Finite Element Analysis of Magneto- Rheological Fluid Damper

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Abstract- *In recent years, the semi-active suspension has been gaining attention as it provides an adaptable control in damping applications. Magneto-Rheological (MR) Damper is an active control device, filled with magneto rheological (smart) fluid that is controlled by the magnetic field. This study discusses the components, design, working of the MR Damper. A 2D axisymmetric model based on Finite Element Method (FEM) was generated using COMSOL Multiphysics for examining the magnetic flux density in the damper. Results of the analysis are used for calculating characteristics of damping force and velocity relation of the damper. Parameters in MR damper design are varied for understanding the effects on performance. The results of this paper will be help in understanding influential design parameters and the data can be used in future studies for generating an optimized design of the device according to the required application.*

Keywords- Magneto-Rheological Fluid, Damper, Semi- active Suspension, Finite Element Method

I. INTRODUCTION

Passive suspension systems are limited in performance as its components can only store or dissipate energy with constant damping and will not generate energy which is not sufficient for satisfying comfort, control, or handling requirements. The passive suspension includes a spring with a hydraulic or pneumatic damper with fixed coefficients. Semi- active suspension employs similar arrangement but with an adjustable damper with a fast response time (< 10 ms), where the damping force is controlled in real time [14]. Active vibration control devices are in need due to increasing performance demands with precise control in several applications like automobiles, buildings, aerospace, and robotics. For such system MR Damper can be successfully used, as it has a simple construction, quick response to the given control signals, low control power and reduced need of maintenance.

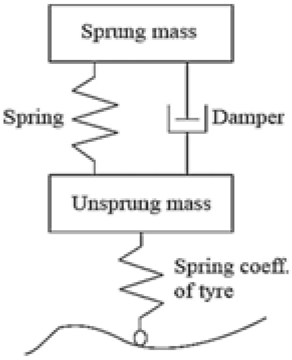

Figure 1: Passive Suspension

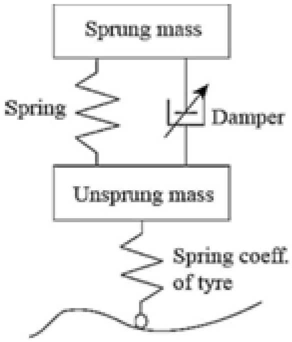

Figure 2: Active Suspension

Magneto-Rheological Fluid

MR fluid consists of 20-40% by volume of relatively pure 3– 10-micron diameter sized magnetizable particle such as iron oxide, iron carbide, low-carbon steel, silicon steel, nickel, cobalt, iron nitride, unreduced carbonyl iron, chromium dioxide, reduced carbonyl iron and combinations, suspended in carrier fluids such as mineral oil, synthetic oil, water, ethylene glycol [10]. Rheological properties of the MR fluid (smart material) can be varied by applying a magnetic field. It has two states of operation, if no magnetic field is applied it acts as a free-flowing liquid known as OFF state and its viscosity, yield stress can be controlled (increased or decreased) on application of magnetic field known as ON state. There are different modes of operationin MR fluids depending on the application like flow mode, shear mode, squeeze mode and pinch mode (Figure 2). [15]

a. Flow Mode: Fluid flow is parallel to the fixed contact surfaces and perpendicular to the direction of applied magnetic field
b. Shear Mode: One of the contact walls move with a given velocity in the direction of the wall and perpendicular to the applied magnetic field
c. Squeeze Mode: Direction of the velocity of the wall is perpendicular to the wall and parallel to the direction of applied magnetic field
d. Pinch Mode: Magnetic field is applied in the direction of fluid flow and the only activated part of the MR fluid is near the separating non-magnetic spacer

