

Finite Element Analysis Based Modeling of
Magneto Rheological Dampers

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Abstract

A Finite Element model was built to analyze and examine a 2-D axisymmetric MR damper. This model has been validated with the experimental data. The results obtained in this thesis will help designers to create more efficient and reliable MR dampers. We can create some design analysis 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. We can detect saturation by looking at the nodal solution for the magnetic flux density. Increasing the current in the model, results in an increase in magnetic induction.

We studied four different configurations of an MR damper piston in order to determine how changing the shape of the piston affects the maximum force that the damper can provide. In designing MR dampers, the designer always faces the challenge of providing the largest forces in the most compact and efficient envelope. Therefore, it is important to identify the configuration that gives more force in less space.

In chapter 4, shows the 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 from the MR fluid gap to the piston centerline.

In chapter 5, we provided a reasonably good amount of force in model 4 at 1.4 Amps, but it reaches saturation before the other models. For cases with power constraint or heat build up limitations, this model could work the best among the four designs that we considered. For cases where higher electrical currents can be tolerated, model 3 would be the most advantageous design, since it provides the largest force among the four models.

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Chapter 1

Introduction

The purpose of this chapter is to introduce the theoretical and practical applications of magneto-rheological (MR) fluid for a controllable MR damper and the primary objectives of this research. It will also include a brief description of the approach used here, and an outline of the contributions that have been made.

1.1 Magneto-Rheological Fluids

The information included in this section has been adopted from reference [1]. Magneto-rheological fluids are materials that exhibit a change in rheological properties (elasticity, plasticity, or viscosity) with the application of a magnetic field. The MR effects are often greatest when the applied magnetic field is normal to the flow of the MR fluid. Another class of fluids that exhibit a rheological change is electro-rheological (ER) fluids. As the name suggests, ER fluids exhibit rheological changes when an electric field is applied to the fluid. However, there are many drawbacks to ER fluids, including relatively small rheological changes and extreme property changes with temperature. Although power requirements are approximately the same [2], MR fluids require only small voltages and currents, while ER fluids require very large voltages and very small currents. For these reasons, MR fluids have recently become a widely studied 'smart' fluid.

Besides the rheological changes that MR fluids experience while under the influence of a magnetic field, there are often other effects such as thermal, electrical, and acoustic property changes. In the area of vibration control, however, the MR effect is most interesting because it is possible to apply the effect to a hydraulic damper. The MR fluid essentially allows one to control the damping force of the damper by replacing mechanical valves commonly used in adjustable dampers. This offers the potential for a superior damper with little concern about reliability since if the MR damper ceases to be controllable, it simply reverts to a passive damper.

1.2 Construction of an MR Damper

Magneto-rheological fluids consist of ferromagnetic particles that are suspended in a carrier fluid. The ferromagnetic particles are often carbonyl particles, since they are relatively inexpensive. Other particles, such as iron-cobalt or iron-nickel alloys, have been used to achieve higher yield stresses from the fluid [3]. Fluids containing these alloys are impractical for most applications due to the high cost of the cobalt or nickel alloys.

A wide range of carrier fluids such as silicone oil, kerosene, and synthetic oil can be used for MR fluids. The carrier fluid must be chosen carefully to accommodate the high temperatures to which the fluid can be subjected. The carrier fluid must be compatible with the specific application without suffering irreversible and unwanted property changes. The MR fluid must also contain additives to prevent the sedimentation of, and promote the dispersion of, the ferromagnetic particles.

A functional representation of an MR damper, with schematics of the components necessary for operation, is shown in Fig. 1.1. The fluid that is transferred from above the piston to below (and vice versa) must pass through the MR valve. The MR valve is a fixed-size orifice with the ability to apply a magnetic field, using an electromagnet, to the orifice volume. This magnetic field results in a change in viscosity of the MR fluid, causing a pressure differential for the flow of fluid in the orifice volume. The pressure differential is directly proportional to the force required to move the damper rod. As such, the damping characteristic of the MR damper is a function of the electrical current flowing into the electromagnet. This relationship allows the damping of an MR damper to be easily controlled in real time.

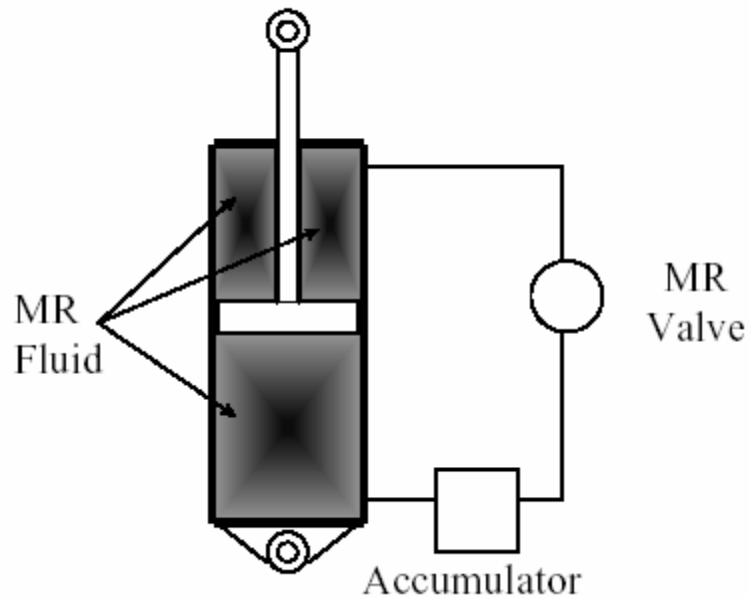


Figure 1.1 Functional Representation of an MR Damper

The accumulator is a pressurized volume of gas that is physically separated from the MR fluid by a floating piston or bladder. The accumulator serves two purposes. The first is to provide a volume for the MR fluid to occupy when the shaft is inserted into the damper cylinder. The second is to provide a pressure offset so that the pressure in the low pressure side of the MR valve does not induce cavitation in the MR fluid by reducing the pressure below the vapor pressure of the MR fluid.

The actual configuration of an MR damper is shown in Fig. 1.2. All of the external components have been incorporated internally, providing a compact design that is very similar in size and shape to existing passive vehicle dampers. The only external parts are the two electrical leads for the electromagnet, which are connected to the current source.

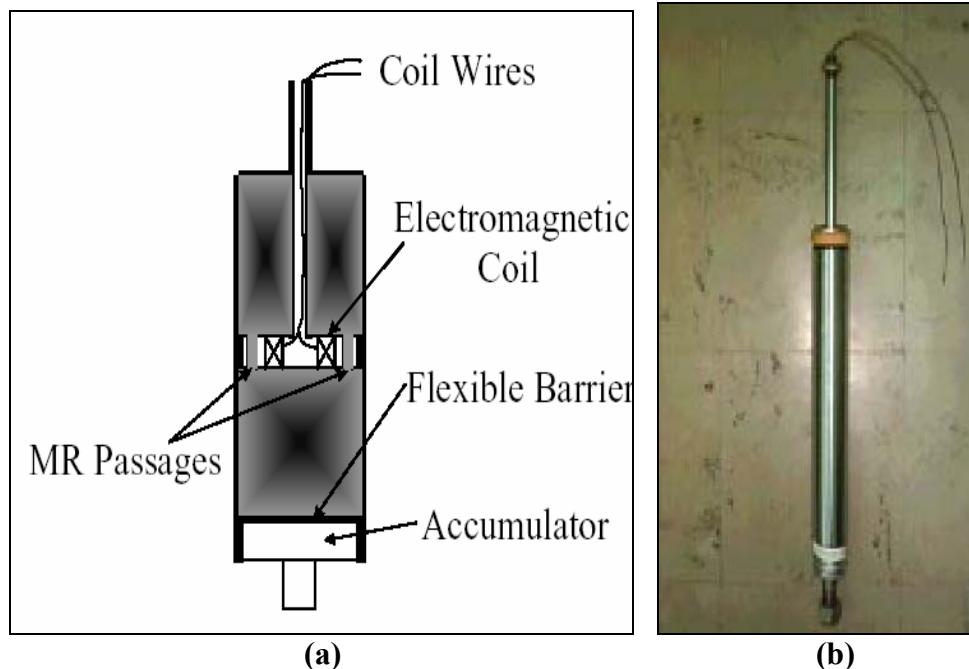


Figure 1.2 Configuration of a Magneto Rheological Damper
(a) Schematic Representation, (b) Actual Hardware

1.3 Performance of the MR Damper

For typical passive dampers, the damper performance is often evaluated based on the force vs. velocity characteristics. For a linear viscous damper, the force vs. velocity performance is shown in Fig. 1.3. The slope of the force vs. velocity line is known as the damper coefficient, C . In practice, however, the force vs. velocity line is frequently bilinear and asymmetric, with a different value of C for jounce (compression) and rebound (extension), as shown in Fig. 1.4. The reason for having asymmetric damping characteristics stems from the final application of the damper in a vehicle suspension. When working in series with the primary spring of the vehicle suspension, the damper is working against the spring force in compression and is greatly aided by the spring force in rebound. If the vehicle encounters a pothole or momentary loss of contact with the road, the only mechanism preventing the suspension from rebounding to the physical stops is the rebound damping [4].

Since the characteristics of a passive damper are such that there is only one force corresponding to a given velocity, the damping curve is tuned by a ride engineer for each

particular application. Therefore, the operational envelope of a passive damper is confined to one pre-designed force-velocity characteristic.

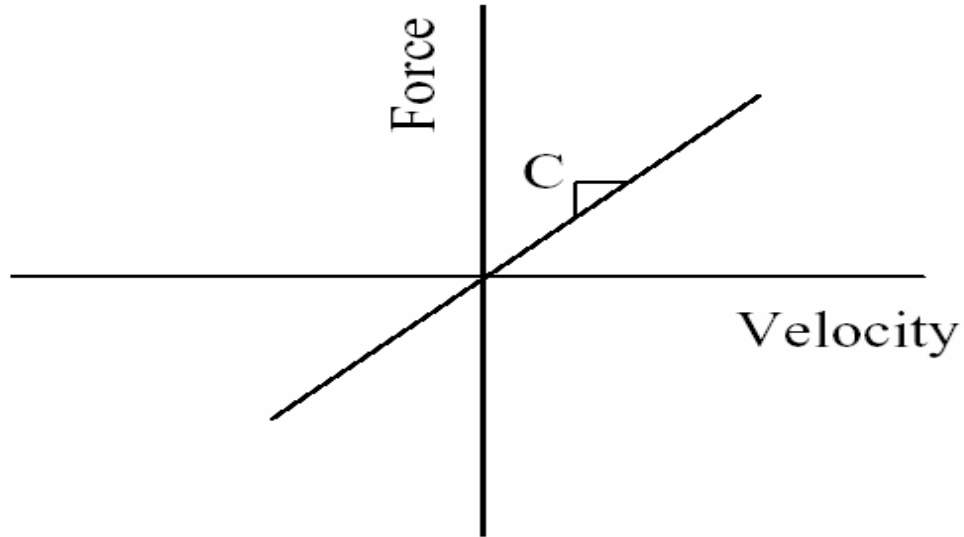


Figure 1.3 Linear Damper Characteristics

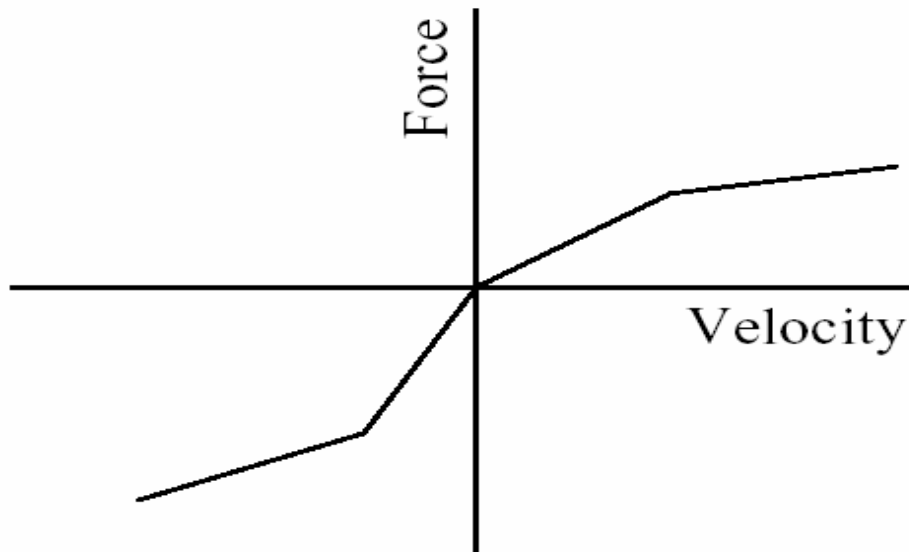


Figure 1.4 Bilinear and Asymmetric Damping Characteristics

In the case of MR dampers, the ideal force-velocity characteristics are as shown in Fig. 1.5. The result is a force vs. velocity envelope that is spanned by an area rather than

a line in the force-velocity plane. In this ideal case, the damper force is independent of the shaft velocity, and is only a function of the current going into the coil. Effectively, the controller can be programmed to emulate any damper force-velocity characteristic or control policy within the envelope.

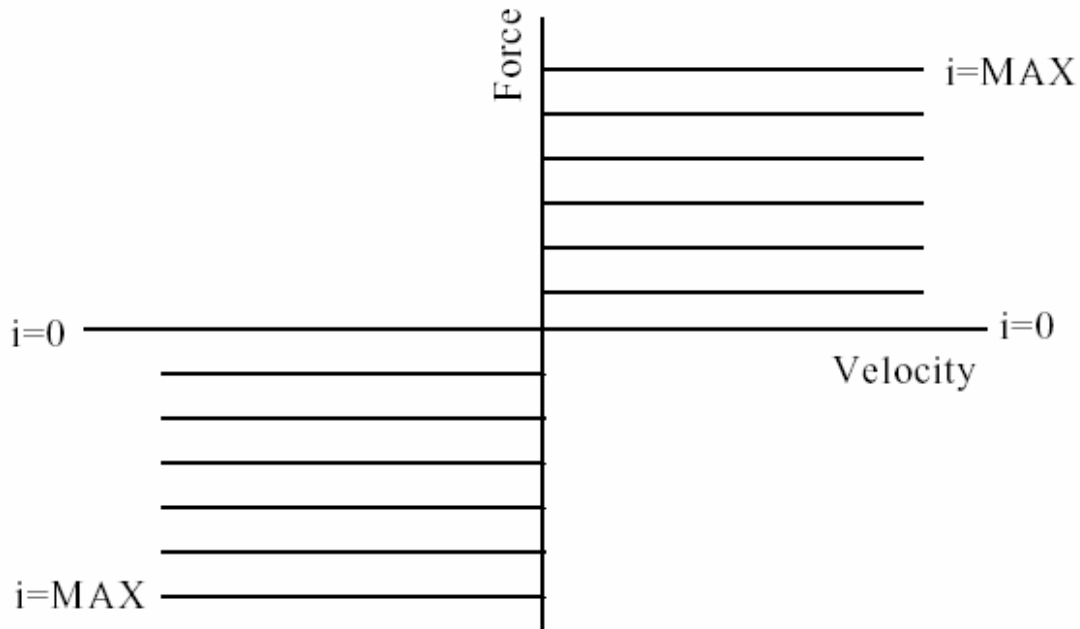


Figure 1.5 Ideal MR Damper Performance

We can model the ideal MR damper according to

$$F_{MRDAMPER} = \alpha i \quad (1.1)$$

Where α is a constant and i is the damper current. Figure 1.6 shows the actual nonlinear force-velocity characteristics for the MR damper. The model in Fig. 1.5 does not capture the fine details of the actual MR damper; some of the effects missing from the model include the magnetic field saturation, hysteresis, and the force due to the pressurized accumulator. As will be shown in later chapters, this approximation is sufficient for designing MR dampers for most applications, including vehicle suspensions.

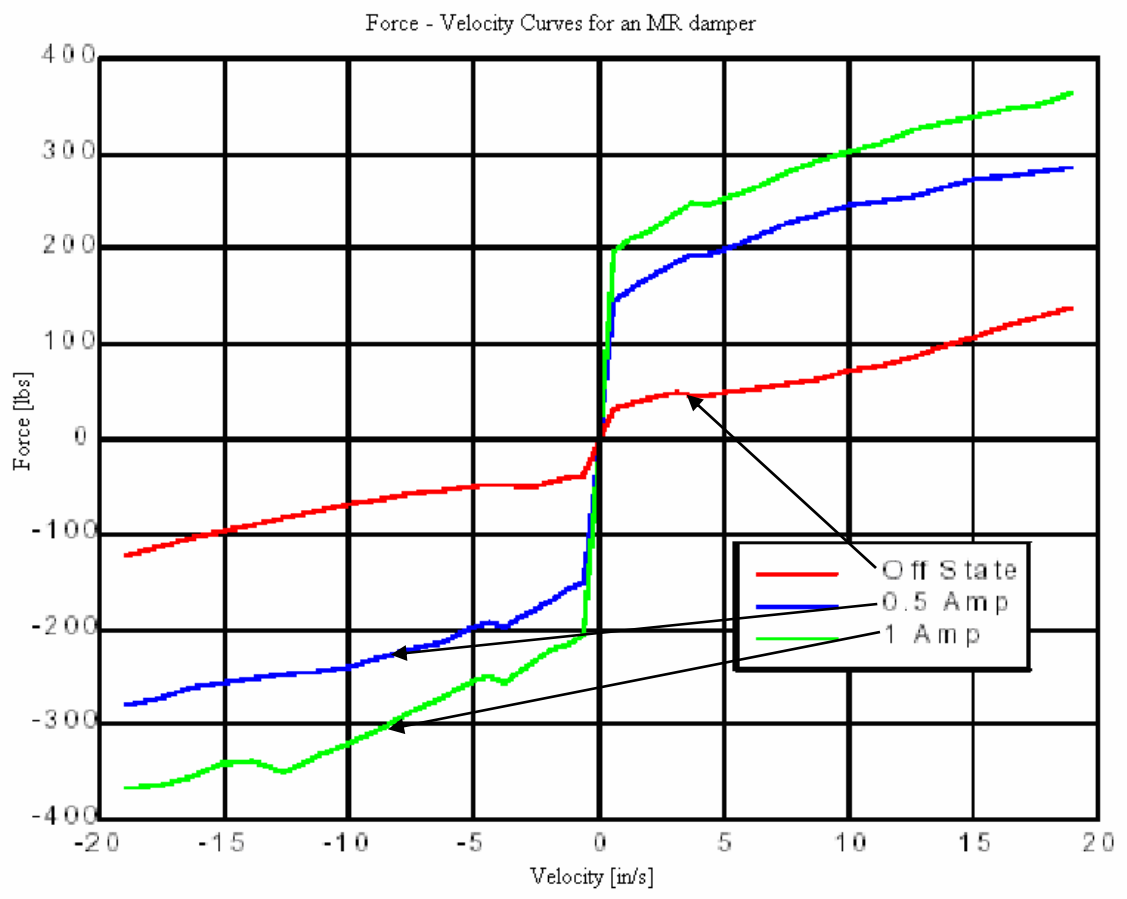


Figure 1.6 MR Damper Performance Envelope from Experimental Data[1]

1.4 Objectives

The primary objectives of this study are to

1. provide a detailed finite element analysis tool for modeling magneto-rheological dampers,
2. provide a design analysis of some of the parameters in MR dampers that can have a significant effect on the force-velocity characteristics of MR dampers, and
3. evaluate the effect of different geometric designs on increasing the damping force that can result from an MR damper with a given size.

1.5 Approach

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 engine, MR Fluid and the housing. After we generate the magnetic flux table for each case, we will use some mathematical equations to solve the force provided from the model. After that we can establish the force-velocity plot at different current.

1.6 Outline

Chapter 2 presents the background information on MR fluids, MR dampers and MR dampers modeling. Chapter 3 presents the finite element analysis based of modeling magneto rheological 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 explains the model results. Here, we talk about the magnetic flux density generated at the MR fluid gap and how we can establish the force-velocity plot at different current. Chapter 5 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 6 is the conclusion chapter and ties everything together by presenting the important points of this study and recommendations for future research.

1.7 Contributions

The primary contributions of this study are to

1. create and design a 2-D axisymmetric MR damper using ANSYS software,
2. generate the magnetic flux density at the MR fluid gap which will leads us to establish the force or shear stress at that gap,
3. develop different models with different piston geometries that will effect the performance of the damper and the force-velocity characteristics, and
4. detect magnetic saturation by analyzing the 2-D contour nodal solution for the magnetic flux density at the MR fluid gap.

Chapter 2

Background

This chapter provides an overview of MR fluids, MR dampers, and some of the other MR devices that have already been commercialized or proposed for commercial applications. It further provides a summary of past studies that have been conducted on 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 [5]. 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. In ferrofluids, these particles' magnitudes are smaller than those of MR fluids; i.e. they are 1 – 2 microns, in contrast to 20 –50 microns for MR fluids. For the first few years, there was a flurry of interest in MR fluids but this interest quickly waned. In the early 1990's there was resurgence in MR fluid research that was primarily due to Lord Corporation's research and development.

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 [6]. When exposed to a magnetic field, the ferrous particles that are dispersed throughout the fluid form magnetic dipoles. These magnetic dipoles align themselves along lines of magnetic flux, as shown in Figure 2.1.

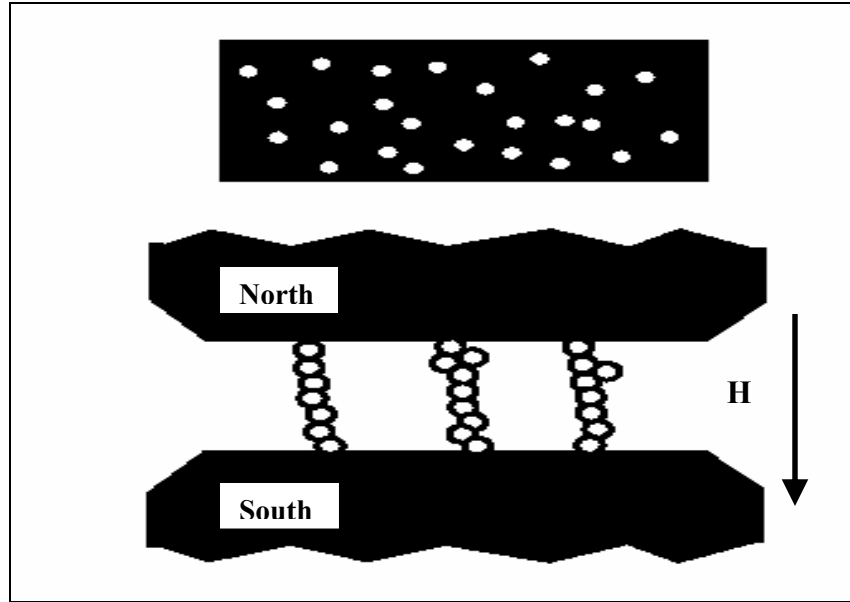


Figure 2.1 MR fluid Ferrous particle Arrangement in unenergized and energized modes

Typically, MR fluid can be used in three different ways, all of which can be applied to MR damper design depending on the damper's intended use. These modes of operation are referred to as the squeeze mode, valve mode, and shear mode. A device that uses a squeeze mode has a thin film (on the order of 0.02 inch) of MR fluid that is sandwiched between pole surfaces as shown in Figure 2.2.

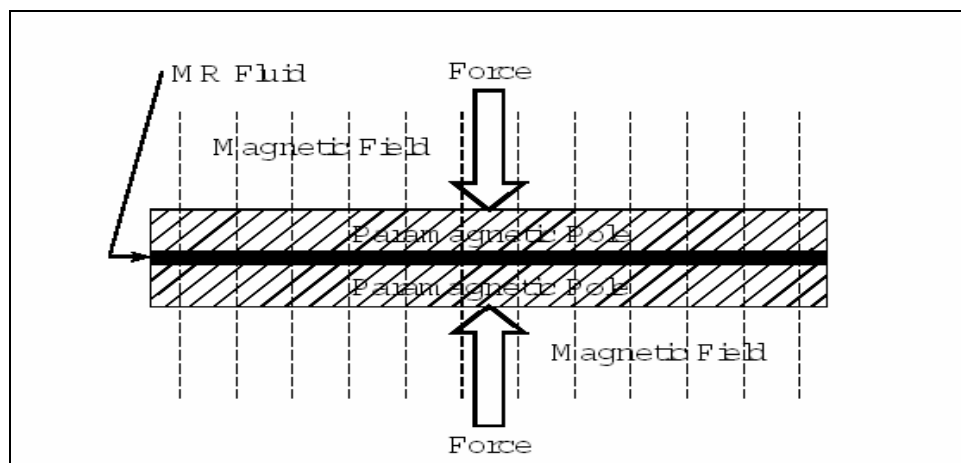


Figure 2.2 MR fluid used in squeeze mode[1]

As depicted in Figure 2.3, MR fluid device is said to operate in shear mode when a thin layer (≈ 0.005 to 0.015 inch) of MR fluid is sandwiched between two paramagnetic moving surfaces. The shear mode is primarily useful for dampers that are not required to provide large forces or for compact clutches and brakes.

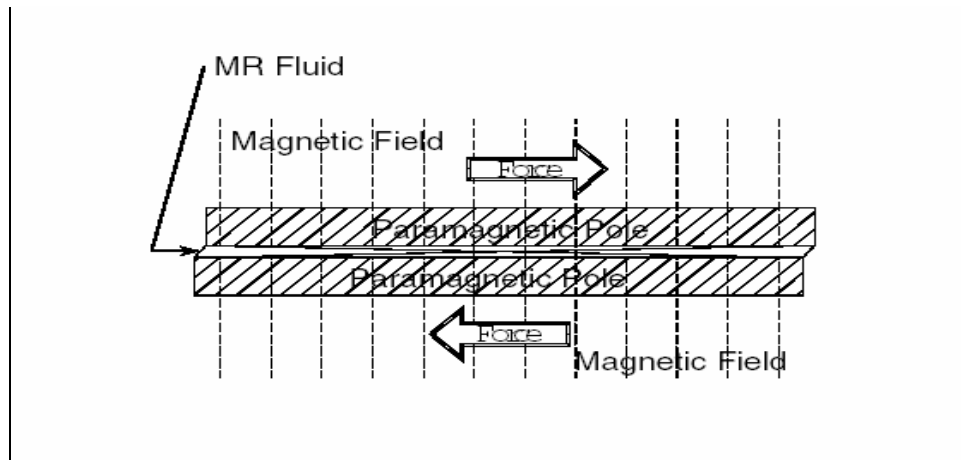


Figure 2.3 MR fluid used in shear mode[1]

The last mode of MR damper operation, valve mode, is the most widely used mode of the three. An MR device is said to operate in valve mode when the MR fluid is used to impede the flow of MR fluid from one reservoir to another, as is shown in Figure 2.4.

