FINITE ELEMENT BASED MODELING OF MAGNETORHEOLOGICAL DAMPERS

A Thesis by

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FINITE ELEMENT BASED MODELING OF MAGNETORHEOLOGICAL DAMPERS

The following faculty members have examined the final copy of this thesis for form and content and recommend that it be accepted in practical fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

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Behnam Bahr, Committee Chair

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Hamid M. Lankarani, Committee Member

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Bayram Yildrim, Committee Member
Dedicated To My Parents
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ABSTRACT

For an efficient damper design, a design engineer always faces the challenge of providing the largest forces in the most compact and efficient envelope. It is important to identify the nature of the force required at the output in order to configure the damper to produce more force in less space. This thesis takes into consideration the role of MagnetoRheological (MR) fluids played when used in conjunction with dampers. In order to achieve this purpose, a finite element model is constructed to analyze and examine a 2-D axisymmetric MR damper. The results obtained in this thesis will help designers to create more efficient and reliable MR dampers. With the help of finite element tools, some design analyses are created to change the shape of the piston in the damper or other parameters in the model. The main benefit of this research is to show a 2-D MR damper and generate the magnetic flux density along the MR Fluid gap.

Three different configurations of an MR damper piston were studied in order to determine how changing the shape of the piston affects the maximum force which the damper provides. The variations provided in the MR fluid gap were plotted for magnetic flux density contour before and after reaching the rheological saturation. By increasing the current, the color spectrum of the magnetic flux density will shift to the piston centerline. As the current provided to a reasonably good amount, the force obtained was to a good extent. Thus for constraint or heat buildup limitations, the second model could work the best among the three designs that we considered.

For cases where higher electrical currents can be tolerated, model 2 would be the most advantageous design, since it provides the largest force among the three models.
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CHAPTER 1
INTRODUCTION

1.1 Background for Magneto-Rheological Fluids

Magnetorheology is a branch of rheology that deals with the flow and deformation of the materials under an applied field. The discovery of MR fluids is credited to Jacob Rabinow [1, 2] in 1949. Magnetorheological (MR) fluids are suspensions of non-colloidal (~0.05-10μ m), multi-domain, and magnetically soft particles in organic or aqueous liquids. Upon application of a magnetic field, the rheological properties of these materials are rapidly and reversibly altered [3]. This property comes from the transient aggregation of the solid phase due to the attractive forces between the dipolar moments induced on each particle by the external field and are maximum when the magnetic field applied to any part or object is perpendicular to the flow of the fluid. Another distinct category which also carries or possesses similar characteristics as MR fluids is electro-rheological (ER) fluids. These types of fluids depict As the rheological changes when an electric field is applied to the fluid. Although both fluids exhibit similar traits, ER fluids have a tendency to show relatively small rheological changes and extreme property changes with temperature which are its significant drawbacks & lead to consideration of MR fluids. This consideration comes from the fact that MR fluids require very small amount of voltage and current for the same amount of power output. This is the main reason for MR fluids to be sought after in current research world as a new ‘smart’ fluid.

In addition to the known effects of flow & magnetic field, there are lots of other parameters that do affect the behavior of MR fluid such as thermal, electrical, and acoustic parameters & their associated properties. With the use of MR fluid in application such as a damper, we can easily achieve same damping characteristics by merely replacing the mechanically adjustable springs
with a MR damper. This damper is more effective & gives accurate responses to ensure smooth ride to passengers. Other advantages include superior ride quality, cost effectiveness, less maintenance

1.2 Electrorheological and Magnetorheological Fluids

Electrorheological (ER) and Magnetorheological (MR) fluids are typical phase-change materials where electrical and magnetic fields are applied to control the phase-change [5, 6]. Electrorheological Fluids are suspensions of dielectric particles in non-conducting or weakly conducting solvents. When electric fields are applied across these suspensions they tend to show altered viscous behavior above a critical value of the electric field, with the apparent viscosities increasing by several orders-of magnitude at low shear rates. Above this critical electric field, at low shear stresses the suspensions behave like solids, and at stresses greater than a ‘‘yield stress’’ the suspensions flow with enhanced viscosity. The rheological response is observed to occur in milliseconds, and is reversible. Figure 1.1 shows the dielectric particle distributions in form of BCT structure in the direction of applied the electric field [6]

![Figure 1.1. Formation of Chains in Electrorheological fluids](image-url)
This process is reversible, with a transition time of less than 1 microsecond. Since a phase-change in ER materials is induced by an electric field, the ER effect covers a wide range of temperatures and need not cause temperature changes in the workpiece. In addition, an induced ER solid is much stronger than a system with close-packed particles under earth gravity, employed in pseudo-phase-change fixtures.

Similarly, MR fluids consist of a suspension of ferromagnetic or paramagnetic particles of micrometer size in a non-magnetic carrier fluid. When a magnetic field is applied, the particles become polarized and are thereby arranged into chains or clusters. The chains can further aggregate into columns, when the MR fluid exhibits a solid-like mechanical behavior. Its strength further increases with the external field. Field-induced solidification is reversible and the timescale for the chain formation is in the order of milliseconds. The performance of MR fluids depends on their chemical and physical stability, temperature dependence, zero-field viscosity, response time, and the yield stress. Among these factors, the yield stress, being an indication how strong MR fluids are in a magnetic field, is the key parameter for applications, especially in flexible fixturing [5].

ER and MR fluids have attracted considerable attention recently because the mechanical properties of these fluids can be electrically controlled. The field-induced shear stresses in MR fluids are even larger than for ER fluids in magnitude, which is especially advantageous when processing non-ferrous metals. The property requirements of ER and MR phase change materials for flexible fixturing must be satisfied, such as chemical stability, phase change property stability, fast phase-change, uniformity throughout all the material volume, and fast operation time. The mechanical characteristics of the materials are also important in flexible fixturing applications, such as strength and stiffness in the solid state, variation range of viscosity and
density in the solid and fluid states, and complexity of control and operation. The shear and
tensile strength and stiffness are required to be large, which implies that the viscosity of ER or
MR fluids is required to be very large. The zero-field viscosity is relatively less important in this
specific application. It is crucial to synthesize phase-change materials with acceptable shear and
tension strength in the solid state for fixturing, with a low production.

1.2 Construction of an MR Damper

The basic construction of a MR fluid damper is a suspension of ferromagnetic particles in
any carrier fluid with the particles mostly containing carbon particles as they are relatively cheap
for procurement and also easily available. There are other materials also available commercially
such as alloys of Iron-Cobalt or Iron Nickel and there have been successful attempts to try and
use them for obtaining holding forces and stress of greater magnitude. But, this process is still in
early stages and the high cost of materials such as cobalt and nickel alloys further hinder
exploration opportunities for them. Few names to mention of the available carrier fluids are
silicone oil, kerosene and synthetic oils. A very important factor that needs to be considered is
the application environment for MR damper as that will significantly affect the selection of the
fluid due to the physical properties of these fluids. A variety of carrier fluids being used wide
range of carrier fluids. Apart from temperature, the carrier fluid must be compatible with the
specific applications and not exhibit any irreversible and unwanted property changes. It must
also contain solvents or additives which will prevent sedimentation and promote uniform mixing
of ferromagnetic particles.

A detailed schematic of an MR damper is shown in Fig 1.1. It working is such that the
fluid that’s flows above & below piston cylinder must pass through the valve known as MR
valve which is a fixed diameter opening called as orifice. This orifice has the ability to apply
magnetic field to a fixed volume of magnetic fluid within its volume with the help of an electromagnet. As the magnetic field is turned ON, these results in a change in the behavior of the particles are now aligned rigid due to change in their viscosity. There is a pressure differential created due to change in viscosity which is directly proportional to the force required to move the piston cylinder. The dampening or change in viscosity characteristics of the damper are function of the electric current applied to the electromagnet and one can control it in real time for better and accurate responses.

![Functional representation of an MR damper](image)

Figure 1.2. Functional representation of an MR damper [3]

A typical MR damper will consist of an accumulator which is a pressurized volume of gas and separated from the fluid chamber with the help of a floating piston. This accumulator acts twofold purpose; one is to provide a separation volume for the fluid to fill in as the piston moves down into the cylinder. The second is to provide a pressure offset to the low pressure side.
to avoid cavitations in the MR fluid by reducing the pressure. A working model of MR damper is represented in Fig. 1.3. A careful look and you will see a compact design but still similar to a passive vehicle damper in dimensions. This was achievable due to the design which incorporated the components internally and leaving only two electrical leads for the electromagnet as external parts which are connected to the source. The accumulator serves as the storage for MR fluid when the piston moves downwards and as a barrier to prevent MR fluid getting in contact with the damper housing.