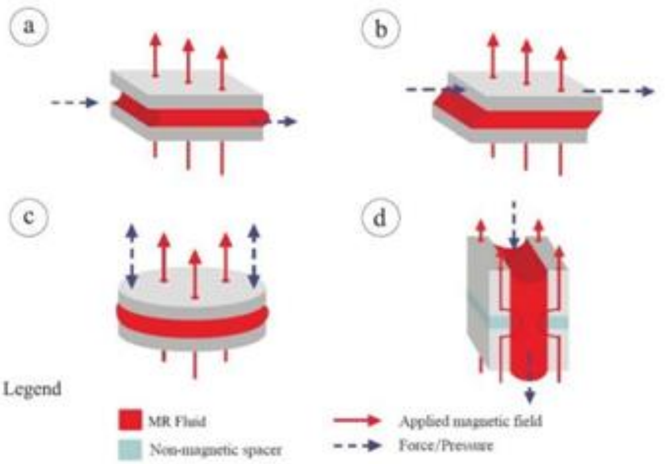

Figure 2: MR fluid working modes [15]

MR fluid behaves in a Newtonian manner in its OFF state. As a magnetic field is applied it causes the microscopic suspended particles in the fluid to become uniformly orientated and form chains along the magnetic flux lines (Figure 3). This temporarily changes the rheological behavior of the fluid [12]. When the fluid is operating in flow mode (i.e., flow perpendicular to magnetic flux lines), there is a nonlinear yield stress exhibited due to the resistance of the micro particle chains in the fluid. In the MR Damper, during active state, MR fluid in fluid gap is subjected to magnetic flux lines due to the electromagnetic circuit. Therefore, it behaves similarly as a Bingham plastic.

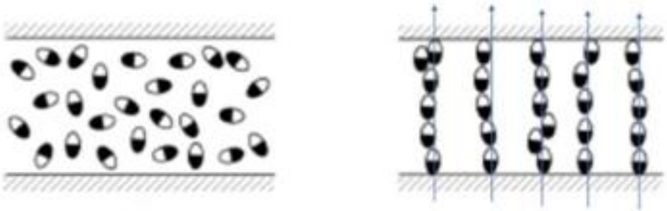

Figure 3: Particle orientation in absence and presence of the magnetic field

MR damper

There are several types MR dampers like Mono tube, Twin Tube, and Double ended. The main components that can be seen in a MR damper are as following:

- Cylinder
- Piston
- Coil
- MR fluid
- Electric supply wires
- Piston rod
- Bearing and seal

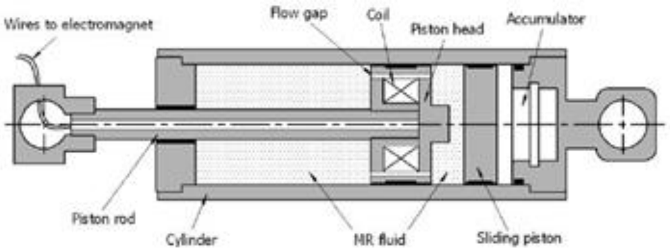

Figure 4: Monotube Damper

This device works in flow mode, here the piston moves inside the cylinder while maintaining a fluid gap in which the coil and the MR fluid stay continuously in contact. The coil is energized through the supply wires in the hollow piston rod. Out of the total MR fluid available only a small percentage of fluid is energized during application. The energized fluid in the gap affects the damping properties of the device. A rod-volume compensator (e.g. the accumulator in Figure 4) needs to be incorporated into the damper because the volume occupied by the piston rod varies when the rod moves. Proper tuning of the parameters of the feedback system greatly reduces the vibrations and improves structural performance.

- **Mono Tube**

This type of damper has only one reservoir for the MR fluid. As the piston rod moves there is a change in reservoir volume, to accommodate this change an accumulator (sliding piston) is used, which provides a barrier between a compressed gas and MR fluid. (Figure 4) [2]

- **Twin Tube**

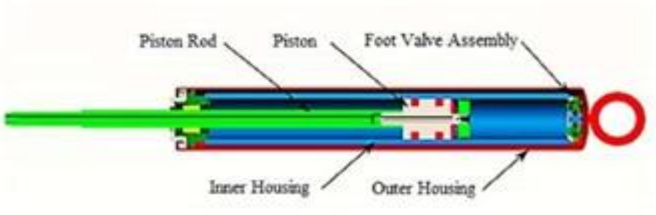

Figure 5: Twin tube MR damper [2]

