Design and Development of MR Damper

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I would like to thank Ordnance Factory Medak, for giving me this opportunity. This internship provided me a great chance of learning new things and helped me to utilize my technical skills into the practical world.

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I will use the knowledge and skills gained by working on this project for further improvement in my career. I hope to continue this relation with Ordnance Factory Medak, whenever and wherever my contribution will be required.

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Chapter 1

INTRODUCTION

One of the most recent and promising technologies in vehicle damper design is implementing Magnetorheological (MR) fluids. These smart fluids have the capability to continuously and rapidly change their rheological behavior (viscosity) under applied magnetic fields. Due to these unique characteristics,MR based dampers can provide variable damping force semi-actively by varying the applied magnetic field (varying current), thus they have the capability to control vibration in a wide range of road conditions. Magnetorheological fluid (MRF) consists of a suspension of microscopic magnetizable particles in a non-magnetic carrier medium, the fluid behaves in a Newtonian manner. Applying a magnetic field causes the microscopic particles suspended in the fluid to become uniformly oriented and form chains along the magnetic flux lines. This temporary internal structure changes the fluid's rheological behavior. When flow occurs perpendicular to the magnetic flux lines, the resistance of the micro particle chains causes the fluid to exhibit an yield stress that is not uniform. Thus, when a magnetic field is applied to an MRF in a fluid gap which has flux lines due to electromagnetic circuits, the fluid behaves similarly to a Bingham plastic. Generally, an active suspension system provides high control performance in a wide frequency range, but it requires high power sources, complicated components such as sensors, servo valves, and a sophisticated control algorithm. The semi-active suspension configuration addresses these drawbacks by effectively integrating a tuning control scheme with tunable passive devices. For this, active force generators are replaced by modulated variable compartments such as a variable rate damper and stiffness. Therefore, semi-active suspension can offer desirable performance without requiring large power sources and expensive hardware.

Chapter 2

Design and Modelling of MR damper

Dissipation of energy via volume change is the basic operating principle of dampers. Magneto rheological dampers have the ability to change the viscosity of the fluid because of the magnetic excitation provided to operating fluid. Increasing excitation results in both increased magnetic flux through the fluid and an increased resistance to fluid flow, which ultimately results in increased dissipation of energy per cycle. While all MR dampers operate on the same principle, their fabrication varies. Based on the principle of construction, used MR dampers are classified as either twin tube, mono tube, or double end dampers.Monotube dampers, operate at highest pressures resulting in lowest cavitation and most efficient operation of the damper. Hence the best choice for an automotive damper per the construction consideration is monotube MR damper which was used in this study . The MR damper consists of a main damper housing, a piston and piston rod assembly, and an accumulator. The piston is wound by a multi-turn coil which is the main source of magnetic flux. The piston rod, piston and cylinder are all analyzed using magnetic material through which current is passed to the coil making the electromagnetic circuit in the damper and creating magnetic flux. The main reservoir contains the piston and piston rod assembly submerged in the MR fluid, while the accumulator reservoir contains a compressed, non-oxidizing gas (usually nitrogen) or it can act as secondary reservoir for MR fluid. As the piston rod moves into the damper housing, a volume of fluid equivalent to the volume of the intruding piston rod is displaced through an annular gap of fluid. The accumulator piston then moves toward the bottom of the damper, compressing the nitrogen charge to account for the change in volume. As the piston rod retracts, the accumulator piston elevates the damper tube to counteract the loss of volume.