![Configuration of MR damper](image)

Figure 1.3. Configuration of MR damper
(a) Schematic representation, (b) Actual hardware [3]
1.4 Performance of the MR damper

Current vehicle installation dampers often referenced as ‘passive dampers’ are evaluated for their performance based on force vs. velocity characteristics. Fig 1.3 shows the force vs velocity performance for a typical linear viscous damper. The slope of the force vs. velocity line on this performance curve is called as damper coefficient C. In practice, the behavior showed by this line is often bilinear and asymmetric with a different value of damping coefficient C for compression (bounce in the vehicle) and extension (rebound in the vehicle) as shown in Fig 1.4. This asymmetric behavior is due to the final application of damper in a particular vehicle suspension as explained below. The damper when working in series with the vehicle’s primary suspension; the spring is actually working against its basic force when being compressed. However, it gets all the amount of help and support when the force is being rebounded.

For instance, when we are driving vehicle and the wheel passes over a pothole, there is a momentary loss of its contact with the road. In this situation, rebound damping is the force that prevents suspension from rebounding to a physical stop. Since the characteristics of a passive damper are such that there is only one force corresponding to a given velocity, every application needs to have its own damping curve and that is what a ride engineer will typically tune a vehicle for. Hence every vehicle’s passive damper has a pre designed force velocity characteristic which is the confined and pre-designed operational envelope.
Fig. 1.5 represents a force-velocity characteristics for a typical MR damper. The figure clearly shows that it’s the force vs. velocity envelope spanned by an area instead of a plane which is an ideal case for the force in damper to be independent of the velocity of the shaft and is only a function of the current passed into the coil. We can always introduce a controller that can be programmed to control the points within this force – velocity characteristic envelope to have efficient dampening.

Figure 1.4. Bilinear and Asymmetric damping characteristics [3]
A MR damper can be modeled accordingly by

\[ F_{MRDAMPER} = \alpha \cdot i \]  

(1.1)

Where \( \alpha \) is a constant and \( i \) is the damper current. The model in Fig. 1.5 does not capture the fine details of the actual MR damper. The missing pieces to the fine details are saturation in magnetic field, force changes dependant on pressurized accumulator and hysteresis induced due to the electric current. Later chapters when we design a MR damper will show how this approximation is sufficient for designing MR damper for most applications including vehicle suspensions.

1.5 Research Objectives

The primary objectives of this study are to create and design a 2-D axisymmetric MR damper using ANSYS software. Based on the finite element model, provide design analysis of some of the parameters in MR dampers that can have a significant effect on the force-velocity characteristics exhibited by individual MR dampers. Generate the magnetic flux density at the MR fluid gap which will leads us to establish the force or shear stress at that gap and compare it with the theoretical values obtained. Develop different models with different piston geometries that will affect the performance of the damper and detect magnetic saturation by analyzing the 2-D contour nodal solution for the magnetic flux density at the MR fluid gap.

1.6 Outline of Thesis

To achieve the objectives of this study, an MR damper is to be analyzed as a 2-D axisymmetric model using ANSYS software. For a given current, we can determine the magnetic flux density at the damper piston, MR Fluid gap and the housing. After we generate the magnetic flux table for each case, we will use some mathematical equations to solve the shear stress and magnetic induction provided from the model. After that we can establish the magnetic induction – shear stress plots at different current. We begin with Chapter 1 which presents a brief
introduction to MR fluids followed by research objectives and outline for thesis. Chapter 2
includes background information on types of MR fluids, MR damper types and different methods
for modeling MR dampers. Chapter 3 presents the finite element analysis based approach for
modeling magnetorheological dampers. It will include the details of how the model is setup and
all the steps needed to build the 2-D model. Chapter 4 presents the different design analysis of
some of the parameters that can have a significant effect on the force-velocity plot. It will also
include the study of different shapes of the MR damper piston. Chapter 5 is the conclusion
chapter and ties everything together by presenting the important points of this study and
recommendations for future research.
CHAPTER 2
LITERATURE REVIEW AND BACKGROUND

This chapter has an overview on types of MR fluids, dampers and other typical MR fluid devices which are available as of today in the commercial market and are being used in various applications. It also includes various proposals for possible future applications and looks through the past attempts and research conducted on these MR dampers. The information included in this chapter is adapted from reference [1], entitled "Innovative Designs for Magneto-Rheological Dampers", by James Poynor

2.1 MR Fluid

MR fluids are non-colloidal suspensions of magnetizable particles that are on the order of tens of microns (20-50 microns) in diameter. The fluid was developed by Jacob Rabinow at the US national Bureau of Standards in the late 1940’s [7]. Although similar in operation to electro-rheological (ER) fluids and ferrofluids, MR devices are capable of much higher yield strengths when activated. The major difference between ferrofluids and MR fluids is the size of the polarizable particles. Ferrofluids are 1-2 microns in contrast to MR fluids which are 20-50 microns. Early research began with assurance for MR fluid and great interest was developed but it quickly waned off

During the 1990’s it came back into light due to one corporation’s consistent research and development in this field. The name of that corporation was Lord’s Corporation. MR fluid is composed of oil, usually mineral or silicone based, and varying percentages of ferrous particles that have been coated with an anti-coagulant material. When inactivated, MR
fluids display Newtonian-like behavior [8]. Upon activation by a magnetic field or electric current, the ferrous particles dispersed in oil solution, quickly align themselves along the lines of magnetic flux as shown in Figure 2.1.

![Figure 2.1 Arrangement of MR fluid particles in nonenergized and energized modes [7]](image1)

There are three typical modes of operation for MR fluid’s operation. Squeeze mode, valve mode and shear mode. As shown in Fig. 2.2 a device with squeeze mode has a thin wall film ~ 0.02 inch of MR fluid sandwiched between pole surfaces.

![Figure 2.2 MR fluid used in squeeze mode [1]](image2)
As shown in Fig. 2.3 a device with shear mode has a thin wall film (~ 0.05 to 0.015) inch of MR fluid sandwiched between two paramagnetic moving surfaces. The last mode; shear mode is useful in applications where large force is not required such as clutches and brakes.

![Figure 2.3 MR fluid used in shear mode [1]](image)

Most widely used and last mode of operation of MR damper is the valve mode and impedes the flow of MR fluid between two reservoirs as shown in Fig. 2.4.

![Figure 2.4 MR fluid used in valve mode [1]](image)
When MR fluid is used in the valve mode, the areas where MR fluid is exposed to magnetic flux lines are referred to as “activation regions”, for the purpose of this study. In the case of the damper depicted in Figure 2.5, there exist two activation regions. These regions resist the flow of fluid from one side of the piston to the other when a magnetic field is present.

![Figure 2.5 Typical MR damper Design Configuration](image)

As we vary the magnetic field strength, the apparent viscosity of MR fluid gets affected. In this case, the carrier fluid exhibits no change in viscosity; however the mixture of MR fluid becomes thick and even becomes a solid when exposed to magnetic field. This changes the shear strain rate such that the fluid becomes sensitive to shearing as the magnetic field increases. Increase in magnetic field increases the fluid flow resistance at the activation region until we reach saturation current. This saturation current is a stage or a point at which there is no further increase in the damping force even as we increase the electric current for a given velocity. The fluid flow resistance in the activation regions is the force that evidenced in the MR dampers. This can be compared to hydraulic dampers where the force provided is due to the passages of a hydraulic fluid through an orifice. Variable resistance to fluid flow allows us to use MR fluid in electrically controlled viscous dampers and other devices.
2.2 MR Devices

A variety of commercial and industrial applications of MR fluids in addition to dampers or shock absorbers are rotary brakes, clutches, prosthetic devices, and even for uses such as polishing and grinding. One of most innovative commercial applications for MR fluids is the rotary brake. Lord Corporation currently manufactures a MR rotary brake, shown in Figure 2.6, which can be used for exercise equipment, pneumatic actuators, steer-by-wire systems, and other similar applications; according to their sales brochures [7]. This device offers high controllability, fast response time (10 to 30 milliseconds), high torque at low speed, and requires very low power. Other benefits of this device include ease of integration, programmable functionality, rugged construction, and long service life. Functionally, this rotary brake consists of a steel disk that rotates in a bath of MR fluid. The MR fluid is used in shear mode and is activated by an electromagnetic coil that surrounds the periphery of the device [7].

Figure 2.6 Lord Corporation’s rotary MR brake [7]
It’s a single tube construction with an extended length of 8.2 inches and compressed lengths of 6.1 inches measured from centre of one eye to the other eye. In compression stage, this damper is measured from centre of one eye to the other eye.

The damper is capable of exhibiting a minimum of 500 lbs of damping force at velocities larger than 2 in/sec when current of 1 Amp is provided. In no-current or off state, its force is less than 150 lb/sec at velocity of 8 in/sec. The Rheonetic RD-1005-3 MR damper is used in a seat suspension system called the “Motion Master”, which consists of the elements shown in Figure 2.7. This system, which is intended as a retrofit to existing hydraulic truck seat dampers, and used by the original equipment manufacturer, has been very well received by the industry. In fact, in an effort to reduce worker compensation claims, West Virginia school transportation officials are considering a proposal to specify that Motion Master Ride Management Systems be used for all new bus purchases later this year [9].