This type of damper has two fluid reservoirs, one inside of the other. The inner housing is filled with MR fluid that guides the piston assembly. To accommodate the change in the volume due to movement, an outer casing which is partially filled with MR fluid is used. A foot valve assembly is attached to the inner casing to regulate the flow between the two casings. As the piston moves up or down in the inner casing, an equivalent volume of MR fluid is transferred through the valve in between the reservoirs. For proper operation of the twin tube MR damper, the valve stiffness must be adjusted according to the working parameters. [2]

In the twin tube dampers, maintaining suspension of the iron particles (which are an integral part of MR fluid) is a major issue since these iron particles can settle into the valve area and prevent the damper from operating properly. All MR dampers are affected by MR fluid settling, but this problem is particularly prevalent in the twin tube variety.

- **Double ended**

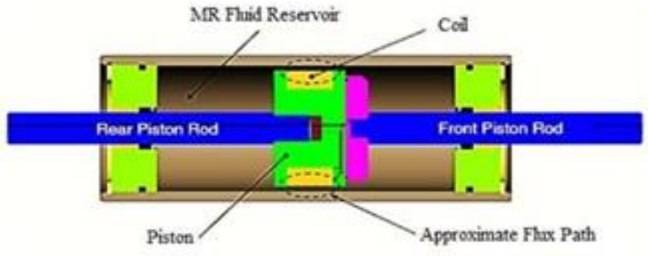

Figure 6: Double ended MR damper [2]

It has 2 piston rods of equal diameter protruding through both ends of damper. Since there is no change in volume as the piston rod moves relative to the damper body, the double-ended damper does not require an accumulator mechanism. They can be used in bicycle applications, gun recoil applications, and for controlling building sway motion caused by wind gusts and earthquakes

II. MATHEMATICAL MODEL FOR MR DAMPER

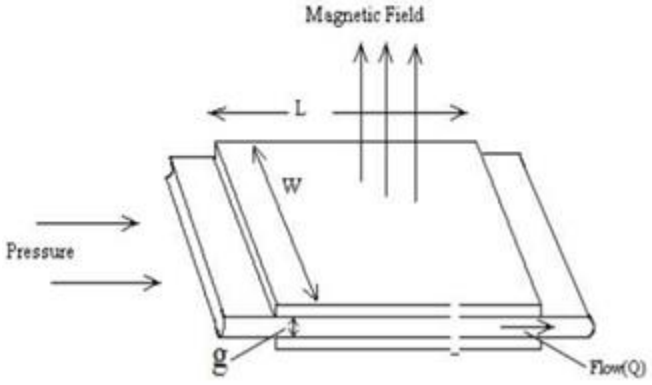

Figure 7: Flow Mode in MR Damper

As stated, the MR fluid has two modes of operation: ON state and OFF state. The fluid has Newtonian like behavior in its off state, while it behaves like a Bingham plastic with variable yield properties in its on state. The following mathematical model provides a good representation of the behavior of the fluid. [1] [8]

The Bingham equations are used to predict the shear stress associated with the flow of MR fluid

$$\tau = \tau_y(B) + \eta\gamma \ , \ \tau > \tau_y \qquad (1)$$

This equation is valid when fluid stresses and above the field dependent yield stress. The MR fluid behaves as a visco-elastic material if fluid stresses are below the field dependent yield stress

$$\tau = G\gamma \ , \ \tau < \tau_y \qquad (2)$$

The pressure drop in the damper is contributed by two components: pressure loss due to viscous drag and pressure loss due to field dependent yield stress [1]

$$\Delta P = \Delta P_\tau + \Delta P\eta$$

$$= \frac{6\eta QLt}{\pi R1_{gg}{}^3} + \frac{c\tau_y L}{gg} \qquad (3)$$

Where R1 is mean circumference of damper’s flow path, is given by R1 = Rp + 0.5g, Lt is total axial length of the piston and *c* is the coefficient that depends on the flow velocity profile and has a value ranging from minimum 2.07 (for ΔPτ/ ΔPη less than 1) to a maximum value 3.07 (for ΔPτ/ ΔPη greater than 100), it is given by following equation [1]

