Design, development and analysis of a magnetorheological damper

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Abstract. Magnetorheological Dampers or MR Dampers are advanced shock absorbers known for their fast response rate, wide dynamic range, mechanical simplicity and low power requirement. MR dampers use smart fluids called MR Fluids which can change dynamic yield stress when acted upon by a magnetic field. The damping force is changed by varying the rheological properties of the fluid magnetically. MR dampers are usually used in high-end automobiles. In this paper, an attempt has been made to make an alternative damper to the existing high-priced MR dampers which can be used in the mid-segment vehicles of today. A new design is proposed by the authors which incorporate the flow of the MR fluid through a hollow passage and focuses on making use of the strong magnetic field created at its center. Silicone oil as a carrier fluid, Carbonyl Iron power and White lithium grease as an additive are selected after studying fluid components. Before fabrication of the new design, numerical calculations are made to evaluate the strength of the magnetic field that is needed to provide suitable yield stress. A permeability around 3000 NA⁻² is expected. This is estimated from the B-H curve for a commercial MR fluid called MRF - 32D. It is noted that a 43 SWG is the most suitable for the damper and with 4 - 5 windings, a maximum induced field of 1.2T (theoretically) can be produced at the center of the primary fluid column. This fluid column exists to a length of 80 mm while the coiling spanned up to 65 mm of the column. It is also concluded that these design parameters will be sufficient to create a strong magnetic field which can exert enough yield stress to give the desired results needed for damping.

1. Introduction

The MR Dampers have seen an increased interest in recent decades due to the various advantages they have over conventional dampers. These fluids are special materials that respond to an applied magnetic field with a dramatic change in their rheological behavior. MR Dampers are well known for dissipating energy on the application of a magnetic field. MR Fluids have special characteristics by which their particles can be instantly and reversibly reorganized within milliseconds on the application of a magnetic field. When the magnetic field is no longer present, the MR Fluid still behaves like a Non-Newtonian Fluid and its closest representation can be given in Bingham plastics [1]. On the application of a field, the suspended particles become polarized which move further to reduce the energy stored in the group. The research on MR fluid has been popular since decades. It was first started in 1948 at the US National Bureau of standards by Jacob Rainbow [2][3] and so has the study on the applications of it. Primarily the MR fluid Dampers were installed at the base of the buildings in an earthquake-prone area to absorb the seismic vibrations following onto a building, in the event of an earthquake. The application of MR fluid appliances was only restricted to buildings, but with a smaller size of MR devices, a wider range
of applications can be expected. There has been a significant amount of study on the MR fluids and its applications. These applications are ranging from MR dampers used in building to reduce seismic shocks to MR fluids used in brakes [4][5]. There has been development by Lord Corporation in the commercial production of MR fluids for the seat of trucks and heavy vehicles [6]. Various designs have been studied in the literature for the MR dampers. One such design uses 3 coils on the piston of the damper adding up to a total of 750 turns, 2 coils on the bottom and top caps having 625 turns of copper wire 26AWG. This damper used the MRF-132DG fluid and would operate at a maximum of 0.4amp [6]. With this assembly, they were able to produce a magnetic flux density of 0.22T at 0.4amp. Similarly, another design of MR damper is presented with 5 coils and can produce a magnetic flux of 2T [7].

In the present work, the authors have developed an MR damper which allows the flow of the MR fluid through the area of maximum flux density (produced by the coil on the damper piston) at the center of the coil. A new MR fluid is produced taking inspiration from work presented by Kcuik et al. [8]

2. Methodology

2.1 Procedure for production of MR fluid
The procedure for making the desired MR Fluid in a laboratory is outlined in the paper by S Elizabeth Premalatha et al (2012) Shreedhar Kolekar (2014) in detail [9]. However, few of the steps have been included here.

Step 1: A mechanical stirrer was used to mix the silicone oil with grease. The mixing was carried out for 1 hour till the grease was visible as suspended particles in the oil.

![Grease mixed with silicone oil.](image)

Step 2: After this solution is prepared, the iron powder is poured into this mixture in small quantities while constantly stirring. As more iron particles are added the fluid becomes more viscous and blacker in colour. This stirring is carried out for about an hour and the result obtained is MR Fluid.
The MR prepared using this method is up to 92% like the reference MR Fluid described earlier.

### 2.2 Material selection for MR Fluid

In order to reduce the cost of MR Fluid, there needs to be an easy way to procure raw materials. There should also be a way to easily manufacture the required MRF at a reasonable price.

