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Performance Evaluation of Magnetorheological Damper Using Finite Element Analysis

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Abstract

Magnetorheological (MR) dampers are semi-active controllable devices that utilize magnetorheological fluids (MRF) for generating governable force. The MR fluid contains magnetic micro-sized/nano-sized iron (Fe) particles, non-magnetic-based fluid, and some additives to mitigate sedimentation and agglomeration. The addition of magnetic nano-sized particles exhibits better sedimentation stability relative to common dispersed additives without affecting the MR effect. MR dampers may be treated as fail-safe as they behave as passive dampers in case of a breakdown of the control mechanism. These dampers are simple in construction, own fewer moving parts, make use of less power, are brisk in response, and mitigate the tolerances. MRF have the special potential to vary dynamic yield stress on the application of a magnetic field and damping force is varied by magnetically varying the rheological characteristics of the fluids. This paper investigates the magnetized field produced in the damper using finite element analysis (FEA) and verified using magnetic circuit theory. A 2D axi-symmetric MR damper has been firstly modelled using SolidWorks software and then magnetic field density in MRF space on the application of current has been determined using ANSYS Maxwell software v16. For analytical modeling of the MR damper, a program in "C" language for electromagnetic circuit theory has been used to evaluate the shear stress for the MR damper. The "C" program results and FEA results indicated a small variation of 3.63% in magnetic flux density generated for the current flow of 1 A through the coil and this led to the validation of this study.

Keywords

Magnetorheological fluid, Magnetorheological damper, Shear stress, Magnetic field density, Magnetic circuit

Introduction

Semi-active control device systems containing MRF laid revealing emphasis largely on vehicles, structure, suspensions, biomedical practices, etc., leading to their distinctive controls. This article aims to enhance the damping characteristics of the modelled MR damper by alteration of geometrical specifications. MRF belong to smart materials whose flow or shear properties may be governed by applying a magnetic field to enable vibration control devices [1]. As a result of these special characteristics, MR dampers impart varying damping force semi-actively on changing the current sweeping across the MR damper's circuit, which enables them to govern vibrations in a broad span of road surface conditions. In MRF, micro-sized/nano-sized magnetic particles are suspended inside a non-magnetized medium and this fluid acts as a Newtonian fluid shown in figure 1a. These particles get uniformly aligned as shown in figure 1b and chains are formed along magnetic flux lines when a magnetic field is imposed [2, 3].

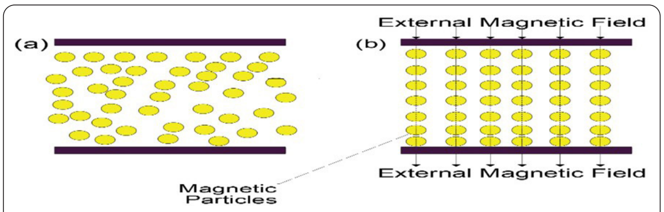

Figure 1: Micro-sized/nano-sized particle's orientation in the **(a)** absence and **(b)** presence of magnetic field.

When fluid is flowing in a direction normal to magnetic flux lines, the micro-sized/nano-sized particle's chain affects the fluid to exhibit a varying yield stress. Hence, the fluid acts as a Bingham plastic medium on imposing a magnetic field inside a fluid gap [4]. The dispensable agglomeration of micro-sized/nano-sized particles in MRF is an important issue for various technological applications. MRF contains mineral oil, spherical Fe particles (2.3 µm), and nano-sized particles as an additive (average size 7.8 nm). The addition of magnetic nanoparticles enhanced the dispersibility characteristic relative to common dispersed additives without affecting the MR effect [5].

Parlak et al. [6] carried out the electromagnetic analysis using the FEA for obtaining optimum magnetic flux and damping force. Zhang et al. [7] present the magnetized design of the MR damper. The magnetic saturation has been obtained utilizing the FEA on the magnetic circuit for enhancing the damping force. Ferdaus et al. [8] developed a 2D axisymmetric along with a 3D prototype of the MR damper with different piston shapes to obtain the optimum design. The MR dampers with various values of fluid gap and air gap were simulated for improvement of the existing design. Kumar and Mangal [9] developed a MRF and evaluated the off and on-state viscosity and ultimately the damping force for the modelled MR damper. Zalewski et al. [10] simulated and analyzed a lumped mass thermo-mechanical damper model containing MRF. The frictional and thermal effects have been studied and the equation of energy balance for temperature was derived.