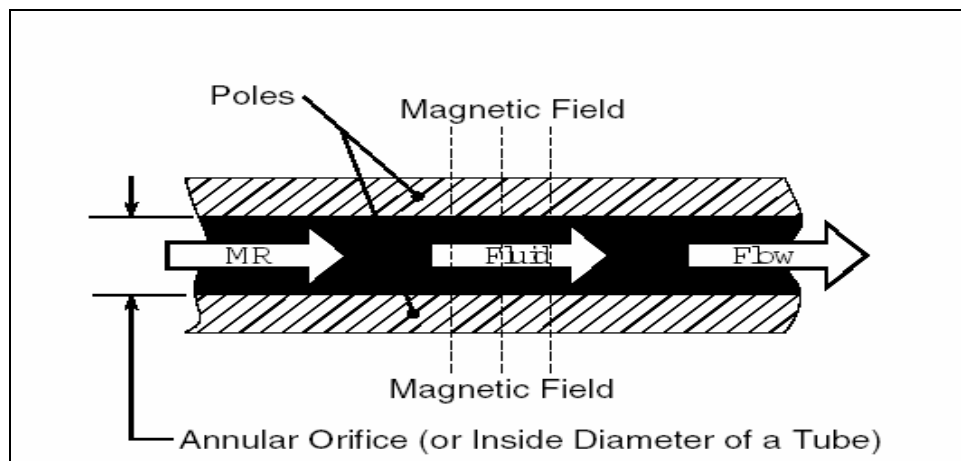


Figure 2.4 MR fluid used in valve mode[1]

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.

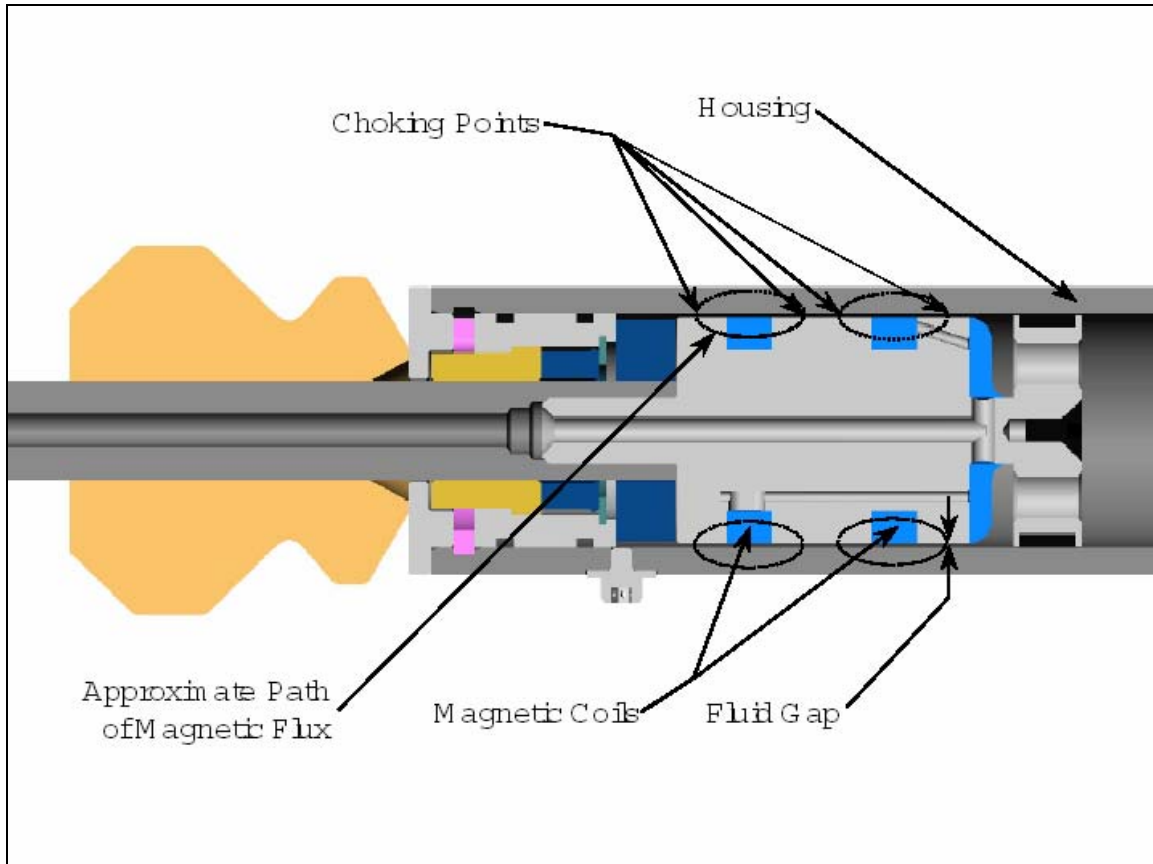


Figure 2.5 Typical MR damper Design Configuration[1]

Varying the magnetic field strength affects the apparent viscosity of the MR fluid. The reason why the phrase “apparent viscosity” is used instead of “viscosity” is that the carrier fluid exhibits no change in viscosity, but the MR fluid mixture thickens – even becomes a solid – when it is exposed to a magnetic field. The magnetic field changes the shear strain rate of the MR fluid, in the same sense that the fluid becomes more sensitive to shearing with an increasing magnetic field. As the magnetic field’s strength increases, the resistance to fluid flow at the activation regions increases until the saturation current

has been reached. A saturation current occurs when an increase in the electric current fails to yield an increase in the damping force for a given velocity. The resistance to fluid flow in the activation regions, is what causes the force that MR dampers can produce. This mechanism is similar to that of hydraulic dampers, where the force offered by hydraulic dampers is caused by fluid passage 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

In addition to dampers or shock absorbers, MR fluid can be used in a variety of other devices, including rotary brakes, clutches, prosthetic devices, and even for uses such as polishing and grinding.

One of the 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.



Figure 2.6 Lord Corporation's rotary MR brake [7]

Probably the most commercially successful MR device to date is the Rheonetic RD-1005-3 MR damper that is manufactured by Lord Corporation [8]. The damper has a mono tube construction and an extended and compressed length of 8.2 and 6.1 inches, respectively measured from eye to eye. When compressed, the damper is 6.1 inches long also measured from eye to eye. The RD-1005-3 MR damper is capable of having a minimum of 500 lbs of damping force at velocities of larger than 2 in/sec with 1 Amp of current. When no current is supplied to the damper (i.e. the off-state), the damper has a force of less than 150 lbs at 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 leg that is being developed by Biedermann Motech GmbH [11]. For the seat damper application, these small mono tube MR dampers are used in conjunction with a control unit and an accelerometer to minimize driver fatigue in large trucks. 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.

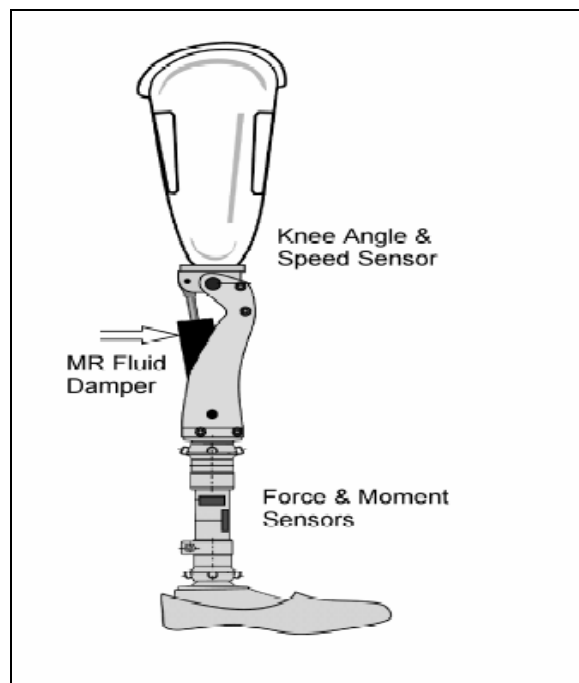


Figure 2.8 Biedermann Motech prosthetic leg[11]

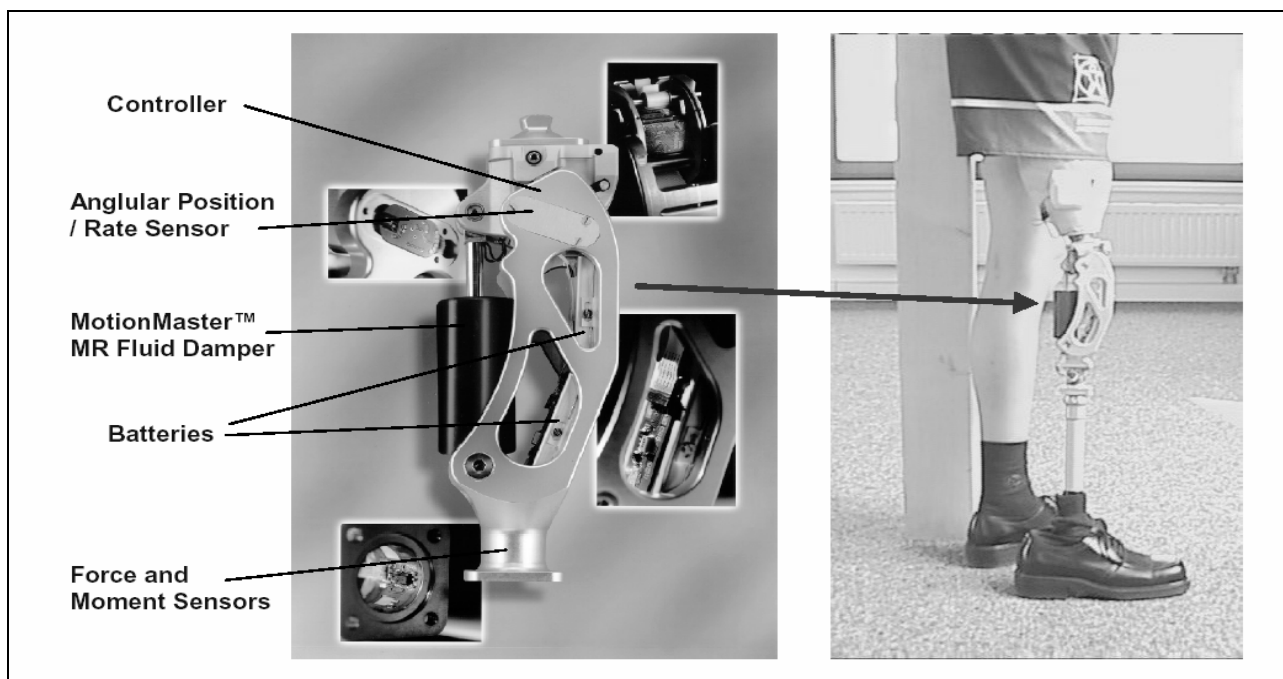


Figure 2.9 Diagram and picture of prosthetic leg[11]

2.3 MR Damper Basics

Among MR devices, MR dampers have been most widely studied and developed for commercial applications. The commercialized success of MR damper reaches beyond the Motion Master System by Lord Corporation, described earlier. It also includes automotive applications such as the recent announcement by Delphi Corporation to manufacture MR dampers for certain 2003 Cadillac models [12]. Other proposed applications for MR dampers include building control systems, use in 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

There are three main types of MR dampers. The mono tube, the twin tube, and the double-ended MR damper. Of the three types, the mono tube is the most common since it can be installed in any orientation and is compact in size. A mono tube MR damper, shown in Figure 2.10, 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 accumulator piston provides a barrier between the MR fluid and a compressed gas (usually nitrogen) that is used to accommodate the volume changes that occur when the piston rod enters the housing.

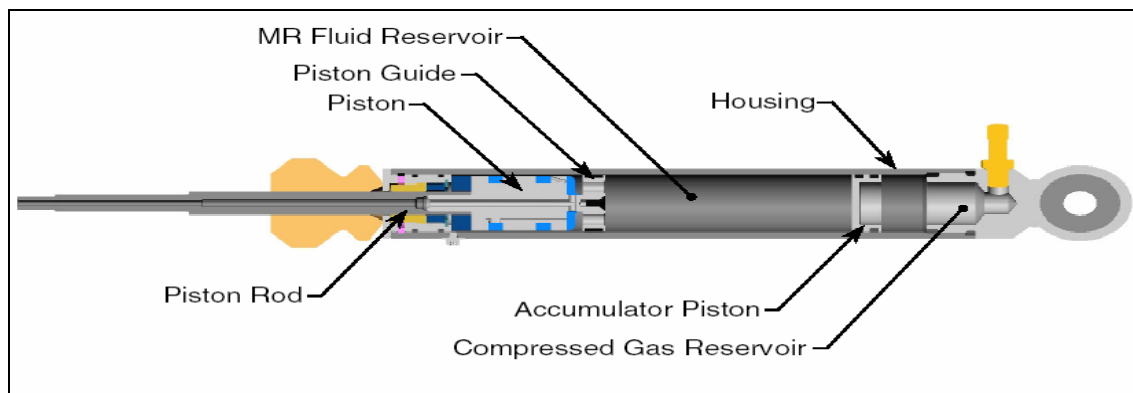


Figure 2.10 Mono tube MR damper section view[1]

The twin tube MR damper is one that has two fluid reservoirs, one inside of the other, as shown in Figure 2.11. In this configuration, the damper has an inner and outer housing, which are separated from each other by a foot valve shown in Figure 2.12. The inner housing guides the piston rod assembly, in exactly the same manner as in a mono tubes damper. The volume enclosed by the inner housing is referred to as the inner reservoir. Likewise, the volume that is defined by the space between the inner housing and the outer housing is referred to as the outer reservoir. The inner reservoir is filled with MR fluid so that no air pockets exist.

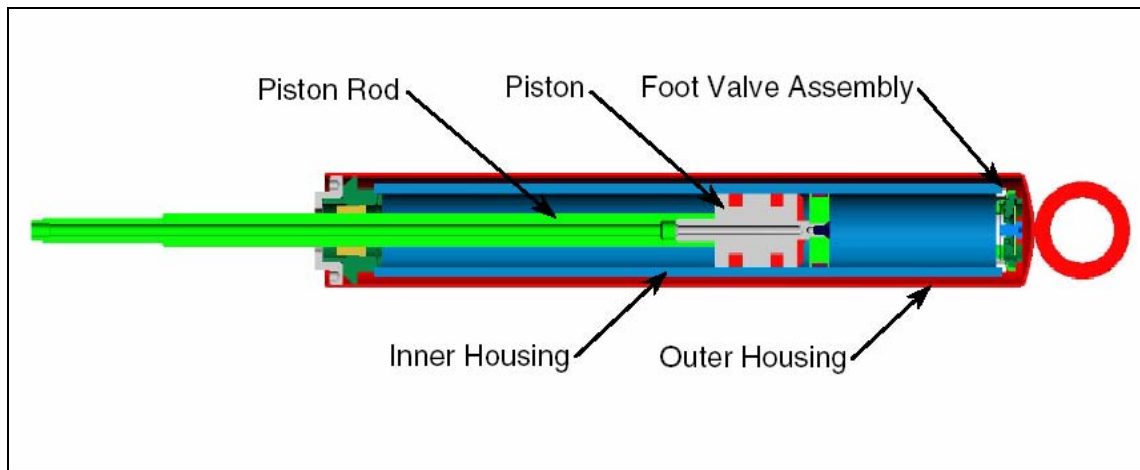


Figure 2.11 Twin tube MR damper[1]

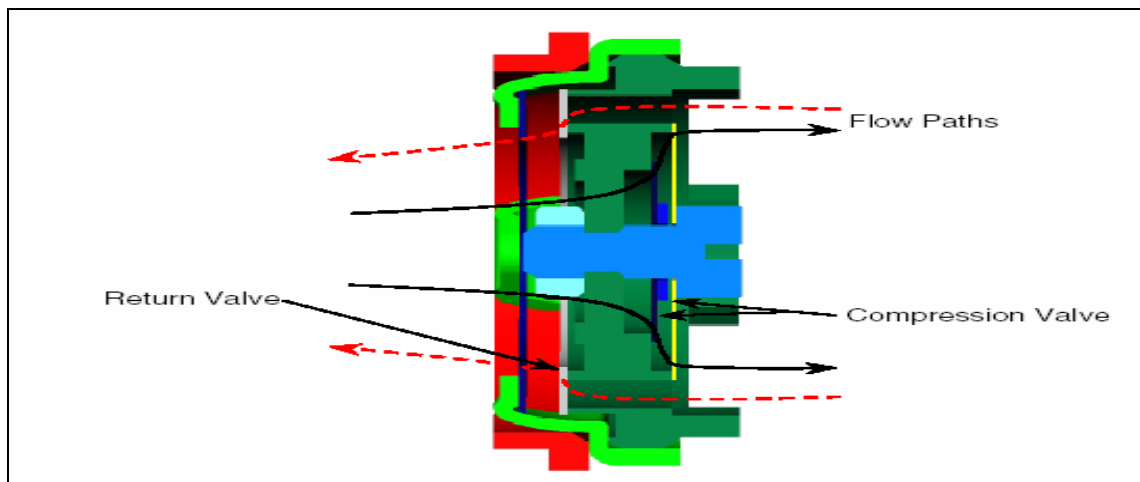


Figure 2.12 Detail of Foot Valve[1]

To accommodate changes in volume due to piston rod movement, an outer reservoir that is partially filled with MR fluid is used. Therefore, the outer tube in a twin tube damper serves the same purpose as the pneumatic accumulator mechanism in mono tube dampers. In practice, a valve assembly called a “foot valve” is attached to the bottom of the inner housing to regulate the flow of fluid between the two reservoirs. As the piston rod enters the damper, MR fluid flows from the inner reservoir into the outer reservoir through the compression valve, which is part of the foot valve assembly. The amount of fluid that flows from the inner reservoir into the outer reservoir is equal to the volume displaced by the piston rod as it enters the inner housing. As the piston rod is withdrawn from the damper, MR fluid flows from the outer reservoir into the inner reservoir through the return valve, which is also part of the 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].

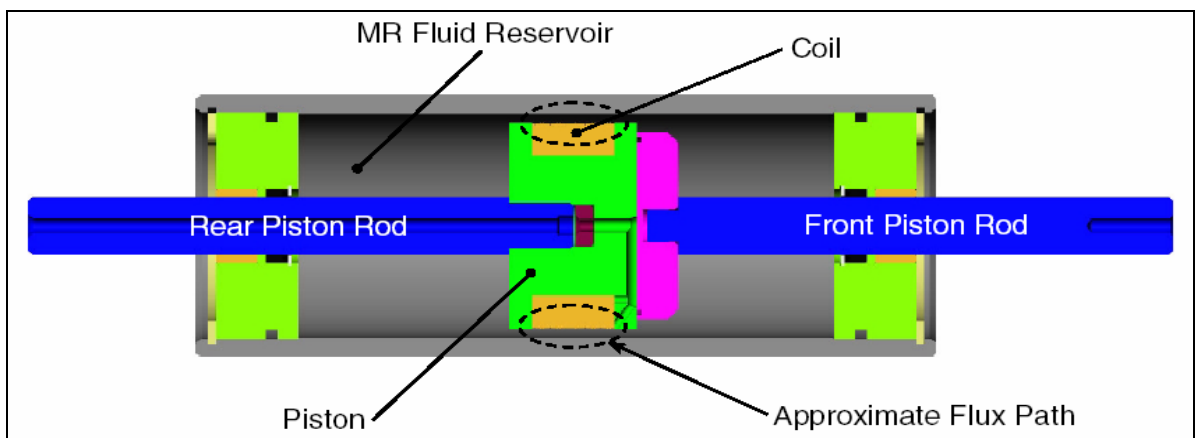


Figure 2.13 Double-ended MR damper[8]

2.4 Mathematical Fundamentals of MR Dampers

To assist the reader in understanding the following mathematical discussion, Table 2.1, which lists all nomenclature that is used, has been included.

Table 2.1 Mathematical Nomenclature

Symbol	Description
τ	Fluid stress
τ_y	Field dependent yield stress: Found in MR fluid spec sheets
H	Magnetic field
η	Plastic viscosity ($H=0$): Found in MR fluid spec sheets
$\dot{\gamma}$	Fluid shear rate
γ	Fluid shear
G	Complex material modulus
ΔP	Pressure drop
ΔP_η	Viscous component of pressure drop
ΔP_τ	Field dependent induced yield stress component of pressure drop
Q	Pressure driven fluid flow
L	Length of fluid flow orifice
b	Outer Radius of the Piston
D	Piston Diameter
g	Fluid gap
w	Width of fluid flow orifice
c	Constant*
F	Force that is developed between pole plates in shear mode
F_η	Viscous shear force
F_τ	Magnetic dependent shear force
S	Relative velocity between pole plates used in shear mode
A	Pole area
V	Activated fluid volume
k	Constant
λ	Control ratio
W_m	Required controllable mechanical power level

* $c=2$ (for $\Delta P_\tau / \Delta P_\eta$ less than ~ 1); $c=3$ (for $\Delta P_\tau / \Delta P_\eta$ greater than ~ 100)

MR fluid is often modeled as a Bingham solid that has yield strength [6]. For this model, fluid flow is governed by Bingham's equations, which are displayed below as Equations (2.1a) and (2.1b).

$$\tau = \tau_y(H) + \eta\dot{\gamma} \quad (2.1a)$$

$$\tau < \tau_y \quad (2.1b)$$

In Equations (2.1a) and (2.1b), τ represents the fluid stress, τ_y represents the field dependent yield stress, H represents the magnetic field, $\dot{\gamma}$ represents the fluid shear rate, and η represents the plastic viscosity; in other words, the viscosity when $H=0$. Below the fluid's yield stress (pre-yield state), the fluid displays viscoelastic behavior. This viscoelastic behavior can be represented by Equation (2.2), where G represents the complex material modulus.

$$\tau = G\gamma, \quad \tau < \tau_y \quad (2.2)$$

The pressure drop in an MR fluid device that is used in the flow mode can be represented by Equation (2.3), where the pressure drop (ΔP) is assumed to be the sum of a viscous component (ΔP_η) and a field dependent induced yield stress component (ΔP_τ).

$$\Delta P = \Delta P_\eta + \Delta P_\tau = \frac{12\eta QL}{g^3 w} + \frac{c\tau_y L}{g} \quad (2.3)$$

In Equation (2.3), Q represents the pressure driven MR fluid flow, and L , g , and w represents the length, fluid gap, and the width of the flow orifice that exists between the fixed magnetic poles as can be seen in Figure 2.14.

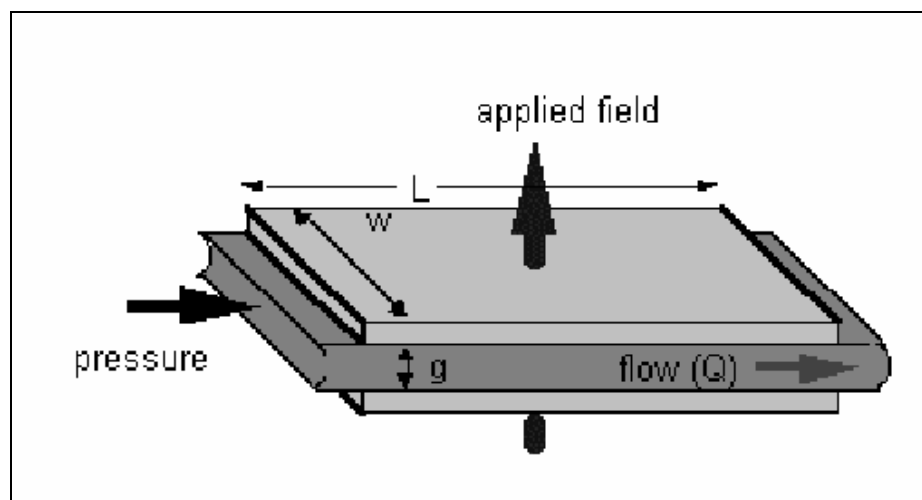


Figure 2.14 MR fluid in valve mode[1]

The constant c , varied from 2 to 3 depending on what $\frac{\Delta P_\tau}{\Delta P_\eta}$ ratio is present in the device being considered. For $\frac{\Delta P_\tau}{\Delta P_\eta}$ ratios of approximately 1 or smaller, the value for c is chosen to be 2. For $\frac{\Delta P_\tau}{\Delta P_\eta}$ 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

$$F = F_\eta + F_\tau = \frac{\eta SA}{g} + \tau_y A \quad (2.4)$$

To calculate the force that is developed between the two pole plates when one pole plate is moved relative to the other and parallel to the fluid gap. This equation assumes that the total force developed is the sum of a viscous shear force component and magnetic field dependent shear force component. In Equation (2.4), F represents the force that is developed between the pole plates, F_η is the viscous shear force, F_τ is the magnetic dependent shear force, and A is the pole plate area, which is defined by $A=LW$.