$$cc = 2.07 + \frac{6QQ\mu}{6QQ\mu + 0.4\pi R_1 gg^3 \tau_y}$$

The total damping force has two components: Viscous force component and force due to induced yield stress, and is given by

$$F = F_c + F_y + F_{ff}$$

$$F = \Delta P_\tau A_p \mathrm{sgn}(v) + \Delta P\eta A_p \qquad (5)$$

Where,

$$\text{Effective area of piston} = A_p = \pi\left(R_p^2 - r^2\right)$$

$$\text{Flow rate} = QQ = A_p \times u$$

The dynamic range is used to evaluate the overall performance of an MR Damper. Large value of D is desirable to maximize the effectiveness of the damper.

$$D = 1 + \frac{F_c}{F_{ff} + F_y}$$

Ff is the frictional force in between the moving components

The minimum active volume, which is exposed to the magnetic field, is given by

$$V = k\left(\frac{\mu}{\tau_y^2}\right)\left(\frac{L_t}{L}\right)\lambda W_m$$

Where, k = 12/c

$$\lambda = \Delta P\tau / \Delta P\eta$$

$$W_m = Q \cdot \Delta P\tau$$

III. FEM MODEL SETUP OF MR DAMPER

Analysis Type

In this study, COMSOL Multiphysics FEM tool was used with the AC/DC module to analyze the magnetic field produced in the MR damper. The geometry of the damper is an axisymmetric solid, the computational cost is reduced by using a 2D axisymmetric model (as shown in Figure 9) for the electromagnetic analysis. The piston, MR fluid, and the cylinder are assumed to be stationary components which forms a magnetic circuit around the electromagnetic coil.

3.2 Geometry and Meshing

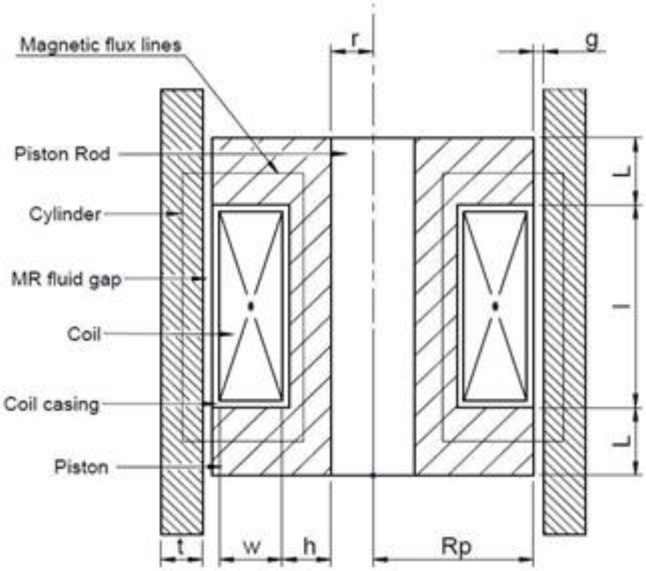

Figure 8: Magnetic circuit in damper

The geometry of the damper is shown in Figure 8. A 2D geometry is generated in COMSOL consisting of coil, air gap, fluid gap, cylinder, and piston (Figure 9). Meshing is done using fine triangular elements. The dimensions of the damper are mentioned in table 1.