Figure 2.7 Motion Master MR damper [9]
Variations of this damper are being used for the Lord Motion Master™ truck seat damper [10] as well as for a prosthetic led that is being developed by Biedermann Motech Gmbh [11]. A seat damper application has a control unit and an accelerometer in addition to the small mono tubes which aid in minimizing driver fatigue due to long drives. As demonstrated in Figure 2.9, the prosthetic leg mentioned earlier uses a damper that is very similar to the one that is shown in Figure 2.7.

![Diagram and picture of prosthetic leg](image)

**Figure 2.8** Diagram and picture of prosthetic leg [11]

### 2.3 MR Damper Basics

From gamut of MR devices, until now only MR dampers have been elaborately studied and researched for commercial applications. The success in commercial application areas is beyond the Motion Master System by Lord Corporation [10]. Delphi Corporation recently announced that they plan to manufacture MR dampers and use this technology further in the 2003 Cadillac models [12]. Other proposed applications that still need to be investigated and successfully implemented include building control systems during earthquake mitigation, and gun recoil dampers, for managing the impact dynamics of the gun. Therefore, for the remainder
of this document, we will focus our discussions by describing the common types of MR dampers and the mathematical fundamentals of MR dampers.

2.3.1 Types of MR Dampers

The three main commercially available & developed MR damper types are the mono tube, the twin tubes, and the double-ended MR damper. Of the three; mono tube has been the most common as it can be installed in any orientation and is very compact in size. Fig.2.9. shows a typical mono tube MR damper. It has only one reservoir for the MR fluid and an accumulator mechanism to accommodate the change in volume that results from piston rod movement. The piston accumulator separates the MR fluid and compressed gas (usually nitrogen) by acting as a barrier between them. The compressed gas is used to accommodate changes in volume which occur as the piston rod moves into the accumulator housing.

![Mono tube MR damper section view](image)

Figure 2.9  Mono tube MR damper section view [10]

Twin tube MR damper is fairly similar to mono tube where it has two fluid reservoirs instead of one in mono tube as shown in Fig. 2.10. This type of damper has an inner and outer housing which is separated by a foot valve. Inner housing is responsible to guide the piston rod
assembly which is exactly similar to the working of a mono tubes damper. The enclosed volume by inner housing is called inner reservoir. There is a void or a gap exhibited within inner housing and outer housing which is called as outer reservoir. MR fluid is filled in the inner reservoir and has to be ensured that there are no air pockets in this reservoir.

![Figure 2.10 Twin tube MR damper [10]](image)

As the piston rod moves within the confines of chamber, a volume differential is created and to compensate for the same, the outer reservoir is also partially filled with MR fluid. This construction serves same purpose as that of pneumatic accumulator and mechanism is similar to monotube dampers. A valve assembly called as ‘foot valve’ assembly is also attached to the bottom of inner housing. This valve aids in the flow regulation between the two reservoirs. As the piston rod starts to move from top to bottom within its chamber, the MR fluid is pushed from inner reservoir to the outer reservoir via a compression valve which is a part of foot valve assembly. The quantity of fluid flowing from inner to outer reservoir is equal to the volume displaced by the piston rod while entering the housing. Similarly, as the piston rod starts to move from bottom to top, the MR fluid is pushed from outer reservoir to the inner reservoir via a return valve which is also a part of foot valve assembly.
The final type of MR damper is called a double-ended damper since a piston rod of equal diameter protrudes from both ends of the damper housing. Figure 2.13 illustrates a section view of a typical double-ended MR 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. Double-ended MR dampers have been used for gun recoil applications [13], bicycle applications [14], and for controlling building sway motion caused by wind gusts and earthquakes [15].

![Figure 2.11 Double-ended MR damper](image)

2.4 Mathematical Fundamentals of MR Dampers

In order to understand the following mathematical discussion, please reference to contents of Table 2.1 which lists all the nomenclatures below.
Table 2.1
Mathematical Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>Fluid stress</td>
</tr>
<tr>
<td>$\tau_y$</td>
<td>Yield stress (magnetic or electric field dependant)</td>
</tr>
<tr>
<td>H</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Plastic viscosity ($H=0$)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Shear rate of fluid</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Fluid shear</td>
</tr>
<tr>
<td>G</td>
<td>Complex material modulus</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Pressure drop</td>
</tr>
<tr>
<td>$\eta\Delta P$</td>
<td>Viscous component of pressure drop</td>
</tr>
<tr>
<td>$\tau\Delta P$</td>
<td>Field dependent induced yield stress component of pressure drop</td>
</tr>
<tr>
<td>Q</td>
<td>Pressure driven fluid flow</td>
</tr>
<tr>
<td>L</td>
<td>Length of fluid flow orifice</td>
</tr>
<tr>
<td>b</td>
<td>Outer Radius of the Piston</td>
</tr>
<tr>
<td>D</td>
<td>Piston Diameter</td>
</tr>
<tr>
<td>g</td>
<td>Fluid gap</td>
</tr>
<tr>
<td>w</td>
<td>Width of fluid flow orifice</td>
</tr>
<tr>
<td>c</td>
<td>Constant*</td>
</tr>
<tr>
<td>F</td>
<td>Force developed between pole plates in shear mode</td>
</tr>
<tr>
<td>$F\eta$</td>
<td>Viscous shear force</td>
</tr>
<tr>
<td>$F\tau$</td>
<td>Magnetic dependent shear force</td>
</tr>
<tr>
<td>S</td>
<td>Relative velocity between pole plates used in shear mode</td>
</tr>
<tr>
<td>A</td>
<td>Pole area</td>
</tr>
<tr>
<td>V</td>
<td>Activated fluid volume</td>
</tr>
<tr>
<td>k</td>
<td>Constant</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Control ratio</td>
</tr>
<tr>
<td>Wm</td>
<td>Required controllable mechanical power level</td>
</tr>
</tbody>
</table>
MR fluid is often modeled as a Bingham solid that has yield strength \[6\]. In this model, fluid flow is dictated by Bingham’s equations, which are displayed below as Equations (2.1a) and (2.1b).

\[
\tau = \tau_y(H) + \eta \cdot \gamma \quad \text{(2.1a)}
\]

\[
\tau \leq \tau_y \quad \text{(2.1b)}
\]

In Equations (2.1a) and (2.1b), \(\tau\) represents the fluid stress, \(\tau_y\) represents the yield stress (magnetic or electric field dependant), \(H\) represents the magnetic field, \(\gamma\) & represents the fluid shear rate, and \(\eta\) represents the plastic viscosity; i.e. viscosity when \(H=0\).

MR fluid will display viscoelastic behavior which is represented by Equation (2.2), where \(G\) represents the complex material modulus.

\[
\tau = G \cdot \gamma, \quad \tau \leq \tau_y \quad \text{(2.2)}
\]

Equation (2.3) shows the pressure drop in a MR fluid device that is used in the flow mode can be shown where the pressure drop \((\Delta P)\) is assumed to be the sum of a viscous component \((\Delta P_{\eta})\) and a field dependent induced yield stress component \((\Delta P_{\tau})\).

\[
\Delta P = \Delta P_{\eta} + \Delta P_{\tau} = \frac{12\eta Q L}{g^3 w} + \frac{c \tau_y L}{g} \quad \text{(2.3)}
\]

In above Equation (2.3), \(Q\) = pressure related to MR fluid flow

\(L, g,\) and \(w = \) length, fluid gap, and the width of the flow orifice that exists between the fixed magnetic poles as shown in Figure 2.14.
Figure 2.12 MR fluid in valve mode [6]

The constant $c$, varied from 2 to 3 depending on what $\frac{\Delta P}{\Delta P_\eta}$ ratio is present in the device being considered. For $\frac{\Delta P}{\Delta P_\eta}$ ratios is 1 or smaller, the value for $c$ is chosen to be 2. For $\frac{\Delta P}{\Delta P_\eta}$ ratios of approximately 100 or larger, the value for $c$ is chosen to be 3. For a direct shear mode MR device, shown in Figure 2.15, we can use

$$F = F_\eta + F_\tau = \frac{\eta SA}{g} + \tau_y A$$

(2.4)

The force developed between two plates in a situation when its moving relative to the other and parallel to fluid gap. An assumption used in this equation is that the total force developed is summation of shear force of component and its magnetic field which is dependent on that shear force. In Equation (2.4), $F$ represents the force that is developed between the pole plates, $F_\eta$ is the viscous shear force, $F_\tau$ is the magnetic dependent shear force, and $A$ is the pole plate area, which is defined by $A= LW$. 
Equations (2.3) and (2.4) can be algebraically manipulated to yield the volume of MR fluid that is being activated, which is represented by

\[ V = k \left( \frac{\eta}{\tau^2 y} \right) \lambda W_m \] (2.5)

In Equation (2.5), \( V \) can be regarded as the minimum active fluid volume that is needed to achieve a desired control ratio \( \lambda \) at a required controllable level of mechanical power dissipation \( W_m \) [6]. This volume represents the amount of MR fluid that is exposed to the magnetic field. The parameters in Equation (2.5) can be calculated as

\[ k = \frac{12}{c^2} \] (2.6a)

\[ \lambda = \frac{\Delta P_r}{\Delta P_o} \] (2.6b)

\[ W_m = Q \Delta P_r \] (2.6c)

Further, for shear mode operation, they can be calculated as
\( k = 1 \) \hspace{1cm} (2.7a)

\[ \lambda = \frac{F\tau}{F\eta} \] \hspace{1cm} (2.7b)

\[ W = F\tau S \] \hspace{1cm} (2.7c)
CHAPTER 3
FINITE ELEMENT APPROACH AND RESULTS

3.1 Introduction

An MR damper is to be analyzed as a 2-D axisymmetric model. For a given current, we can determine the magnetic flux density at the Piston, MR Fluid and the Damper Housing.