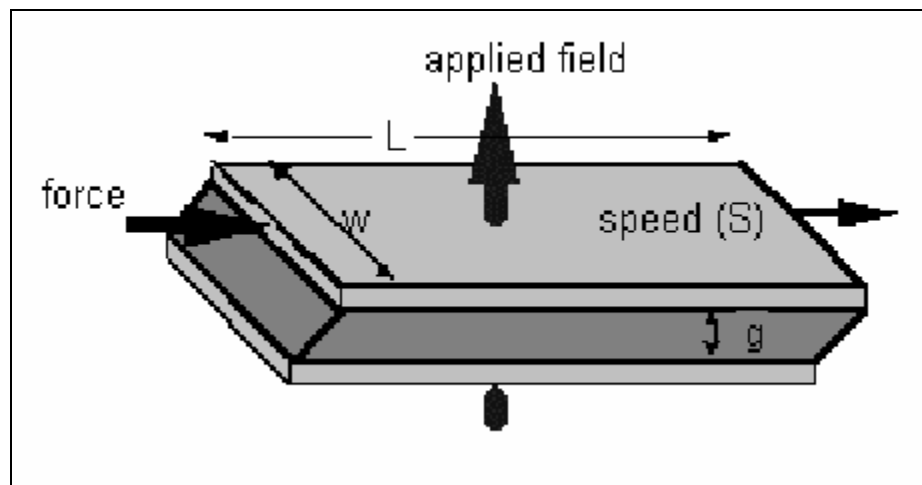


Figure 2.15 MR fluid in direct shear mode[1]

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

$$V = k \left(\frac{\eta}{\tau^2_y} \right) \lambda W_m. \quad (2.5)$$

In Equation (2.5), V can be regarded as the minimum active fluid volume that is needed to achieve a desired control ratio λ 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

$$k = \frac{12}{c^2} \quad (2.6a)$$

$$\lambda = \frac{\Delta P_\tau}{\Delta P_\eta} \quad (2.6b)$$

$$W_m = Q \Delta P_\tau \quad (2.6c)$$

For valve mode operation. Further, for shear mode operation, they can be calculated as

$$k = 1 \quad (2.7a)$$

$$\lambda = \frac{F_\tau}{F_\eta} \quad (2.7b)$$

$$W_m = F_\tau S \quad (2.7c)$$

Summary

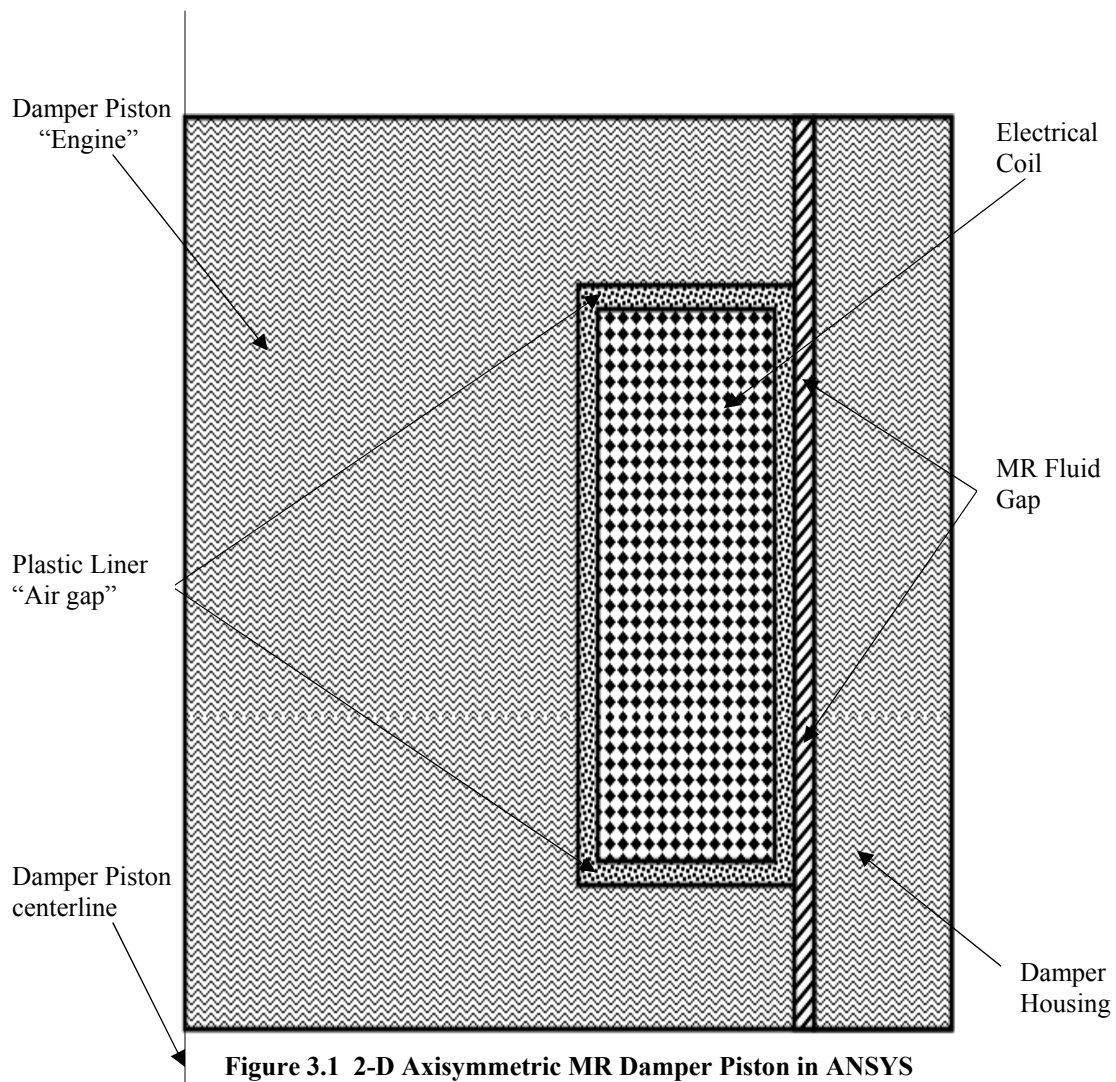
Looking back at this chapter, we provided an overview of MR fluids, MR dampers, and some of the other MR devices. It also covered the mathematical fundamentals of MR dampers, which will be used in chapter 4 to generate the force at each different magnetic flux density.

Chapter 3

Finite Element Analysis – Based MR Model

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 Engine, MR Fluid and the Damper Housing.



The dimensions of the MR Damper are in meters. The Damper piston (here, frequently referred to as “Engine”, MR fluid gap and the damper housing are the stationary

component that completes the magnetic circuit around the coil. A wound *coil* of 650 windings, shown in Figure 3.2, provides the magnetic flux field that is 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.

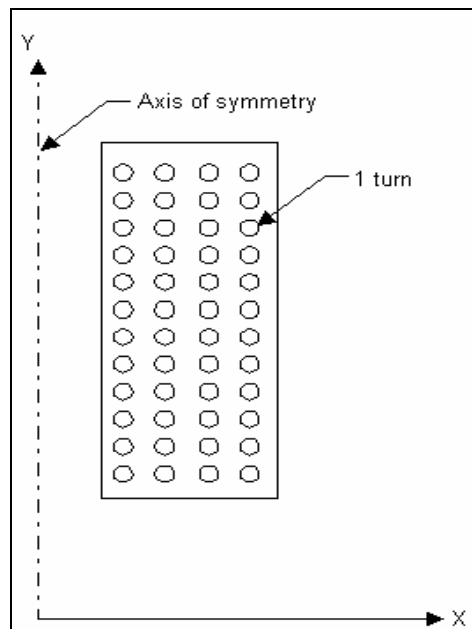


Figure 3.2 Electrical Coil Cross Section

To assist the reader in understanding the following discussion, Table 3.1, lists the magnetic terms that are used in this study.

Table 3.1 Nomenclature used for the Magnetic Analysis

Symbols	Meaning
B_{SUM}	Magnetic Flux Density or Magnetic Induction
H_{SUM}	Magnetic Field
A_Z	Magnetic Vector Potential
J_S	Current Density
N	Numbers of turns of wires
I	Current
μ	Permeability of material used in the Model

3.1 Approach and Assumption

The flux leakage out of the engine and housing at the perimeter of the model is assumed to be negligible enough that no saturation of the material occurs. 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. The non magnetic gap is modeled so that a quadrilateral mesh is possible. 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).

$$JS = \frac{NI}{A} \quad (3.1)$$

ANSYS is used to compute the current density from the number of turns (N), the current (I), and the coil area (A). The assumption of no leakage at the perimeter of the model means that the flux will be acting parallel to this surface. This assumption is enforced by the "flux parallel" boundary condition placed around the model. This boundary condition is used for models in which the flux is contained in an iron circuit. In postprocessing, the forces are summarized for the engine, MR fluid and the engine housing, using a Maxwell stress tensor and a virtual work calculation. Flux density also is displayed. The final postprocessing operation computes the terminal parameters including coil inductance.

3.2 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.

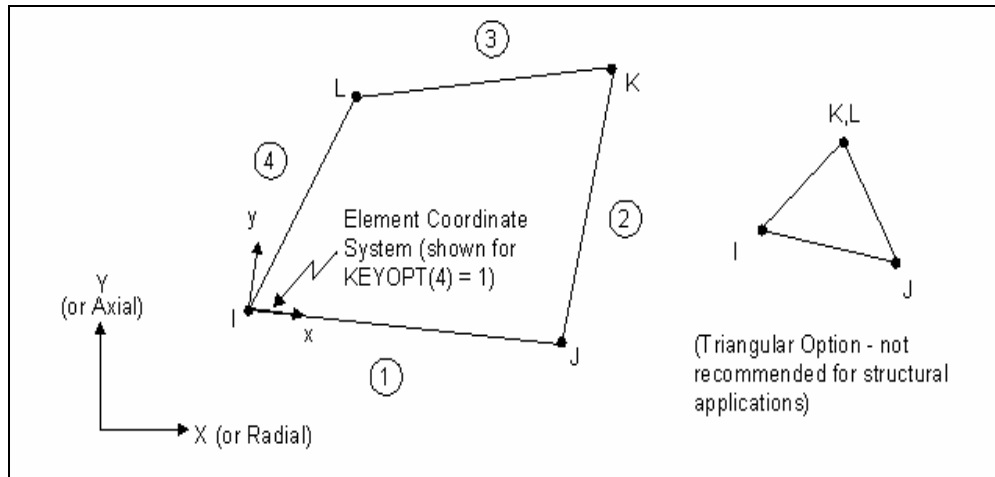


Figure 3.3 Plane13 2-D coupled-field-solid [16]

3.2.1 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 μ_0 (free-space permeability) which is equal to $4\pi * 10^{-7}$ henries/meter. In addition to μ_0 , constant relative permeability for each material is specified through the μ_x 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.

3.2.2 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.

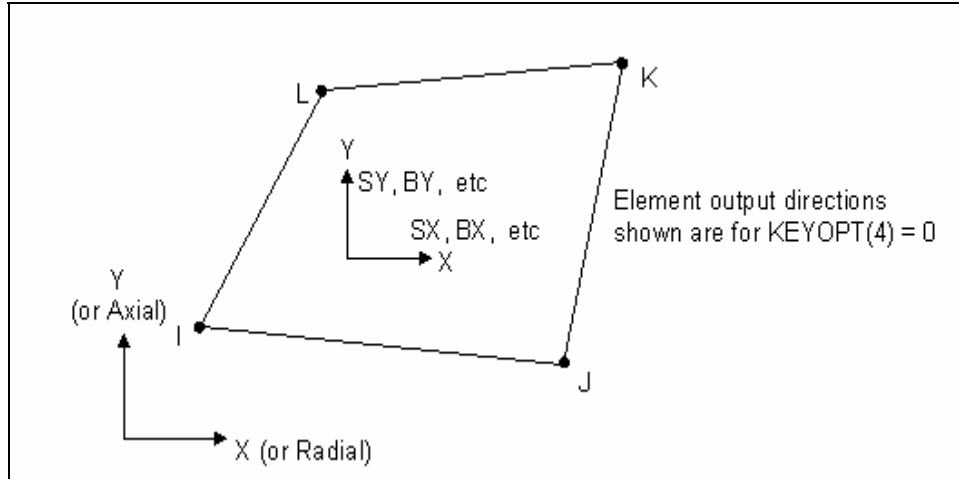


Figure 3.4 Plane13 Element Output [16]

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 B_x and B_y along the x and y axis. The term B_{sum} is the vector magnitude of B, defined by

$$B_{sum} = \sqrt{B_x^2 + B_y^2} \quad (3.2)$$

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 (μ_x - μ_y) and the magnetic field intensity components H_x and H_y .

3.3 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 (A_z) 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 (μ_0, μ_x), 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.

3.4 Steps in a Static Magnetic Analysis

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

- 1- Create the physics environment
- 2- Build and mesh the model and assign physics attributes to each region within the model
- 3- Apply boundary conditions and loads (excitation)
- 4- Obtain the solution
- 5- Review the results

3.4.1 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- Define the analysis title
- 3- Define element types and options
- 4- Define a system of units
- 5- Define material properties

3.4.1.1 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.

3.4.1.2 Defining an Analysis Title

We should give the analysis a title that reflects the problem being analyzed, such as “2-D MR Damper static analysis.” Save the model as database file only (.db). To assign a title we use the following:

Utility Menu>File> Save As

3.4.1.3 Specifying 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 regions 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

To specify KEYOPT settings, use the following:

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

3.4.1.4 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:

Main Menu>Preprocessor>Material Props>Electromag Units

Based on the input units we specify, the free-space permeability μ_0 is determined automatically as follows:

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

3.4.1.5 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 coordinate's points of the MR fluid by choosing any point on the B-H curve, as shown in Figure 3.5.

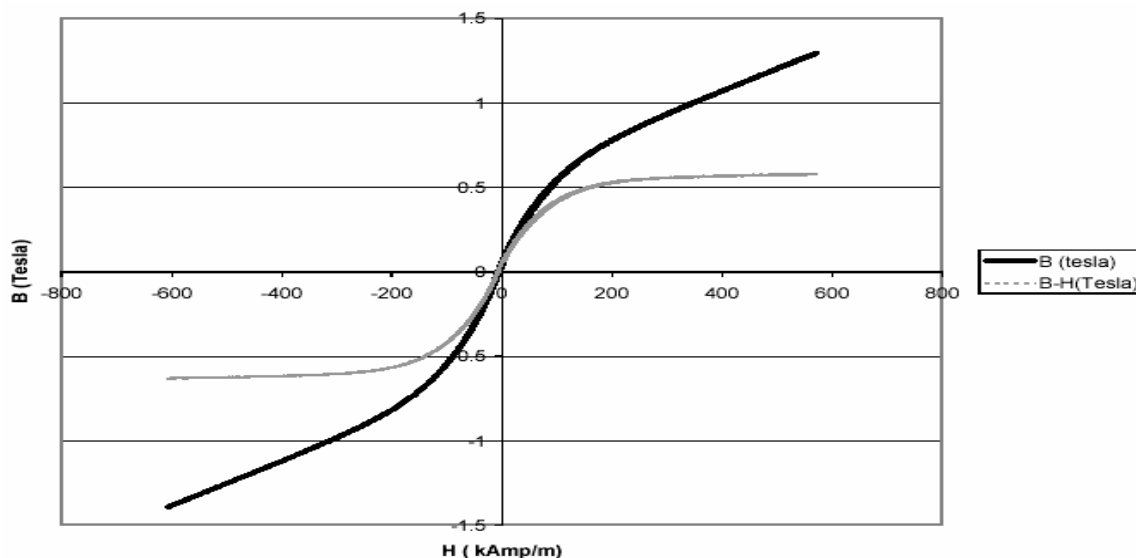


Figure 3.5 B-H curve for MR fluid

To do so, we use the following:

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

3.4.2 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.

Then we assign attributes to each region in the model (Attributes are the element types and options, element coordinate systems, and material properties, as were defined earlier).

To assign attributes, we perform these tasks:

- 1- Choose *Main Menu>-Attributes->Define>Picked Areas*. The Meshing Attributes dialog box appears.
- 2- Pick the area(s) comprising one of the regions in my model.
- 3- On the dialog box, we specify the material number, element type and element coordinate system to use for the area or areas. Click OK.
- 4- Repeat the process for the next region, the region after that, and so on 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.

3.4.3 Applying Boundary Conditions and Loads

We can apply boundary conditions and loads to a 2-D static magnetic analysis either on the solid model 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. When we choose *Main Menu>Solution>-Loads->Apply>-Magnetic-*, the ANSYS program lists available boundary conditions and three load categories (-Excitation-, -Flag-, -Other-).

3.4.3.1 Boundary Conditions

In our model, we need to specify the magnetic vector potential to be zero, i.e., $A_z=0$. Under the *Flux-Parallel*, we choose *On Lines*, and we pick all the lines surrounding the model. The *Flux-Parallel* boundary conditions force the flux to flow parallel to a surface.

To do so, we use the following steps:

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

3.4.3.2 Excitation Loads

Source Current Density (*JS*): This specifies applied current to a source conductor. The units of *JS* are *amperes / meter²* in the metric system. For a 2-D analysis, only the *Z* component of *JS* 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.

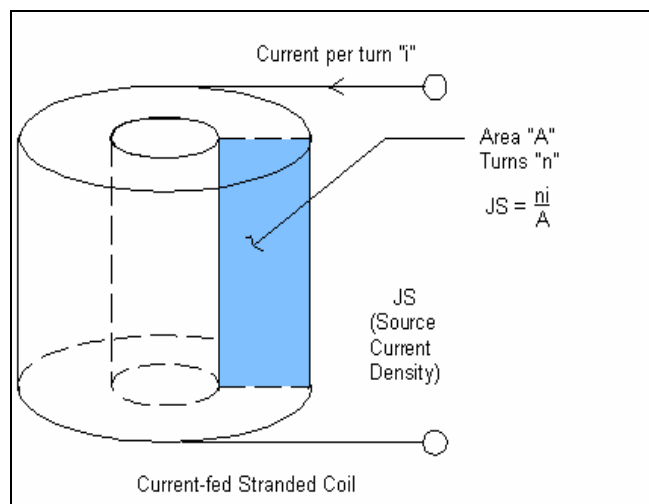


Figure 3.6 Current – Fed Electrical Coil [16]

Usually, we apply current density directly to the area. To do so, we use the following:

Main Menu>Preprocessor>Loads>-Loads-Apply>-Magnetic-Excitation>-Curr Density-On Areas.

3.4.4 Solving the Analysis

This section describes the tasks that we perform to solve a 2-D static magnetic analysis problem.

3.4.4.1 Defining the Analysis Type

Before we define the analysis type and the type of equation solver the analysis will use, we need to enter the SOLUTION processor. To do so, we use :

Main Menu>Solution

To specify the analysis type, we use:

Main Menu>Solution>New Analysis

Then we choose a static analysis. We can always restart an analysis only if we previously completed a 2-D static magnetic analysis.

3.4.4.2 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:

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.

3.4.4.3 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 in case the computer fails while analysis is in progress. To retrieve a model, re-enter ANSYS and use the following:

Utility Menu>File>Resum Jobname.db

3.4.4.4 Starting the Solution

In this step, we specify magnetic solution options and initiate the solution. For a nonlinear analysis, we use two-step solution sequence:

- 1- Ramp the loads over three to five substeps, each with one equilibrium iteration.
- 2- Calculate the final solution over one substep, with five to ten equilibrium iterations.

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

Main Menu>Solution>Electromagnet>Opt & Solv

3.4.4.5 Tracking Convergence Graphically

As nonlinear electromagnetic analysis proceeds, 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 displays the computed convergence norm and criteria while the solution is in progress.

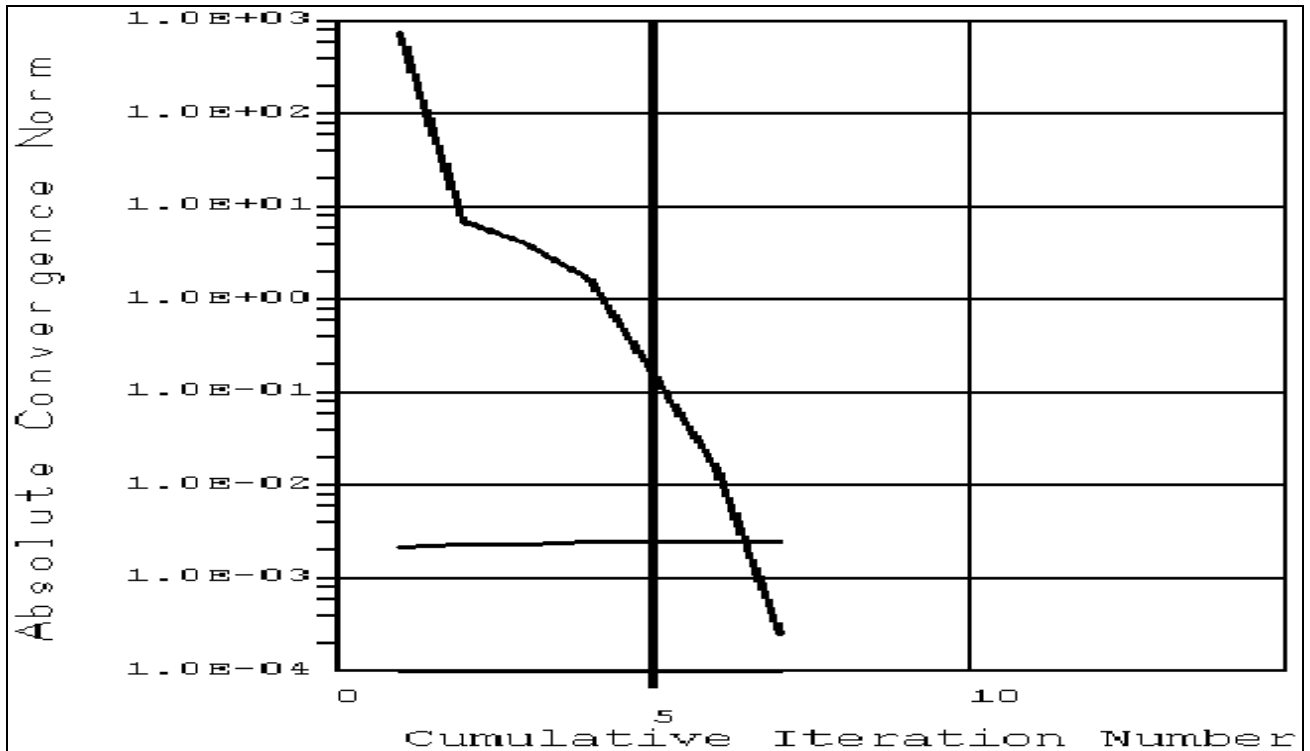


Figure 3.7 Convergence Norms Displayed by the Graphical Solution Tracking (GST) Features

3.4.4.6. Finishing the Solution

To leave the SOLUTION processor, we use the following:

Main Menu>Finish

3.4.5 Reviewing Results

ANSYS and ANSYS/E_{mag} programs write results from a 2-D static analysis to the magnetic results file, Jobname.RMG. Results include the data listed below:

Primary data:

- Nodal Magnetic DOF's (A_z , CURR)

Derived data:

- Nodal magnetic flux density (B_x , B_y , B_{sum})
- Nodal magnetic field intensity (H_x , H_y , H_{sum})
- Nodal magnetic forces (F_{MAG} : components X, Y, SUM)

- Nodal reaction current segments (CSGZ)
- Element source current density (JS_z)

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

Main Menu>General Postproc

3.4.5.1 Reading in Results Data

To review results in POST1, ANSYS database must contain the same model for which the solution was calculated. Also, the results file (Jobname.RMG) must be available.

To read the data from the result file into the database, we use :

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.

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 substep numbers or by time.

1- Flux Lines

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

Utility Menu>Plot>Results>Flux Lines

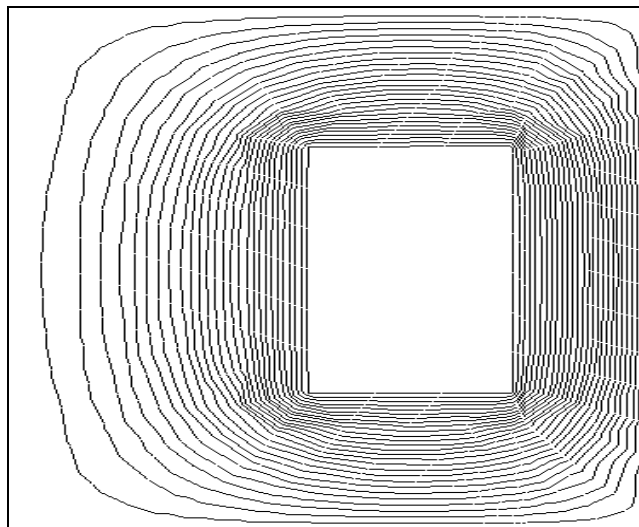


Figure 3.8 2-D Flux Lines around the Electrical Coil

2- Contour Displays

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

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> B_{SUM}

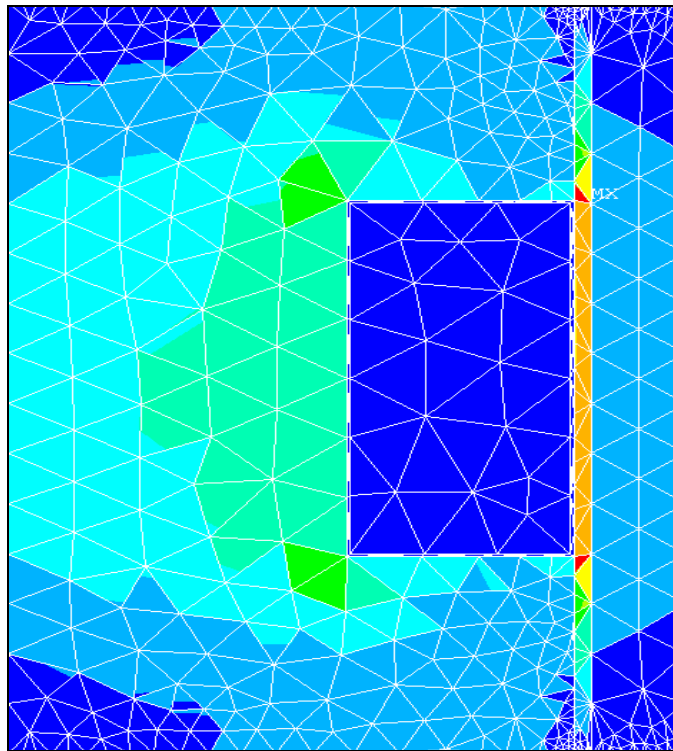


Figure 3.9 Element Solution- Magnetic Flux Density (B_{SUM})

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> H_{SUM}

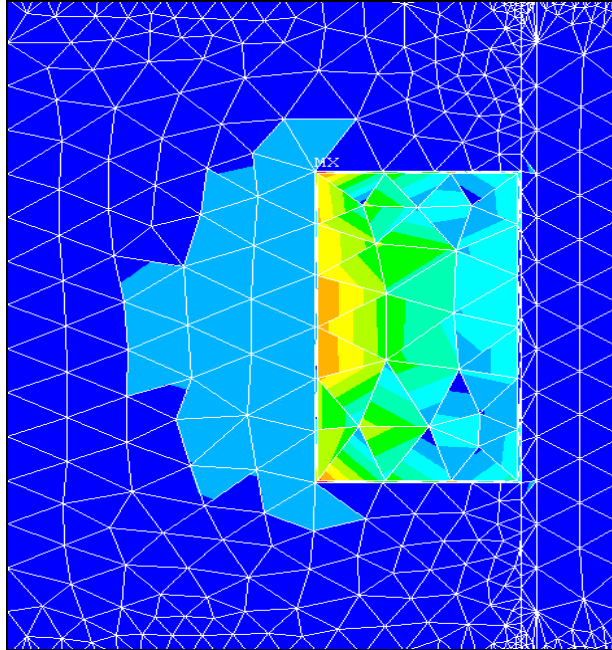


Figure 3.10 Element Solution- Magnetic Fields (H_{SUM})

