity *vs* Excitation frequency graphs of modified MR damper with AMT- Dampro MR fluid

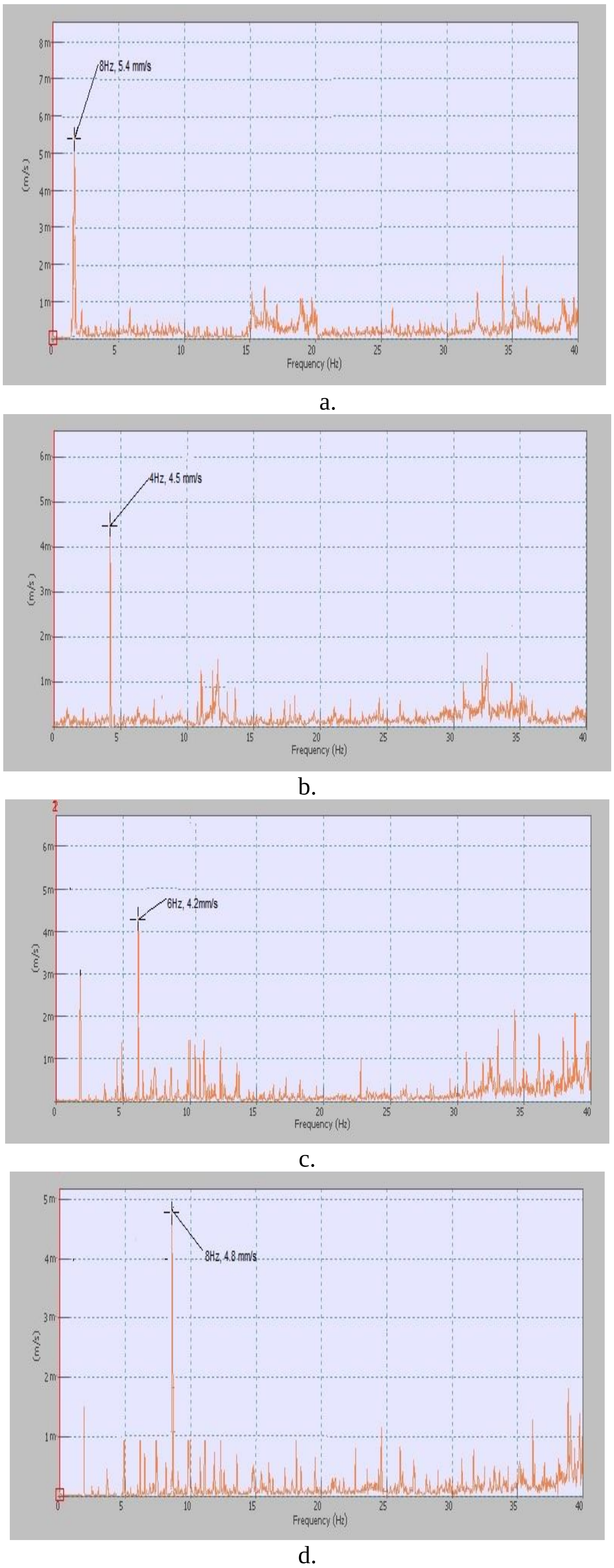


Figure 8. Velocity *vs* Excitation frequency graphs of modified MR damper with AMT- Smartech MR fluid