The dimensions of the MR Damper are in meters. The damper piston, MR fluid gap and the housing are regarded as stationary components that complete the magnetic circuit coil. A wound coil of 650 windings, shown in Figure 3.2, provides the magnetic flux field that is 25
necessary for energizing the MR fluid. The electrical current through the coil can be varied to change the magnetic flux density, therefore the extent to which the MR fluid is energized. The plastic liner gap is the thin rectangular region between the (Engine/MR Fluid gap) and the electrical coil.

![Figure 3.2 Electrical Coil Cross Section](image)

Figure 3.2. Electrical Coil Cross Section

In order to understand the following mathematical discussion, please reference to contents of Table 3.1 which is list of terms from magnetic field of study.

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{SUM}$</td>
<td>Magnetic Flux Density or Magnetic Induction</td>
</tr>
<tr>
<td>$H_{SUM}$</td>
<td>Magnetic Field</td>
</tr>
<tr>
<td>$Az$</td>
<td>Magnetic Vector Potential</td>
</tr>
<tr>
<td>$JS$</td>
<td>Current Density</td>
</tr>
<tr>
<td>$N$</td>
<td>Numbers of turns of wires</td>
</tr>
<tr>
<td>$I$</td>
<td>Current</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Permeability of material used in the Model</td>
</tr>
</tbody>
</table>
3.2 Approach and Assumptions

Assumption made for the analysis is that there is negligible flux leakage between the engine and the housing perimeter of the model for any saturation to occur. This allows a single iteration linear analysis. This assumption simplifies the analysis and allows the model to remain small. The model would normally be created with a layer of air surrounding the iron equal to or greater than the maximum radius of the iron to model the effects of flux leakage. A quadrilateral mesh option is used from Ansys modeling tool so that a non magnetic gap can be modeled. A quadrilateral mesh allows for a uniform thickness of the air elements adjacent to the engine where the virtual work force calculation is performed.

For a static (DC) current, ANSYS requires the current to be input in the form of current density (current over the area of the coil).

\[
J_S = \frac{NI}{A} \quad (3.1)
\]

ANSYS is used to compute the current density from the number of turns (N), the current (I), and the coil area (A). As the main area of concern is the MR fluid gap, certain assumptions are made during modeling it such as no leakage at the model corners. This is done so that the flux acts parallel to the surface of the model “Flux parallel” is the boundary condition option available in ANSYS modeling software to enforce this assumption around the model and is used when flux is contained in Fe (iron) circuit for the models. In post processing, the forces are summarized for the engine, MR fluid and the engine housing, using a Maxwell stress tensor and a virtual work calculation. The final post processing operation computes the terminal parameters including coil inductance.
3.3 Element description

The ANSYS program includes a variety of elements that we can use to model electromagnetic phenomena. After some research, we determine that PLANE13 was the most suitable element for our model because it is a 2-D quadrilateral Coupled-Field- Solid, which contains four nodes, as shown in figure 3.3. PLANE13 has a 2-D magnetic, thermal, electrical and piezoelectric field capability with limited coupling between the fields. Four nodes with up to four degrees of freedom per node define PLANE13. The element has nonlinear magnetic capability for modeling B-H curves.

![Plane13 2-D coupled-field-solids](image)

Figure 3.3. Plane13 2-D coupled-field-solids [16]

3.4 Input Data

The geometry, node locations, and the coordinate system for a Plane 13 element are shown in Figure 3.3. The element input includes four nodes and magnetic, electrical properties. The type of units used is metric and it is specified through the EMUNIT command. EMUNIT also determines the value of $\mu$ (free-space permeability) which is equal to $4\pi \times 10^{-7}$ henries/meter. In addition to $\mu$, constant relative permeability for each material is specified through the $x \mu$.
material property labels. The B-H curve will be used in each element coordinate direction where a zero value of relative permeability is specified. Only one B-H curve may be specified per material. Body loads – source current density – may be input as an element value or may be applied to an area.

3.5 Output Data

The solution output associated with the element is in two forms:

- Nodal degrees of freedom included in the overall nodal solution
- Additional element output like the electromagnetic components

The element output directions are parallel to the element coordinate system, as shown in Figure 3.4.

![Figure 3.4 Plane13 Element Output](image)

Because of different sign conventions for Cartesian and polar coordinate systems, magnetic flux density vectors point in opposite directions for planar and axisymmetric analyses. In ANSYS, we define the magnetic flux density as Bx and By along the x and y axis. The term Bsum is the vector magnitude of B, defined by
Along with the magnetic flux density, we have a list of names that define all the electromagnetic component of an element. We can name the magnetic permeability \((\mu_x - \mu_y)\) and the magnetic field intensity components \(H_x\) and \(H_y\).

### 3.6 Assumptions and Restrictions

In any 2-D axisymmetric model, we have to have some assumptions and restrictions which will allow us to create the model and be able to revolve it around the axis of symmetry. The assumptions made for this study are:

- The area of the element must be positive
- The element must lie in a global X-Y plane
- \(Y\)-axis must be the axis of symmetry for axisymmetric analysis
- An axisymmetric structure should be modeled in the \(+X\) quadrants.
- The only active degrees of freedom are the magnetic vector potential (\(AZ\)) and the time integrated electric potential.
- The element used in the model has only magnetic and electric field capability
- The element does not have structural, thermal, or piezoelectric capability
- The only allowable material properties are the magnetic and electric properties plus the B-H data table
- A Maxwell force flag is the only applicable surface loads and the element does not allow any special features.
3.7 Steps in a Static Magnetic Analysis

This section describes the procedure for a static magnetic analysis, consisting of the following five main steps:

1) First step is to develop a physics environment which basically means to construct an apt model through any modeling software such that it can be imported in Ansys for analysis
2) Next is meshing which allows assigning physical attributes to each part of the model and also to different regions
3) Apply boundary conditions and loads (excitation)
4) Solve the model for a solution
5) Review the results

3.7.1 Creating the Physics Environment

In defining the physics environment for an analysis, one needs to enter the ANSYS preprocessor and establish a mathematical simulation model of the physical problem. To do so, the following steps need to be taken:

1) Set Graphical User Interface (GUI) preferences
2) Assign file name to the model - analysis title
3) Define element types and options
4) Define a system of units
5) Assign material properties

3.7.2 Setting GUI Preferences

Upon completing the GUI, we choose the menu path Main Menu>Preferences and select Magnetic-Nodal from the list of magnetic analysis types on the dialog box that appears. Setting
the preferences is really important before doing anything to the model. We have to specify Magnetic-Nodal to ensure that we can use the elements needed for 2-D static analysis.