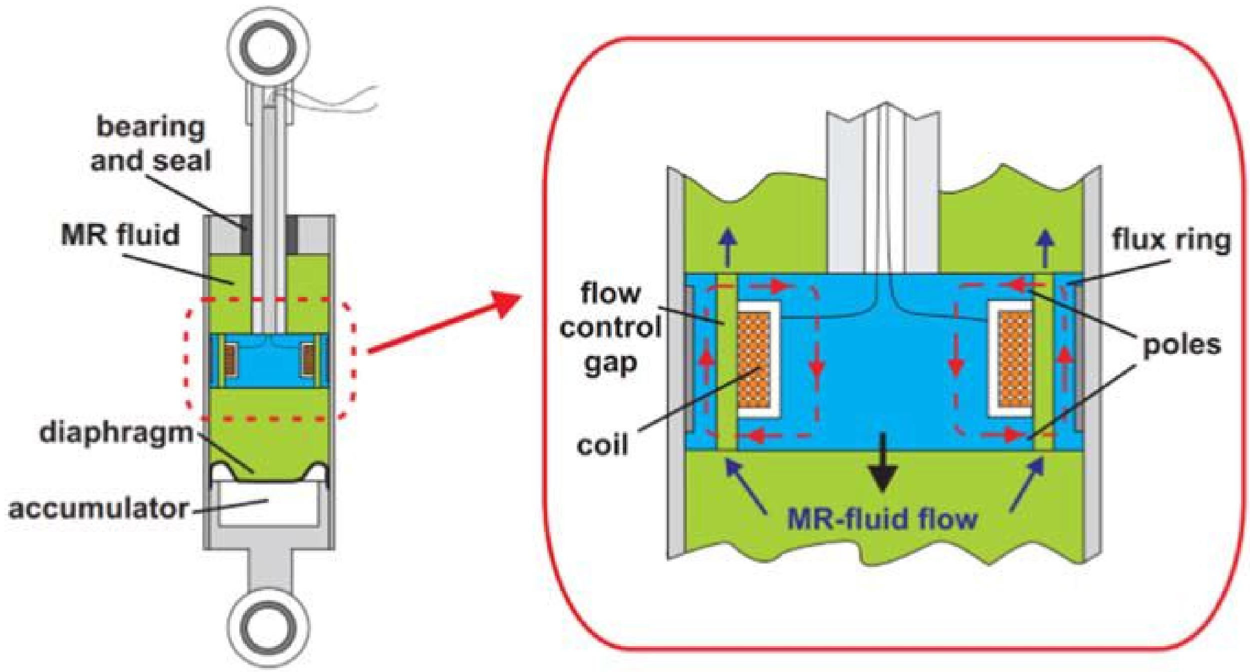


Fig - Design of monotube MR damper

2.1 MR fluids

MR fluids are suspensions of micron-sized (5µm), magnetizable particles in an appropriate carrier liquid which in the absence of an applied magnetic field, exhibit Newtonian-like behavior. In the presence of the field, the induced dipoles force particles aligned with the external field that causes particles forming chain-like structures which restrict the flow of the fluid. This will cause a sudden and significant change in the rheological behavior of MR fluid which is mainly manifested as an increase in the dynamic yield stress or the apparent viscosity of the fluid . This capability of MR fluids to develop a controllable yield stress which is drastically related to the applied magnetic field provides a unique feature to interface mechanical systems with electrical devices in order to control vibration. The change in the yield stress due to the applied magnetic field is very fast and typically yields stress (ranging between 50-100 KPa) and a wider operational temperature range (typically between 233 K to 423 K). MR fluids are much less sensitive to external contaminants.

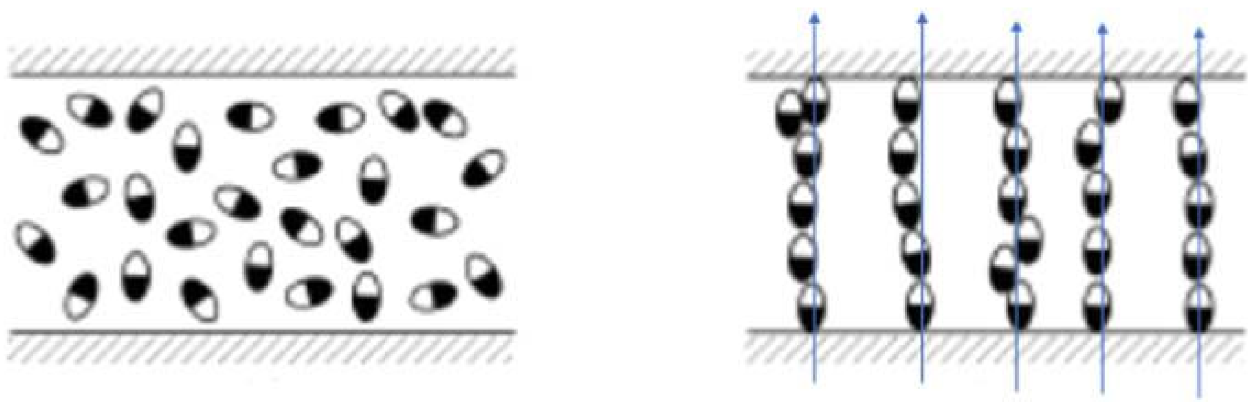


Fig - Example of particle orientation in the (a) absence and (b) presence of magnetic field in the fluid space.

2.2 Mathematical Modelling of MR valves

The equations are derived based on the assumption that the MR fluid exhibits Bingham plastic behavior and the flow is fully developed in the ducts.