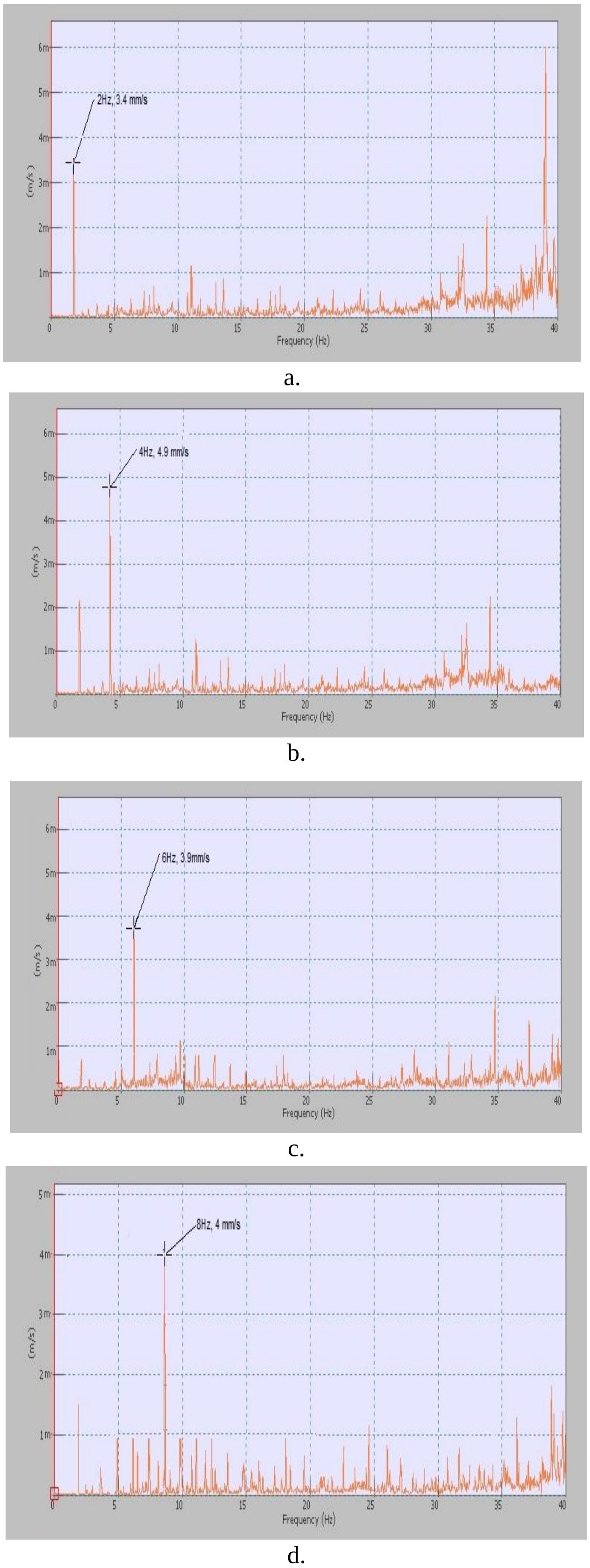
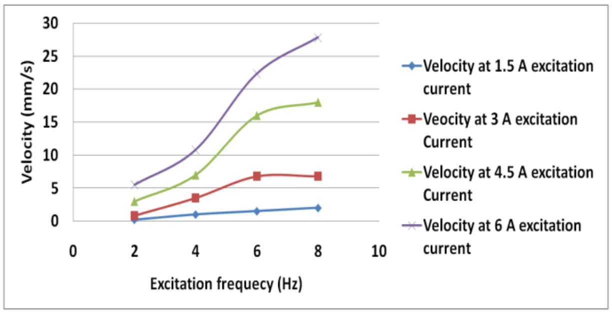


Figure 9. Velocity vs Excitation frequency graphs of Conventional MR damper

The motivation to use an FFT analyzer is to note exact velocity amplitude. In Figs. 7 to 9, some additional velocity curves can be seen. These additional velocity plots existed due to seismic vibration. It is considered noise. Its magnitude is very less as compared to recorded exact velocity at certain excitation frequencies. Hence, these are neglected. The velocity amplitude at various frequencies recorded as indicated in Figs. 7 to 9 is used to study the effect of excitation frequency on velocity amplitude. The graph plotted in Figure 10 is showing it for modified MR damper with AMT- Dampro and AMT-Smartech MR fluid at 7000 G magnetic field. It can be seen that, as excitation current at certain frequency increases, the velocity amplitude also increases. It means the excitation current is directly proportional to the velocity. The maximum difference in velocity occurs at 8 Hz excitation frequency and excitation current of 6 A. The velocity range is reduced when AMT-Smartech fluid is used with a modified MR damper. It means the used MR fluid, provided the magnetic field with external permanent magnet assembly and modified MR damper are responsible for velocity reduction. The generated magnetic field and AMT-Smartech MR fluid (which contains more nos. of iron particles) make velocity fall from 27.8 mm/s to 13.8 mm/s. It proves that damper performance is affected by external magnet assembly and nos. of iron particles. The sedimentation effect is responsible for 0 velocities at 1.5 A excitation current for all excitation frequencies. It can be seen in Fig. 10 (b).