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> JS_{SUM}*

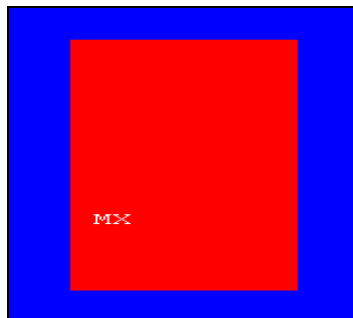


Figure 3.11 Element Solution- Current Density (JS_{SUM})

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 3.12, we use the following:

Main Menu>General Postproc>Plot Results>Contour Plot>Nodal Solution>Flux & Gradient>MagFLuxDens> B_{SUM}

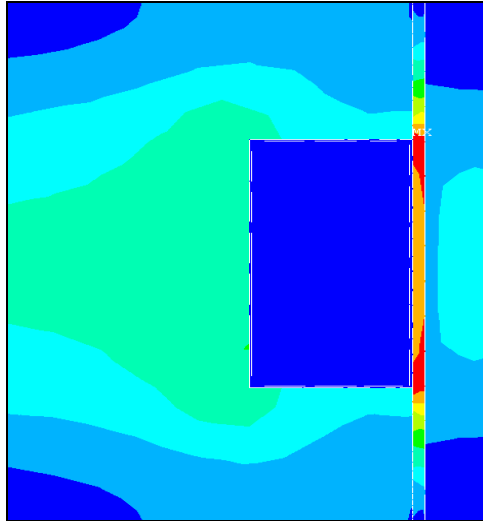


Figure 3.12 Nodal Solution- Magnetic Flux Density (B_{SUM})

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> H_{SUM}

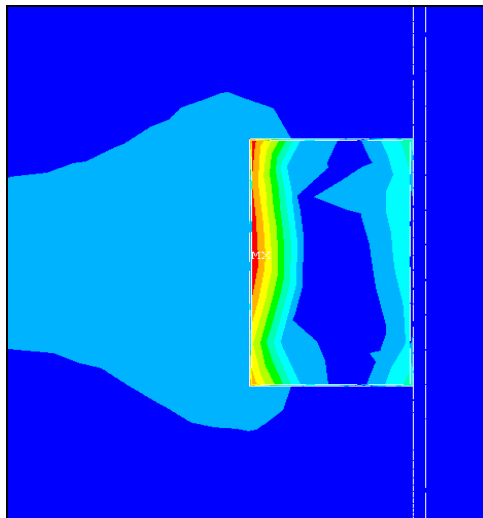


Figure 3.13 Nodal Solution- Magnetic Fields (H_{SUM})

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 Postproc>Plot Results>Contour Plot>Nodal
Solution>DOF Solution>MagVectPoten> A_z*

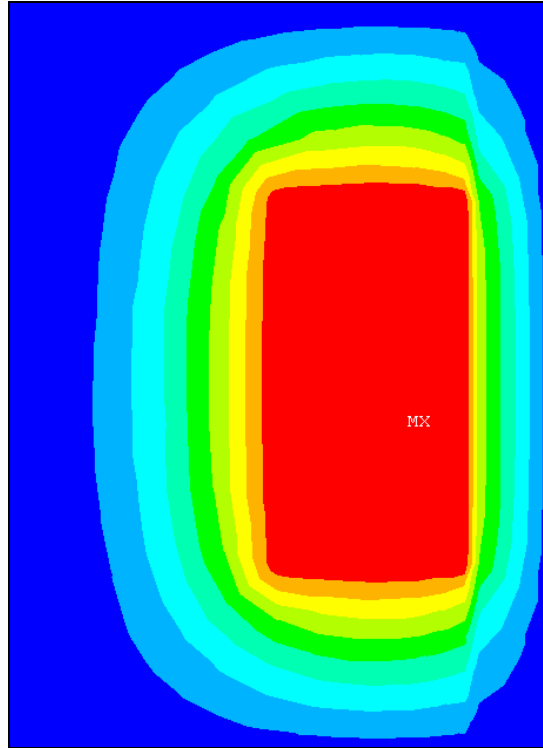


Figure 3.14 Nodal Solution- Magnetic Vector Potential (A_z)

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 (B_{SUM})

```

PRINT B      SUM DIRECTIONS PER NODE
          ***** POST1 NODAL MAGNETIC FLUX DENSITY SUM DIRECTIONS *****
LOAD STEP   1  SUBSTEP= 1|
TIME=       1.0000      LOAD CASE= 0
NODE        BSUM          DIRECTION VECTOR (X,Y,Z)
 1  0.7841E-01  1.000000  -0.00135  0.000000
 2  0.4388E-01  0.999994  -0.01105  0.000000
 3  0.5265E-01  1.000000  -0.00001  0.000000
 4  0.6267E-01  0.999999  -0.00445  0.000000
 5  0.5809E-01  0.999972  -0.02378  0.000000
 6  0.6478E-01  0.999963  -0.02702  0.000000
 7  0.4038E-01  1.000000  0.00002  0.000000
 8  0.4922E-01  0.999986  -0.01693  0.000000
 9  0.4712E-01  0.999998  -0.00672  0.000000
10  0.3693E-01  1.000000  0.00000  0.000000
11  0.5474E-01  0.999999  -0.00473  0.000000
12  0.3600E-01  1.000000  -0.00001  0.000000
13  0.3831E-01  0.999999  -0.00332  0.000000
14  0.4441E-01  1.000000  -0.00005  0.000000
15  0.2355      0.56913  -0.82225  0.000000
16  0.2669      0.40250  -0.91542  0.000000
17  0.1881      0.59339  -0.80491  0.000000
18  0.1791      0.58130  -0.81369  0.000000
19  0.1728      0.49350  -0.86974  0.000000
20  0.1157      0.82827  -0.56033  0.000000
21  0.1262      0.74564  -0.66635  0.000000
22  0.1164      0.79770  -0.60306  0.000000
23  0.1150      0.74043  -0.67213  0.000000
24  0.9730E-01  0.91866  -0.39504  0.000000
25  0.9681E-01  0.89653  -0.44299  0.000000
26  0.8902E-01  0.95263  -0.30414  0.000000
27  0.8675E-01  0.98966  -0.14345  0.000000
28  0.8790E-01  0.99923  -0.03914  0.000000
29  0.1317      0.99989  -0.01463  0.000000
30  0.1222      1.000000  -0.00196  0.000000
31  0.1137      0.99915  -0.04120  0.000000
32  0.1091      0.98679  -0.16202  0.000000
33  0.1082      0.96226  -0.27214  0.000000
34  0.1203      0.94432  -0.32903  0.000000
35  0.1291      0.92087  -0.38987  0.000000

```

Summary

Looking back at this chapter, we conclude that we can define all the magnetic flux along the MR fluid gap. From the magnetic flux, we can generate the shear stress along the gap and calculate the force. Chapter 4 will discuss in details the modeling results and how we can generate a force-velocity plot for a MR damper.

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 Engine, the second area is the engine housing, third area is the fluid gap (between the engine and the damper housing), fourth area is the plastic liner gap between the electrical coil and the engine/fluid area and the fifth area is the electrical coil. The coil is supplied a current which can be varied from 0 to 2.0 amperes. The program requires the current to be input in the form of current density (current over the area of the coil). Table 3.1 can be consulted for all the magnetic terms used in this Chapter.

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 Figure 4.1, was characterized by a 4th order polynomial of the form,

$$\tau_y = 6.298 B_f^4 - 25.824 B_f^3 + 26.639 B_f^2 - 0.438 B_f \quad (4.1)$$

which is shown in Figure 4.1 with the data points obtained experimentally.

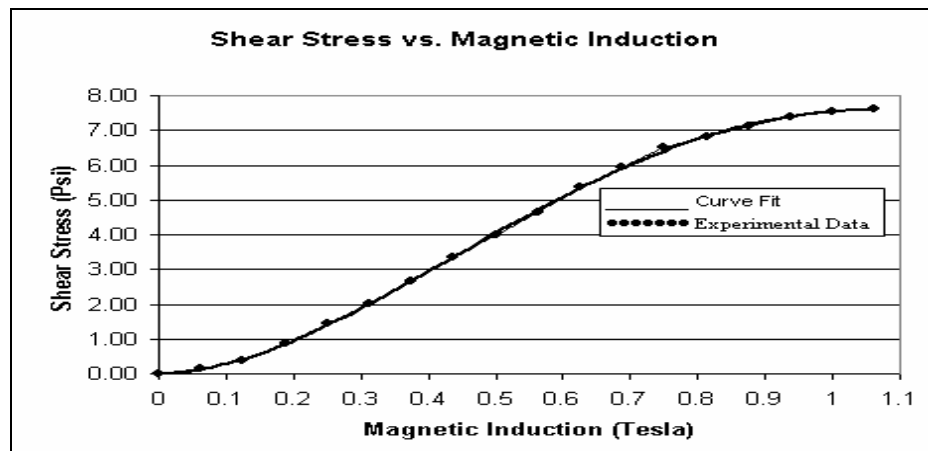


Figure 4.1 Shear Stress vs. Magnetic Induction

From the ANSYS model, one can generate the magnetic induction at the gap of the MR fluid (Figure 4.2). For each value of B_{SUM} , we can calculate the shear stress using equation (4.1).

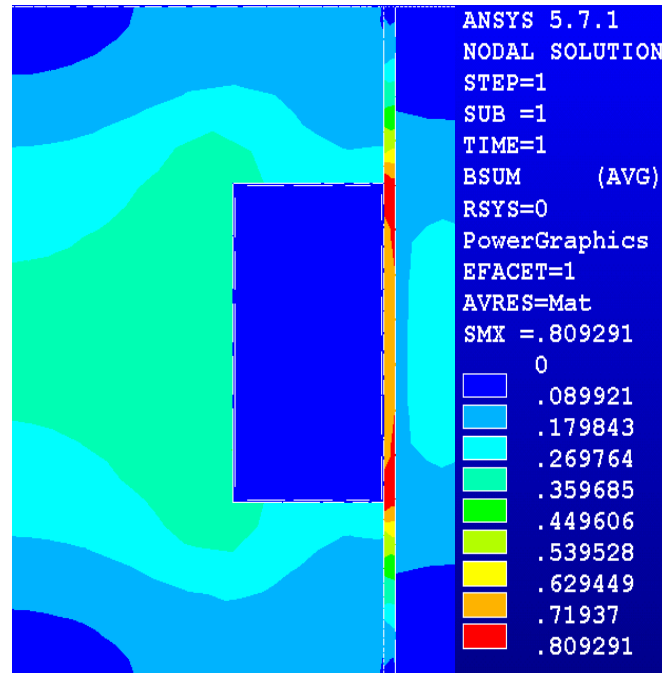


Figure 4.2 2-D Magnetic Flux Density (B_{SUM})

Zooming in to the gap area, as shown in Figure 4.3, we can get the magnetic induction at the MR fluid gap. Using the numbers generated from the nodal solution, we can find the average value of the magnetic flux density by using the following:

$$B_{AVE} = \frac{B_{max} + B_{min}}{2} \quad (4.2)$$

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.

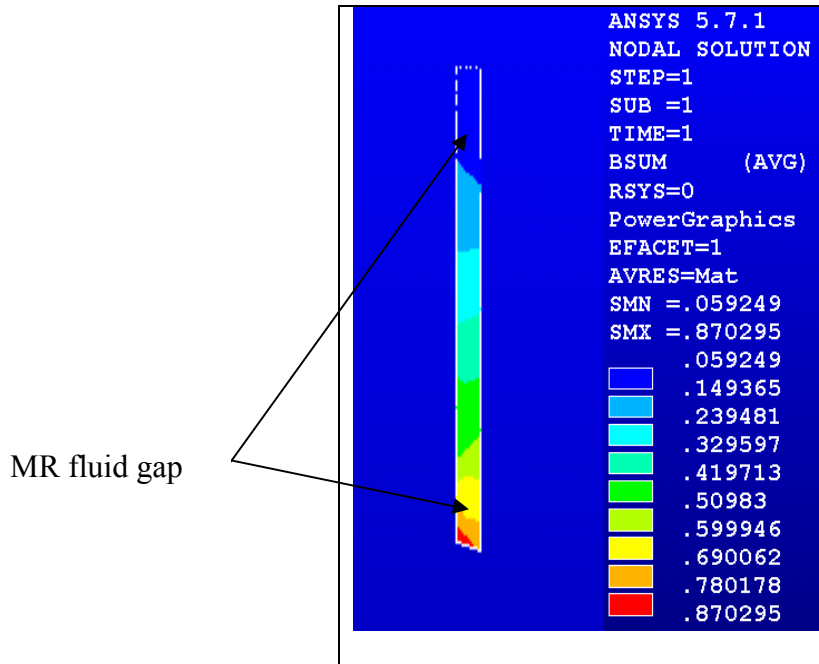


Figure 4.3 A close up of the Magnetic Flux Density in the Gap

Each time we increase the electrical current to the coil, the magnetic induction will increase and we'll get a new set of data. The contour plot shown in Figure 4.2 is generated for applying a current of 0.2 Amps 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 4.2.

The simulation results for 10 different currents are shown in Table 4.2. For each case, we can change the current value in the current density equation:

$$JS = \frac{NI}{A} ; \quad A = \text{Electrical Coil Area} \quad (4.3)$$

Equation (4.3) indicates that the magnetic induction is proportional to the supplied current. Therefore, increasing the current would increase the magnetic induction.

Table 4.2 Summaries of Simulation Results for various Magnetic Inductions

Current (Amps)	Magnetic Induction, B(f) (Tesla)
0	0
0.2	0.465
0.4	0.679
0.6	0.721
0.8	0.768
1.0	0.812
1.2	0.859
1.4	0.91
1.6	0.96
1.8	1.02
2.0	1.09

4.2 Force vs. Velocity characteristics

Using equation 4.1, we can generate the shear stress along the MR fluid gap. Because magneto-rheological fluids behave as non-Newtonian fluids, the viscosity is not constant with varying fluid velocity. Therefore, it is important to model the viscosity as a function of the shear rate.

Shear rate, [1/sec], is defined as:

$$\dot{\gamma} = \frac{v}{g} \quad (4.4)$$

Where v = relative fluid velocity, [in/sec]

g = annular gap, [in]

The shear rate ($\dot{\gamma}$) is a function of the plastic viscosity (η). The plastic viscosity- shear rate data for a typical MR fluid, shown in Figure 4.4, was characterized by an exponential equation of the form:

$$\eta = 0.0006\dot{\gamma}^{-0.6091} \quad (4.5)$$

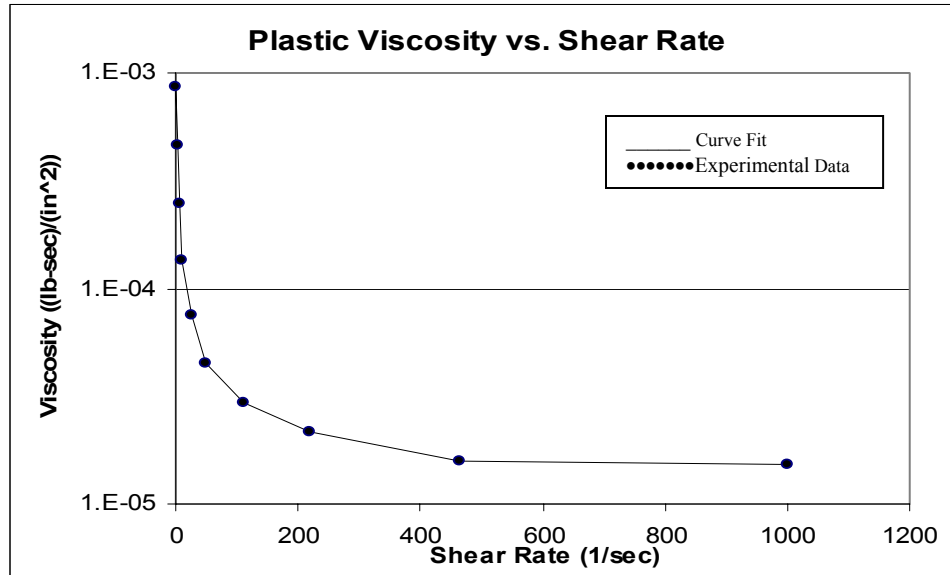


Figure 4.4 Plastic Viscosity vs. Shear Rate

In order to correctly model the force response of the MR damper as a function of velocity, it is necessary to separate the system into two states. The “*off-state*” condition is defined as the response of the damper when no current is applied. The “*on-state*” condition is defined as the response of the damper when any current greater than zero is applied. In Chapter 2, we defined the Mathematical Fundamentals of MR dampers. The pressure drop in an MR fluid device that is used in the flow mode can be represented by Equation (2.3), where the pressure drop (ΔP) is assumed to be the sum of the *off-state* pressure component (ΔP_η) and the *on-state* pressure component (ΔP_τ). To calculate the force that is developed along the MR fluid gap, we simply multiply each delta pressure with the associated areas. We multiply the off-state pressure with the area of the piston, and the on-state pressure with the active fluid area.

$$F = \Delta P_\eta \cdot A_\eta + \Delta P_\tau \cdot A_\tau \quad (4.6)$$

Where

$$A_\eta = \frac{\pi D^2_{Piston}}{4}$$

and

$$A_\tau = A_{Fluid} = 2\pi b(L + g)$$

All terms in the above equations are defined in Table 2.1.

Equation (4.6) assumes that the total force developed is the sum of a viscous shear force component and magnetic field dependent shear force component. F represents the force that is developed along the MR fluid gap.

Using Microsoft Excel; we provided the force – velocity plot of the model designed in ANSYS for a velocity input (0-0.635 m/sec), as shown in Figure 4.5 and described in detail in Appendix B.

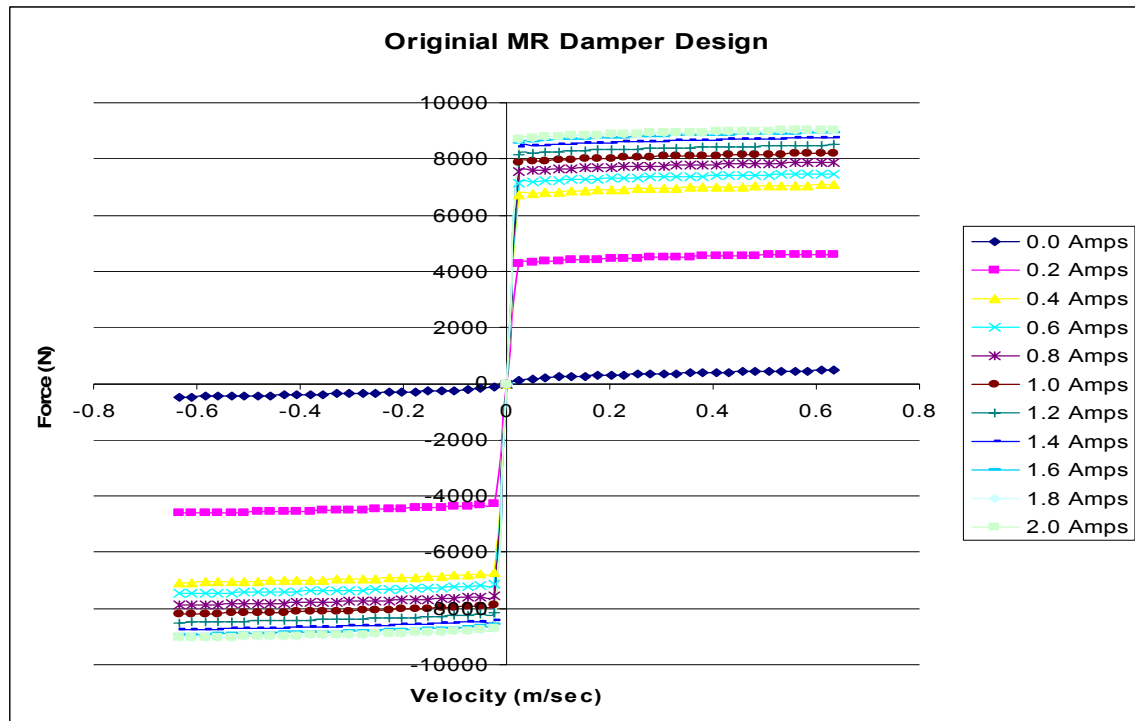


Figure 4.5 Damper Force Characteristics

Referring to Figure 4.5 and Table 4.2, we can conclude that the fluid reached rheological saturation at approximately 1.8 ~ 2.0 Amps. The force provided at 1.8 Amps is almost the same as the one at 2.0 Amps (i.e., 9045 N). Beyond this current, we can barely generate any more force. So the maximum force that we can generate for the damper that was modeled for this analysis is approximately 9045 N.

4.3 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, μ is in Henry/m, and the magnetic field H is in Amp/m.

Referring to the results generated from ANSYS, one can see a light colored blue on the left side of my coil, as shown in Figure 4.6. 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 as shown in Figure 4.6, we can see that we have a contour that will range from 107- 3381 A/m. The farther we move away from the coil, the more the magnetic field decreases, as shown in Figure 4.7 by the slope of the H_{sum} curve. The x-axis in Figure 4.7 represents the distance of the MR fluid gap. The magnetic field is indirectly proportional to the distance from the MR fluid gap.

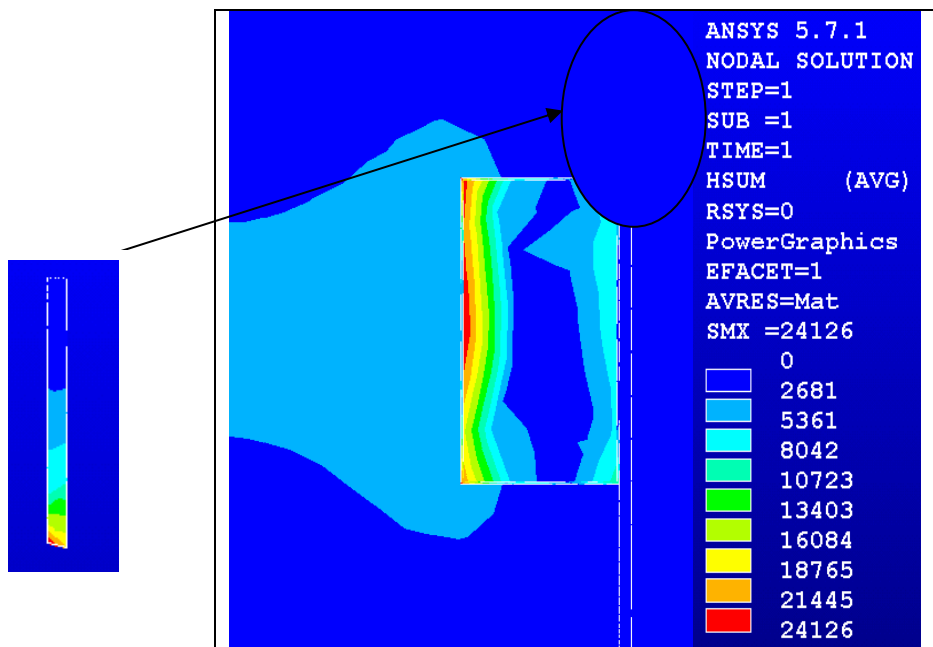


Figure 4.6 Magnetic Field (H_{SUM})-Nodal Solution

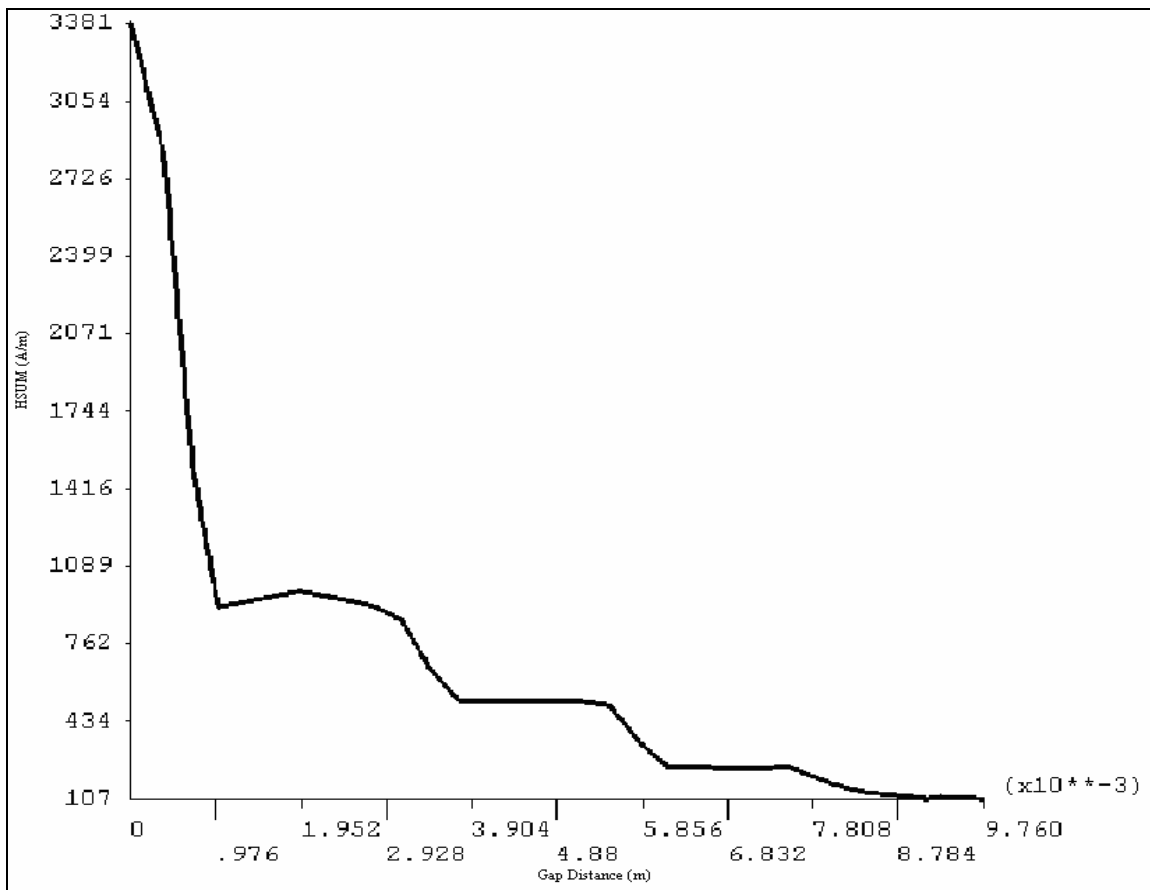


Figure 4.7 - Magnetic Field along the MR Fluid Gap (0.2 Amps)

4.4 Magnetic Flux Lines

The assumption of no leakage at the perimeter of the model means that the flux will be acting parallel to this surface. This assumption is enforced by the "flux parallel" boundary condition placed around 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.