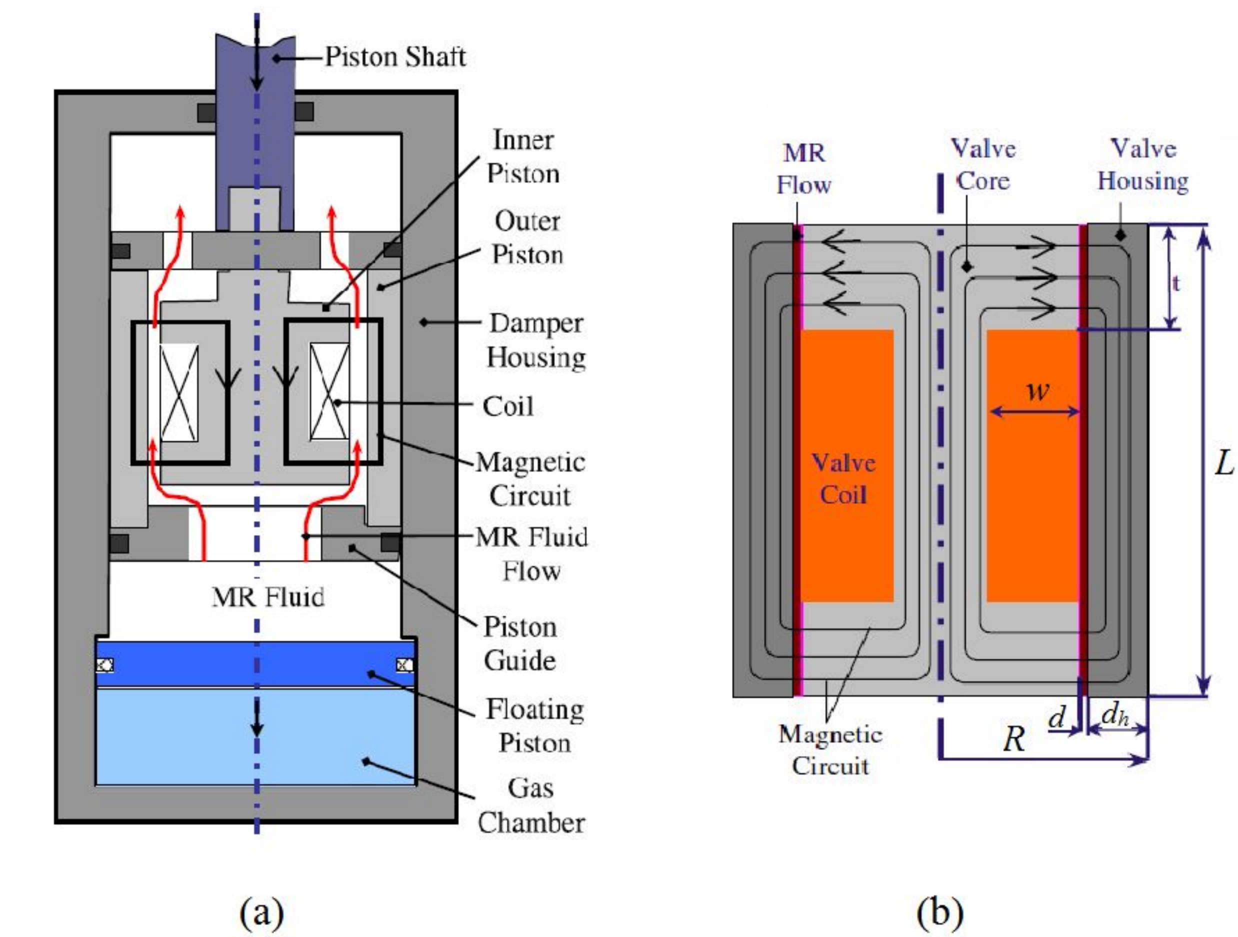


Fig- Schematic configuration of a single-coil MR valve and damper. (a) Single coil MR damper , (b) single coil MR valve

When the coil is electrified, a magnetic circuit appears as shown in the figure. At the two end flanges, flux lines are perpendicular to the flow direction which causes a field dependent resistance on the flow. The pressure drop developed in such kind of MR valve is given by

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{6\eta L}{\pi d^3 R_1} Q + 2c \frac{t}{d} \tau_y \qquad (2.1)$$

According to the above equation, the pressure drop can be divided into a field independent viscous component ΔP_n and an applied field dependent induced yield stress component ΔP_t . In the above equation Q is volumetric rate of flow, η is the viscosity with no applied magnetic field and τ is the yield stress developed as a result of applied field. L, d and w are also length, fluid gap and the pole length of the MR valve, respectively. R_1 is the average radius of the annular duct. The parameter c is a coefficient which depends on the flow velocity profile which can be approximately estimated as follows

$$c = 2.07 + \frac{12Q\eta}{12Q\eta + 0.8\pi R_1 d^2 \tau_y} \tag{2.2}$$

The developed yield stress τ_y in the MR fluid due to the applied magnetic field has been typically characterized for different MR fluids.The experimentally generated yield stress (τ_y) in this kind of MR fluid as a function of the applied magnetic field intensity (H_{MR}) is analytically expressed as

$$\tau_y = C_0 + C_1 H_{MR} + C_2 H_{MR}^2 + C_3 H_{MR}^3 \tag{2.3}$$

in which the unit of the yield stress is kPa, and the unit of magnetic field intensity is kAm^{-1}. C_0, C_1,C_2, and C_3 are the coefficients. In order to calculate the pressure drop of the MR valves, first its magnetic circuit should be analyzed to calculate the magnetic field intensity in the activation region. Then, from the magnetic circuit solution, the yield stress of MR fluid in the active volume (the volume of the MR fluid where the magnetic flux crosses) can be determined by Eq. (2.3) , and consequently the pressure drop can be obtained using Eq. (2.1).

2.2.1 Damping Force

The damping force of the MR damper can be expressed as follows:

$$F_d = P_2 A_P - P_1 (A_p - A_s) \tag{2.4}$$

where A_p and A_s are the piston and the piston-shaft areas, respectively. P_1 and P_2 are pressures in the upper and lower chamber of the damper, respectively. The relations between P_1, P_2 and the pressure in the gas chamber, $P_{a,}$ can be expressed as follows:

$$P_2 = Pa \tag{2.5}$$

$$P_1 = Pa - \Delta P \tag{2.6}$$

ΔP is the pressure drop of the MR fluid flows through passing the orifice gap of the valve.The pressure in the gas chamber can be calculated as follows:

$$P_a = P_0 \left(\frac{V_0}{V_0 + A_s x_p} \right)^{\gamma} \tag{2.7}$$

where P_0 and V_0 are the initial pressure and volume of the accumulator. γ is the coefficient of thermal expansion, which ranges from 1.4 to 1.7 for adiabatic expansion. x_p is the piston displacement. From equations (2.4) , (2.5) and (2.6) the damping force can be written as:

$$F_d = P_a A_s + \Delta P(A_p - A_s) \tag{2.8}$$

Combining eqs. (2.1) and (2.8) and considering $Q = (A_p - A_s)\dot{x}_p$
The damping force of the MR damper can be calculated by:

$$F_d = P_a A_s + c_{vis}\dot{x}_p + F_{MR}\,\mathrm{sgn}(\dot{x}_p) \tag{2.9}$$

where,

$$C_{vis} = \frac{6\eta L}{\pi\left(R - d_h - d/2\right)d^3}\left(A_p - A_s\right)^2 \tag{2.10}$$

and

$$F_{MR} = \left(A_p - A_s\right)\frac{2ct}{d}\,\tau_y \tag{2.11}$$

The first term in equation (2.9) represents the elastic force from the gas compliance. The second term represents the damping force due to MR fluid viscosity. The third term is the force due to the yield stress of the MR fluid, which can be continuously controlled by the intensity of the magnetic field through the MR fluid ducts. This is the dominant term of the damping force, which is expected to have a large value in MR damper design.

2.2.2 Dynamic Range

The dynamic range of the damper (defined as the ratio of the peak force with a maximum current input to the one with zero current input) can be approximately expressed as follows:

$$\lambda = \frac{\Delta P_\eta}{\Delta P_\tau} = \frac{3\eta LQ}{\pi d^2 R_1 c t \tau_y} \tag{2.12}$$

The dynamic range is also an important parameter in evaluating the overall performance of theMR damper. A large value of the dynamic range is expected to provide a wide control range of the MR damper.

2.2.3 Inductive time constant of the valves

For real-time control applications, fast time response of the system is desired. Therefore, in MR valve design, the inductive time constant of the valve is an important factor to implement MR damper in practical application. The inductive time constant of the valves, can be stated as:

$$T = L_{in}/R_w \tag{2.13}$$

where L_{in} is the inductance of the valve coil given by $L_{in} = N^* \Phi/I$ and R_w is the resistance of the coil wire. I is the electric current applied to the valve. N is the number of coil turns and Φ is the magnetic flux generated in the circuit.

Chapter 3

Magnetic circuit theory

It is well-known that modeling MR fluids based systems is a multi-physics analysis problem: based on both electromagnetic analysis and fluid system analysis. To facilitate the depth of this research, electromagnetic analysis was the sole focus. The purpose of such modeling was to find the relation between the applied electric power (usually the current applied to the coils) and the output magnetic flux density and intensity which changes yield stress of the fluid. In order to accurately and effectively model MR damper, first the magnetic circuit of this damper was calculated using Ampere's law stated in equation

$$\int H * dl = N * I \tag{3.1}$$

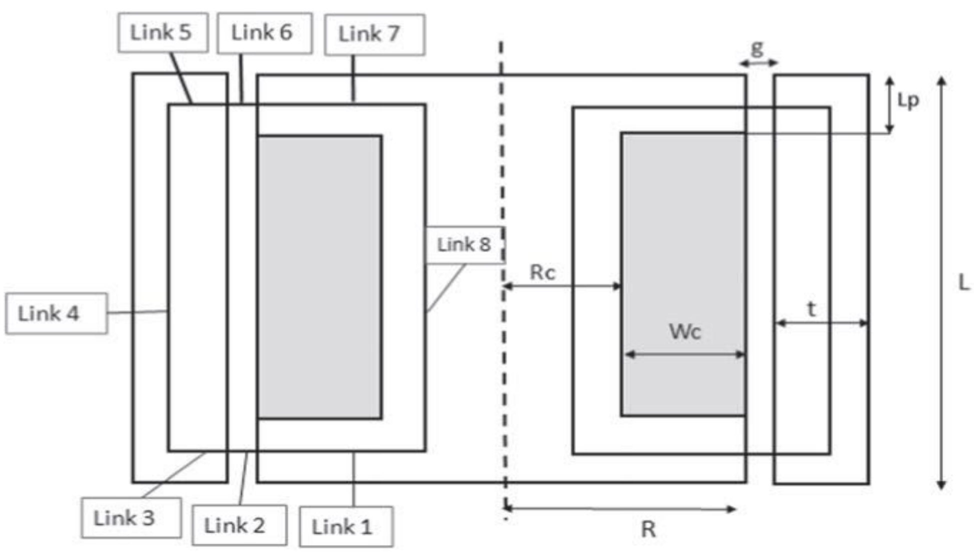


Figure 4. Magnetic circuit of Piston head of MR damper.

eqn(3.1) is rewritten as:

$$\sum_{i=1}^{8} H_i L_i = N * I$$

(3.2)

Magnetic flux is generated because of the current and the number of turns of coil. Magnetic circuit is in the piston head of the MR damper where magnetic flux is generated in the piston head and MR fluid.

$$M_t = \sum_{i=1}^{8} (L_i / \mu_i * A_i) \tag{3.3}$$

L_i is the length of links as shown and μ_i is the relative permeability of material. The Magnetic flux generated in the circuit is given by:

$$\Phi = B_i * A_i \tag{3.4}$$

Parameters used for calculation of magnetic flux:

Parameter	Expression
Piston radius	R
Piston internal radius	Rc
Pole length	Lp
Piston outer thickness	t
Length of piston head	L
Width of coil	Wc
Fluid annular gap	g