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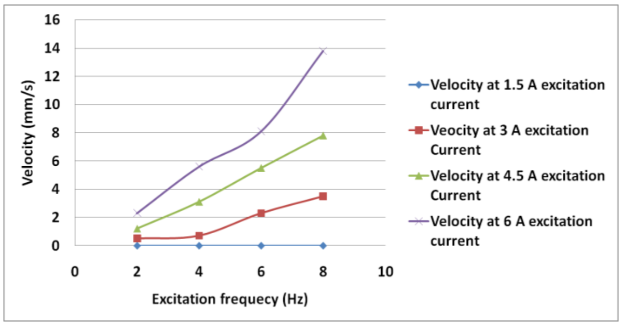
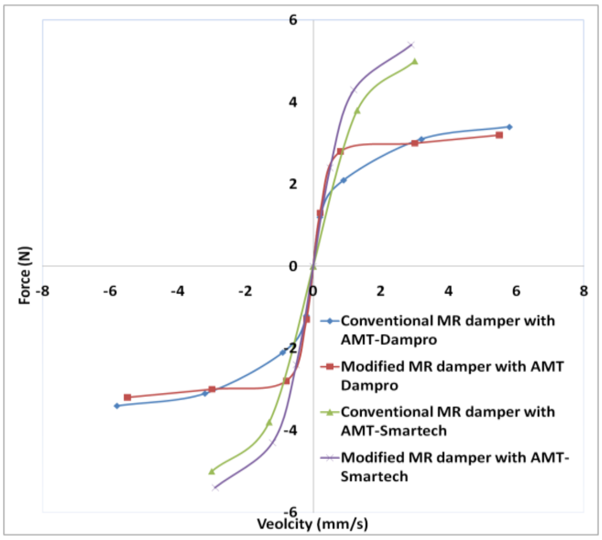


b.

Figure10. Velocity Vs Excitation frequency graphs of Modified MR damper when a) AMT-Dampro MR fluid is used b) AMT- Smartech MR fluid is used at 7000 G



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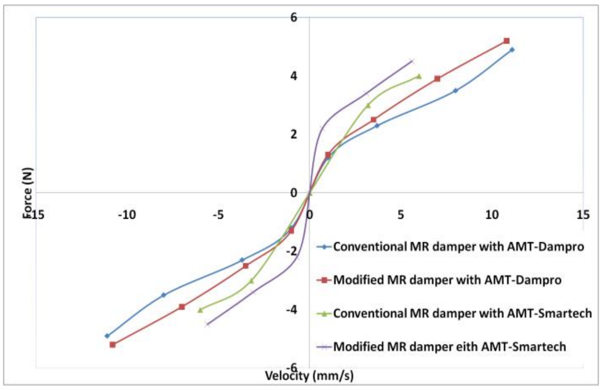

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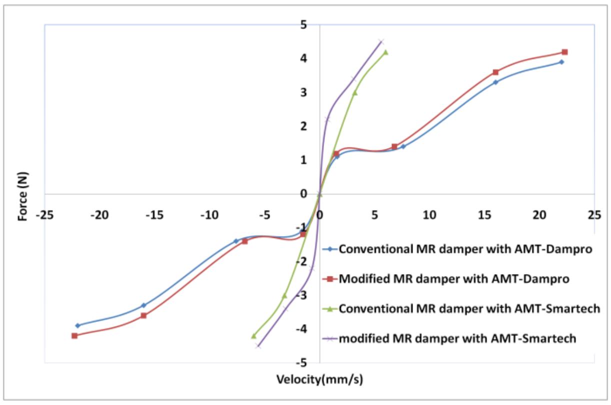

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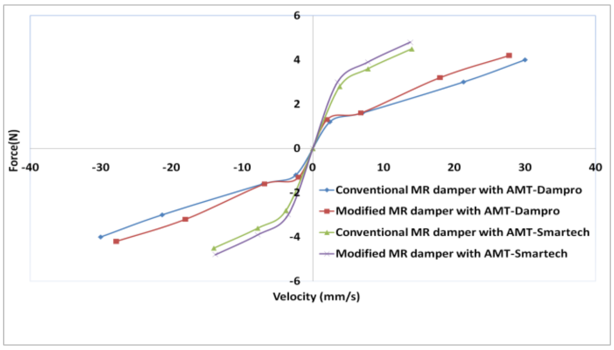
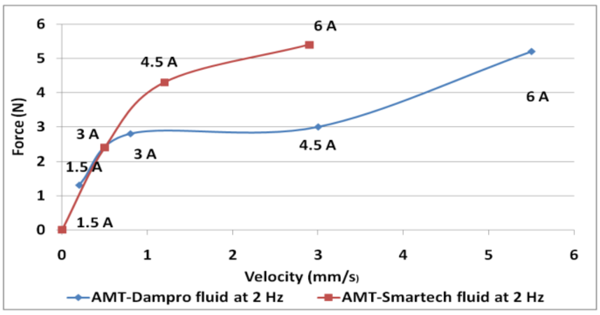


d.