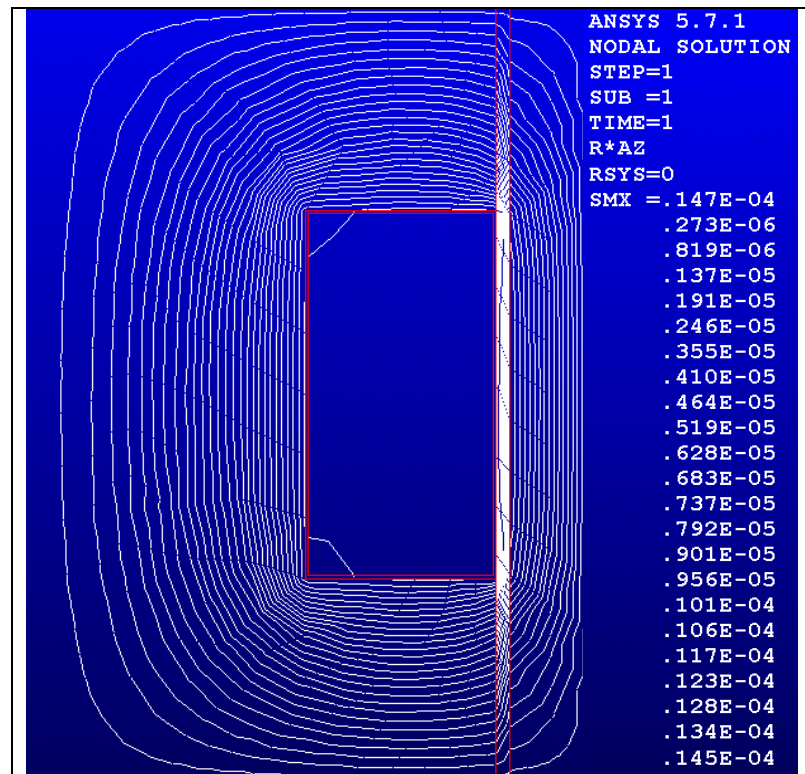


Figure 4.8 Flux line around the Electrical coil

Summary

In this chapter, we studied the results generated from a finite analysis of an MR damper model. Using the equations in section 4.2, we can define the force at the MR fluid gap. Applying different current at the electrical coil, we can stimulate 10 different forces and from there we can generate the force – velocity plot.

Chapter 5

Design Analysis

This chapter will evaluate four different shapes of the MR damper piston by increasing the length of the outer radius or curving the edges and create a chamfer at the corner of the MR fluid passage. The first model is the curved corner farthest from the coil. The second model is the chamfered corner farthest from the coil. The third model is the two curved edges at the corners of the MR fluid passage. The fourth model involves increasing the length of the outer radius (b) of the damper piston by 50% from its nominal value.

5.1 Model 1: 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 5.1. We will refer to this configuration as “Model 1” for the purpose of this discussion. In model 1, the MR fluid 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).

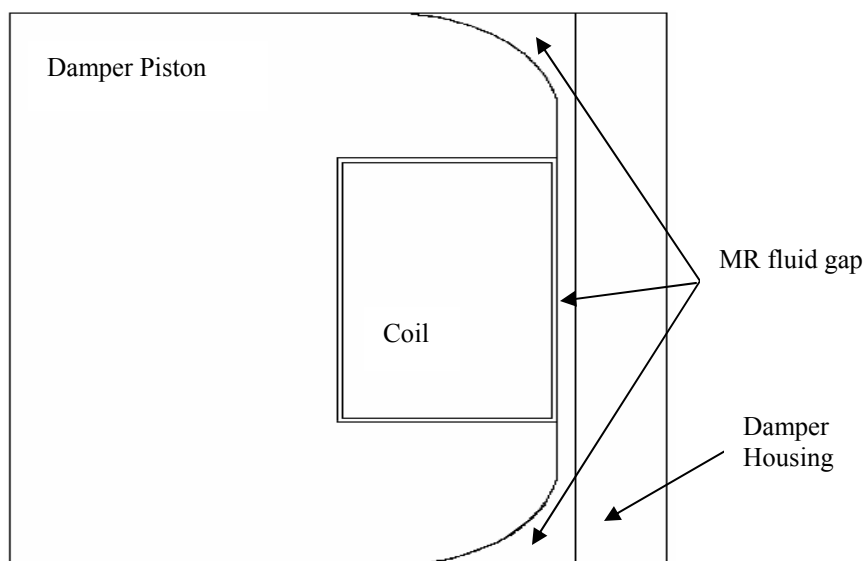


Figure 5.1 Magneto Rheological Damper Piston Configuration for Model 1

Using the terminology outlined in Table 3.1, we will next describe the modeling results.

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 (4.1).

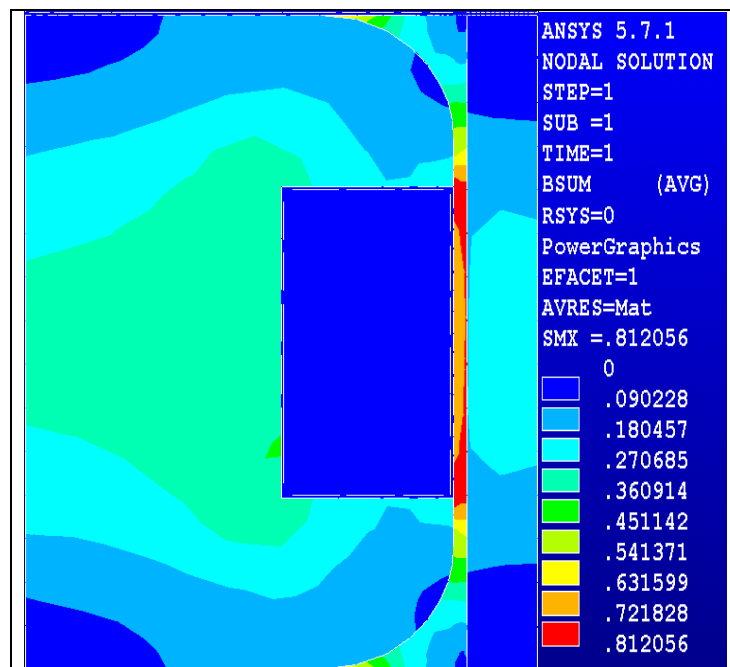


Figure 5.2 2-D Magnetic flux Density (Model 1)

Zooming in to that gap area, we can get the average magnetic induction at the MR fluid gap, as shown in Figure 5.3.

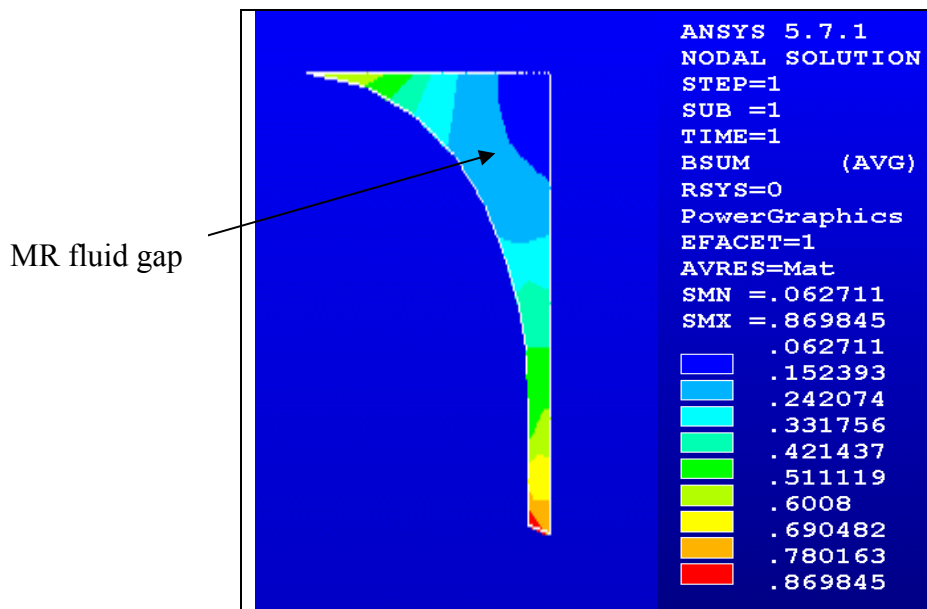


Figure 5.3 Magnetic Flux Density at the Fluid Gap (Model 1)

The contour plot shown in Figure 5.3 is generated after applying a current of 0.2 Amps on the coil. The simulation results for 10 different currents are shown in Table 5.1.

Table 5.1 Summaries of Simulation Results for various Magnetic Inductions For Model 1

Current (Amps)	Magnetic Induction, B(f) (Tesla)
0	0
0.2	0.466
0.4	0.684
0.6	0.730
0.8	0.7777
1.0	0.827
1.2	0.878
1.4	0.930
1.6	0.98
1.8	1.04
2.0	1.1

Referring to section 4.2 and the equations (2.3) – (2.4), we can generate the MR damper force response as a function of the *on* and *off-state* pressure delta's and associated areas.

Using Microsoft Excel, documented in Appendix B, we establish the force-velocity plot for model 1 in velocity range of 0 to 0.635 m/sec, as shown in Figure 5.4.

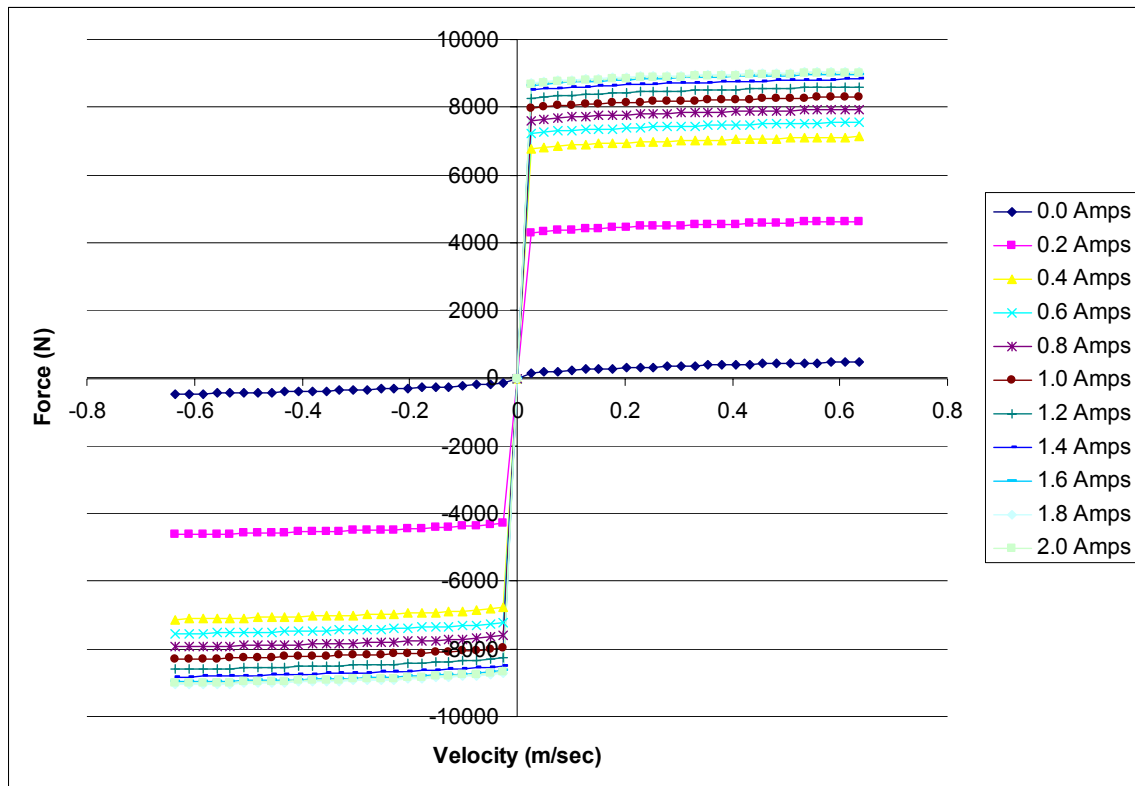


Figure 5.4 – Damper Force Characteristics for Model 1

Looking at the F-V plot and Table 5.1, we can conclude that the fluid reached saturation at approximately 1.8 to 2.0 Amps. The maximum force, results from 1.8 Amps, is nearly the same as the one at 2.0 Amps (i.e., 9060 N). Beyond 2.0 Amps, the damper would not provide a much higher force than 9060 N, because it has reached its rheological saturation point, as discussed earlier.

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 5.5 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. If we zoom in to the MR fluid gap, we can establish the contour that will range from 83-3043 A/m, as shown in Figure 5.5. The more we move away from the coil, the more the magnetic field decreases.

Figure 5.6 shows the slope of the H_{sum} curve, where the x-axis represents the distance of the MR fluid gap. The more we increase the distance, the smaller the magnetic field becomes. Specifically it reduces from 3032 A/m to 83 A/m.

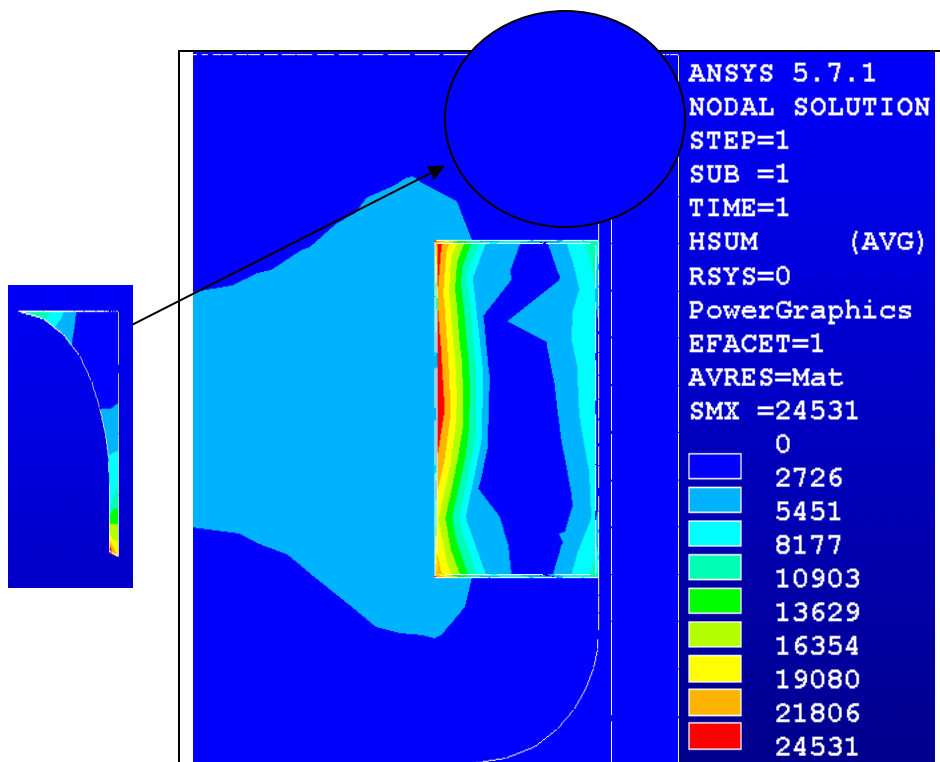


Figure 5.5 Magnetic Field (H_{sum}) Contours – Model 1

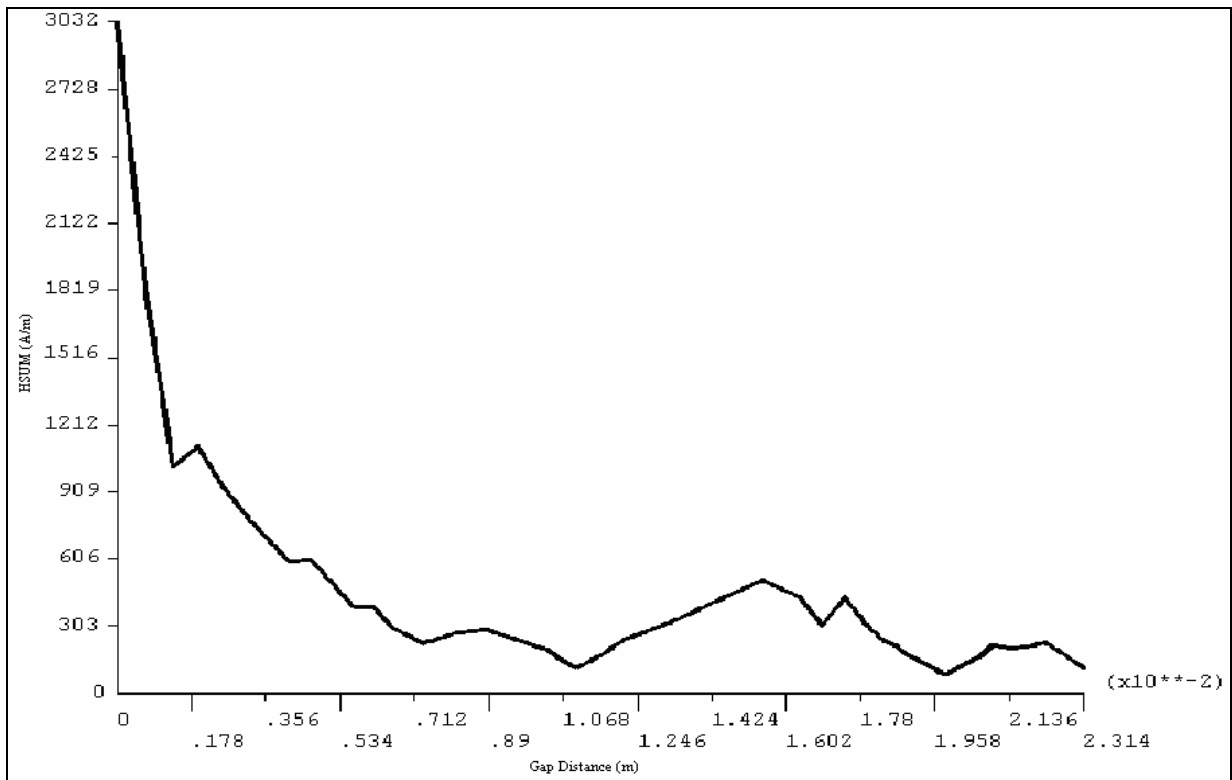


Figure 5.6 Magnetic Field along the MR fluid gap (0.2 Amps) – Model 1

5.1.3 Magnetic Flux Lines

Figure 5.7, 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 5.2 is also shown in this Figure.

Figure 5.8, which represents the contour of the magnetic flux lines, indicates the shift of the color spectrum between the MR fluid gap and the Engine/ Damper Housing areas.

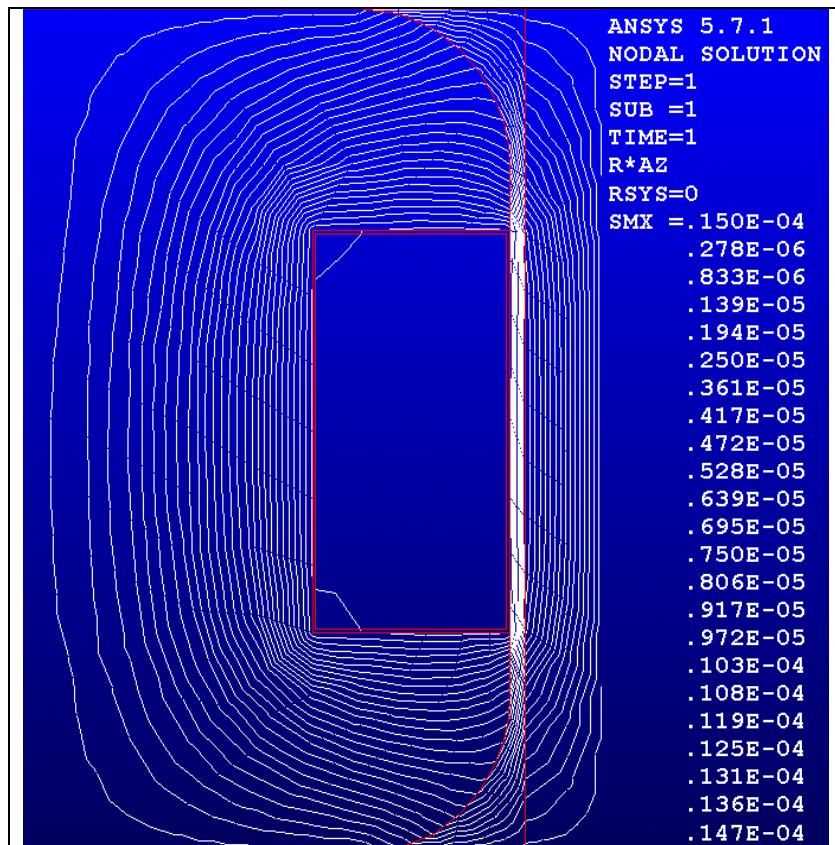


Figure 5.7 Magnetic Flux Line around the Electrical Coil – Model 1

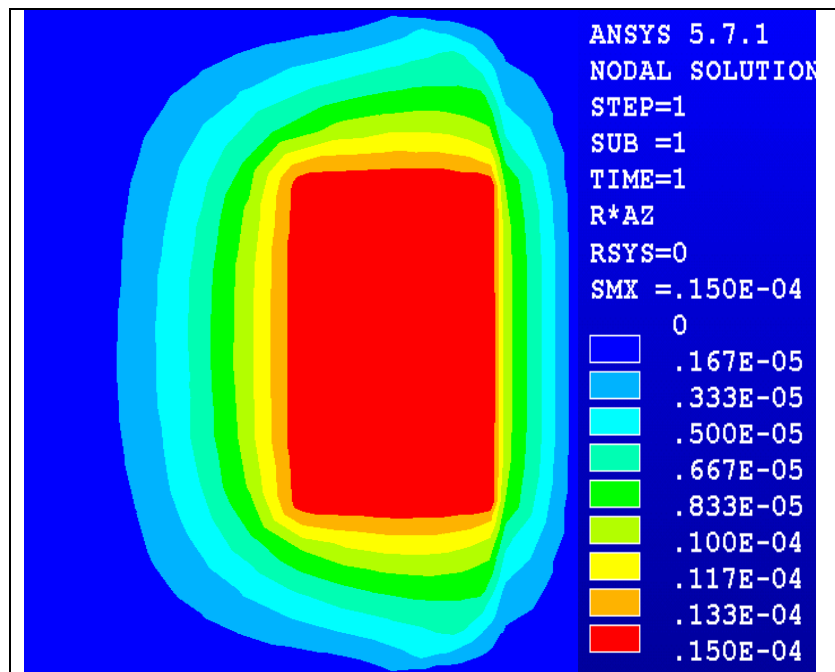


Figure 5.8 Magnetic Vector Potential – Model 1

The magnetic flux lines represent the magnetic flux density vectors (B_{sum}). In Figure 5.7, we notice the many concentration flux lines along the MR fluid gap. These concentration flux lines are a result of the high magnetic flux density along the gap. When saturation is reached the redness disappears and the flux lines decrease in numbers, as shown in Figure 5.9.

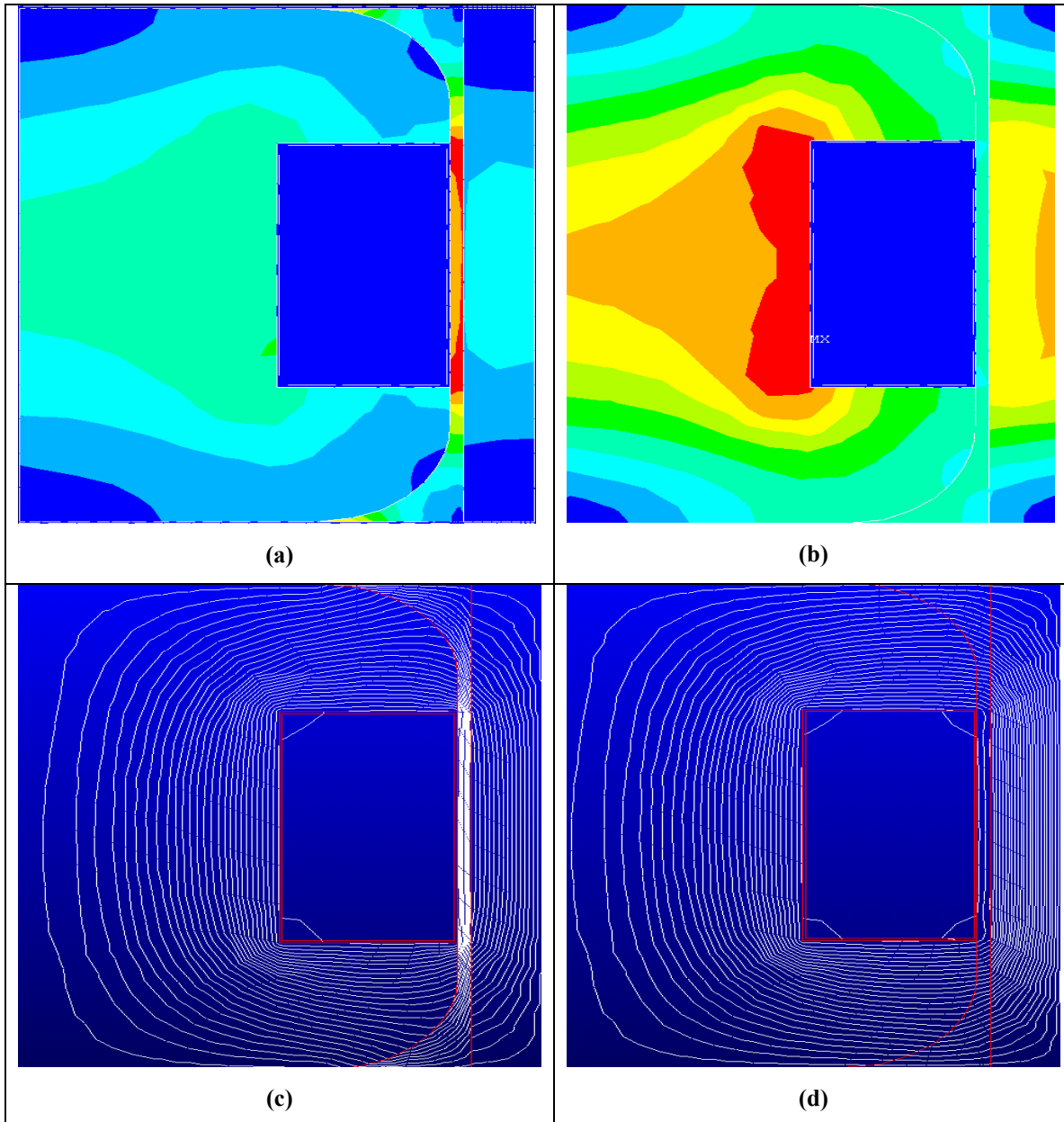


Figure 5.9 Comparison of Model 1 before and after reaching saturation

(a) and (b) represent the magnetic flux density before and after saturation
(c) and (d) represent the magnetic flux lines before and after saturation

5.2 Model 2: Chamfered corner farthest from the coil

This section will provide all results generated from a second piston configuration, which we will refer to as “Model 2”, for the purpose of this discussion. In ANSYS, a model was built with chamfered corner farthest from the coil, as shown in Figure 5.10. In this model, the MR fluid gap will be larger 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.