The commonly used carrier fluid are mineral oil, synthetic oil and silicone oil. Mineral oils are bad for the environment as they are non-biodegradable. However, synthetic oils cost more. Synthetic oils have various advantages such as better flash point, low IUT (In Use Thickening) at rough working conditions, low friction, high strength and greater viscosity index. Silicone oil, on the other hand, is stable at greater temperatures and possesses the ability to transfer heat easily, it is immune to oxidation, low vapour pressure and high flashpoints. The change in physical properties with respect to temperature is low or negligible and the fluid can be used across a temperature range around -40 to 204 C Hence silicone oil was chosen as our carrier fluid.

Following the above parameters, the following materials have been chosen: Silicon oil (viscosity 0.340 Pas, Density=0.9659gm/ cm-3), Iron particles-4.7μm (BASF 2006) & white lithium grease as an additive:

| Variations | wt. % of materials for the preparation of MR Fluid |
|------------|--------------------------------------------------|
|            | Silicone oil | Fe Particles | Grease |
| A          | 78          | 22           | 12     |
| B          | 60          | 40           | 12     |
| C          | 70          | 30           | 12     |
2.3 Permeability

We aim at achieving a magnetic field of at least 0.5 Tesla so that even with some losses in the magnetic field we can still achieve enough magnetic field for the proper functionality of the MR damper, which is nearly 0.2T.

So, in order to achieve 0.5T, we take the value of H as 85.93 A/m (from Appendix)

\[ B = \mu H \]

Where

- \( B \rightarrow \) Induced field
- \( \mu \rightarrow \) Permeability
- \( H \rightarrow \) Magnetic Field Intensity

\[ \Rightarrow 0.5 = \mu \times 85.9 \]
\[ \Rightarrow \mu = 0.00582072176 \]
\[ \Rightarrow \mu = 5.82 \times 10^{-3} \text{ N.A}^{-2} \]

We know that the permeability of air,

\[ \mu_0 \approx 4\pi \times 10^{-7} \text{ N.A}^{-2} \]  \hspace{1cm} (2)

Therefore, the relative permeability of MR fluid

\[ \mu_r = \frac{\mu}{\mu_0} \]  \hspace{1cm} (3)

Hence the relative permeability of MR Fluid

\[ \mu_r = 4631.98320989 \text{ N.A}^{-2} \]
\[ = 4.63 \times 10^3 \text{ N.A}^{-2} \] (approx.)

Since the Magnetic fluid is taken as reference MRF-132DG which is a commercially produced MR fluid and our production of an MR fluid is not as professional as this, so in order to compensate for the losses, we can assume the permeability of the MR fluid to be 3000 N.A^{-2}.

2.4 Configuration

The selection of an appropriate wire was essential in order to obtain accurate results. So, for the calculation of the diameter of the coil, it was needed to know the length of the area to be coiled. Therefore, different lengths of the coil were taken from 20mm to 80mm. This length is going to be the length between the 2 piston heads. The current was supposed to vary from 0.1 A to 1 A. So, using the equation \( NI = HL \) (2.1), (H obtained from the B-H curve corresponding to B=0.5T).
Table 2. Calculation of the Diameter of the wire to be used for coiling

| Length of the groove (L) | Current (I) | Number of turns (N) | The upper limit of d (mm) | Length of wire (l) | Radius (r) (mm) | Diameter (D) (mm) | Wire Standard | Gauge |
|-------------------------|-------------|---------------------|--------------------------|-------------------|-----------------|------------------|---------------|-------|
| 0.065                   | 0.1         | 359                 | 0.18                     | 44.875            | 0.04            | 0.09             | 39            | 43    |
| 0.065                   | 0.2         | 180                 | 0.36                     | 22.5              | 0.05            | 0.09             | 39            | 43    |
| 0.065                   | 0.3         | 120                 | 0.54                     | 15                | 0.05            | 0.09             | 39            | 43    |
| 0.065                   | 0.4         | 90                  | 0.72                     | 11.25             | 0.05            | 0.09             | 39            | 43    |
| 0.065                   | 0.5         | 72                  | 0.91                     | 9                 | 0.05            | 0.09             | 39            | 43    |
| 0.065                   | 0.6         | 60                  | 1.09                     | 7.5               | 0.05            | 0.09             | 39            | 43    |
| 0.065                   | 0.7         | 52                  | 1.27                     | 6.5               | 0.05            | 0.09             | 39            | 43    |
| 0.065                   | 0.8         | 45                  | 1.45                     | 5.625             | 0.05            | 0.09             | 39            | 43    |
| 0.065                   | 0.9         | 40                  | 1.63                     | 5                 | 0.05            | 0.09             | 39            | 43    |
| 0.065                   | 1           | 36                  | 1.81                     | 4.5               | 0.05            | 0.09             | 39            | 43    |

So, with this knowledge different values of N were calculated. The number of turns divided by the groove length will give the maximum diameter of the wire and using the relation of voltage to current and resistance and the relation of resistance to resistivity, length and area, we calculate the minimum diameter. With this knowledge, we check the corresponding wire gauge.