Design of MR damper

MR dampers can vary the fluid's viscosity due to magnetic excitation [11]. The rise in magnetic excitation enhances the magnetic flux density and enhances the viscosity of the fluid, which finally improves energy dissipated per cycle. Hong et al. [12] formulated a non-dimensional model pertaining to Bingham's equation of MRF. The damping force for the modeled damper was formulated involving non-dimensional plug thickness, hydraulic amplifying proportion, Bingham number, and equal viscous damping coefficient. Zhang et al. [13] investigated magnetic saturation property, nonlinear hysteretic behavior, fatigue resistance capability, and energy dissipation capacity of a composite MR damper under varying currents, frequencies, and amplitudes of displacement. Moghadam et al. [14] modeled a MR damper by employing the dissipative particle dynamics technique and investigated the influence of MRF properties on damping force. A modified Bouc-wen model was utilized as a computational strategy for validating the modeling results with experimental data. Abdalaziz et al. [15] compared MR dampers having bypass packages along with combined annular-radial fluid's flow channels with conventional MR dampers having radial fluid's flow gaps. Li and Yang [16] established the mathematical modeling for predicting the value of the damping force of the modeled MR damper having a magnetic passage into the piston. Qiu et al. [17] observed and explored the chain structure of MRF magnetic particles.

Liu et al. [18] studied a MR damper containing folded resistance gaps. Hu et al. [19] proposed an optimal design mechanism for the MR damper dependent on a multi-physics coupling model using COMSOL software. Deng et al. [20] proposed an innovative seat suspension positioned with varying stiffness and varying damping rotating kind of MR damper. A controlling approach comprising a no-jerk skyhook dampening control alongside nonlinear stiffness control was also produced. The vibration depletion potential under the influence of bump excitation, harmonic excitation and random excitation was assessed and a remarkable improvement in vibration depletion potential has been depicted. Jiang et al. [21] produced a unique MR damper with specified potential variables to enhance the environment adaptableness of vibrational setups provided with a particular damper. Yang et al. [22] proposed a stepped bypass MR damper to fulfill the damper performance need of heavy vehicles. A mathematical model was developed, and a simulation of the developed model was done. Mata et al. [23] prepared a MRF carrying fiber-like elongated carbonyl ferrous particles and evaluated the dynamic performance of a 3-wheel vehicle having installed the MR damper. A significant improvement in ride comfort and stability was noticed when co-related to the passive suspension system. Gao et al. [24] presented a compensatory backstep technique meant for MRF-suspended setups. An integrated phenomenological model was presented for simulating the nonlinear characteristics and an adaptive radii-based function neural network for building up the inversed model of MRF damper. The potential of the MRF damper, inverse MRF model and compensatory backstepping controlling mechanism was determined. Krauze [25] produced a methodology to represent control-linked signalling paths assigned to a MR damper. The harmonic kind of road-linked excitation was accepted for its apparent filtrations from linked signals.

Katiyar et al. [26] investigated the MR behavior of paraffin oil-based MR nanofluid containing different proportions of Fe-Ni nanoparticles (≤ 15 nm). The viscosity was enhanced by increasing the particle concentration and an optimum particle concentration of 10 wt.% of Fe-Ni within the range of magnetic flux density 0 to 1.2 Tesla. The yield stress for the MRF containing 10 wt.% of Fe-Ni nanoparticles improved significantly from 10 Pa to 240 Pa, when the magnetic field density increased from 0 to 1 Tesla. Wang et al. [27] designed a solvent-free nanofluid containing a multi-core of graphene oxide and Fe_3O_4 nanocrystalline to enhance damping and mechanical characteristics. The prepared nanofluid exhibited a liquid-like behavior at room temperature and excellent dispersion stability. The nanofluids easily adjust the interface between the graphene oxide and epoxy matrix and the impact strength, bending strength, and loss factor of epoxy have been significantly enhanced. Yagnasri et al. [28] analyzed the MR performance of nano MRF containing iron-nickel oxide quasi-spherical nanoparticles. The rheological and viscoelastic action of nano MRF has been revealed at varying strain and shear rates. The shear stress gets enhanced with an increase in the magnetic field density whereas the loss modulus gets mitigated. The MR response exhibited an improvement and the sedimentation stability also improved significantly. Imran et al. [29] critically investigated different technological applications of iron oxide nanoparticle-based ferro-nanofluids. The chemical engineering applications focused on mass transfer processes, and the electrical and electronics engineering applications focused on magnetic field sensors, tilt sensors, temperature sensors, actuators, microelectromechanical systems, and photovoltaic thermal setups. Mechanical engineering applications such as sealings, dampers, etc., and environmental engineering applications such as water and air purification have been involved.