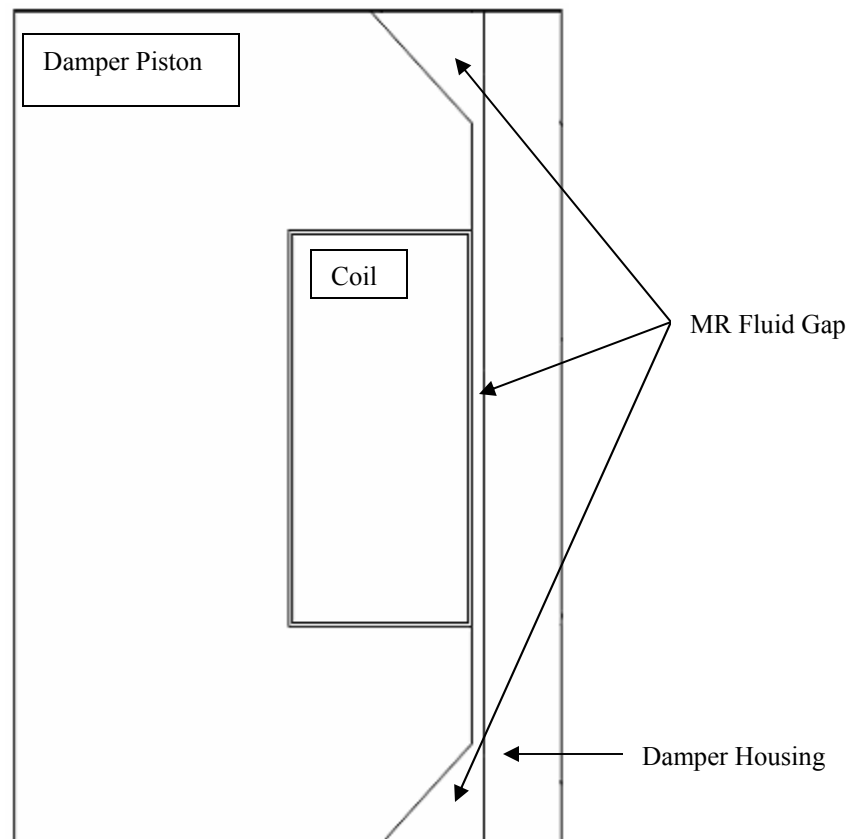


Figure 5.10 Magneto Rheological Damper Piston Configuration For Model 2

5.2.1 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 (4.1).

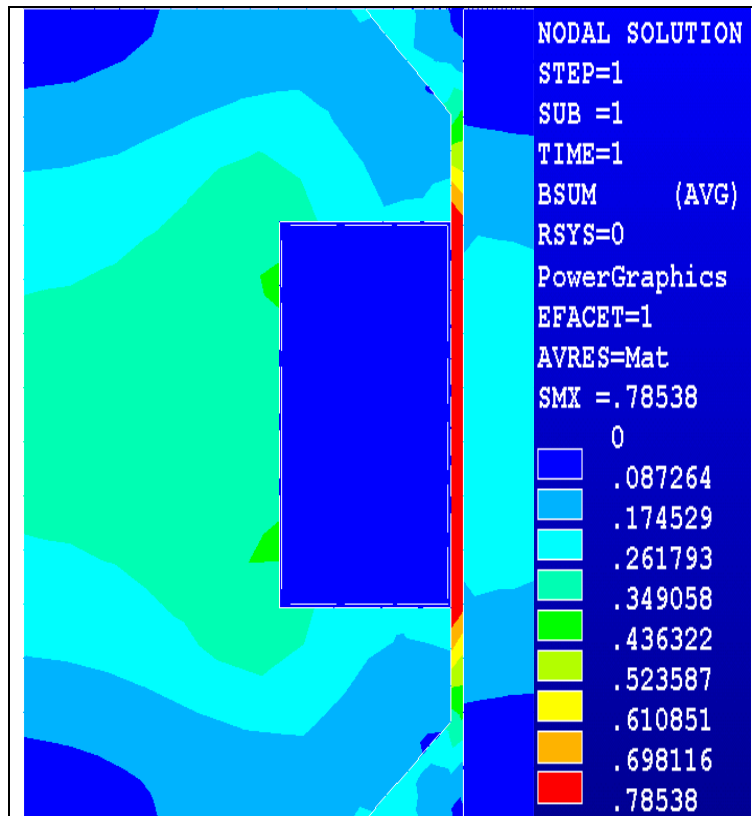


Figure 5.11 2-D Magnetic Flux Density (B_{sum}) – Model 2

Zooming in to that MR fluid gap area, we can establish the average magnetic induction at the MR fluid gap, as shown in Figure 5.12.

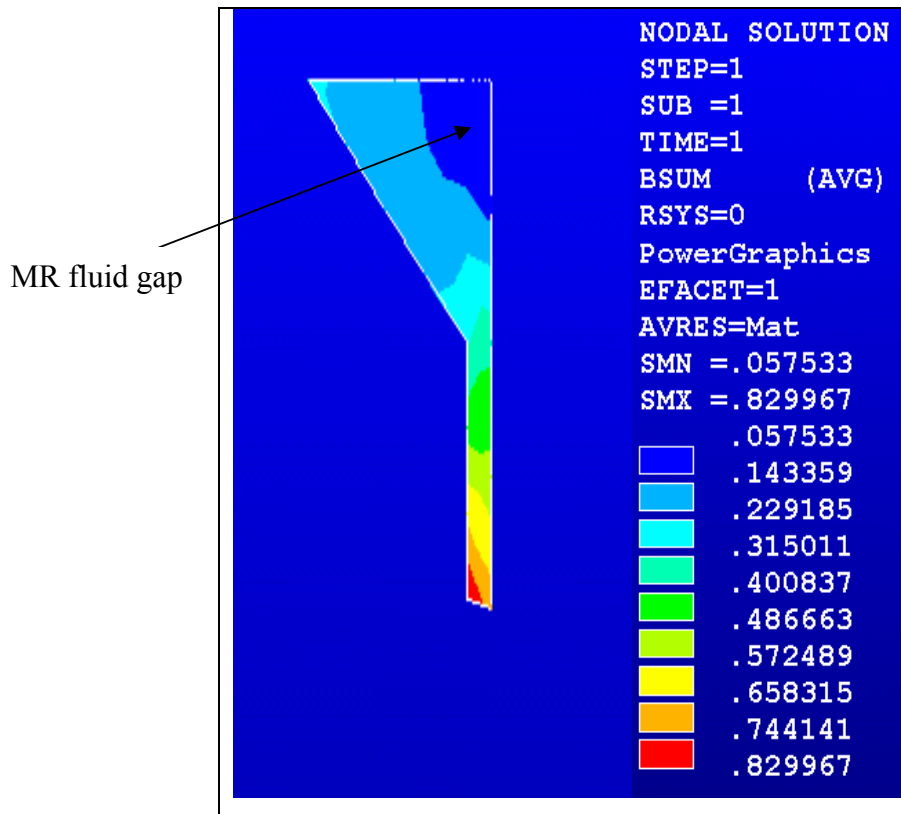


Figure 5.12 Magnetic Flux Density at the Fluid MR Gap – Model 2

Following the same procedures in section 5.1, the simulation results for 10 different currents are shown in Table 5.2.

Table 5.2 Summaries of Simulation Results for various Magnetic Inductions for Model 2

Current (Amps)	Magnetic Induction, B(f) (Tesla)
0	0
0.2	0.444
0.4	0.674
0.6	0.717
0.8	0.760
1.0	0.805
1.2	0.854
1.4	0.904
1.6	0.958
1.8	1.02
2.0	1.08

Using Microsoft Excel, documented in Appendix B, we establish the force-velocity plot for model 2 in velocity range of 0 to 0.635 m/sec, as shown in Figure 5.13.

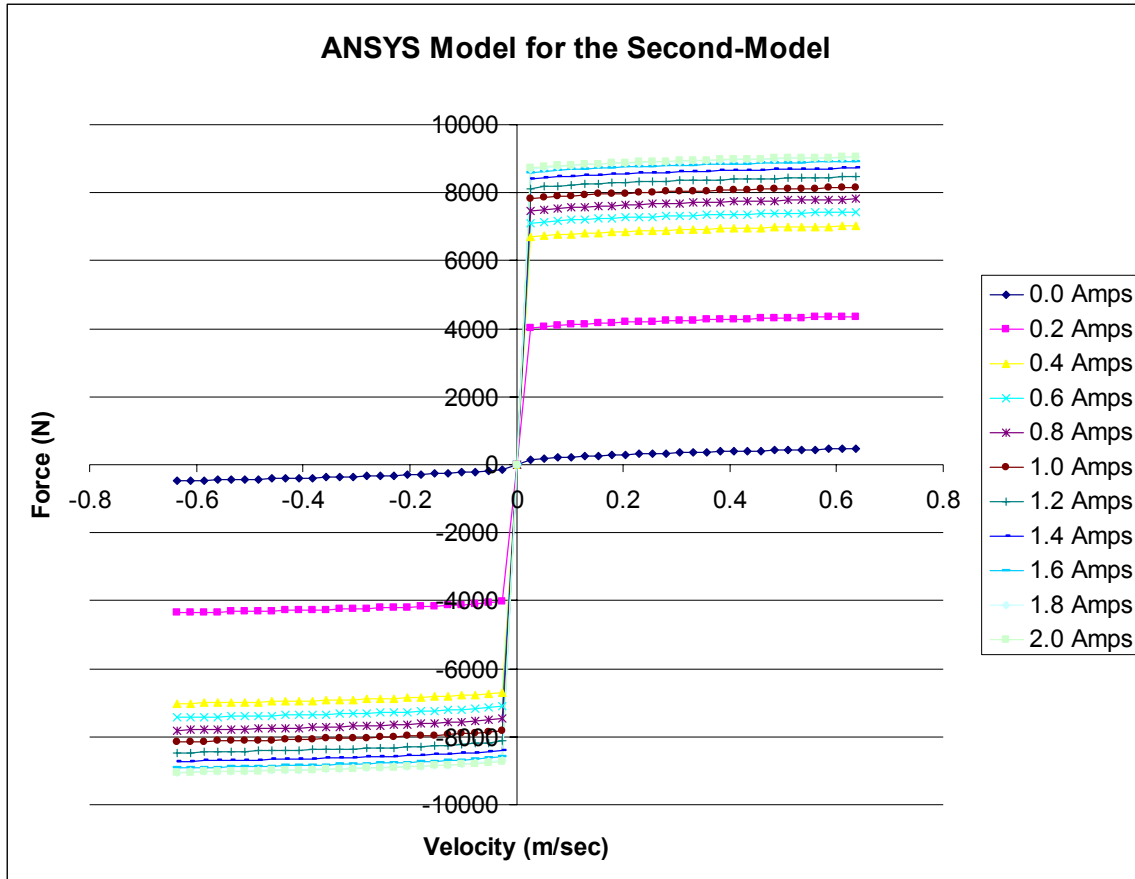


Figure 5.13 Damper Force characteristics for Model 2

Looking at the F-V plot and Table 5.2, we can conclude that the fluid reached the saturation at approximately 1.8 to 2.0 Amps. The maximum force, results from 1.8 Amps, is nearly the same as the force at 2.0 Amps (i.e., 9054 N). The percentage error between the two forces is around 0.099%. Beyond 2.0 Amps, the damper would not provide a much higher force than 9054 N, because it has reached its rheological saturation point, as discussed earlier.

5.2.2 Magnetic Field

Looking at the results generated from ANSYS, we can see in Figure 5.14 this light colored blue on the left side of the coil. If we zoom into the MR fluid gap, we can establish the magnetic field contour that will range from 76 - 2755 A/m, as shown in Figure 5.14. Figure 5.15 shows the slope of the H_{sum} curve, where the x-axis represents the distance of the MR fluid gap. The more we increase the distance, the smaller the magnetic field becomes.

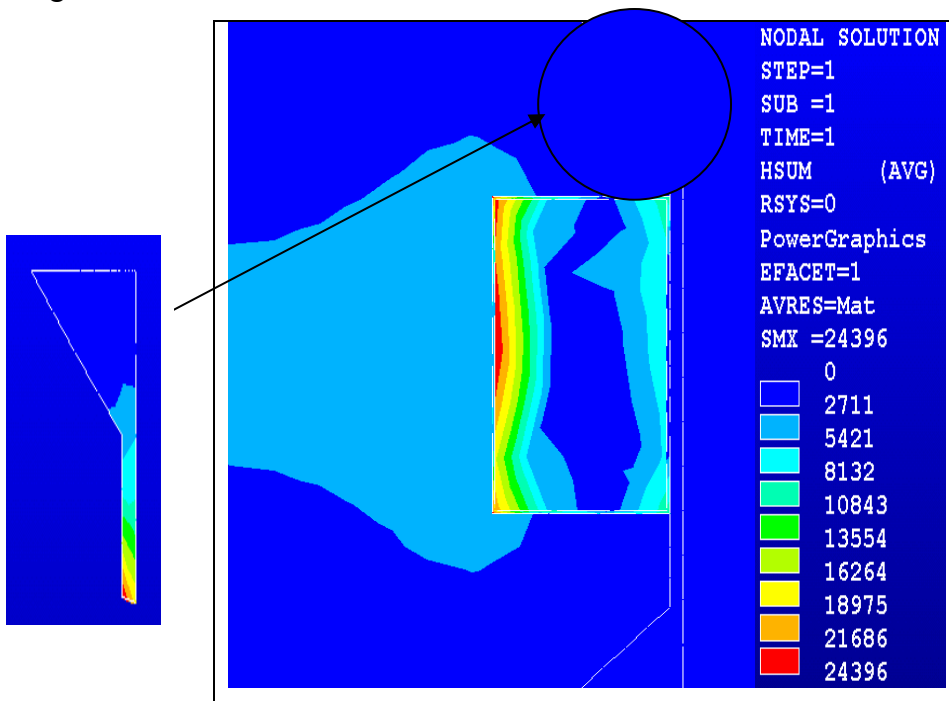


Figure 5.14 Magnetic Field (H_{sum}) Contours – Model 2

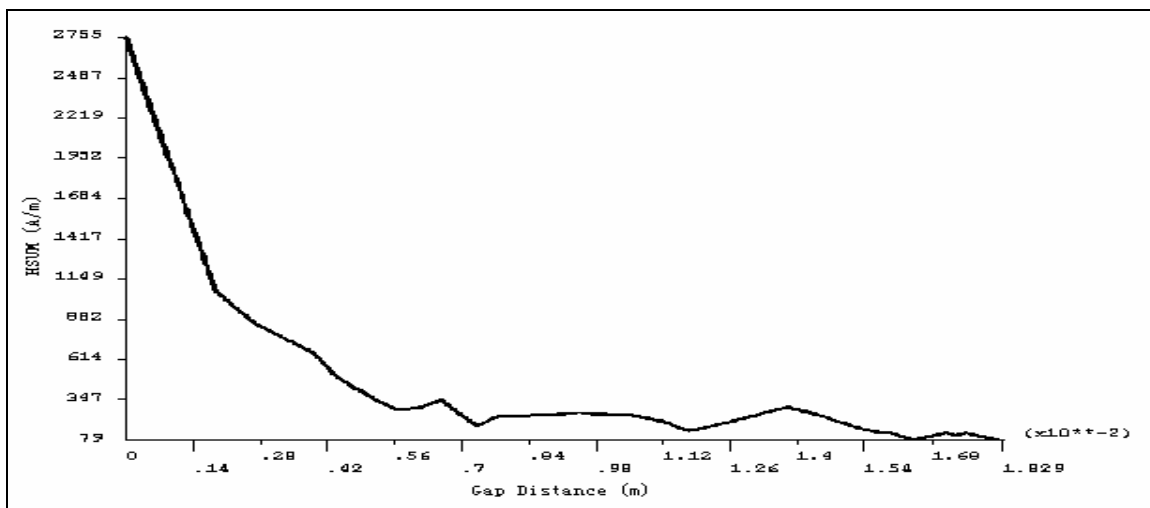


Figure 5.15 Magnetic Field along the MR Fluid Gap (0.2 Amps) – Model 2

5.3 Model 3: Two Curved Edges at the Corners of the MR Fluid Passage

This section will provide all results generated from a third configuration of the piston, which we will refer to as “Model 3”. In ANSYS, a model was built with two curved corners at the MR fluid passage, as shown in Figure 5.16. In this model, the MR fluid gap will be little bit larger than the original model and the damper 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.

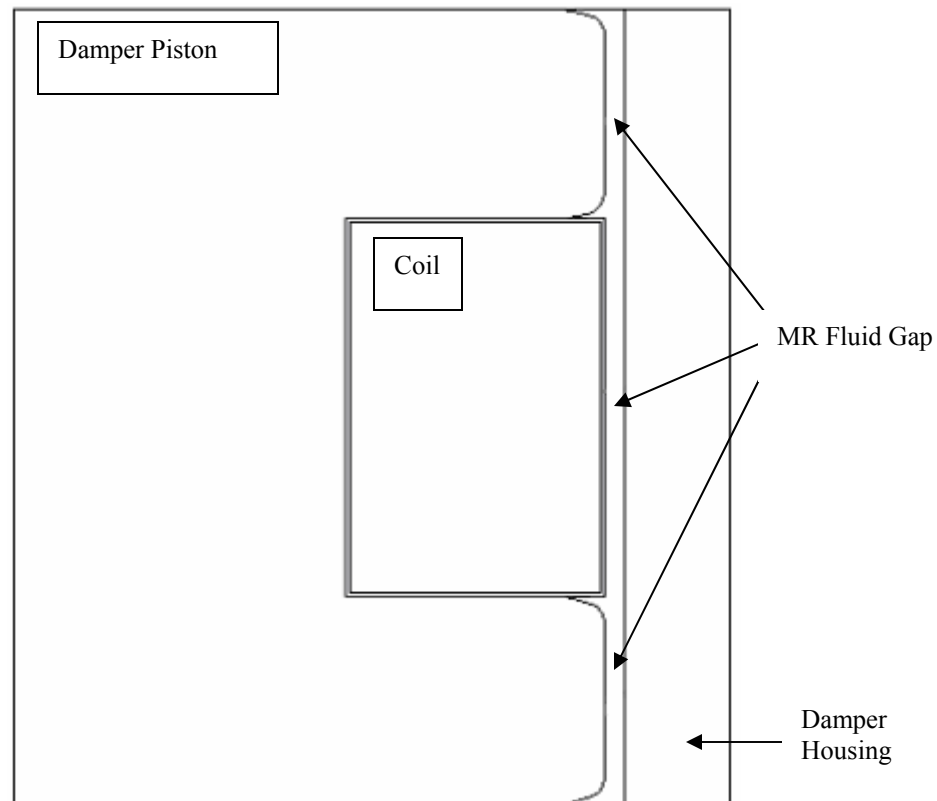


Figure 5.16 Magneto Rheological Damper Piston Configuration for Model 3

Following the same procedures as in section 5.1. First we will talk about the magnetic flux density and how we can generate the force/velocity. Second, we will talk about the magnetic field and the contour generated at the MR fluid gap.

5.3.1 Magnetic Flux Density

The ANSYS model provides the magnetic induction at the MR fluid gap, as shown in Figure 5.17. For each value of B_{sum} , we can calculate the shear stress using equation (4.1).

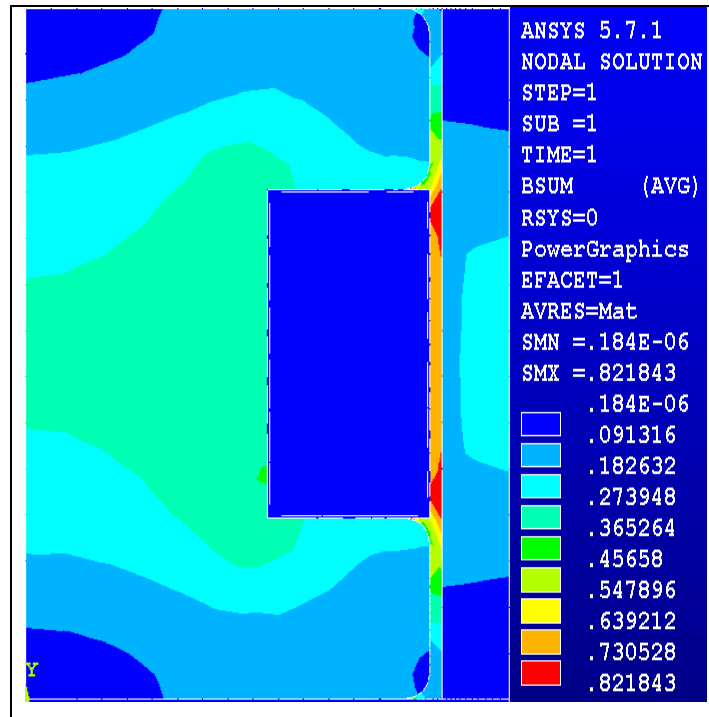


Figure 5.17 2-D Magnetic Flux Density (B_{sum}) – Model 3

Zooming in to that MR fluid gap area, we can establish the average magnetic induction at the MR fluid gap, as shown in Figure 5.18.

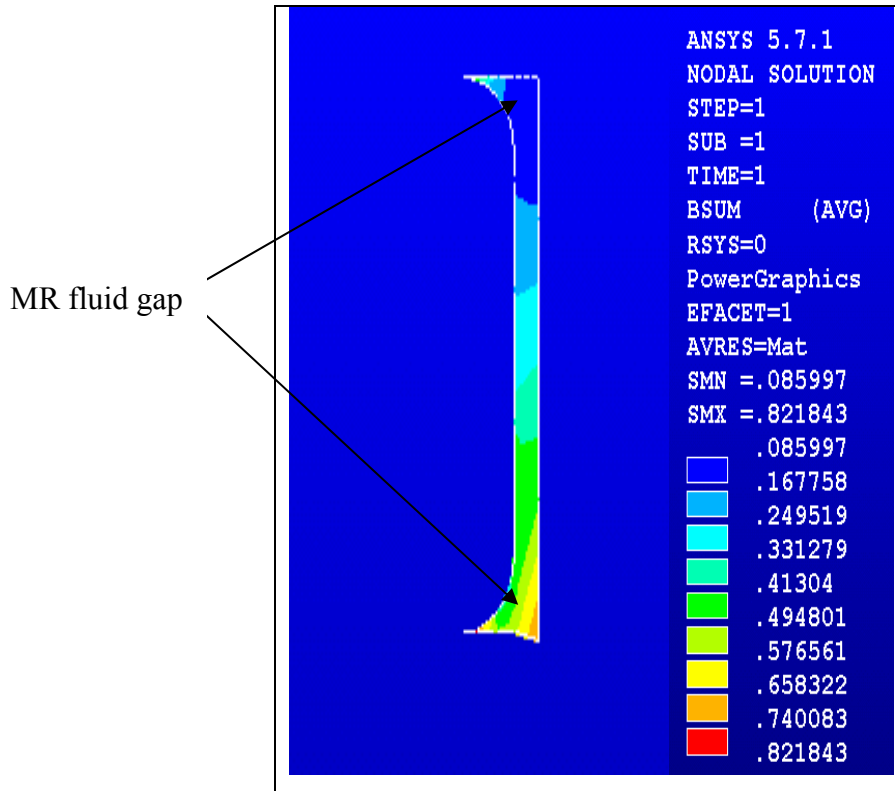


Figure 5.18 Magnetic Flux Density at the Fluid Gap – Model 3

Following the same procedures in section 5.1, the simulation results for 10 different currents are shown in Table 5.3.

Table 5.3 Summaries of Simulation Results for various Magnetic Inductions for Model 3

Current (Amps)	Magnetic Induction, B(f) (Tesla)
0	0
0.2	0.454
0.4	0.647
0.6	0.747
0.8	0.801
1.0	0.849
1.2	0.896
1.4	0.944
1.6	0.995
1.8	1.05
2.0	1.09

Using Microsoft Excel, documented in Appendix B, we can establish the force-velocity plot for model 3 in velocity of 0 to 0.635 m/sec, as shown in Figure 5.19.