That is,

\[ L = d \times N; \quad (4) \]

\[ V = I \times R; \quad (5) \]

\[ R = \frac{\rho}{4l} \frac{4l}{\pi d^2}; \quad (6) \]

Table 3. Number of turns per ampere for different currents

| Current (A) | No. of turns (N) | No. of winding |
|------------|------------------|---------------|
|            | 1                | 2            | 3            | 4            |
| 0.1        | 360              | 3600         | 7200         | 10800        | 14400         |
| 0.2        | 180              | 900          | 1800         | 2700         | 3600          |
| 0.3        | 120              | 400          | 800          | 1200         | 1600          |
3. Design of damper

3.1. Modified MR damper design

The design of the MR Damper is based on the required load capacity, size constraints and material availability. An industry-standard damper was chosen as a reference (Maruti Suzuki Baleno) damper and various components of the existing damper were used in the development of the new damper design. The damper design was completely modified. The piston rod dimensions, cylinder dimensions and other dimensions were kept the same as the existing damper while the valves (piston valve and base valve) present in existing damper were removed and replaced. The oil seals were retained from the existing damper and were reused in the new model. The inner tube of the twin-tube damper was regarded as the only tube of the monotube damper.

The main components of an MR damper are the piston, piston-cylinder, electromagnetic coil, MR fluid, electrical wires (copper) and rubber seals. The new design of the MR Damper incorporates the use of a piston which is hollow at the bottom. A groove has been made for the provision of wrapping a copper wire across the surface of the piston. This copper wire wound on the stainless-steel cylinder acts as an Electromagnet. Steel had good permeability, and this enables the creation of a much stronger and intense magnetic field at the of the piston. The piston is wrapped with copper wire of 43 gauge (BWG standard) and wrapped along its length to generate a Magnetic field. Winding the copper wire around the piston helps in creating a magnetic field with field lines flowing through the core and generating maximum strength at the center of the piston. The MR fluid flows through this center of maximum field intensity and is thus affected by it.

This way, by creating an intense magnetic field the viscosity of the MR fluid flowing through the piston can be changed and thus the damping effect whenever current is passed through the coil can also be changed. This helps to dampen the piston while making use of a modified version of Valve mode which is usually seen in conventional dampers. The current was provided to the copper wire using a 12 Volt battery and the copper wire was wrapped onto the surface of the piston between the piston seals.

3.2. Design

Stainless steel AISI (American Iron and Steel Institute) 416 is selected as a suitable material. It is magnetic stainless steel with good relative permeability, excellent machining, good strength and hardness along with corrosion resistivity. Other damper parts materials (inner cylinder, outer cylinder, rubber seals, O-rings) selected were the same which were being used in the existing market dampers.

Going by the concept of the magnetic field generated in a solenoid, the maximum intensity of the field produced is where the crowding of field is maximum at the center of the coil. So we selected the center of the coil to be the activating area for the MR fluid. The dimensions of this were inspired by the damper currently used for the front suspension in a Maruti Suzuki Baleno. The design consists of a piston head, a sleeve, a groove for coiling, hollow columns for the inlet and outlet of the fluid, holes for the wiring.
In the case of the downward motion of the piston, i.e., compression the MR fluid would flow from the bottom of the primary channel and would come out from the secondary channel placed laterally to the primary channel. As the piston would start coming down, it would cause the fluid which was underneath to rise up travelling through the primary channel. This channel will have an activated area which will cause the iron particles to concentrate at that point causing a greater pressure requirement for the fluid to travel hence causing a damping effect. The intensity of the magnetic field can be varied according to the requirement of the stiffness of the damper by changing the current applied. Similarly, when the piston goes up, the fluid rushes down from the top. The second sleeve enables fluid to go through the secondary channel rather than flowing down directly from the walls. It then flows to the primary channel, through the activated area and according to the requirement and the current produces damping effect.
4. Magnetostatic analysis

For the analysis, the intensity of the magnetic field is analysed in 2 positions, 1. Along the axis of the primary column and 2. along a line perpendicular to the axis at the base of the primary column. The goal to obtain a magnetic field of at least 0.5T theoretically. The current is taken to be 600 turns per ampere. This is 1A current and 600 windings in the coil. On analysis, it is found that the magnetic field generated is about 0.015T at the entrance of the primary channel.
Figure 7 Magnetic flux vs distance at bottom of the primary channel.