3.7.3 Assign Title or filename to Analysis

The file being analyzed needs to reflect the actual problem that is being solved such as “2-D MR Damper static analysis.” Save the model as database file only (.db). Follow the below path to assign title to model

*Utility Menu*->*File*->*Save As*

3.7.4 Identify and assign Element Types and Options

Element types establish the physics of the problem domain. We decided to use the PLANE13 element to represent all interior regions of the model magnetic and permanent regions. Most element types have additional options known as KEYOPTs, which we use to modify element characteristics. For example, element PLANE13 have the following KEYOPTs:

- **KEYOPT (1)** selects the element’s DOFs
- **KEYOPT (2)** specified whether the element uses extra shapes or not
- **KEYOPT (3)** selects plane or axisymmetric option
- **KEYOPT (4)** sets the type of element coordinate system
- **KEYOPT (5)** specified whether the element uses extra element output

KEYOPT settings can be specified through the following path:

*Main Menu*->*Preprocessor*->*Element Type*->*Add/Edit/Delete*

3.7.5 Choosing a System of Units in our Analysis

The default system of units is the metric system which can be changed to other unit systems using the following steps:

*Go to Main Menu*->*Preprocessor*->*Material Props*->*Electromag Units*
Depending on the inputs specified, the free-space permeability $\mu$ is determined automatically as follows:

$$\mu_0 = 4\pi * 10^{-7} \text{ H/m in MKS units}$$

### 3.7.6 Specifying Material Properties

The ANSYS material library contains definitions of several materials with magnetic properties. In our model, we simply define the constant relative permeability for each material. Working with MR fluids, we can define the properties by the B-H curves. To define the constant relative permeability for a specific material, we use the following:

*Main Menu* $>$ Preprocessor $>$ Material Props $>$ Material Models $>$ Electromagnetics

$>$ Relative Permeability $>$ Constant

In the case of the MR fluids, we specify the B-H curve by creating our own curve. We can specify the coordinates points of the MR fluid by choosing any point on the B-H curve, as shown in Figure 3.5.
Follow the below path for B-H curve

*Main Menu*>Preprocessor>Material Props>Material Models>Electromagnetics>BH Curve

### 3.8 Building and Meshing the Model and Assigning Region Attributes

To build the model, we simply create five rectangles that will represent all different areas of the MR damper. We can build all the rectangles first, and then use the overlap command on all areas to make sure that we do not have any duplicated regions. The next step following which is to assign attributes to the various regions in the model. What this means further in ANSYS language is to select the element types and options, co-ordinate systems and material properties). To assign attributes, we perform these tasks:

1) Go To *Main Menu>*-Attributes->Define>Picked Areas. The Meshing Attributes dialog box appears.
2) Select or highlight the area(s) to include one of the regions from the model.

3) In the same box, we can specify the material number, element type and element coordinate system to use for the area or areas. Click OK.

4) Repeat the steps 1 through 3 to proceed with the regions until all regions have defined attributes. When we finish assigning all regional attributes, we mesh the model using the meshing Attributes dialog box. We simply click on the Mesh button, and we pick all the areas defined. We can always refine our mesh in different areas of the model.

3.9 Assign and Apply Boundary Conditions and Loads

The boundary conditions and loads can be assigned in two ways in ANSYS when simulating a 2-D static magnetic analysis. You can do it wither on the solid model itself or on the finite element model. The ANSYS program automatically transfers loads applied to the solid model to the mesh during solution. We can access all loading operation through a series of cascading menus.

Go To Main Menu>Solution>-Loads->Apply>-Magnetic-, the ANSYS program lists available boundary conditions and three load categories (-Excitation-, -Flag-, -Other-).

3.9.1 Boundary Conditions

In our model, we need to specify the magnetic vector potential to be zero, i.e., AZ=0. Under the Flux-Parallel, we choose On Lines, and we pick all the lines surrounding the model. The advantage of selecting the Flux-Parallel boundary condition is that it forces the flux to flow parallel to a surface. Follow the below steps to do so

3.9.2 Excitation Loads

Source Current Density ($J_S$): This specifies applied current to a source conductor. The units of $J_S$ are amperes/meter$^2$ in the metric system. For a 2-D analysis, only the Z component of $J_S$ is valid, a positive value indicates current flowing in the $+Z$ direction in the planar case and the $-Z$ (hoop) direction in the axisymmetric case.

The current density can be directly applied to area by below path in model


![Current per turn 'n'](image)

**Figure 3.6. Current – Fed Electrical Coil [16]**

3.10 Solving the Analysis

This section will go through the steps involved to solve the analysis after careful modeling & meshing is done per the above steps and element properties have been accurately assigned.

3.10.1 Defining the Analysis Type

The first step is to enter the SOLUTION processor so that analysis type can be defined and the type of equation solver the analysis will use. Enter the SOLUTION processor by following the below path:

[37]
Go To: *Main Menu*> *Solution*

Select the analysis type by:

Go To: *Main Menu*> *Solution*> *New Analysis*

Next will be to choose a static analysis. We can always restart an analysis only if we previously completed 2-D static magnetic analysis.

**3.10.2 Defining Analysis Options**

ANSYS provides various equation solvers, including:

- Sparse solver
- Frontal solver
- Jacobi Conjugate Gradient (JCG) solver
- Incomplete Cholesky Conjugate Gradient (ICCG) solver
- Preconditioned Conjugate Gradient (PCG) solver

To select an equation solver, one can specify:

Go To: *Main Menu*> *Solution*> *Analysis Options*

For our Model, we use the Jacobi Conjugate Gradient (JCG) solver, because it is more useful for large 2-D models.

**3.10.3 Saving a Backup Copy of the Database**

Use the SAVE_DB button on the ANSYS Toolbar to save a backup copy of the ANSYS database. This enables us to retrieve the model incase the computer fail while analysis in progress. To retrieve a model, re-enter ANSYS and use the following:

*Utility Menu*> *File*> *Resume Jobname.db*
3.10.4 Starting the Solution

This section will help user understand the steps to go through for specifying a magnetic solution option and initiate the solution. For a nonlinear analysis, we use two-step solution sequence:

1) Ramp the loads over tree to five sub steps, each with one equilibrium iteration.
2) Calculate the final solution over one sub step, with five 10-equilibrium iterations.

We can specify the two-step solution sequence and initiate the solution using:

Main Menu>Solution>Electromagnet>Opt & Solve

3.10.5 Tracking Convergence Graphically

As we select and being the nonlinear electromagnetic analysis, ANSYS computes convergence norms with corresponding convergence criteria each equilibrium iteration. ANSYS considers a solution to be converged whenever specified convergence criteria are met. Convergence checking may be based on magnetic potential, magnetic field, or magnetic flux density. In our case, we need to check the magnetic flux density, so if we specify 1.2 as the typical value for magnetic flux and 0.01 as the tolerance, the convergence criterion for magnetic flux would be 0.012. If ANSYS cannot converge the solution within the specified number of equilibrium iterations, ANSYS either stops the solution or moves on to the next load step. When the two lines intersect, as shown in Figure 3.7, (Flux and CSG), that means we reach the convergence. The Graphical Solution Tracking (GST) feature available in software helps by displaying the computed convergence norm and criteria instantaneously as the solution is in progress.
3.11 Finishing the Solution

To leave the SOLUTION processor, we use the following:

Go To: Main Menu \textgreater Finish

3.12 Reviewing Results

ANSYS software and its ANSYS/Emag program transfers the results from a 2-D static analysis to the magnetic results file, Jobname.RMG. The results from post processing include the data listed below:

Primary data:

- Nodal Magnetic DOF’s (AZ, CURR)

Secondary data:

- Nodal magnetic flux density (Bx, By, Bsum)
- Nodal magnetic field intensity (Hx, Hy, Hsum)
- Nodal magnetic forces (FMAG: components X, Y, SUM)
- Nodal reaction current segments (CSGZ)
- Element source current density (JSz)

We can always review the analysis results in POST1, by choosing the following:

Go To: Main Menu>General Postproc

### 3.12.1 Reading in Results Data

In order to review the results in POST1, its absolutely essential that the database contain the same model for which solution is being determined. In addition to this, the results file (Jobname.RMG) must be available. Follow the below steps to review the data from the results file into the database:

Go To: Utility Menu>File>Results>Load Step Summary

If the model is not in the database, restore it using the menu path listed below and then use appropriate menu path to read in the desired set of results.

Go To: Utility Menu>File>Resume Jobname.db

Now we can review the solutions available in the result file. We can identify the data set by the load step and sub step numbers or by time.

**1- Flux Lines**

Flux lines show lines of constant AZ (or constant radius-times-AZ for axisymmetric problems). We can display the flux lines, as shown in Figure 3.8, by using the following menu path:

Go To: Utility Menu>Plot>Results>Flux Lines
2- Contour Displays

We can contour almost any result item, including magnetic flux density, field intensity, and total current density (JSZ)

**Element Solution:**

We can generate the magnetic flux density around the electrical coil, as shown in Figure 3.9, by using the following menu path:

*Main Menu* > *General Postproc* > *Plot Results* > *Contour Plot* > *Element Solution* > *Flux & Gradient* > *MagFLuxDens* > *BSUM*
To generate the magnetic field around the electrical coil, as shown in Figure 3.10. We use the following:

Main Menu>General Postproc>Plot Results>Contour Plot>Element Solution>Flux & Gradient>Mag field>HSUM
To show the area where we applied the current density, as shown in Figure 3.11, we use the following:

*Main Menu*->*General Postproc*->*Plot Results*->*Contour Plot*->*Element Solution*->*Current density*->*JSSUM*

---

**Figure 3. 10** Element Solution- Magnetic Fields (HSUM)

**Figure 3. 11** Element Solution- Current Density (JSSUM)
Nodal Solution:

We use nodal solution to obtain our results because it establishes the values at each node instead of looking at the element in general (element solution). To obtain the magnetic flux density using nodal solution, as shown in Figure we use the following:

*Main Menu* > *General Postproc* > *Plot Results* > *Contour Plot* > *Nodal Solution* > *Flux & Gradient* > *MagFLuxDens* > *BSUM*

![Figure 3.12 Nodal Solution- Magnetic Flux Density (BSUM)](image)

To generate the magnetic field using nodal solution, as shown in Figure 3.13, we use the following:

*Main Menu* > *General Postproc* > *Plot Results* > *Contour Plot* > *Nodal Solution* > *Flux & Gradient* > *Mag field* > *HSUM*
The magnetic vector potential is the contour representation of the magnetic flux lines, as shown in Figure 3.14. To obtain the contour for $A_z$, we simply follow the following: 

Main Menu>General Posproc>Plot Results>Contour Plot>Nodal Solution>DOF Solution>MagVectPoten>Az

Figure 3. 13 Nodal Solution- Magnetic Fields (HSUM)

Figure 3. 14 Nodal Solution- Magnetic Vector Potential (AZ)
For our studies, we need to use the magnetic flux density values, as shown in Table 3.2, along the MR fluid gap to generate the shear stress and produce the force – velocity characteristics along this gap. This option can be obtained by using the following:

*Utility Menu* > *List* > *Results* > *Vector Data* > *Flux & Gradient* > *Mag Flux Density* > *B*

---

Table 3.2 Magnetic Flux Density (BSUM)

<table>
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<tr>
<th>PRINT B</th>
<th>SUM DIRECTIONS PER NODE</th>
</tr>
</thead>
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<tr>
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<td></td>
</tr>
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<td>LOAD STEP</td>
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<tr>
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</table>

<table>
<thead>
<tr>
<th>NODE</th>
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<th>DIRECTION VECTOR (X,Y,Z)</th>
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<td>1.00000 -0.00135 0.00000</td>
</tr>
<tr>
<td>2</td>
<td>0.438E-01</td>
<td>0.99994 -0.00115 0.00000</td>
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<td>0.526E-01</td>
<td>1.00000 -0.00001 0.00000</td>
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<td>0.580E-01</td>
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</tr>
<tr>
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<td>0.647E-01</td>
<td>0.99963 -0.02702 0.00000</td>
</tr>
<tr>
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<td>1.00000 -0.00002 0.00000</td>
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<td>0.99986 -0.01693 0.00000</td>
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<td>35</td>
<td>0.1291</td>
<td>0.92887 -0.38987 0.00000</td>
</tr>
</tbody>
</table>
CHAPTER 4

FINITE ELEMENT MODEL RESULTS

This chapter will provide all results generated by the finite element model described in the earlier chapter. The model included an axisymmetric MR damper that contains five different areas, as shown in Figure 3.1 and described in details in the previous chapter. The first one represents the Damper piston, the second area is the engine housing, third area is the fluid gap (between the piston and the damper housing), fourth area is the plastic liner gap between the electrical coil and the piston/fluid area and the fifth area is the electrical coil. All these areas are constructed using key point option in ANSYS and then overlapped over each other using the Boolean option. Thus we are able to obtain a uniform area to apply the boundary conditions of flux parallel to the damper piston and current in the form of current density to the coil. The coil is supplied a current which can be varied from 0 to 2.0 amperes. Its required to solve for the program that the current get input into the form of current density (current density is equal to current over the area of the coil). Table 3.1 can be consulted for all the magnetic terms used in this Chapter. The below figures mention the different output results compared theoretically with the Bingham equations and the ANSYS output obtained.

4.1 Magnetic Flux Density

The magnetic induction is a function of the fluid shear stress. The magnetic induction shear stress data for a typical MR fluid, shown in equation 4.1, was characterized by a 4th order polynomial of the form,

\[ \tau_y = 6.298B_f^4 - 25.824B_f^3 + 26.639B_f^2 - 0.438B_f \]  

(4.1)

From the ANSYS model, one can generate the magnetic induction at the gap of the MR fluid (Figure 4.1). For each value of \( B_{SUM} \), we can calculate the shear stress using equation (4.1)
Figure 4. 1. 2-D Magnetic Flux Density (BSUM)

We can get the magnetic induction at the MR fluid gap by using the numbers generated from the nodal solution and find the average value of the magnetic flux density by using the following equation:

\[
B_{\text{AVE}} = \frac{B_{\text{max}} + B_{\text{min}}}{2}
\]  \hspace{1cm} (4.2)

Since we have linear analysis, we can simply add the maximum and minimum value and divide them by 2, as shown in equation 4.2. Each time we increase the electrical current to the coil, the magnetic induction increases and we get a new set of data. The contour plot shown in Figure 4.1 is generated for applying a current of 0.4 A on the coil (by keeping the number of turns and the area of the coil constant). By looking at the contour, we conclude that we have not yet reached
saturation along the MR fluid gap, which can be further noticed in Figure 4.1. For each new case, we can change the current value in the current density equation

\[ JS = \frac{NI}{A}; \quad A = \text{Electrical Coil Area} \]  \hspace{1cm} (4.3)

4.2 Magnetic Field

The magnetic field is associated with the magnetic flux density and the permeability of the ferrous material that is used in the MR damper design. The more we increase the permeability of the ferrous material, the larger the flux field will be. The equation that covers the magnetic field is given by:

\[ B = \mu H \]

Where all the terms are defined in Table 3.1 and \( B \) is in Tesla, \( \mu \) is in Henry/m, and the magnetic field \( H \) is in Amp/m. Referring to the results generated from ANSYS, we don’t see the color distributed on the rest of the model because of the high value of \( H \) at this specific area. If we zoom in to the MR fluid gap, we can observe that the farther we move away from the coil, the more the magnetic field decreases.

4.3 Magnetic Flux Lines

As we have made an initial assumption while modeling that there is no leakage at the boundary of the model, the magnetic flux will be acting parallel to the surface of the model. The boundary condition which enforces or helps apply it is “flux parallel” condition from the model. This boundary condition is used for models in which the flux is contained in an iron circuit. In Figure 4.8, the flux path is surrounding the coil and if we look closely at the MR fluid gap, we can see the concentration of many flux lines. Additionally, the lines shift as soon as they hit the gap, therefore indicating the effect of the MR fluid on the electric circuit. Since the properties of
the MR fluid are different than the engine and damper housing, the magnetic induction vectors are changing in directions once they hit the MR fluid gap. These magnetic flux lines represent the magnetic flux density vectors. So we have a high magnetic induction along the gap, as was observed in Figure 4.2. These concentration lines of magnetic flux will decrease by the time rheological saturation is reached.

Figure 4.2 Flux lines around the Electrical coil
CHAPTER 5
DESIGN ANALYSIS

This chapter will evaluate three different shapes of the MR damper piston by curving the edges and create a chamfer at the corner of the MR fluid passage. The first model is the original model and regarded as baseline model for comparison between the other two models. The second model will have the curved corner away from the coil design and the third model is the chamfered corner farthest from the coil design.

5.1 Model 1: Original model with straight edges

This section will provide all results generated by the finite element model in ANSYS. A model was built with straight edges as shown in Figure. We will refer to this configuration as “Model 1” for the purpose of this discussion. In model 1, the MR fluid gap and piston area remain the same. The rest of the areas in the model remain the same with no shape modification to them. The coil is supplied a current which can be varied from 0 to 2.0 Amps. The program required the current to be input in the form of current density (current over area of the electrical coil). The various results in ANSYS are as below. The theoretical magnetic flux (inductance) and shear stress are calculated as follows:-

\[
B_f = \frac{\mu_0 NI}{2g + \mu_f A_f} \left[ \frac{d + L}{\mu_1 A_1} + \frac{d + L + e}{\mu_4 A_4} + \frac{1}{\mu_2 2\pi L} \ln \left( \frac{2b}{a} \right) \right] \quad \ldots \ldots \text{(Eq 1)}
\]

\[
\tau = 6.298B_f^4 - 25.824B_f^3 + 26.639B_f^2 - 0.438B_f \quad \ldots \ldots \text{(Eq 2)}
\]

Following table explains both the values: - Theoretical magnetic induction as well as the one obtained using ANSYS software.
Figure 5.1 Magneto rheological damper piston configurations for model 1

The basic dimensions for the model 1 are as shown in figure 5.1. All the dimensions are in mm. The model is mainly divided into five areas; the piston, the housing, the coil, the MR fluid gap and the plastic liner or the air gap. All the areas are plotted using key points and then are overlapped to get the above figure.