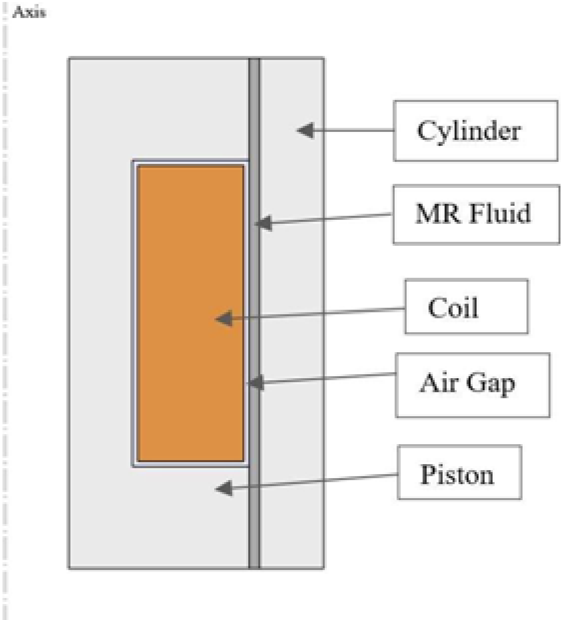

Figure 9: Geometry in COMSOL Multiphysics

Table 1: Design Parameters

Parameters	Dimension (mm)
Pole Length (L)	20
Distance between the poles (l)	30
Radius of Piston (R_p)	23
Piston rod radius (r)	6
Distance from piston rod to coil width (h)	7
Fluid gap (g)	1
Thickness of cylinder (t)	6

Materials

The MR fluid used in the damper in Lord MRF 132-DG and for cylinder, piston a low carbon steel C1010 is used. Both materials exhibit a non-linear magnetic property, their respective B-H curve are shown in Figure 10 & 11. Accordingly, the B-H curve data is linked to the materials in COMSOL. The electromagnetic coil is made up of copper and the coil casing is considered as an air gap.

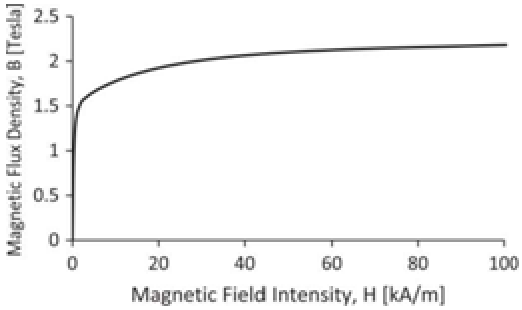

Figure 10: B-H Curve of C1010 Steel

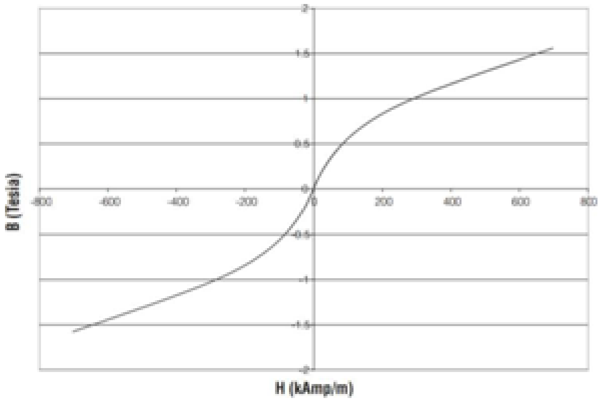

Figure 11: B-H Curve of MRF 132-DG [4]

Table 2: MRF 132-DG properties [4]

Property	Value
Viscosity Pa-s @ 40 °C (104 °F)	0.112 ± 0.02
Density g/cm3	2.95–3.15
Flash Point, °C (°F)	>150 (>302)
Magnetic field strength(H)	150–250 [kA/m]
Operating temperature °C (°F)	−40 to +130 (−40 to +266)

Inputs and Boundary Condition

The coil consists of 500 turns wounded around the piston, a variable input of current ranging from 0-2 A was applied to the coil. Axial symmetry boundary condition is used in the Magnetic Field module. Outer walls of the geometry are insulated. Several parameters like number of turns of coil, Pole length, fluid gap is varied using the parametric sweep function in COMSOL.

IV. RESULTS AND CALCULATIONS

The FEM gave the results of magnetic flux density distribution in the damper. Average magnetic flux density in the annular fluid gap was evaluated, for calculating the values of the field dependent yield stress and damping force. Here 1A current was supplied to a 500-turn coil and the following surface plots were achieved. The arrow plot and contour plots show the magnetic flux direction and affected area when current is supplied to the coil.