Figure 11. Force-velocity characteristics at a) 2 Hz b) 4Hz c) 6 Hz and d) 8 Hz and 7000 G

Fig. 11 shows the Force-velocity characteristics of conventional and modified MR dampers The AMT-Dampro and AMT- Smartech have been used as MR fluids. When AMT-Dampro MR fluid is used in testing, it is observed that there is an increment in force as velocity increases in both dampers. However, these graphs are non-linear hysteresis curves. MR dampers are well known to have such curves in force-velocity characteristics presentation. A very small difference in the force amplitude is observed in modified MR damper at the same velocity as compared to conventional MR damper. This effect has been recorded for all values of excitation current viz. 1.5 A, 3 A, 4.5 A, and 6 A at all excitation frequencies, especially at 7000 G magnetic field density. There are considerable variations in force-velocity characteristics at excitation frequencies of 6 Hz and 8 Hz. The Force and Velocity vary from 1.2 N - 4.9 N and 0.2 mm/s to 30 mm/s for conventional MR dampers. For modified MR damper, these values vary from 1.2 N - 5.2 N and 0.2 mm/s to 27.8 mm/s. So it can be stated that a modified MR damper controls the velocity and produces more force than the conventional MR damper. The performance of conventional and modified MR dampers improves when AMT-Smartech MR fluid is used in it. The highest force difference has been recorded in graphs at 7000 G magnetic field applied in both the dampers. The highest value of the force is noted at 6 A excitation current, 2 Hz excitation frequency, and magnetic field 7000 G viz 5.4 N for modified MR damper. The same parameter recorded for the conventional MR damper is at 6 A excitation current, 2 Hz excitation frequency, and magnetic field 7000 G viz. 5 N (highest). The magnetic saturation starts occurring at 4 Hz, 6 Hz, and 8Hz at 1.5 A excitation current.



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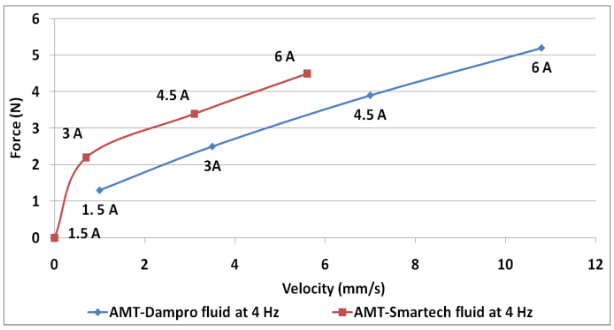

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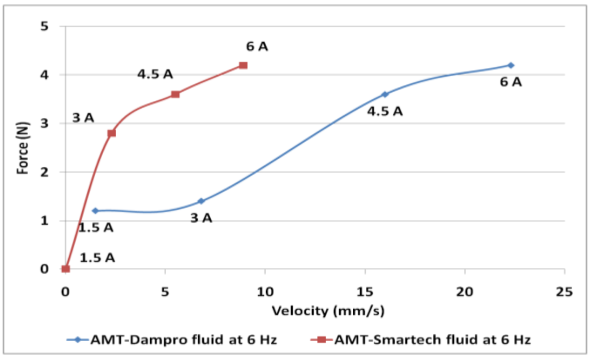

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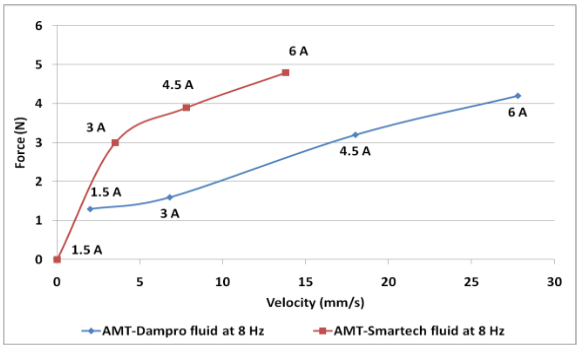


d.

Figure 12. Force-velocity characteristics of modified MR Damper for different excitation currents at a) 2 Hz b) 4 Hz c) 6 Hz and d) 8 Hz and 7000 G

The excitation current effect of modified MR damper on the Force-Velocity characteristics has been part of this study too. The optimization for excitation current is performed by using recorded data. Fig. 12 shows the Force-velocity characteristics of AMT-Dampro and AMT-Smartech MR fluid for different excitation currents at different excitation frequencies viz. 2 Hz, 4 Hz, 6 Hz, and 8 Hz. The force-velocity curve indicated at different excitation currents has only one curve because the force-velocity data at 7000 G have been considered to plot it. The data from different currents at a single excitation frequency under 7000 G magnetic field clubbed together to plot these graphs.