Table 5.1 Values of Magnetic Induction for Original Damper Configuration

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Theor Mag. Indn (T)</th>
<th>Shear Stress (psi)</th>
<th>ANSYS (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.0434</td>
<td>0.0291</td>
<td>0.0360</td>
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<td>0.8</td>
<td>0.08692</td>
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<td>0.0720</td>
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<td>1.2</td>
<td>0.1348</td>
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<td>0.1825</td>
</tr>
<tr>
<td>1.6</td>
<td>0.1658</td>
<td>0.5571</td>
<td>0.1391</td>
</tr>
<tr>
<td>2</td>
<td>0.2241</td>
<td>0.9124</td>
<td>0.1839</td>
</tr>
</tbody>
</table>
From the above graph it is clearly visible that both the curves follow a linear path. The values for theoretical values of shear stress are more as compared to the ANSYS values and differ from the in the range 0.03-0.18 %

5.1.1 Magnetic Flux Density

The ANSYS model provides the magnetic induction at the gap of the MR fluid, as shown in Figure 5.2. For each value of $B_{sum}$, we can calculate the shear stress using equation.
5.1.2 Magnetic field

The magnetic field is associated with the magnetic flux density and the permeability. The more we increase the permeability, the more flux field we will generate. Looking at the results generated from ANSYS, we can see in Figure 5.3 this light colored blue on the left side of the coil. We don’t see the color distributed on the rest of the model because of the high value of H at this specific area. The more we move away from the coil, the more the magnetic field decreases. The values of magnetic field vary from minimum being 1886 and maximum being \( .337 \times 10^8 \). The color intensity shown in the figure 5.4 indicates red being the area of high magnetic field and blue being the least.
Figure 5.3 Magnetic Flux Lines

Figure 5.3, which represents the magnetic flux vector for Model 1, indicates that the more we move away from the coil the smaller magnetic flux density becomes. The higher flux density in the MR gap that was observed in Figure 5.1 is also shown in this Figure.

5.2 Model 2: Curved corner farthest from the coil

This section will provide all results generated by the finite element model in ANSYS. A model was built with curved corners farthest from the coil, as shown in Figure. We will refer to this configuration as “Model 2” for the purpose of this discussion. While solving for and analyzing model 1, the MR fluid gap and the piston area was kept constant but in this model, the gap has changed and the piston area has shrunk from its original shape. The rest of the areas in the model remain the same with no shape modification to them. The coil is supplied a current which can be varied from 0 to 2.0 Amps. The program required the current to be input in the
form of current density (current over area of the electrical coil). Using the terminology outlined, we will next describe the modeling results.

![Figure 5. 5 MR damper piston configurations for model 2](image)

**Table 5.2 Values of Magnetic Induction for Curved Configuration**

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Theor Mag. Indn (T)</th>
<th>Shear Stress (psi)</th>
<th>ANSYS (T)</th>
</tr>
</thead>
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</table>
From the above graph it is clearly visible that both the curves follow a linear path. The theoretical values differ from the actual calculated values in the range 0.44-1.68%.

5.2.1 Magnetic Flux Density

The ANSYS model provides the magnetic induction at the gap of the MR fluid, as shown in Figure. For each value of $B_{sum}$, we can calculate the shear stress using Bingham’s equations.
5.2.2 Magnetic Field

The magnetic field is associated with the magnetic flux density and the permeability. The more we increase the permeability, the more flux field we will generate. Looking at the results generated from ANSYS, we can see in Figure this light colored blue on the left side of the coil. We don’t see the color distributed on the rest of the model because of the high value of H at this specific area. The more we move away from the coil, the more the magnetic field decreases.
Figure 5.8 Magnetic Field for model 2 at 0.4A

5.2.3 Magnetic Flux Lines

Figure which represents the magnetic flux vector for Model 2 indicates that the more we move away from the coil the smaller magnetic flux density becomes. It was observed that the MR gap showed higher flux densities in this figure which represents the contour of the magnetic flux lines and indicates the shift of the color spectrum between the MR fluid gap and the Piston/Damper Housing areas.
5.3 Model 3: Chamfer corner farthest from the coil

This section will provide all results generated from a second piston configuration, which we will refer to as “Model 3”, for the purpose of this discussion. In ANSYS, a model was built with chamfered corner farthest from the coil, as shown in Figure. This model will have larger MR fluid gap than the original model and the piston area has been reduced from its original shape. The rest of the areas in the model remain the same with no shape modification to them. The coil is supplied a current which can be varied from 0 to 2.0 Amps.
Figure 5. 10 Magneto rheological damper piston configurations for model 3

Following table explains both the values: - Theoretical magnetic induction as well as the one obtained using ANSYS software

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Theor Mag. Indn (T)</th>
<th>Shear Stress (psi)</th>
<th>ANSYS (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.3242</td>
<td>1.8551</td>
<td>0.4991</td>
</tr>
<tr>
<td>0.8</td>
<td>0.6751</td>
<td>5.2783</td>
<td>0.8313</td>
</tr>
<tr>
<td>1.2</td>
<td>1.0153</td>
<td>6.6575</td>
<td>1.1565</td>
</tr>
<tr>
<td>1.6</td>
<td>1.3251</td>
<td>7.4153</td>
<td>1.4251</td>
</tr>
<tr>
<td>2.0</td>
<td>1.5578</td>
<td>8.8351</td>
<td>1.6351</td>
</tr>
</tbody>
</table>
5.3.1 Magnetic Flux Density

The ANSYS model provides the magnetic induction at the MR fluid gap, as shown in Figure 5.11. For each value of $B_{sum}$, we can calculate the shear stress using equation.
5.3.2 Magnetic Field

Looking at the results generated from ANSYS, we can see in figure that the coil area is colored and the rest is just blue which suggests that the magnetic field is concentrated around the coil and as we move away from the coil it decreases.
The results for all the three damper models are shown in the below figure 5.14. As we plot a graph to show shear stress values for all these three models, it is evident that the MR fluid gap is directly proportional to the induction in the damper. In other words, more the fluid more will be the dampening effect but also at the same time we have to be cognizant of the size and the application requirements when the design is being made.

Figure 5.14 Comparison of Theoretical and ANSYS values for the three damper configurations
CHAPTER 6
CONCLUSIONS AND FUTURE WORK

We studied three different configurations of an MR damper piston in order to determine how changing the shape of the piston affects the shear stress and the magnetic induction that the damper can exhibit at a particular current. The analytical data obtained for the values of shear stress and magnetic induction were compared to the actual data and corresponding graphs were plotted. The conclusions can be explained as follows:-

• The shear stress increases with the increase in the MR fluid gap. This is evident from the graph for model 3

• Magnetic flux density and Magnetic field depends upon the current density in the coil.

As we move away from the coil the magnetic field decreases

Recommendations and Future Work

There exist several topics related to this research that needs further consideration for future research, these include:

1. Generating a 3-D model and try to animate the motion of the piston compare to the housing.

2. Analyze the fluid flow and its reactions with respect of the motion of the piston along the damper.

3. Generating the force vs. velocity plot without using the mathematical equations.

4. The effect of temperature on the size of iron particles needs to be studied in order to understand the performance of MR fluid.


14. "MagnetoRheological Fluids", online article, Status of Cadillac MR suspension


APPENDIX A
ANSYS Documentation

An MR damper is to be analyzed as a 2-D axisymmetric model. This section will explain how we can build our model using ANSYS software. Also, it will show the reader how we can generate all the results using specific menu commands.
List of Steps for design the damper model in ANSYS [18]

The inputs to solve the problem can be obtained or made available through the problem description itself. The next steps to solve the problem are as below

1. Build Geometry

   Initiate the construction of first rectangle

   Create remaining four rectangles

   Make sure that all rectangles have overlapping areas.

2. Define Materials

   Set preferences.

   Assign material properties

3. Generate Mesh

   Element type and options will be defined first in this section

   Specify material property attributes.

   Define meshing-size controls on air gap.

   Start the meshing process for the model using the MeshTool.

4. Apply Loads

   Specify and Define the armature as a component.

   Specify and Define force boundary conditions to armature.

   Apply the current density.

   Solve to obtain a flux parallel field solution.

5. Obtain Solution

   Solve.
6. Review Results

Create Plot the flux lines in the model.

Summarize magnetic forces.

Create plots for the flux density as vectors.

Create Plot the magnitude of the flux density.

Exit the ANSYS program.

1. Build Geometry

Step 1: Build the first rectangle

Overlapping five rectangles creates the model. Create each rectangle by entering its dimensions in a dialog box (this is an easier way instead of by picking points on the working plane as it might not provide the accurate representation of the co-ordinates needed).

Enter the following: X1 = 0   X2 = 0.812
                        Y1 = 0   Y2 = 1.052

Go To:

Main Menu > Preprocessor > -Modeling- Create > -Areas- Rectangle> By Dimensions

(Enter the following:)

(Note: Press the Tab key between entries to move to the adjacent cells)

2. OK.

3. Go To : Utility Menu > PlotCtrls > Numbering

4. Click on Turn on Area numbers option
Step 2: Create remaining five rectangles

After first rectangle is created, build the remaining rectangles 2, 3, 4, and 5.