The above graph figure 7 shows the variation of the magnetic field generated at the bottom of the piston in a line perpendicular to the axis of the piston. It can be noted that the value is found out to be nearly 0.015T at 4 mm from the wall, that is it would come out to be somewhere in the center of the channel. Which is very insufficient pertaining to the fact that we need at least 0.5 Tesla of magnetic field generated at the center for the MR damper to work properly. The reason for such a low magnetic field at the center can be because of the fact there is a very high amount of magnetic field which is lost in the very thick hollow steel column. So, the thickness of the column needs to be reduced. The thickness is then reduced from 5mm to 2mm. In the next stage, the thickness of the wall is reduced to 2mm and the results obtained were very promising. There is a tremendous increase in the magnetic field obtained in the same area that is the base of the MR fluid column about a line perpendicular to the axis of the damper. The coiling is taken to be the same as in the previous analysis to judge to results, that is, a current of 0.2 amperes through 180 turns. The new magnetic field produced was 0.2T that is nearly an increase of 1200% in the magnetic field. The wall thickness is 2mm therefore, stainless steel being nonmagnetic, the value of the magnetic field inside the 2mm (0mm-2mm & 12mm-14mm) wall of the stainless steel is 0.04, while the magnetic field inside the highly permeable magnetorheological fluid is 0.2 and constant throughout. It was further noted that since there is a space in the piston which allowed for more winding of the coil, 4 windings were done. Now, 4 windings of the coil with 180 turns each carrying a current of 0.2 amperes were taken. With this configuration, there was a visible increase in the magnetic field produced in the subjected area. A longitudinal line segment was drawn along the axis of the damper to check the variation in the magnetic field along the MR fluid column. Which this configuration, the maximum magnetic field obtained was 0.4 T which was at the center of the column. Until now, the magnetic fields were checked with a current of 0.2A, but if we decrease the current and simultaneously increase the number of turns there will be an increase in the magnetic field. A 10800 Turns/Ampere configuration can be obtained by winding the coil 4 times through the core at 360 turns and 0.1A of current. It can be seen from figure 8 which represents the magnetic field produced at the entrance of the primary fluid column. The value of the field here is about 0.78T which is quite enough for the functioning of the damper. This is also predicted that the value of the magnetic field must be higher at the center of the primary column, which was then checked.
Figure 8 Magnetic flux vs distance at the bottom of primary channel.

Figure 9 shows the variation in the magnetic field along the axis of the primary column. As expected, the value slowly increases and then after reaching the peak at the center it decreases. For this configuration, we are able to achieve a maximum field of 1.2T as seen in the figure below. Also, it can be duly noted that for the approximate entirety of the primary column in this case, the magnetic field is above 0.5T (i.e., from 2mm to 65mm) which means the whole of the primary column can act as the activation area of the MR fluid.
Figure 10 gives a virtual representation of the magnetic field produced inside the damper. It can be noticed that the magnetic field produced in this case was 1.2T which was high enough for the damper. With this configuration, even if there is a high loss in the field due to some reason the magnetic field so produced is enough for the operation.

5. Fabrication of the Damper

Firstly, a 32 mm diameter and 350 mm long stainless steel 416 tube was bought and was then taken to the manufacturer for machining processes to be carried out on it. In the initial phase (Step 1 in figure 11) of the process, the stainless-steel rod underwent turning in a lathe machine to reduce its diameter to 30 mm (which was the inner diameter of the cylinder). In the next step (Step 2 in figure 11), a groove of length 65 mm was also created to wrap the coil in that groove onto the piston. Further, (Step 3 in figure 11), a bore of 110 mm was drilled at the bottom of the piston for provision of a column used for fluid flow through the piston. Also, grinding of the piston surface was carried out to fit the other components of the Baleno damper and two grooves were also created on both ends of the seals for the purpose of inserting seal locks to keep the piston seals in place upon the movement of the piston. As part of the next step (Step 4 in figure 11) of the process, an exit route for the fluid flowing through the bore inside the piston was created. For this purpose, two diametrically opposite exit holes were created outside the top piston seal to facilitate the movement of the MR fluid in and out of the fluid column. After these steps, 1800 turns, that is, 360 turns x 5 passes of the 43 SWG copper wire were made over the 65 mm groove length (Step 5 in figure 11) according to the calculations mentioned in table 3.
Then (Step 6 in figure 11) for assembly of the damper, the wires were drawn out from the outside of the sleeve and small grooves were made on the inner side of the metal valves so that there was no damage to the wire. A washer was welded just above the secondary channel to avoid its blockage by the metal valve. A rubber disc was placed in between to avoid noises from the metal clicking while its operation. Then finally, the damper was sealed and pressed on the lathe machine and some nitrogen gas was filled into the damper to avoid foaming.