The observations indicate that the velocity at 1.5 A at 2 Hz and 4 Hz are almost very close at all applied magnetic fields when AMT-Dampro MR fluid is used. But a considerable difference has been observed in force-velocity characteristics at different excitation currents in all excitation frequencies. When AMT-Dampro MR fluid has been selected in testing, it gives better results at high excitation current (4.5 A and 6 A) and high excitation frequency (6Hz and 8Hz). Force-velocity characteristics of AMT-Smartech fluid are also indicated in same graphs. The excellent range of variations in the force-velocity characteristics has been recorded here at every frequency and each excitation current as compared to AMT-Dampro MR fluid. Further, it has been observed that the magnitude of force decreases and the magnitude of velocity increases as the excitation current goes on increasing from 3 A to 6 A. The highest force recorded is 5.4 N at 2 Hz excitation frequency, 6 A, excitation current, and 7000 Gauss magnetic field. The optimization can be done after studying these plots. This optimization will be helpful to decide the combination of excitation current, excitation frequency, magnetic field, and MR fluid for the required application. This will provide the force-velocity range at different excitation frequencies also.

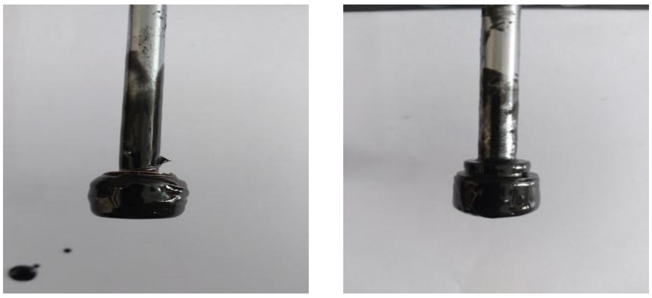
V. Performance Validation of Modified MR Damper

It is necessary to validate the performance of the modified MR damper. The recorded force-velocity readings of modified MR dampers have been used for comparison with those from conventional MR dampers. The percentage difference for conventional and modified MR dampers is calculated and presented in Table IV.

TABLE IV. Percentage Difference in Force-velocity Characteristics Of Conventional and Modified Mr Damper

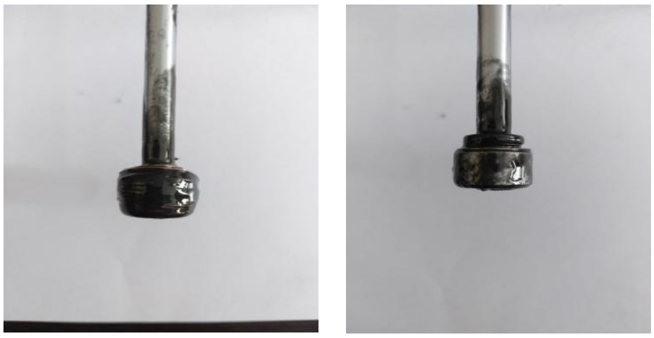
Excitation Frequency	Velocity Difference in %	Force Difference in %	MR Fluid Used
2 Hz	3.17	5.34	AMT-Dampro
4 Hz	3.76	6.61	
6 Hz	4.74	6.09	
8 Hz	6.38	5.39	
2 Hz	6.33	5.27	AMT-Smartech
4 Hz	4.39	5.98	
6 Hz	5.90	6.63	
8 Hz	2.42	6.56	

The minimum percentage of velocity difference for AMT-Dampro MR fluid has been recorded as 3.17 % at 2 Hz excitation frequency while the maximum percentage difference in velocity for the same fluid has been recorded as 6.38 % at 8 Hz. The force percentage differences have been recorded as 5.34 % minimum and 6.61 % maximum. Likewise, the minimum percentage of velocity difference for AMT-Smartech MR fluid has been recorded as 2.42% at 8 Hz excitation frequency while the maximum percentage difference in velocity for the same fluid has been recorded as 6.33% at 2 Hz. The force percentage differences have been recorded as 5.27 % minimum and 6.63 % maximum. From the percentage differences, it is clear that the difference in force and velocity of modified MR damper and conventional MR damper is small that supports the use of modified MR damper.



a. b.