The mono-tube type is the commonly used MR damper as it is closely packed and easy to install. The MR damper as shown in figure 2 has a cylinder, a piston and piston rod assembly. A coil built up of copper is wound over the piston and serves as a major cause of magnetic flux. The cylinder, piston, and piston rod are examined by using magnetic material across which current flows to a coil that creates the damper's electromagnetic circuit and because of which magnetic flux is produced. There is a single pool of MRF having an accumulator to board the volume variation resulting on account of piston rod's action. The accumulator acts as a blockade amid MRF and non-oxidized squeezed gas (generally nitrogen) to accommodate the volume change due to the entry of the piston rod in the housing.

Experimentation

Electromagnetic circuit

The MRF systems modeling depends on fluid analysis and electromagnetic analysis. In this research, the modeled MR damper has been analyzed to obtain magnetic field density and the yield stress value based on FEA.

In case of 2D axis-symmetrical modeling, the assumptions, and constraints for creating the model are as follows: (a) The element's area must be positive, (b) The elements fitted for modeling have only magnetized and electrical field potential, (c) The structural, thermal, or piezoelectric potential for elements has been neglected, and (d) The components such as MRF in the gap, piston along with cylinder are assumed stationary.

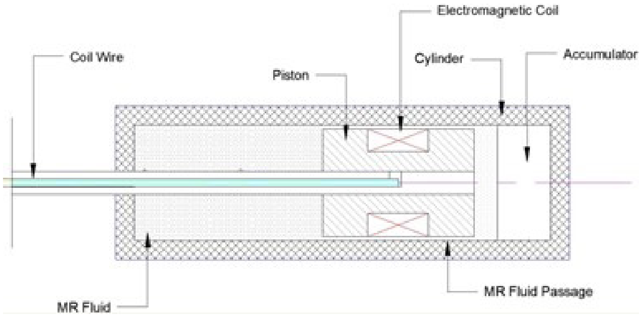

Figure 2: Geometry of MR damper.

The magnetized circuit parameters, as per magnetic ohm's law are mainly magnetic reluctance, magnetic flux, and magnetic potential. The magnetic potential is given in equation 1. The designed magnetized circuit for the modeled damper is demonstrated using figure 3 and a program in "C" language was developed to determine the magnetic field density along with shear stress. The magnetic reluctance (M_t) for the i^{th} element of the magnetic circuit is given in equation 2.

$$F = M_t \text{ x } \phi \tag{1}$$

$$M_t = \sum_{i=1}^{8} \left(\frac{L_i}{\mu_i \text{ x } A_i} \right) \tag{2}$$

$$\phi = \frac{N \text{ x } I}{M_t} \tag{3}$$

$$B = \frac{\mu_o \text{ x } \phi}{A_g} \tag{4}$$

Where 'F' is magnetic potential, 'M_t' is magnetic reluctance, 'L_i' is length of links, 'μ_i' is material relative permeability, 'A_i' is area of cross-section, 'I' is input current flow, 'N' is number of turns for coil, 'ϕ' is magnetic flux, 'μ_o' is magnetic permeability of air, 'A_g' is area of MRF gap, 'B' is magnetic field density.

FEA

In this research, finite element tools i.e., SolidWorks and ANSYS Maxwell software v16 have been utilized for modeling and analyzing the MR damper. The variables of the modeled MR damper are demonstrated in table 1.

A 2D axi-symmetric model of the MR damper has been developed for carrying out electromagnetic analysis.