Length of Links for the calculation of magnetic flux as shown in figure 4 are given below which are :

$$L_1 = L_7 = R - R_c/2 \tag{3.5}$$

$$L_2 = L_7 = g \tag{3.6}$$

$$L_3 = L_5 = t/2 \tag{3.7}$$

$$L_4 = L_8 = L - L_p \tag{3.8}$$

And the cross sectional areas of the links are given below :

$$A_1 = A_7 = 2*\pi* L_p*[R - R_c/4] \tag{3.9}$$

$$A_2 = A_6 = 2*\pi* L_p*[R + g/2] \tag{3.10}$$

$$A_3 = A_5 = 2*\pi* L_p*[R +g +t/4] \tag{3.11}$$

$$A_4 = \pi*[(R +g +t)^2 - (R +g +t/2)^2] \tag{3.12}$$

$$A_8 = \pi*(R_c)^2 \tag{3.13}$$

The magnetic flux intensity can be calculated using the following equation:

$$B = \mu_o* \mu_i* H \tag{3.14}$$

where, μ_o is relative permeability of vacuum = $4\pi * 10^{-7}$ H/m and μ_i is the relative permeability of the i_{th} link material. At low magnetic field , the magnetic field intensity over the MR fluid link can be approximated as:

$$H_{MR} = \frac{N \cdot I}{2g + \frac{2 l_1 \mu_m a_2}{\mu a_1} + \frac{2 l_3 \mu_m a_2}{\mu \cdot a_3} + \frac{l_4 \mu_m a_2}{\mu \cdot a_4} + \frac{l_8 \mu_m a_2}{\mu \cdot a_8}}$$

Chapter 4

Optimization

For fast time response MR damper is also expected in order to improve the controllability of the suspension system.
We need

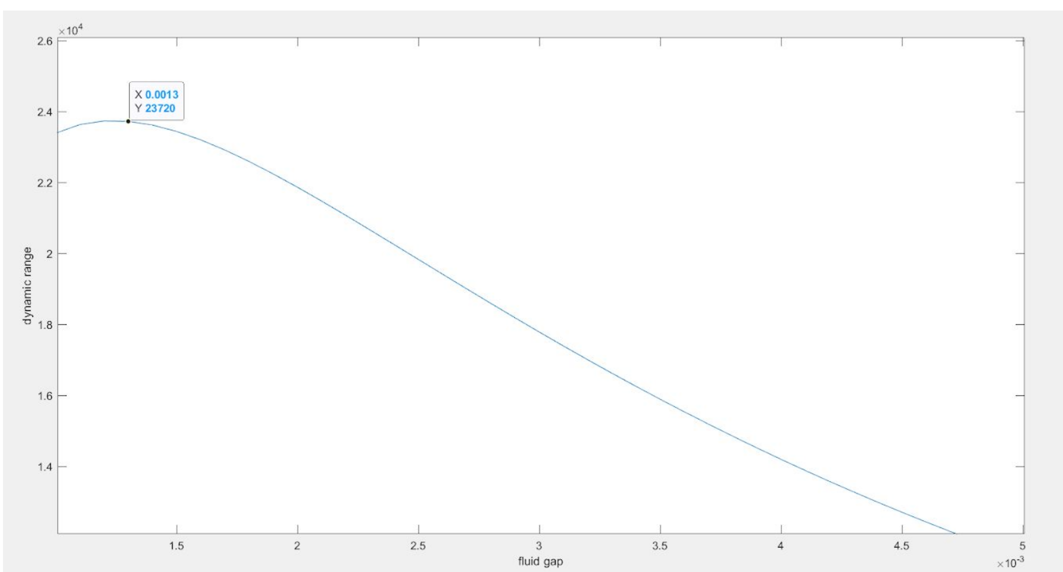
1) High dynamic range

2) More damping force or required damping force

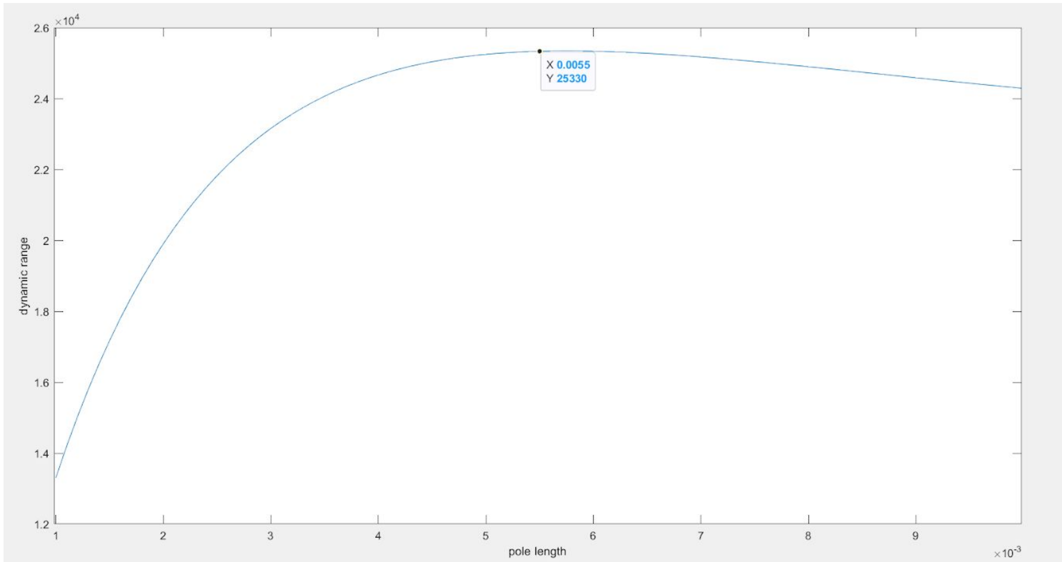
3) Fast time response

By using mathematical model of MR damper and matlab simulation, we optimized the parameters like fluid gap and pole length for maximum dynamic range :