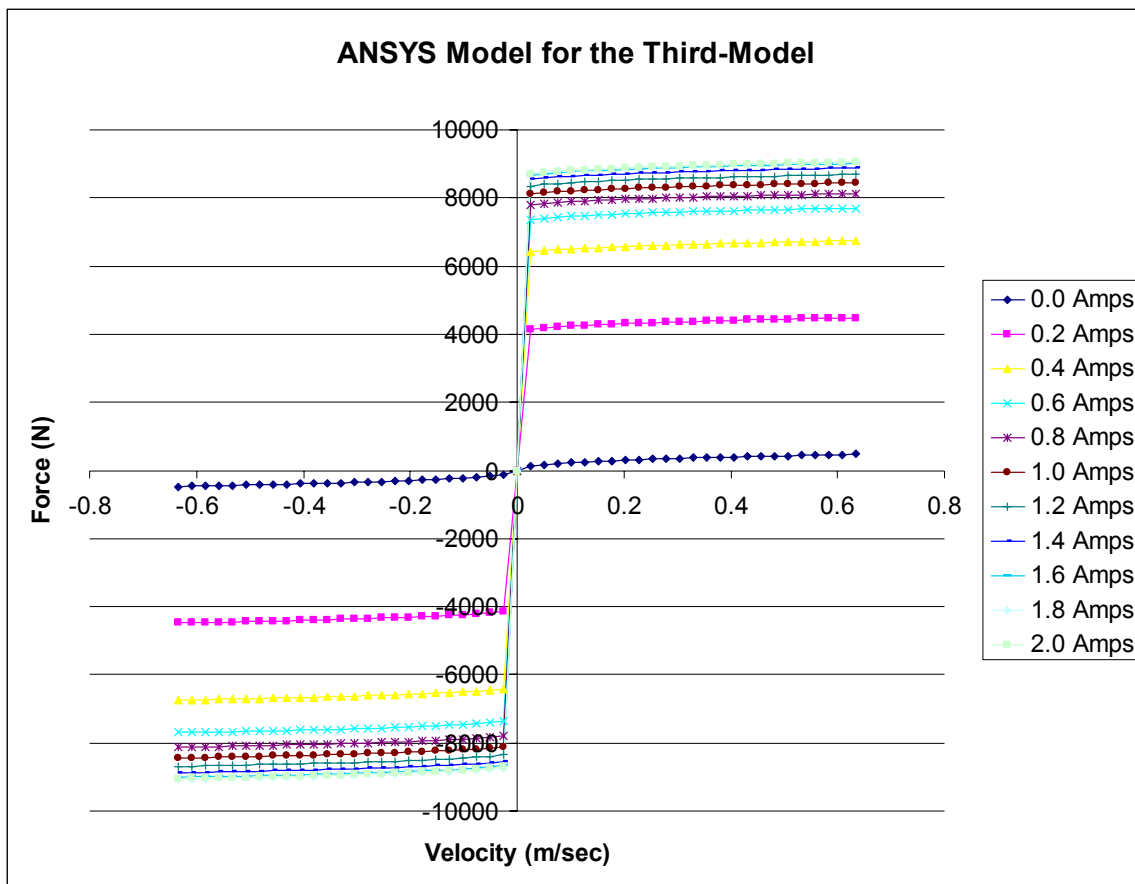


Figure 5.19 Damper Force characteristics For Model 3

Looking at the F-V plot and Table 5.4, we can conclude that the fluid reached saturation at approximately 1.8 to 2.0 Amps. The maximum force, results from 1.8 Amps, is really close to the force at 2.0 amps (i.e., 9063 N). The percentage error between the two forces is around 0.198%. Beyond 2.0 Amps, the damper would not provide a much higher force than 9063 N, because it has reached its rheological saturation point, as discussed earlier.

5.3.2 Magnetic Field

Looking at the results generated from ANSYS, we can see in Figure 5.20 this light colored blue on the left side of the coil. If we zoom into the MR fluid gap, we can establish the magnetic field contour that will range from 115 - 2700 A/m, as shown in Figure 5.20. The more we increase the distance, the smaller the magnetic field becomes and Figure 5.21 shows the slope of the H_{sum} curve, where the x-axis represents the distance along the MR fluid gap.

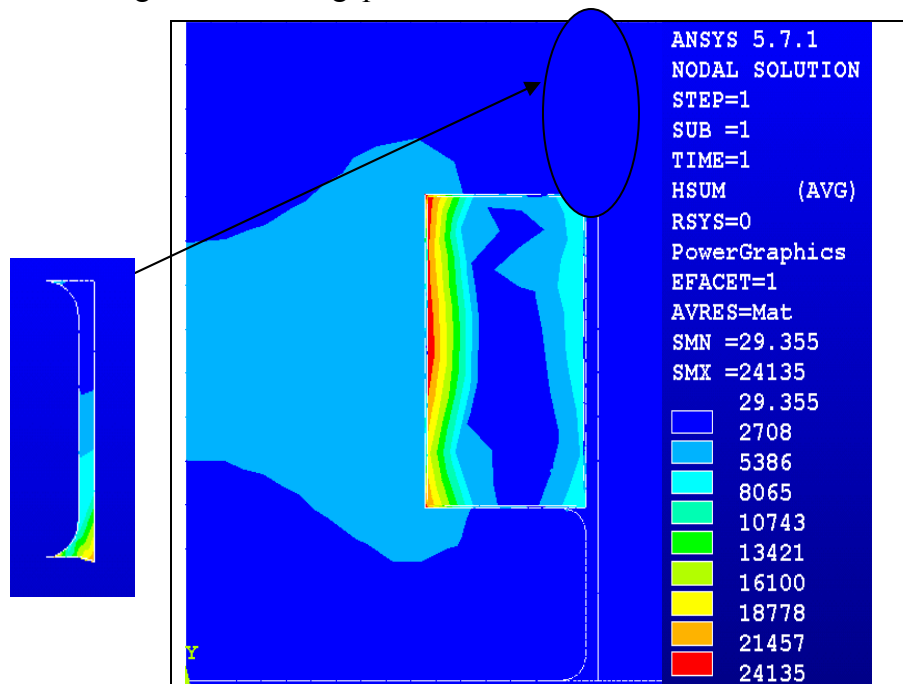


Figure 5.20 Magnetic Field (H_{sum}) Contours – Model 3

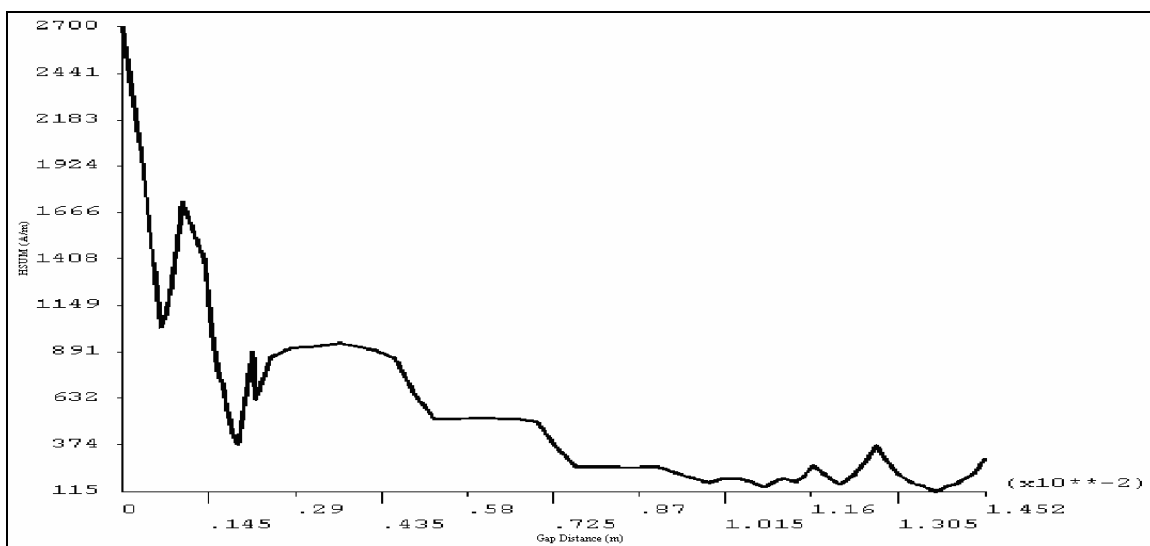


Figure 5.21 Magnetic Field along the MR Fluid Gap (0.2 Amps) – Model 3

5.4 Model 4: Increase the outer radius (b) by 50% of its original value

This section will provide all results generated for the last piston configuration, which we will refer to as “Model 4”, for the purpose of this discussion. In ANSYS, a model was built by increasing the dimension b by 50% from its original value, as shown in Figure 5.22. The dimension (b) represents the outer radius of the Damper piston. In this model, the MR fluid gap will keep the same length and width as the original model and the damper piston area has been increased from its original shape. The rest of the areas in the model remain the same except the electrical coil area because it depends on the outer radius value.

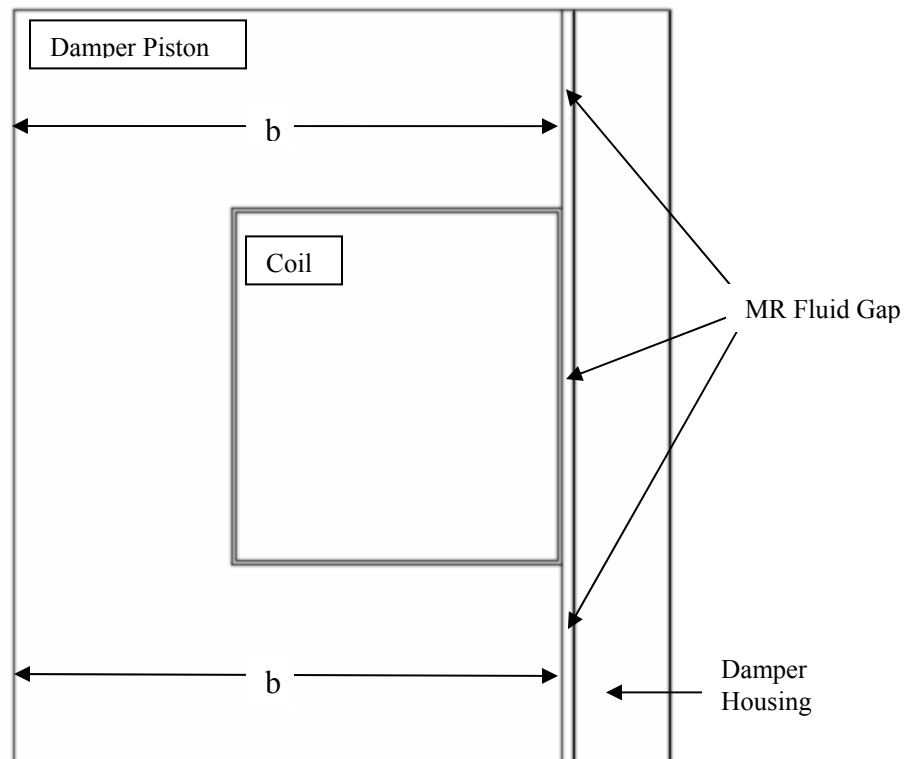


Figure 5.22 Magneto Rheological Damper Piston Configuration For Model 4, in which the dimension b has been increased by 50%.

Again, we follow the same procedures in the first section. First, we will talk about the magnetic flux density and how we can generate the force/velocity. Second, we will talk about the magnetic field and the contour generated at the MR fluid gap.

5.4.1 Magnetic Flux Density

The ANSYS model provides the magnetic induction at the MR fluid gap, as shown in Figure 5.23. For each value of B_{sum} , we can calculate the shear stress using equation (4.1).

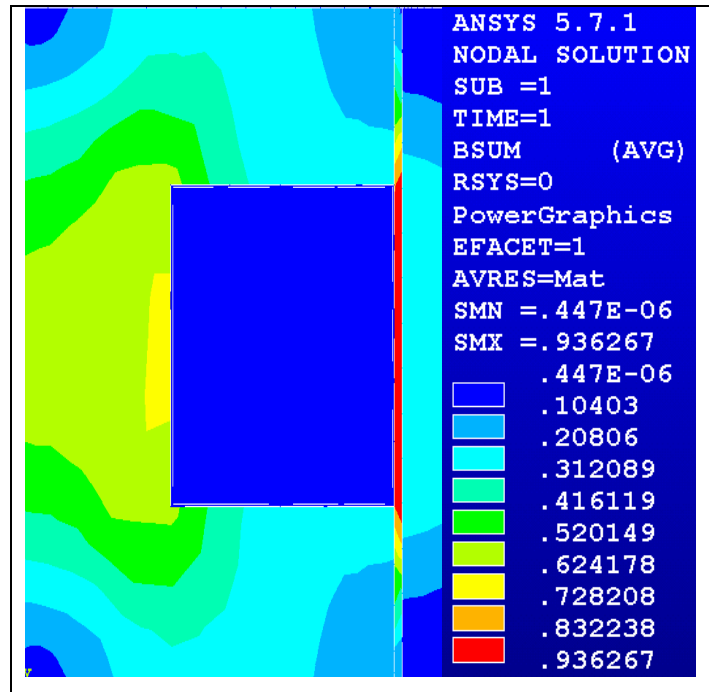


Figure 5.23 2-D Magnetic Flux Density (B_{sum}) – Model 4

Zooming in to that MR fluid gap area, we can establish the average magnetic induction at the MR fluid gap, as shown in Figure 5.24.

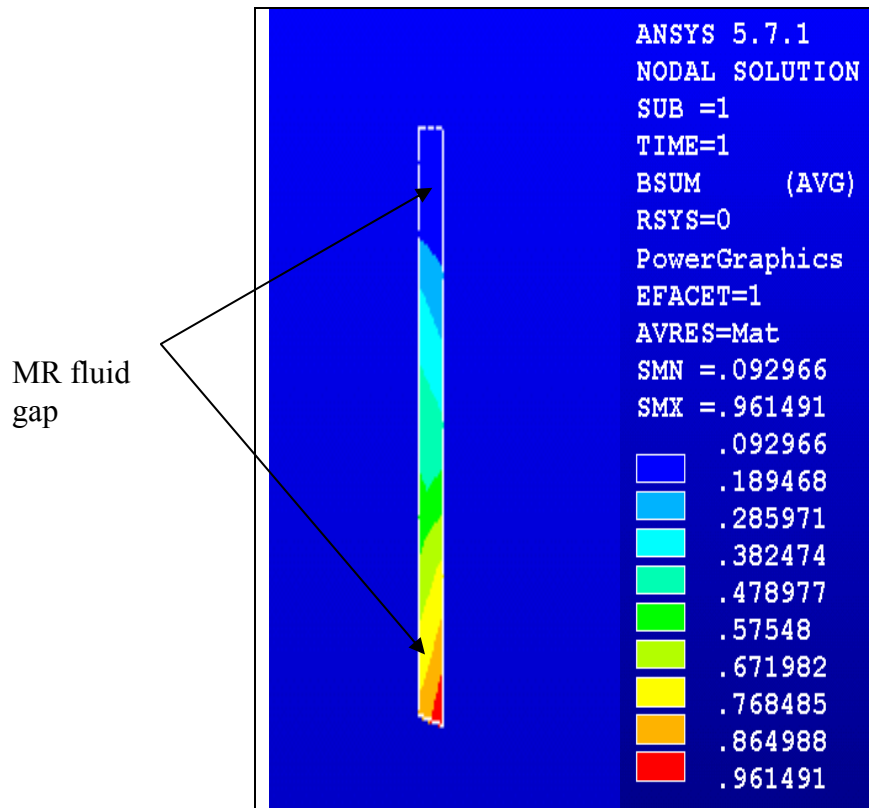


Figure 5.24 Magnetic Flux Density at the Fluid Gap – Model 4

Following the same procedures in section 5.1, the simulation results for 10 different currents are shown in Table 5.4.

Table 5.4 Summaries of Simulation Results for various Magnetic Inductions for Model 4

Current (Amps)	Magnetic Induction, B(f) (Tesla)
0	0
0.2	0.53
0.4	0.725
0.6	0.787
0.8	0.857
1.0	0.924
1.2	1.0
1.4	1.09
1.6	1.22
1.8	1.32
2.0	1.43

Using Microsoft Excel, documented in Appendix B, we can establish the force-velocity plot for model 4 in velocity range of 0 to 0.635 m/sec, as shown in Figure 5.25.

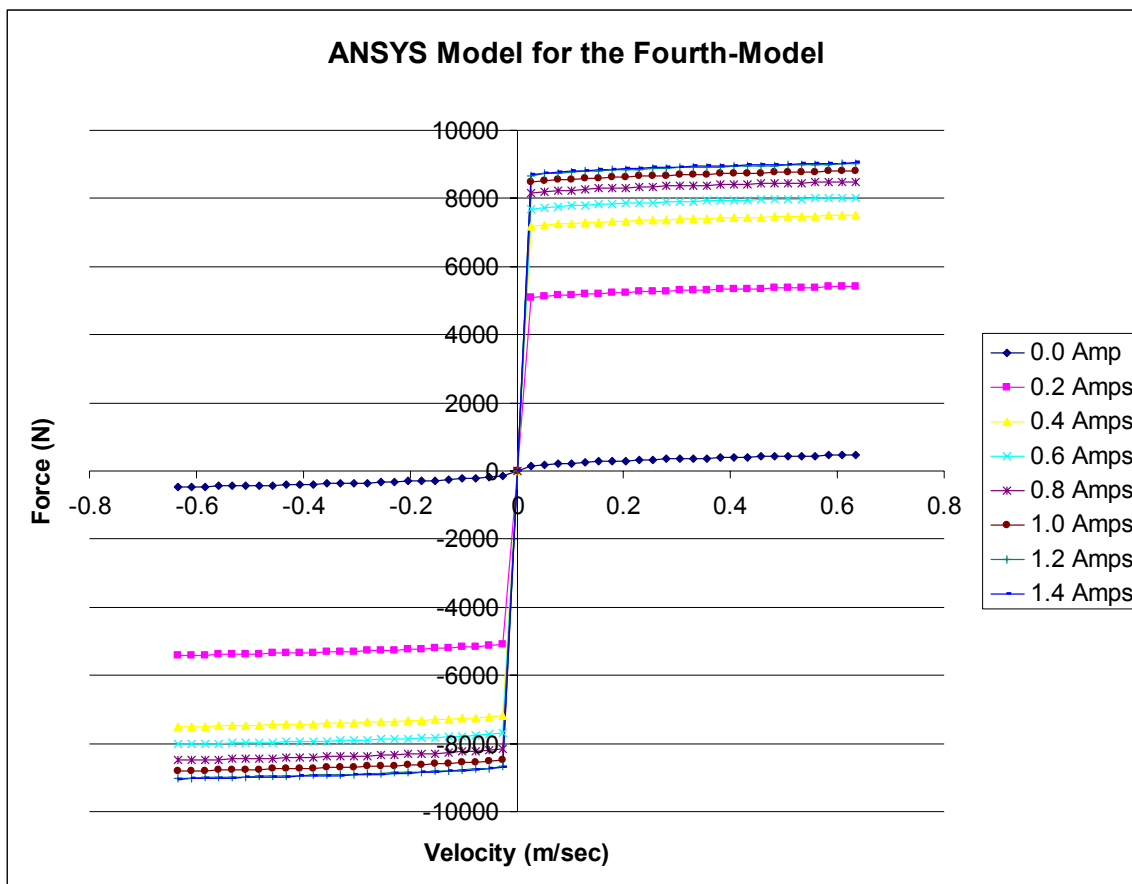


Figure 5.25 Damper Force characteristics for Model 4

Looking at the F-V plot and Table 5.4, we can conclude that the fluid reached saturation at approximately 1.4 Amps. The maximum force, results from 1.2 Amps, is really close to the force at 1.4 Amps (9045 N). The percentage error between the two forces is around 0.27%. Beyond 1.4 Amps, the damper would not provide a much higher force than 9045 N, because it has reached its rheological saturation point, as discussed earlier.

5.4.2 Magnetic Field

Looking at the results generated from ANSYS, we can see in Figure 5.26 the coil area is colored and the rest of the model is just blue. If we zoom into the MR fluid gap, we can establish the magnetic field contour that will range from 126 - 3734 A/m, as shown in Figure 5.26. The more we increase the distance, the smaller the magnetic field becomes. Figure 5.27 shows the slope of the H_{sum} curve, where the x-axis represents the distance along the MR fluid gap.

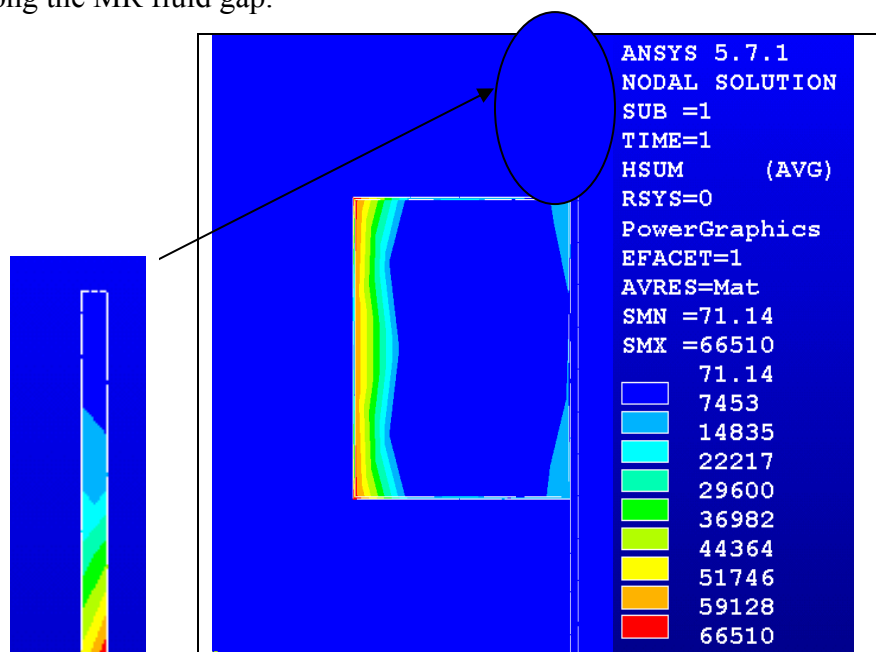


Figure 5.26 Magnetic Field (H_{sum}) Contour – Model 4

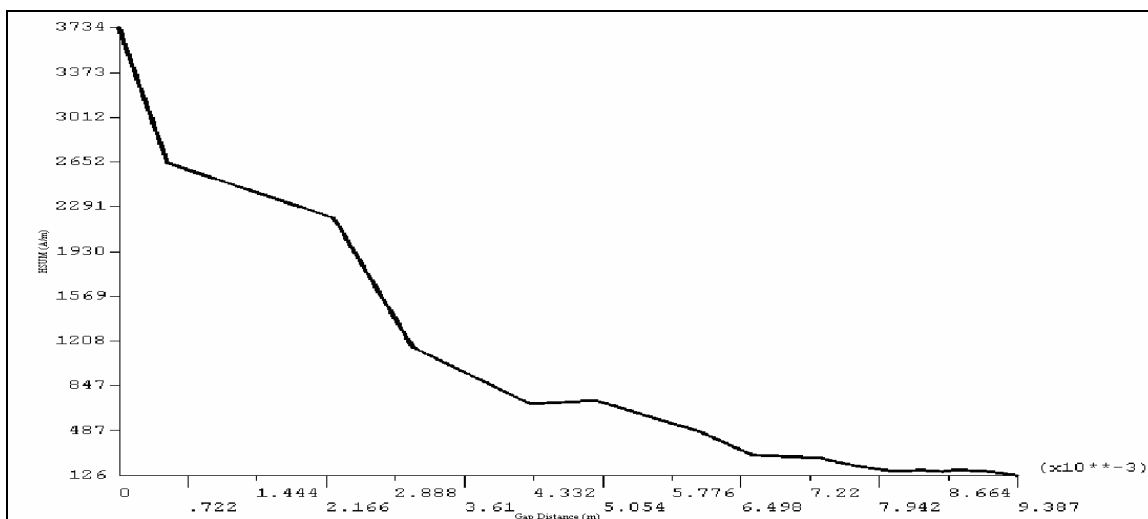


Figure 5.27 Magnetic Field along the MR Fluid Gap (0.2 Amps) – Model 4

5.5 Conclusion

5.5.1 Damper Force Comparison

We studied four different configurations of an MR damper piston in order to determine how changing the shape of the piston affects the maximum force that the damper can provide. In designing MR dampers, the designer always faces the challenge of providing the largest forces in the most compact envelope. Therefore, it is important to identify the configurations that give more force in less space.

The maximum force reached at the saturation current is shown in Figure 5.28 for the four models that were studied here. The first three models reached saturation between 1.8 and 2.0 Amps; whereas the fourth model that has a longer outer radius (b) reached saturation at 1.4 Amps.

Model 4 provides a reasonably good amount of force at 1.4 Amps, but reaches its rheological saturation before the other models. For cases with power constraints or heat build up limitations (higher currents can result in higher heat induced by the electrical current). This model could work the best among the four designs that we considered. For cases where higher electrical currents can be tolerated, model 3 would be the most advantageous design, since it provides the largest force among the four models.

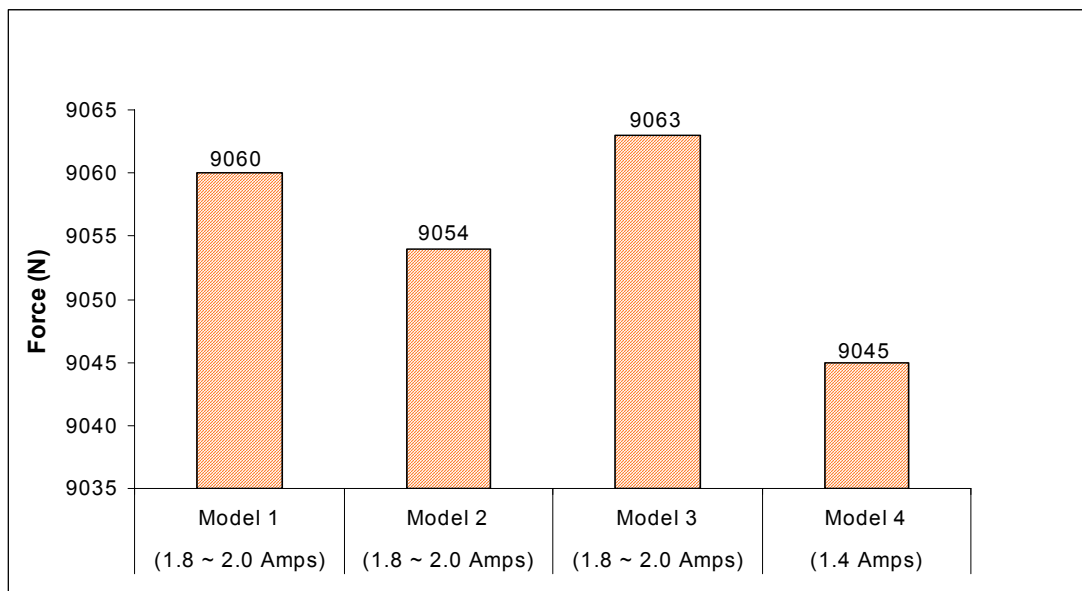


Figure 5.28 Maximum Forces Resulting for Four Different Piston Configurations.

Chapter 6

Conclusion and Recommendations

The purpose of this chapter is to summarize the work that was performed during this research. Additionally, we will summarize the results of the finite element analysis of the original model in chapter 3 and the design analysis of four different models in chapter 5. This chapter ends with recommendations for future work in the field of finite element analysis of magneto rheological dampers.