6. Result
The modified MR damper design had the following specifications which were decided after a series of design and simulation stages. These values were found to be optimal to produce a magnetic field intensity of 0.6 Tesla. The fluid produced with 78% Silicone oil as a carrier fluid, 20% Iron particles as magnetic particles and 2% White lithium grease as additive lead to the successful production of a responsive Magnetorheological fluid. The piston physical specifications are the same as the Maruti Suzuki Baleno damper used commercially. Thus, we can say that this MR damper provides a much wider dynamic range of operation, faster response rate and semi-active damping ability over the conventional dampers while having low power requirements.
### Table 4. Results and Discussions

**PHYSICAL DIMENSIONS OF DAMPER**

| Diameter of Piston Rod | Diameter of Groove | Diameter of Piston Heads | Groove Length | Length of Hollow Bore |
|------------------------|-------------------|--------------------------|---------------|----------------------|
| 20mm                   | 18mm              | 30mm                     | 65mm          | 11mm                 |

**MR FLUID SPECIFICATIONS**

| Carrier Fluid       | Magnetic Particles | Additive                 |
|---------------------|--------------------|--------------------------|
| Silicone Oil (350 Cst) | Iron particles (5m diameter) | White Lithium Grease |

**ELECTROMAGNET COILING SPECIFICATIONS**

| Wire Gauge | Voltage | Allowed Current | Length of Wire | No. Of Turns | Core Length |
|------------|---------|-----------------|----------------|--------------|-------------|
| 38 AWG/43 SWG | 12 V      | 0.1A - 0.3A    | 11.310m         | 1800         | 65mm        |

The maximum magnetic field induced inside the damper was at the very center of the MR fluid primary channel, going up to a maximum of 0.6T theoretically and the minimum was at the bottom and the top of the MR fluid primary channel and that too at the wall of the channel which was about 0.1T and 0.05T for the above windings. A 43 SWG gauge wire can be used to produce enough magnetic field inside the MR fluid column at 0.2A and 0.1A current with 4 windings and the damper should work fine. An extra winding can be used so that the damper can also operate well in a 0.2 A current allowing a greater spectrum of the induced magnetic field.

### 7. Conclusions

The following conclusions have been drawn from the above study:

- When the current was taken to be 2700 turns per ampere in the form of 0.2 amperes through 180 turns, it was found that the magnetic field generated was about 0.015T at the center of the hollow channel. As we need a field of at least 1T or 2T at the center of the damper to work effectively, the thickness of the hollow part of the piston was reduced from 5 mm to 2 mm.
- In the next stage, the thickness of the wall was taken to be 2 mm and there was a shooting increase in the magnetic field obtained in the same area. The coiling was kept the same as in the previous analysis, that is, a current of 0.2 amperes through 180 turns. The new magnetic field produced was 0.2T that is nearly an increase of 1200% from the previous value.
- In order to use the piston area efficiently, 4 windings were used instead of 1. This configuration could produce 0.4T at the center of the hollow channel.
- As there was a significant increase in the magnetic field strength, more windings were used to produce maximum magnetic field strength in the physical constraints of the damper. A magnetic field of 0.6T was produced with 5 windings which were sufficient for the operation of the damper.
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Appendix

figure A1: BH curve of MRF 132DG.

(Courtesy: http://www.lordmrstore.com/ literature 231215/Data_Sheet - MRF-132DG_Magneto-Rheological_Fluid)

table a1: Corresponding table obtained by curve sketching

| H       | B   | H       | B   | H       | B   | H       | B   |
|---------|-----|---------|-----|---------|-----|---------|-----|
| -694.733| -1.58| -96.2383| -0.56| 148.8281| 0.70| 440.0905| 1.21|
| -617.081| -1.47| -56.1762| -0.38| -335.039| -1.08| 492.6212| 1.29|
| -539.435| -1.36| -25.2397| -0.19| -233.387| -0.91| 541.7166| 1.35|
| -461.79 | -1.26| 0       | 0.00| 189.9716| 0.81| 589.6714| 1.41|
| -388.714| -1.16| 18.36929| 0.15| 237.9527| 0.90| 649.0527| 1.50|
| -281.361| -0.99| 43.58269| 0.31| 290.4965| 1.00| 694.7261| 1.56|
| -192.26 | -0.83| 66.48185| 0.42| 352.1625| 1.09| 114.5287| 0.60|
| -139.689| -0.70| 85.93594| 0.50| 400.1238| 1.16|        |     |
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