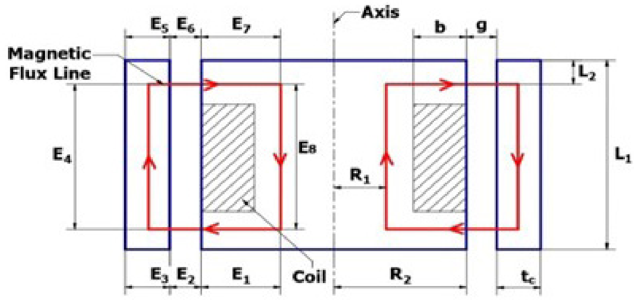

Figure 3: Magnetic circuit of MR damper.

Table 1: MR damper's variables.

Variables	Value (mm)
Piston radius (R_1)	24.1
Internal piston radius (R_2)	12.3
Cylinder thickness (t_c)	3
Pole length (L_2)	12
Length of piston head (L_1)	45
Coil width (b)	11.8
Fluid gap (g)	0.9

The MRF132-DG fluid parameters of the LORD company have been utilized in the analysis due to the broad working temperature range of the fluid. The generated magnetic field density's mean value inside the MRF gap for 1 A current has been determined. A 2D axi-symmetric geometric model is shown in figure 4. The materials selected for the piston, piston rod, and cylinder are low-carbon steel. The coil made up of copper with 350 number of turns has been used and a current of varying magnitude has been supplied to the coil of the modeled MR damper. The magnetic field perpendicular to the copper coil has been generated on passing the current through the circuit.

The value of magnetic field density for current varying between 0.1 A - 1 A has been determined by carrying out the magnetostatic analysis. Further, the shear stress is also calculated, and relation utilized to determine shear stress is given in equation 5.

$$\tau = 52.962 \times B^4 - 176.51 \times B^3 + 158.79 \times B^2 + 13.708 \times B + 0.1442 \quad (5)$$

Where 'τ' is shear stress and 'B' is magnetic field density.

Magnetostatic analysis has been carried out for determining the generated magnetic flux density and relevant shear stress in the region of MRF for the developed MR damper. The various steps for the FEA process have been shown in figure 5. The plots of magnetic field density along with magnetic flux lines for 1 Ampere of applied current obtained using ANSYS Maxwell software v16 have been demonstrated in figure 6a and figure 6b.

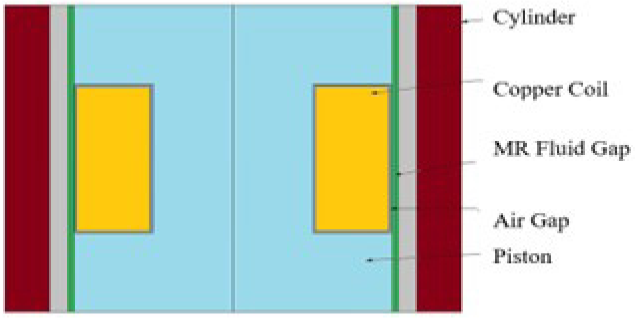

Figure 4: 2D axi-symmetric geometric model of MR damper.

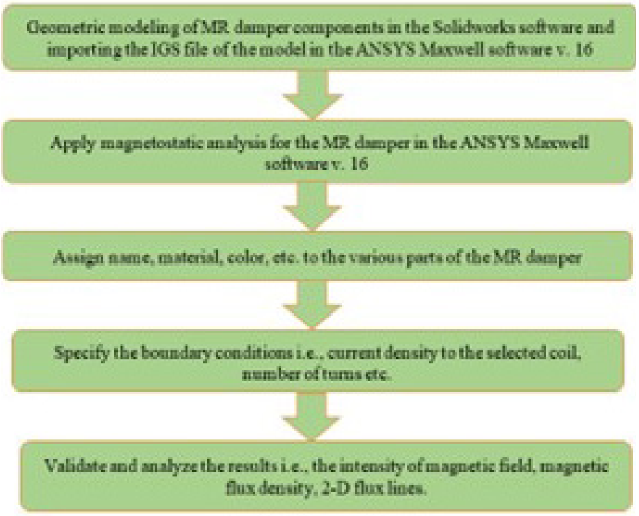

Figure 5: Steps of FEA using ANSYS Maxwell software v16.