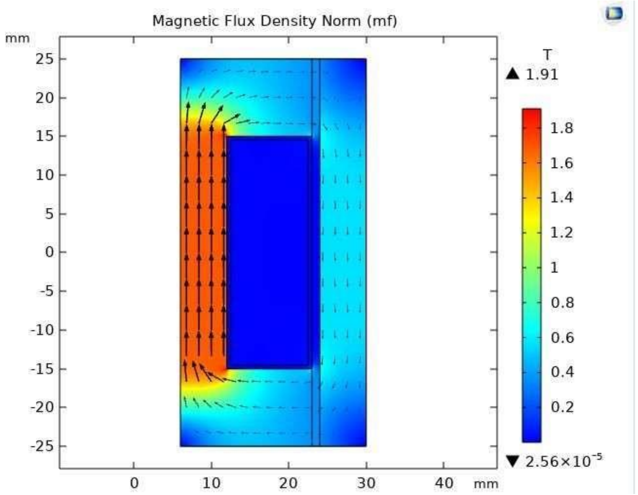

Figure 12: Magnetic Flux Density Surface Plot

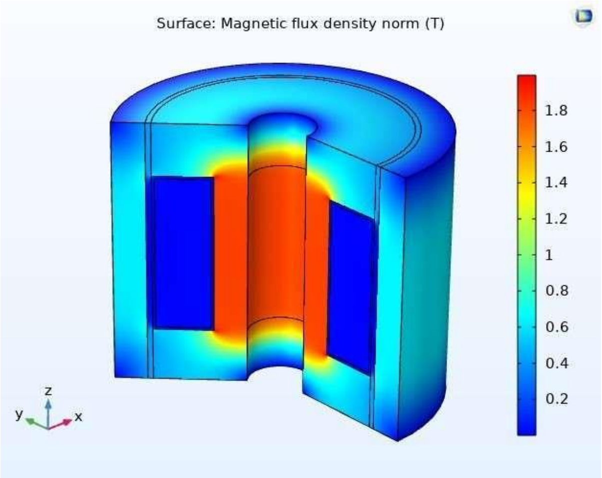

Figure 13: Magnetic Flux Density 3D Plot

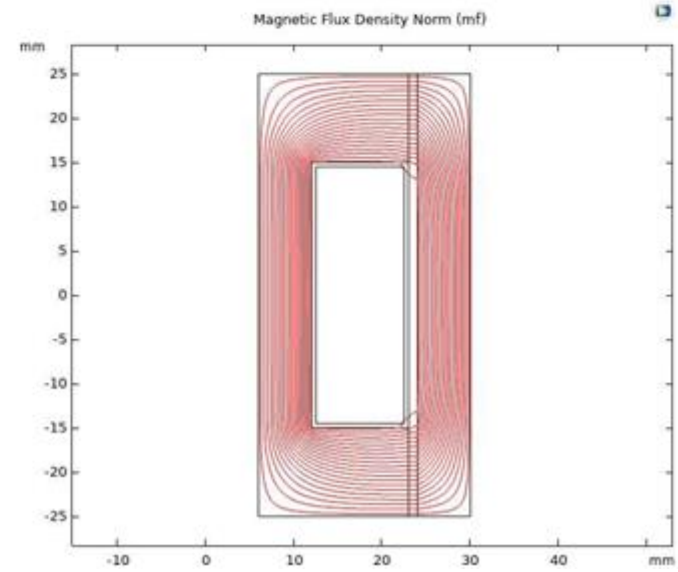

Figure 14: Magnetic Flux Density Contour Lines

Through the contour plot its observed that the flux lines are perpendicular to the fluid gap, thus the device operates in flow mode.

By varying the parameters in the FEM model, we can see the changes in the magnetic flux density in the fluid gap, which influences working characteristics. It is observed that by increasing the current and no. of turns in the coil the magnetic flux increases. As the fluid gap and pole length increases the magnetic flux density decreases. These relationships can be seen in the following graphs.