Figure 13. The remanence phenomenon at Piston when AMT -Smartech MR fluid is used a. Conventional MR damper and b. modified MR damper



a. b.

Figure 14. The remanence phenomenon at Piston when AMT-Dampro MR fluid is used a. Conventional MR damper and b. modified MR damper

The effect of the remanence phenomenon at the piston of conventional and modified MR dampers just after the experiment is shown in Fig. 13 and 14. This effect has been observed to be more in conventional MR dampers due to the effect of an electromagnet. The magnetism effect remains in the electromagnetic piston for a certain time even after the deactivation of current. Iron particles from MR fluid are attracted to the electromagnetic piston and get saturated inside the cylinder. In short, more no's of iron particles from the MR fluid are attracted by conventional MR damper piston. However, in a modified MR damper, once the magnets from the assembly are removed, there is very less magnetism effect on the piston as compared to that on a conventional MR damper piston.

a. b.

Figure 15. Clumping effect on AMT-Dampro MR fluid when it is used it with a. Conventional MR damper and b. modified MR damper


a. b.

Figure 16 Clumping effect on AMT-Smartech MR fluid when it is used with a. Conventional MR damper and b. modified MR damper

The clumping effect (white patches) in MR fluids AMT-Dampro and AMT-Smartech is shown in Fig. 15 and 16. The clumping effect is generated as a result of the long-time operation of the MR damper at a very high direct magnetic field. This effect is responsible for the grouping of iron particle chains which leads to hard cake formation. A significant difference in the clumping effect is observed between conventional and modified MR dampers. Iron particles grouped due to clumping in the case of conventional MR damper can be seen in Fig. 15 'a' and 16 'a'. Reduced white patches in modified MR damper fluid are confirmed from Fig. 15 'b' and 16 'b'.

VI. Conclusions

A conventional MR damper has an internal electromagnet inside it as a damper piston. In a modified MR damper, such an internal electromagnetic piston is removed. The external assembly of the permanent magnet is used in a modified MR damper to generate the magnetic field. The conventional and modified MR damper are tested on the same experimental rig. The force-velocity characteristics of both the dampers are compared. The performance of modified MR damper is found to be at par with that of conventional MR damper. Importantly modified MR damper gives additional benefits of reduced remanence phenomenon and clumping. Other conclusions drawn from the work reported in the paper are as follows:

1) It is observed that force-velocity characteristics improve with nos. of ferromagnetic particles. MR fluid - AMT-Smartech gives better performance in the case of both conventional and modified MR dampers. However, at a low excitation current where the velocity of excitations is low (like 1.5 A), ferromagnetic particle saturation is observed. In the case of AMT-Dampro, considerable changes are observed in force-velocity characteristics at excitation frequency 4 Hz to 8 Hz. The graphs plotted (Fig. 12) help to decide force-velocity characteristics range at different excitation currents. 3 A, 4.5 A, and 6 A excitation currents give a better range of damping force for both kinds of MR fluids.

2) The best suitable combination for force-velocity characteristics is noted with modified MR damper at 8 Hz excitation frequency and 4.5 excitation current at 7000 G magnetic field with AMT-Smartech MR fluid (Fig. 11).

3) In table IV, the percentage difference in force and velocity recorded for conventional and modified MR dampers has been obtained for every excitation frequency. The table shows that minimum differences have been observed in the case of both MR fluids. The minimum percentage difference in the force and velocity readings supports the viability of experimentation too. Results convincingly show that the modified MR damper delivers good performance by generating effective variation in force-velocity characteristics as compared to conventional MR damper.

4) The modified MR damper resolves the problems like hard cake formation-clumping, remanence phenomenon, and excessive heat formation. The new and simple external assembly arrangement makes the modified MR damper handy and convenient for installation and application to the system at the actual site. There will be fewer chances of failure in magnetic circuits when external permanent magnet assembly is connected to the damper.

5) The results reported in the paper shall provide basic data for further study using external permanent magnet assembly to magnetorheological instruments in the field of vibration control.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

All authors contributed to the study conception and the actual experimentation. Mr. Yashpal M. Khedkar performed material preparation, data collection, and analysis. He wrote the first draft of the manuscript. This work is performed under the guidance of Dr. Sunil Bhat. Dr. Sunil Bhat and Dr. H. Adarsha reviewed and edited the manuscript. All authors commented on the previous version of the document. All authors read and approved the final manuscript. All Authors agree to be accountable in every aspect of the work to ensure that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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