1. Go To : Main Menu > Preprocessor > -Modeling- Create > -Areas- Rectangle > By Dimensions [18]

2. Type the following co-ordinates for rectangle 2:

   \[
   \begin{align*}
   X1 &= 0 & X2 &= 2.75 \\
   Y1 &= 0.75 & Y2 &= 3.5 \\
   \end{align*}
   \]

3. Click Apply.

4. Type the following co-ordinates for rectangle 3:

   \[
   \begin{align*}
   X1 &= 0.75 & X2 &= 2.25 \\
   Y1 &= 0 & Y2 &= 4.5 \\
   \end{align*}
   \]

5. Click Apply.

6. Type the following co-ordinates for rectangle 4:

   \[
   \begin{align*}
   X1 &= 1 & X2 &= 2 \\
   Y1 &= 1 & Y2 &= 3 \\
   \end{align*}
   \]

7. Click Apply.
8. Type the following co-ordinates for rectangle 5:

\[ X1 = 0 \quad X2 = 2.75 \]
\[ Y1 = 0 \quad Y2 = 3.75 \]

9. Click Apply.

10. Type the following co-ordinates for rectangle 6:

\[ X1 = 0 \quad X2 = 2.75 \]
\[ Y1 = 0 \quad Y2 = 4.5 \]

11. OK.

**Step 3: Overlap all areas**

Using the Boolean Overlap option in ANSYS, the rectangles created separately can be merged into a single area.

1. Go To: Main Menu > Preprocessor > -Modeling- Operate > -Booleans- Overlap > Areas [18]

2. Pick All.

3. Toolbar: SAVE_DB

2. Define Materials
Step 4: Set preferences

You will now set preferences in order to filter quantities that pertain to this discipline only.

1. Go To: Main Menu > Preferences [18]

2. Turn on Electromagnetic: Magnetic-Nodal filtering (nodal element formulations).

3. OK.

Step 5: Assign material properties

Material properties can be assigned for following: magnetic permeability of air, Engine, coil, and armature. For simple analysis, assumption is made that all these are linear. (Typically, iron is input as a nonlinear B-H curve.) Use Material 1 for the housing elements. Material 2 will be used for the MR fluid elements. Use Material 3 for the engine elements. Use Material 4 for coil elements. Material 5 will be used for the air gap elements.

1. Go To: Main Menu > Preprocessor > Material Props > Material Models

2. On the material models dialog box, Double-click on Electromagnetics, Relative Permeability and Constant.

3. Enter 75 for MURX.

4. OK.
5. Material> New Model

6. Define Material ID: 2

7. Next box, Double-click on Electromagnetics, BH curve

8. Enter the first set of data for H and

9. Add point

10. Enter the second set of data for H and B.

11. Add point.

12. Enter the third set of data for H and

13. OK.

Edit > Copy [18]

14. Then click OK to copy Material Model Number 1 to become Material Model Number 3.

15. On the next screen, double-click on Material Model Number 3, then on Permeability (Constant).

16. OK.
17. Edit > Copy [18]

18. Next screen, Select 1 for from Material Number.

19. Enter 4 for to Material Number.

20. OK.

21. On the next screen, select Material Model Number 4, then on Permeability (Constant).

22. Change the value of MURX from 75 to 1.

23. OK.

24. Edit> Copy [18]

25. Pick 1 for from Material Number.
26. Select 5 for to Material Number.

27. OK.

28. On the next dialog box, click on Material Model Number 5, then on Permeability (Constant).

29. Change the value of MURX from 75 to 0.005

30. Material>Exit

31. Go To: Utility Menu > List > Properties > All Materials

32. Next dialog box, Review the list of materials and then choose: File > Close (Windows)

3. Generate Mesh

**Step 6: Specify element types and options**

Step 6 specifies & helps define the element types and options associated with these element types.

PLANE53 which is the higher-order element is normally preferred, but to keep the model size small, uses the lower-order element PLANE13.

1. Go To: Main Menu > Preprocessor > Element Type > Add/Edit/Delete

2. Add.


4. Choose Vect Quad 4nod13 (PLANE13).

5. OK.

6. Options.

7. Change Element behavior from plain strain to Axisymmetric.

8. OK.

Step 7: Assign Material Properties

Now assign material properties to air gaps, coil, and armature areas.

1. Go To: Main Menu > Preprocessor > MeshTool
2. Choose Areas, Set for Element Attributes
3. Pick the Housing area
4. Select OK
5. Pick 1 for material number
6. Hit Apply
7. Select MR fluid gap area
8. Select OK
9. Choose 2 for Material number.
10. Apply.
11. Pick Engine area.
12. Select OK
13. Choose 3 for Material number.
15. Select the Coil area.
16. Select OK.
17. Choose 4 for Material number.
18. Apply.
19. Pick the air gap area.
20. Choose 5 for Material number.
21. Select OK.
22. Select OK.
23. Toolbar: SAVE_DB.
Step 8: Assign the meshing-size controls on air gap

Adjust meshing size controls to get two element divisions through the air gap.

1. Select Lines followed by Set for Size Controls.
2. Select the four vertical lines through air gap.
3. Click on OK
4. Enter 2 for No. of element divisions.
Step 9: Complete the model meshing by using the MeshTool

1. Assign Global Size Control.

2. Enter the value of 0.25 for Element edge length on the next screen

3. OK.

4. Choose Areas.

5. Select Mesh.

6. Pick All.

7. Click on Close to close the MeshTool dialog box

Note: Due to ANSYS/ED FEA limitations, choose a coarse mesh. However, for production use, a finer mesh can be used, especially in the air-gap region.

8. Go To Utility Menu > PlotCtrls > Numbering

9. Choose Material numbers.

10. OK
4. Apply Loads

Step 11: Define the Engine, MR fluid gap and the Housing as a component

The system can conveniently be defined as a component by selecting its elements.

1. Go To Utility Menu > Select > Entities
2. Choose Elements.

3. Choose By Attributes.

4. Enter the following values 1, 3, and 1 for Min, Max, Inc.

5. OK.

6. Go To Utility Menu > Plot > Elements

7. Followed by Utility Menu > Select Comp/Assembly > Create Component

8. Enter ARM for Component name.


10. OK.
Step 12: Assign force boundary conditions to armature

1. Go To Main Menu > Preprocessor > Loads > Loads- Apply > -Magnetic- Flag > Comp. Force/Torq

2. Choose ARM.

3. OK.

4. Review the information, then choose: File > Close (Windows), or Close (X11/Motif), to close the window.

5. Go To Utility Menu > Select > Everything

6. Followed by Utility Menu > Plot > Elements
Step 13: Assign the current density

The current density is defined as the number of coil windings times the current, divided by the coil area. This equals 1574318.

1. Go To Utility Menu > Plot > Areas
3. Select the coil area, which is the area in the center.

4. Select OK

5. Enter 1574318 for Current density value.

6. OK.

**Step 14: Obtain a flux parallel field solution**

This boundary condition assumes that the flux does not leak out of the iron at the perimeter of the model. Of course at the centerline this is true due to axisymmetry.

1. Go To Utility Menu > Plot > Lines >

2. Followed by Main Menu > Preprocessor > Loads > -Loads- Apply > -Magnetic-Boundary > -Vector Poten-Flux Par'l- On Lines

3. Select all lines around perimeter of model.

4. Click OK

5. Toolbar: $SAVE_DB$.

5. Obtain Solution

**Step 15: Solve**

1. Go To Main Menu > Solution > Solve- Electromagnet > Static Analysis- Opt & Solve

2. Select OK
3. Close the information window when solution is done.

6. Review Results

**Step 16: Plot the flux lines in the model**

1. Go To Main Menu > General Postproc > Plot Results > Contour Plot- 2D Flux Lines.

2. OK
Step 17: Summarize magnetic forces

1. Go To Main Menu > General Postproc > Elec & Mag Calc > Component Based-Force
2. Choose ARM.
3. OK.
4. Review the information, then choose:
   File > Close (Windows).

Step 17: Plot the flux density as vectors

1. Go To Main Menu > General Postproc > Plot Results > Vector Plot- Predefined
2. Select option Flux & gradient.
3. Select option Mag flux dens B.
   OK.
Step 18: Plot the magnitude of the flux density

Without averaging the results across material discontinuities plot

1. Go To Main Menu > General Postproc > Plot Results > Contour Plot-Nodal Solu

2. Select Flux & gradient.

3. Choose BSUM.

4. OK.
1. Go To Main Menu > PlotCtrls > Style > Symmetry Expansion > 2D Axi-Symmetric
2. Choose 3/4 expansion.
3. OK.

Select an isometric view for a more meaningful representation.

4. Go To Utility Menu > PlotCtrls > Pan, Zoom, Rotate
5. Iso.


1. Toolbar: *QUIT*. 
2. Select Quit – Save everything

3. OK.