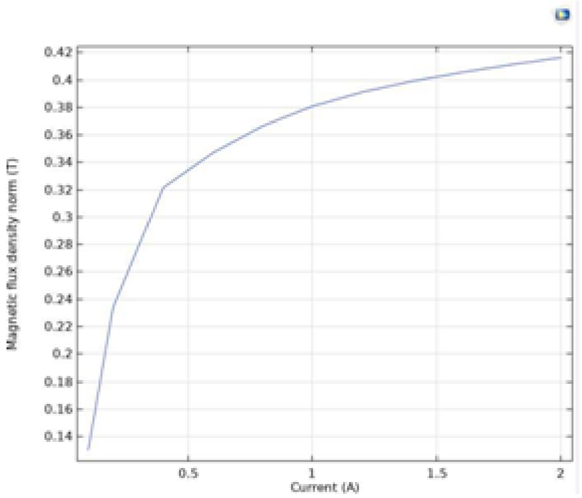

Figure 15: Magnetic Flux Density vs Current

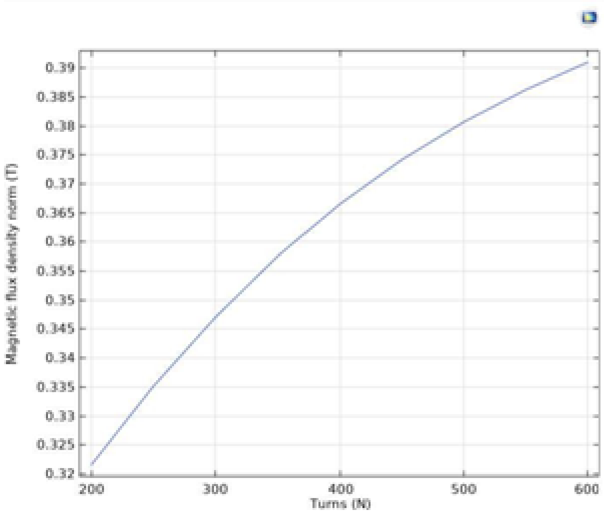

Figure 16: Magnetic Flux Density vs Turns

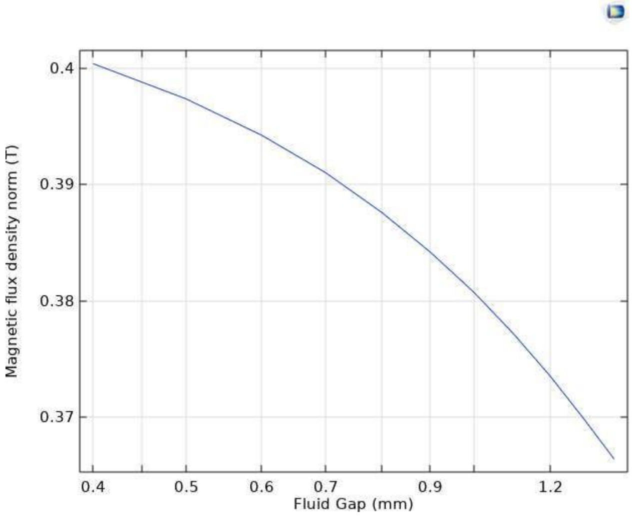

Figure 16: Magnetic Flux Density vs Fluid gap

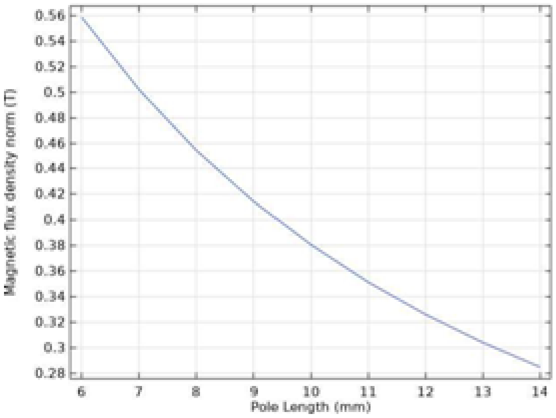

Figure 17: Magnetic Flux Density vs Pole Length

Calculations

In this study, the hydrocarbon-based MR fluid product (MRF-132DG) from Lord Corporation was used. By applying the least-squares curve fitting method to the fluid property specifications (Lord Corporation), the yield stress was determined to be