Results and Discussion

There are several parameters contributing to the potential of MR dampers such as input current, internal radius of the piston, fluid gap, pole length, cylinder thickness, etc. The simulation methods like FEA can be a crucial option on account of the higher cost of MR dampers development. The computational modeling using FEA can easily examine the potential change with alteration in different design factors. The plots for magnetic flux density vs current and shear stress vs current (varying from 0.1 A - 1 A) have been shown in figure 7a and figure 7b, respectively. There is a proportional increase in magnetic flux density and shear stress with the rise in current passing through the coil. In ANSYS Maxwell software v16 analysis, magnetic flux density of 0.688 Tesla has been obtained when 1 A current flows through the coil.

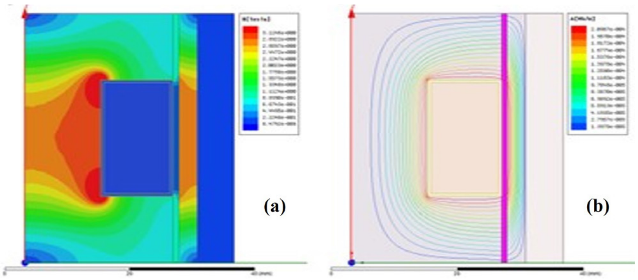

Figure 6: **(a)** Magnetic field density plot and **(b)** Magnetic flux lines plot.

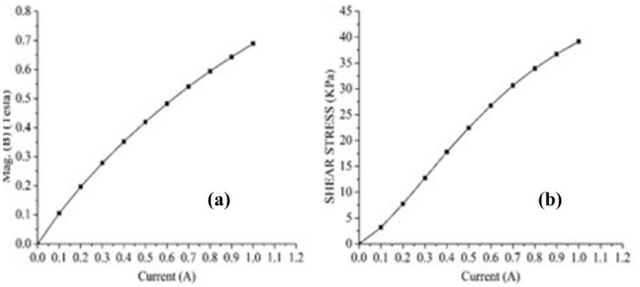

Figure 7: **(a)** Magnetic field density vs current and **(b)** Shear stress vs current.

Table 2 contains the generated magnetic flux density along with shear stress at various currents passing through the coil. A shear stress of 39.15 KPa is generated at 0.688 Tesla of magnetic field density. For analytical modeling of the MR damper, a program in "C" language for electromagnetic circuit theory has been developed to evaluate the produced magnetic field density and shear stress for the modeled MR damper. Electromagnetic circuit theory results indicate a magnetic field density of 0.713 Tesla and shear stress of 40.20 KPa, while FEA simulation results exhibit a value of 0.688 Tesla of magnetic flux density and 39.15 KPa of shear stress for the current flow of 1 A through the coil. On comparing the analytical and FEA results, only a small variation of 3.63% has been observed in the magnetic field density which validated the study. The findings show that both models are appropriate for controlling, designing, and properly depicting the behavior of the MR damper. The results concluded that the value of generated yield stress lies within permissible limits i.e., 50 KPa

Table 2: Impact of variable current on magnetic field density and shear stress.

Current (A)	Magnetic field density (Tesla)	Shear stress (KPa)
0.1	0.1057	3.16
0.2	0.1966	7.72
0.3	0.2777	12.74
0.4	0.3523	17.78
0.5	0.4196	22.46
0.6	0.4826	26.78
0.7	0.5409	30.62
0.8	0.594	33.92
0.9	0.6431	36.74
1	0.6887	39.15

for MRF 132 DG. This clearly shows that the developed FEA model can be used for further analysis.

Conclusion

MR dampers are semi-active controllable devices that utilize MRF which contain magnetic micro-sized/nano-sized Fe particles, non-magnetic-based fluid along with some additives to mitigate sedimentation and agglomeration. The addition of magnetic nano-sized particles improves the sedimentation stability of the fluid relative to other common additives without affecting the MR effect. In this study, magnetostatic analysis and electromagnetic circuit theory have been applied to analyze the modeled MR damper. For analytical modeling of the MR damper, a program in the "C" language has been developed to determine magnetic field density and shear stress. ANSYS Maxwell software v16 is employed to obtain more accurate and realistic results. The software results depict a rise in the value of magnetic flux density and shear stress on increasing the applied current. The value of magnetic field density observed in the MR piston region is much higher than in the MRF region. The FEA results are validated with the help of electromagnetic circuit theory.

Acknowledgments

None.

Conflict of Interest

None.

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