- ❏ Fluid Gap (g):



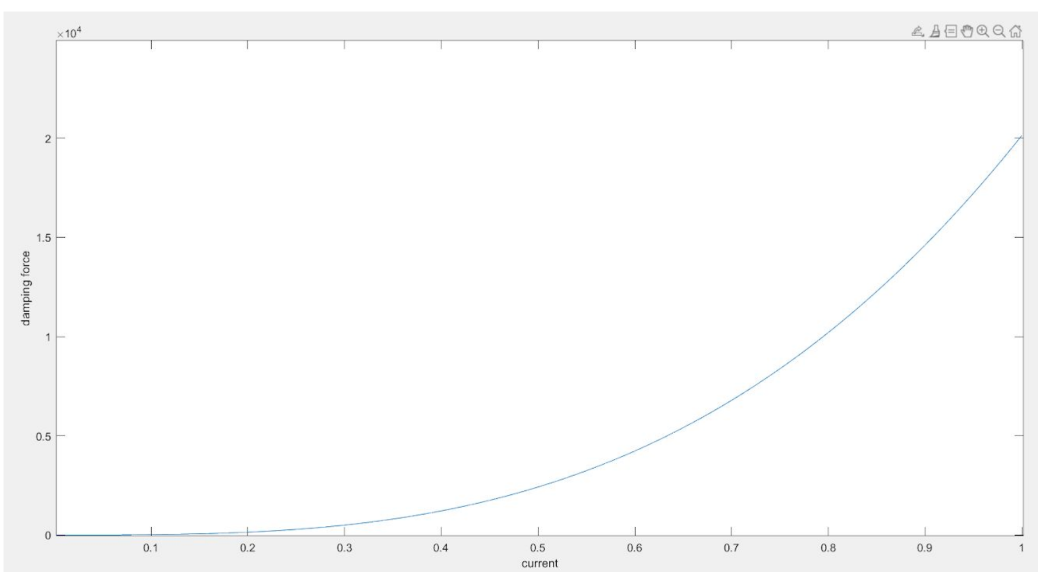
- ❑ Pole Length (L_p):



After optimizing we got:

- ❑ Fluid gap = 1.3 mm
- ❑ Pole length = 5.5 mm

Now we plot the damping force vs current plot:



Chapter 5

Dimensions

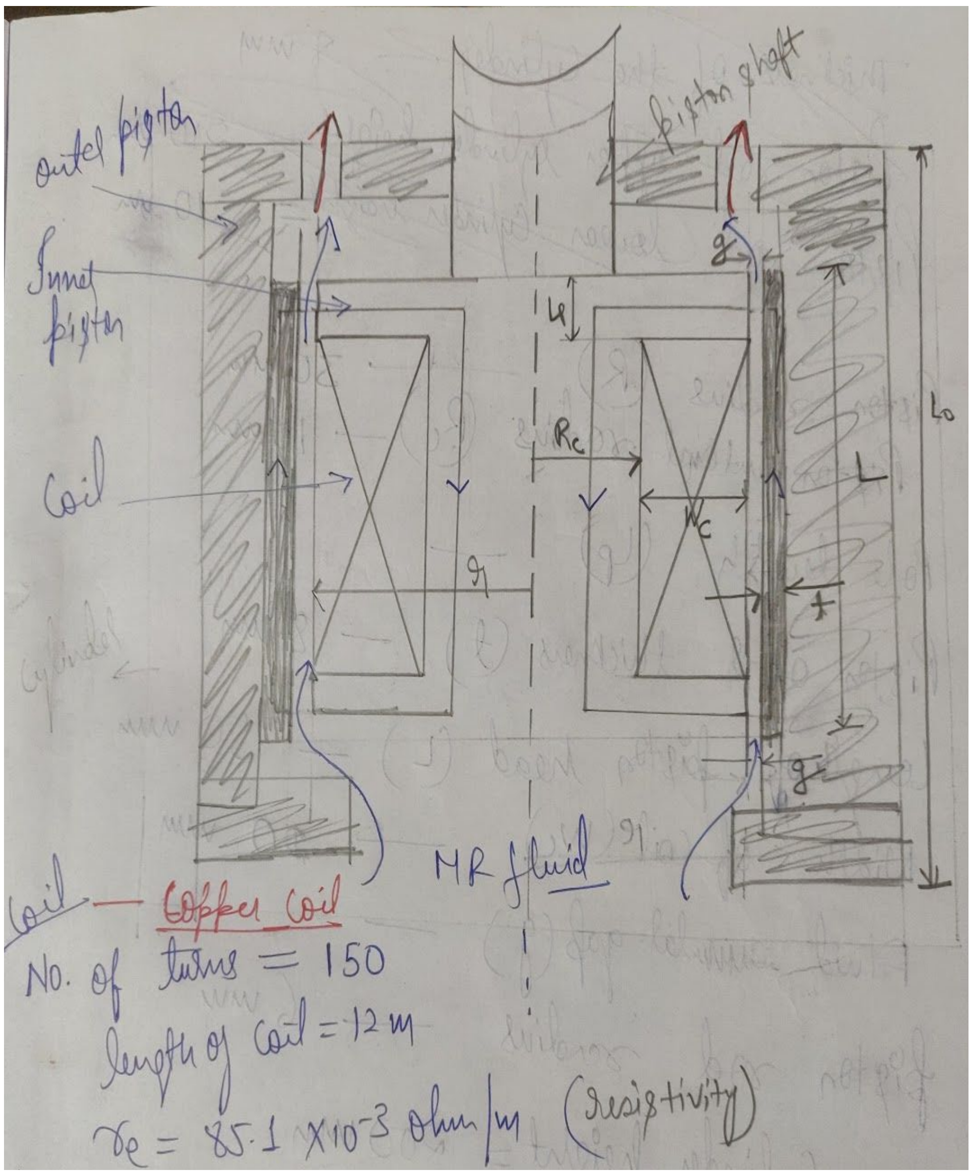


Fig 5 : Schematic diagram of pistons

Piston radius (R) — 30 mm

Piston internal radius (R_i) — 10 mm

Pole length (L_p) — 5.5 mm

Piston outer thickness (t) — 8 mm

Length of piston head (L) — 50 mm

Width of coil (W_c) — 20 mm

Fluid annular gap (g) — 1.3 mm

piston rod radius — 6 mm

Cylinder height = 200 mm

thickness of the Cylinder = 8 mm

Cylinder radius outer = 50 mm

outer piston height (L_o) = 75 mm

Chapter 6

Components and Manufacturing

6.1 Damper Cylinder:-

The cylinder has several purposes including support and protection of the damper's inner parts, casing the liquid and removing heat from the damper liquid to the outsides. One end of the cylinder is fitted with an accumulator with an attachment eye associated therewith by lower end cap. Another or open end of the housing is closed by the end member. MR damper cylinders have more cross sectional surface area for higher value of magnetic saturation. The material of the cylinder should have high permeability, high flux saturation level, small hysteresis loop area and should be magnetically soft. Particularly for this research project, low-carbon steel is selected as a cylinder material. At one end, an accumulator is fitted. At the other end, a cap is fitted in which hole is drilled for passing the piston road with an oil seal.

Low carbon steel AISI 1018

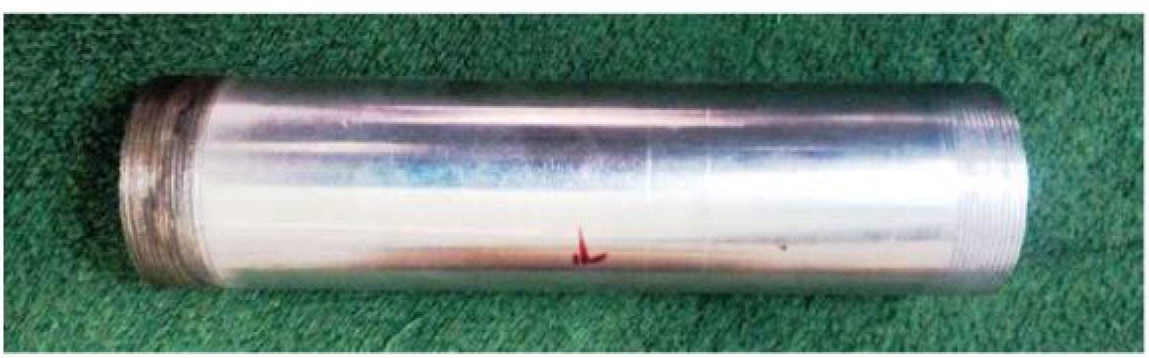


Fig - Damper Cylinder

6.2 Piston and Piston Rod:--

MR damper incorporates the valve as a gap between inside wall of cylinder and piston In MR dampers, movement of the piston has to force liquid through the damper's valving. The piston rod has two purposes. The first purpose is to comprise the channel of the inner cabling which is essential for controlling the damper. Connecting the assembly outside of the damper body for achieving particular application is the second important purpose of the piston rod. Soft iron or steel can be used to achieve better results. For best result, low-carbon steel with high permeability and high flux saturation level is appropriate.