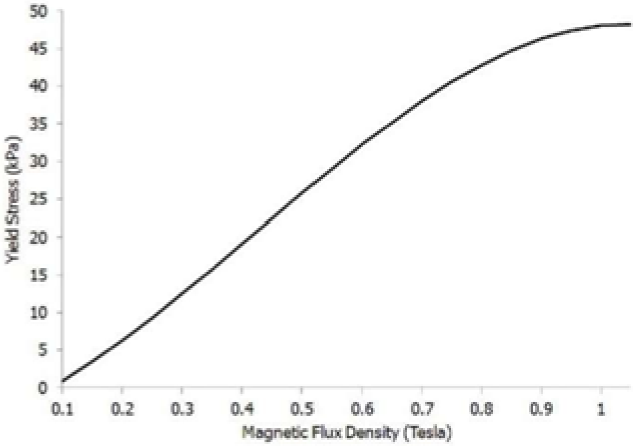

Figure 18: Yield Stress vs Mag. Flux relation in MRF 132DG [4]

$$\tau y = \mathbf{5555.\ 999955}B\mathbf{44} - \mathbf{111199.\ 55}B\mathbf{33} + \mathbf{115511.\ 1199}B\mathbf{55} + \mathbf{1133.\ 117711}B + \mathbf{77.\ 11444455}$$

In the equation, the unit of τ_y is kPa and for magnetic flux desnity B its Tesla (T) [12].

MATLAB was used to calculate damping force values for several velocities of the piston with varying current. The following force and velocity relation is observed in the MR damper. From the graph, its seen that by varying the current, adaptible control is achieved in the damper. The comparison of performance between passive and MR damper suspension is shown in Figure 19.

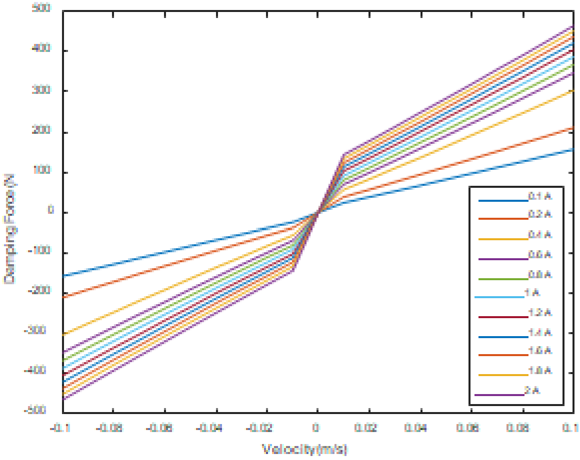

Figure 19: Force-velocity relation in MR damper

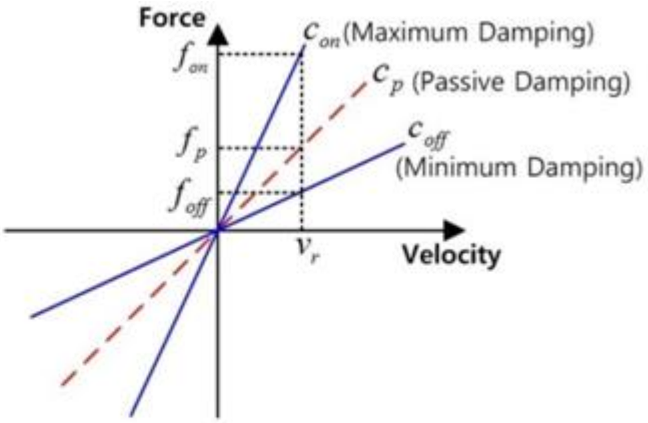

Figure 20: Semi-active and passive damping comparison [8]

The plots show that when the current is low or zero the damping force is very low but as the current is increases the force also increases. Here yield stress force component is greater than the viscous force, which is important factor as good control can be achieved over the damping force.

V. CONCLUSION

In this paper a broad overview of design and modeling of MR dampers is provided as there is an increasing interest and demand for such self-powered and energy harvesting technologies. By performing the FEA in COMSOL Multiphysics, magnetic flux density in the MR fluid was obtained. The damping force was calculated from the analysis results and the controllable range of operation was plotted. Design parameters like turns in coil, fluid gap, pole length is influential for the performance of the damper. The data of performance changes vs the design parameters and will help the designers for generating efficient MR dampers.

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