Low carbon steel AISI 1018

Fig - Piston and Piston rod shown with magnetic coil

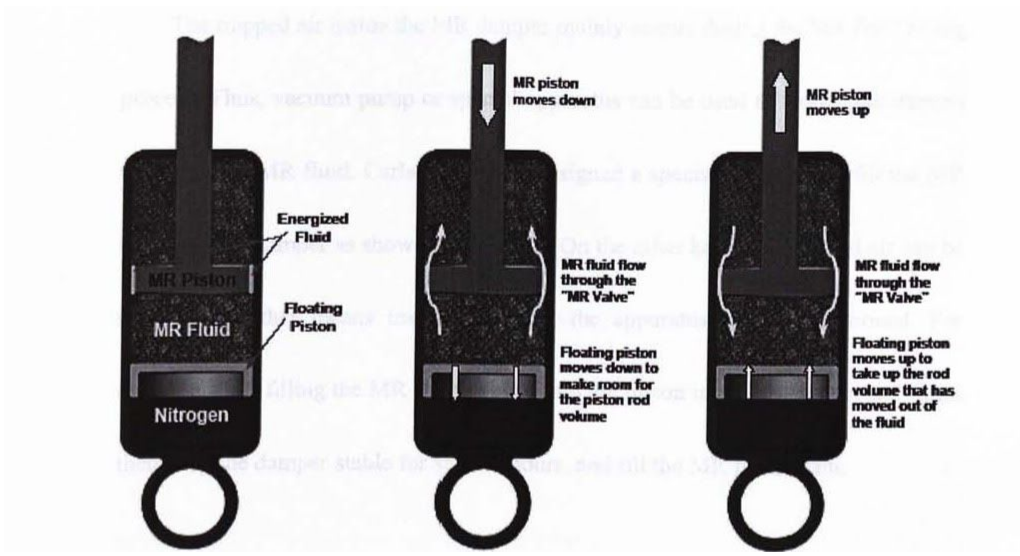
6.3 Accumulator :-

The accumulator has the purpose of compensating for both variations in the volume of MR liquid. One is due to temperature change and other is due to change in the volume available to the liquid as the piston rod comes in and out from the damper body.We can have two types of accumulator ,first containing gas in which accumulator's piston moves up and down compensating the volume change and second ,accumulator acting as the secondary reservoir of MR fluid in which accumulator supplies and takes out MR fluid from the cylinder compensating the volume change due to piston movement.

Any soft steel alloy non-corrosive in nature.

FIGURE 5.17: Accumulator with lower end cap

The function of accumulator is show below:



6.4 Lower and Upper End Caps :-

The lower and upper end caps are screwed on the lower and upper ends of the cylinder respectively. One end cap holds and guides the piston rod with a seal to prevent leakages of MR fluid from cylinder to outside. It also helps to keep the piston in the centre of housing during operation. Other end cap holds the accumulator.

Fig -Upper end cap with seal

6.5 MR Fluids :-

Table 2. Properties of MRF 132 DG.

Property	Value
Viscosity Pa-s @ 40 °C (104 °F)	0.112 ± 0.02
Density g/cm^3	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)

Properties of three different types of MR fluids

MR fluid	MRF-132LD	MRF-240BS	MRF-336AG
Fluid base	Synthetic oil	Water	Silicone oil
Operable temp. range °C	-40-150	0-70	-40-150
Density (g/cc)	3.055	3.818	3.446
Weight percent solids	80.74%	83.54%	82.02%
Coefficient of thermal expansion	$0.55\text{-}0.67\times10^{-3}$	0.223×10^{-3}	0.58×10^{-3}
Specific heat @ 25°C (J/g °C)	0.80	0.98	0.68
Thermal conductivity (w/w °C)	0.25-1.06	0.83-3.68	0.20-1.88
Flash point (°C)	> 150	>93	> 200
Viscosity @ $10s^{-1}/50s^{-1}$ (Pa-sec)	0.94/0.33	13.6/5.0	8.5

6.6 Assembly of Damper :-

The MR damper is brought together in stages. The main subassemblies and full assembly are shown.

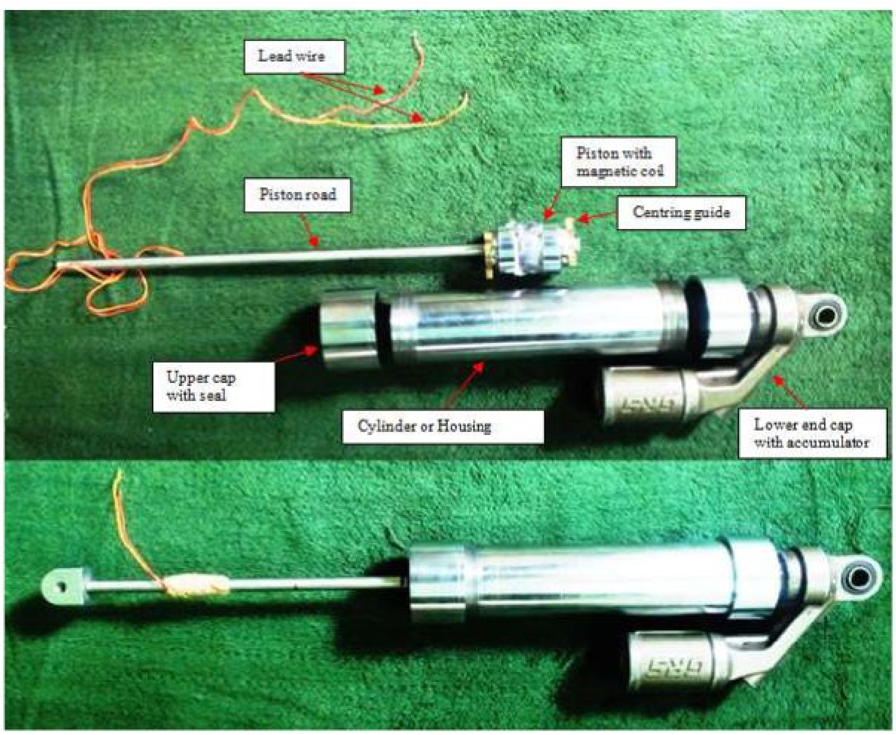


FIGURE 5.19: MR Damper Main Subassemblies

The first step of the assemblies, comprises the piston rod and piston linked together, using the wire taken out from piston to piston road and it passes through inside of the piston road. The second step of assembly consists of the housing with the accumulator via lower end cap. The third step of assembly comprises the upper end cap with seal and piston road. Eye is fitted at the other end of the piston rod for holding the damper in the test rig. After the subassemblies are piece together, the damper is assembled. The final step of assembly comprises filling by addition of MR liquid in the cylinder. This finalises the assembly of the damper.

Chapter 7

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