6.1 Summary

This study provided an axisymmetric model of a MR damper using ANSYS. For a 2-D model of a MR damper, we generated the magnetic flux density along the MR fluid gap. The model has helped with the design in MR dampers and tried to prove the force-velocity characteristics. In ANSYS, we changed the shape of the piston and tried to cut or add some pieces in the engine, so we got similar results generated from the original model. Modeling in FEA, we changed many parameters to improve our design. The Force-velocity plot depended on the magnetic flux density; as the magnetic flux density increased, the shear force provided along the MR fluid gap increased.

In chapter 5, we increased the outer radius (b) in the piston by 50%. This parameter significantly affected on the force-velocity characteristics. In Table 5.6, we reached saturation at 1.4 Amps and the value of the force in model 4 was significantly similar to the force provided in the original model (9045 N). Research of model 4 involved increasing the outer radius, which produced saturation faster than with the original model while the force was similar to the one obtained in chapter 4.

We learned in chapter 5, by decreasing the damper piston shape, we could maintain the same force and still reduce the materials used in constructing the piston.

Model 3 would be the most advantageous design, since it provided the largest force among the four models. Looking at the bar chart, as shown in Figure 5.28, the forces provided by the four models are significantly the same, the main difference was on how to manufacture the piston and adopt the easiest way to build the model.

6.2 Recommendations for Future Research

There exist several topics related to this research that need 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 How the fluid flow will react with respect of the motion of the piston along the damper.
- 3 Generating a multiphysics model, this will include the fluid and the effect of the electromagnetic component on the MR fluid gap and the rest of the system.
- 4 Generating the force vs. velocity plot without using the mathematical equations.

The model used in this research is a 2-D axisymmetric MR damper. Creating a 3-D model, will help the reader to visualize and understand the aspects of an MR damper and how the damper piston interacts with the housing.

The MR damper is filled with MR fluid ferrous particles; we can design a model to study the reaction of the fluid along the gap or even on the damper piston to calculate the effect of the fluid's pressure on that area.

Designing a multiphysics model would be important, especially if we can combine and study the effect of the MR fluid in an electromagnetic model. From that multiphysics model, we can apply a fluid velocity in the system and generate the force along the MR fluid gap.

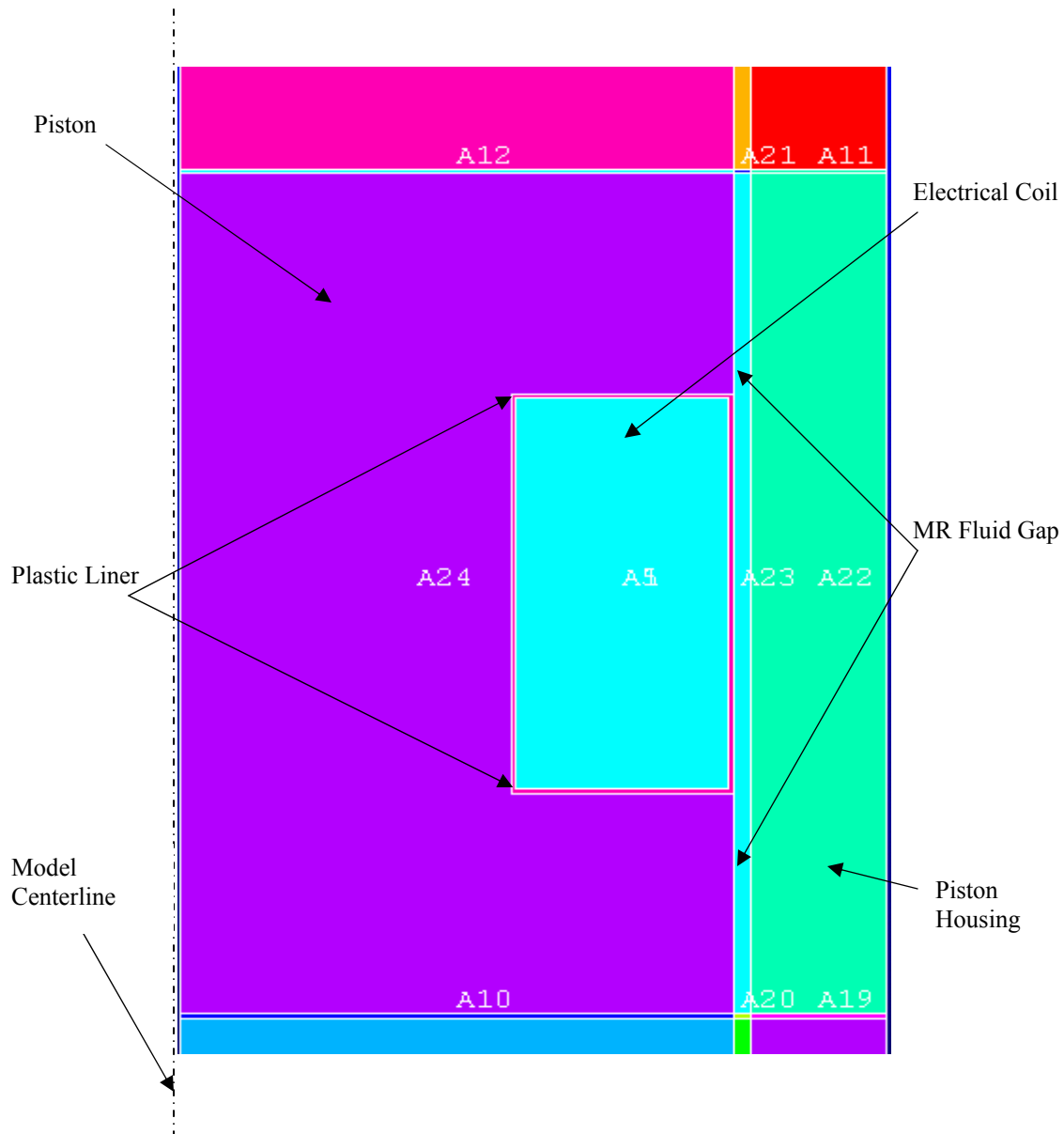
It would be easy to establish a force – velocity plot without using the mathematical equations. Designing a multiphysics MR damper would enable us to generate the force along the MR fluid gap while saving researchers overall work and time.

APPENDICES

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.



Summary of Steps

We can use the information in the problem description and the steps below as a guideline to solve the problem.

1. Build Geometry

1. Create First rectangle.
2. Create remaining four rectangles
3. Overlap all areas.

2. Define Materials

4. Set preferences.
5. Specify material properties.

3. Generate Mesh

6. Define element type and options.
7. Assign material property attributes.
8. Specify meshing-size controls on air gap.
9. Mesh the model using the MeshTool.

4. Apply Loads

11. Define the armature as a component.
12. Apply force boundary conditions to armature.
13. Apply the current density.
14. Obtain a flux parallel field solution.

5. Obtain Solution

15. Solve.

6. Review Results

16. Plot the flux lines in the model.
17. Summarize magnetic forces.
18. Plot the flux density as vectors.

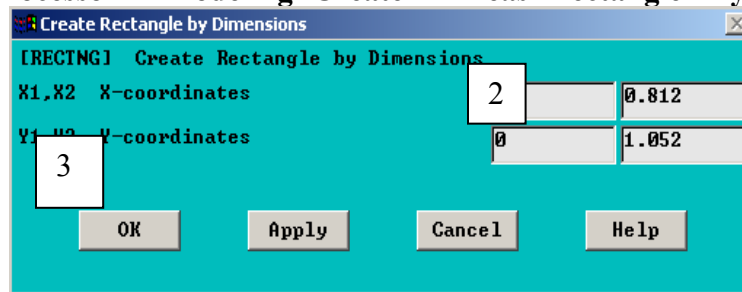
19. Plot the magnitude of the flux density.
20. Exit the ANSYS program.

1. Build Geometry

Step 1: Create first rectangle

Overlapping five rectangles creates the model. Create each rectangle by entering its dimensions in a dialog box (instead of by picking points on the working plane).

1. **Main Menu > Preprocessor > -Modeling- Create > -Areas- Rectangle > By Dimensions**



2. Enter the following:

X1 = 0

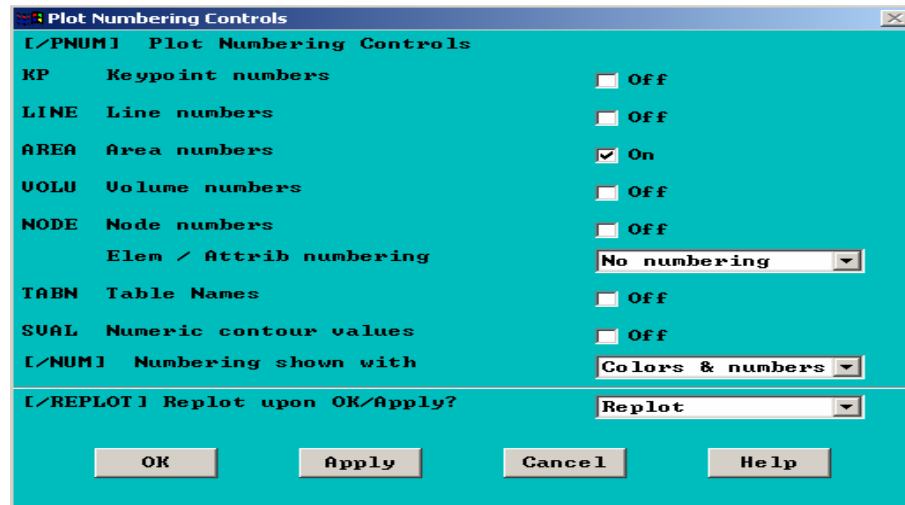
X2 = 0.812

Y1 = 0

Y2 = 1.052

(Note: Press the Tab key between entries.)

3. OK.
4. **Utility Menu > PlotCtrls > Numbering**
5. Turn on Area numbers.



6. OK.

Step 2: Create remaining five rectangles

Now create rectangles 2, 3, 4, and 5.

1. **Main Menu > Preprocessor > -Modeling- Create > -Areas- Rectangle > By Dimensions**
2. Enter the following:

$$X1 = 0$$

$$X2 = 2.75$$

$$Y1 = .75$$

$$Y2 = 3.5$$

3. Apply.
4. Enter the following:

$$X1 = .75$$

$$X2 = 2.25$$

$$Y1 = 0$$

$$Y2 = 4.5$$

5. Apply.
6. Enter the following:

$$X1 = 1$$

$$X2 = 2$$

$$Y1 = 1$$

$$Y2 = 3$$

7. Apply.
8. Enter the following:

$$X1 = 0$$

$$X2 = 2.75$$

$$Y1 = 0$$

$$Y2 = 3.75$$

9. Apply.
10. Enter the following:

$$X1 = 0$$

$$X2 = 2.75$$

$$Y1 = 0$$

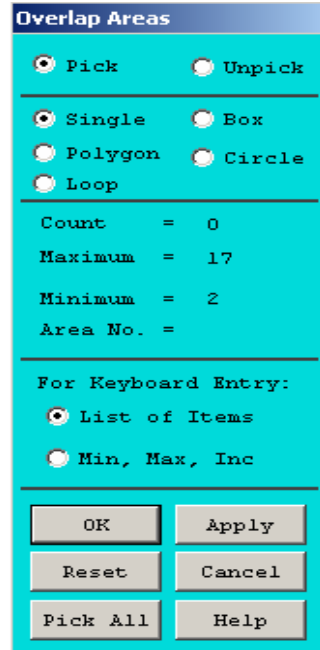
$$Y2 = 4.5$$

11. OK.

Step 3: Overlap all areas

The Boolean Overlap operation will create new areas at all intersections of the six rectangles and remaining areas.

1. **Main Menu > Preprocessor > -Modeling- Operate > -Booleans- Overlap > Areas**



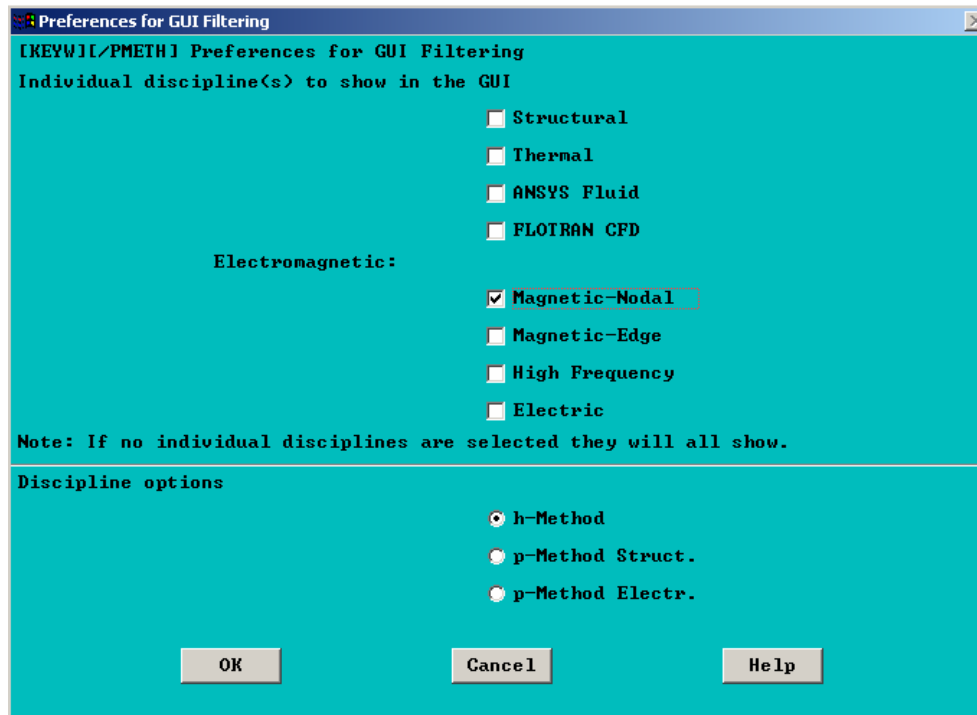
2. Pick All.
3. Toolbar: SAVE_DB

2. Define Materials

Step 4: Set preferences

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

1. **Main Menu > Preferences**
2. Turn on Electromagnetic: Magnetic-Nodal filtering (nodal element formulations).



3. OK.

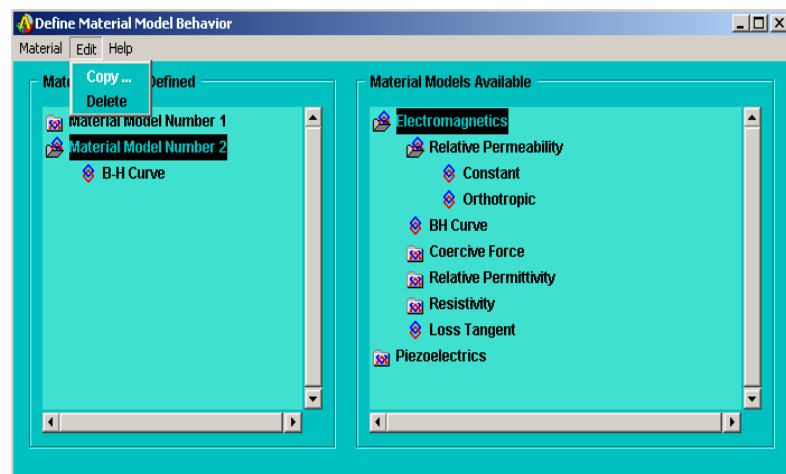
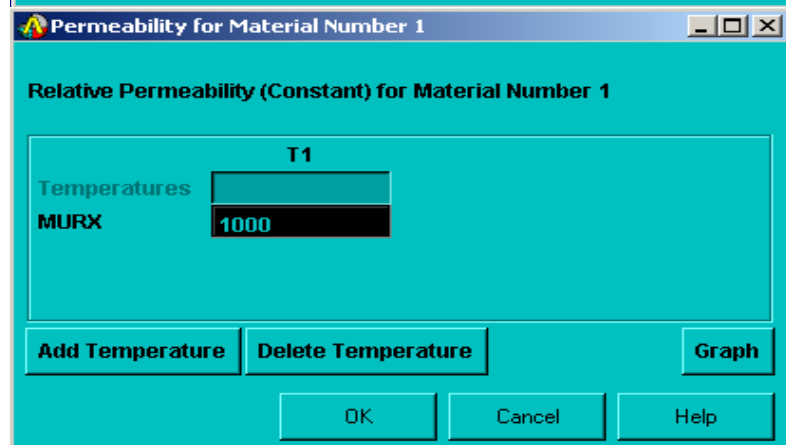
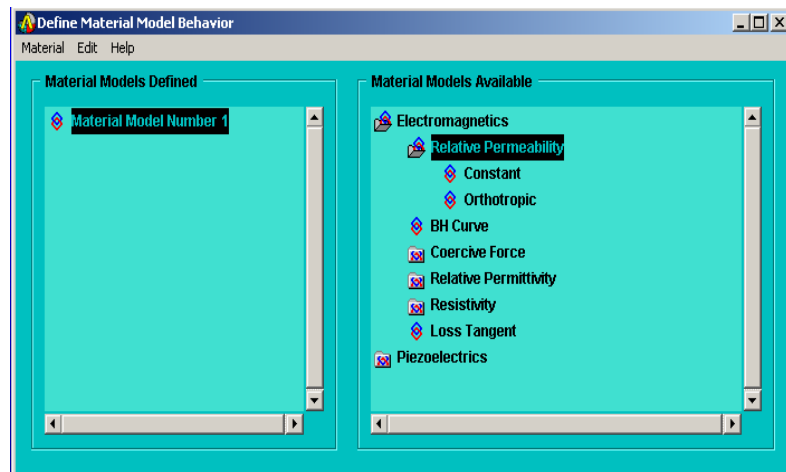
Step 5: Specify material properties

Now specify the material properties for the magnetic permeability of air, Engine, coil, and armature. For simplicity, all material properties are assumed to be linear. (Typically, iron is input as a nonlinear B-H curve.) Material 1 will be used for the housing elements. Material 2 will be used for the MR fluid elements. Material 3 will be used for the engine elements. Material 4 will be used for the coil elements. Material 5 will be used for the air gap elements.

1. **Main Menu > Preprocessor > Material Props > Material Models**
2. 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. Double-click on Electromagnetics, BH curve
8. Enter the first set of data for H and B.
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 B.
13. OK.

Edit > Copy

14. OK to copy Material Model Number 1 to become Material Model Number 3.
15. Double-click on Material Model Number 3, then on Permeability (Constant).
16. OK.
17. **Edit > Copy**



18. Select 1 for from Material Number.
19. Enter 4 for to Material Number.
20. OK.
21. Double-click on Material Model Number 4, then on Permeability (Constant).
22. Change the value of MURX from 75 to 1.
23. OK.
24. **Edit> Copy**
25. Select 1 for from Material Number.
26. Enter 5 for to Material Number.
27. OK.
28. Double-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. **Utility Menu > List > Properties > All Materials**
32. Review the list of materials, then choose:

File > Close (Windows)

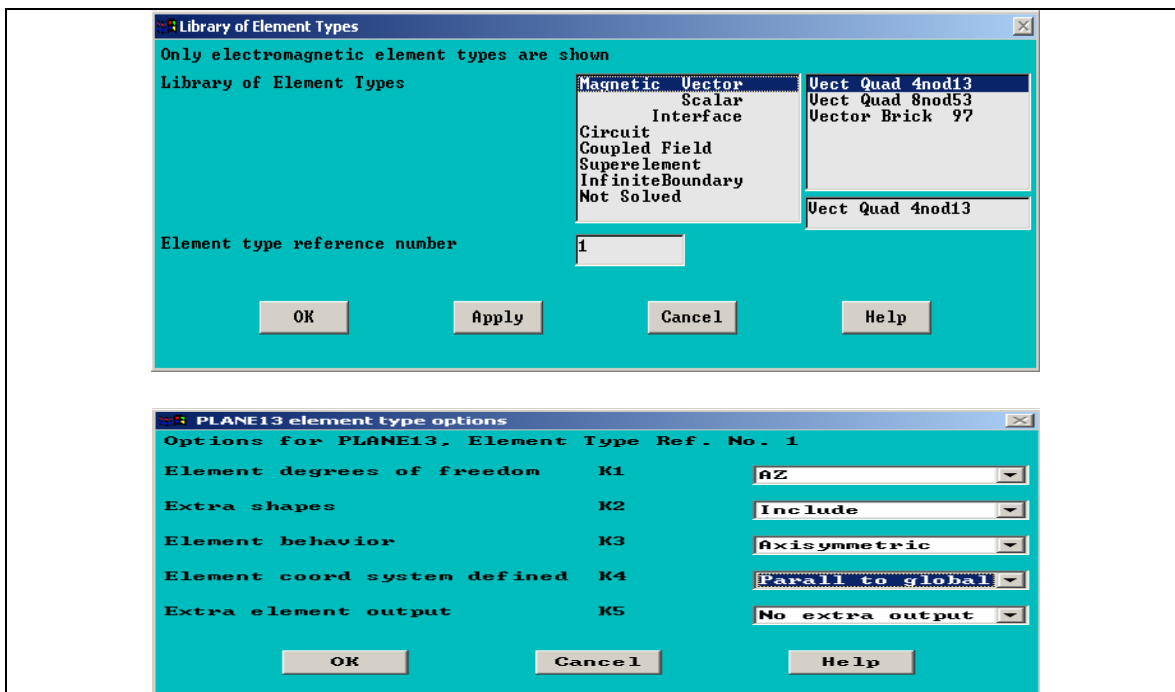
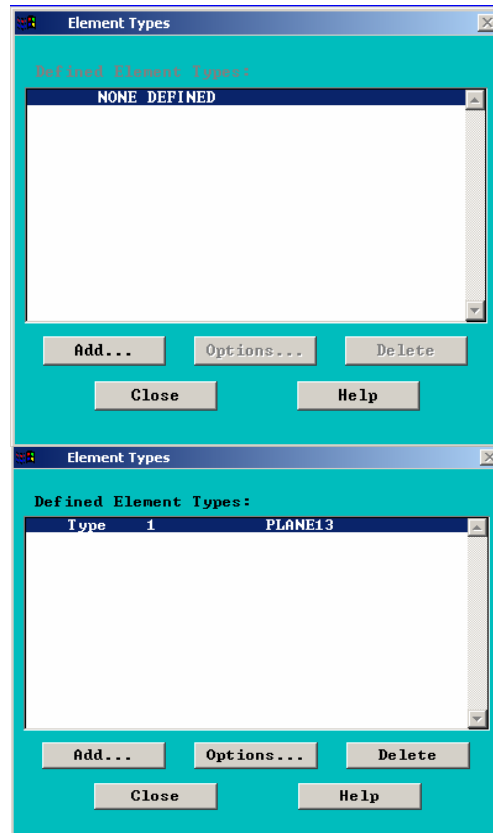
3. Generate Mesh

Step 6: Define element types and options

In this step you will define element types and specify options associated with these element types.

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

1. **Main Menu > Preprocessor > Element Type > Add/Edit/Delete**
2. Add.
3. Choose Magnetic Vector.
4. Choose Vect Quad 4nod13 (PLANE13).
5. OK.
6. Options.
7. Change Element behavior from plain strain to Axisymmetric.
8. OK.
9. Close.



Step 7: Specify Material Properties

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

1. **Main Menu > Preprocessor > MeshTool**
2. Choose Areas, Set for Element Attributes
3. Pick the Housing area
4. OK (in picking menu)
5. Choose 1 for material number
6. Apply
7. Pick the MR fluid gap area
8. OK (in picking menu).
9. Choose 2 for Material number.
10. Apply.
11. Pick Engine area.
12. OK (in picking menu).
13. Choose 3 for Material number.
14. Apply.
15. Pick the Coil area.
16. OK (in picking menu).
17. Choose 4 for Material number.
18. Apply.
19. Pick the air gap area.
20. Choose 5 for Material number.
21. OK (in picking menu).
22. OK.
23. Toolbar: *SAVE_DB*.



Area Attributes

[AATT] Assign Attributes to Picked Areas

MAT Material number 1

REAL Real constant set number None defined

TYPE Element type number 1 PLANE13

ESYS Element coordinate sys 0

OK Apply Cancel Help

Area Attributes

[AATT] Assign Attributes to Picked Areas

MAT Material number 2

REAL Real constant set number None defined

TYPE Element type number 1 PLANE13

ESYS Element coordinate sys 0

OK Apply Cancel Help

Area Attributes

[AATT] Assign Attributes to Picked Areas

MAT Material number 3

REAL Real constant set number None defined

TYPE Element type number 1 PLANE13

ESYS Element coordinate sys 0

OK Apply Cancel Help

Area Attributes

[AATT] Assign Attributes to Picked Areas

MAT Material number 4

REAL Real constant set number None defined

TYPE Element type number 1 PLANE13

ESYS Element coordinate sys 0

OK Apply Cancel Help

Area Attributes

[AATT] Assign Attributes to Picked Areas

MAT Material number 5

REAL Real constant set number None defined

TYPE Element type number 1 PLANE13

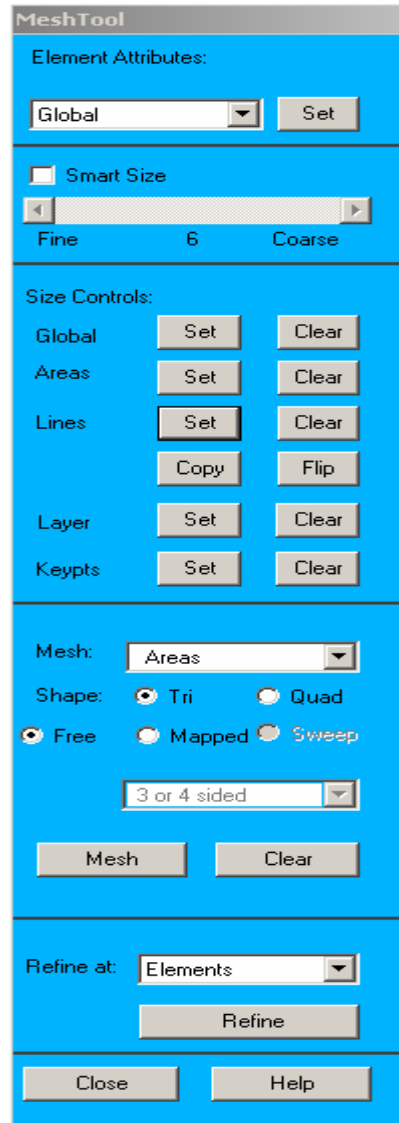
ESYS Element coordinate sys 0

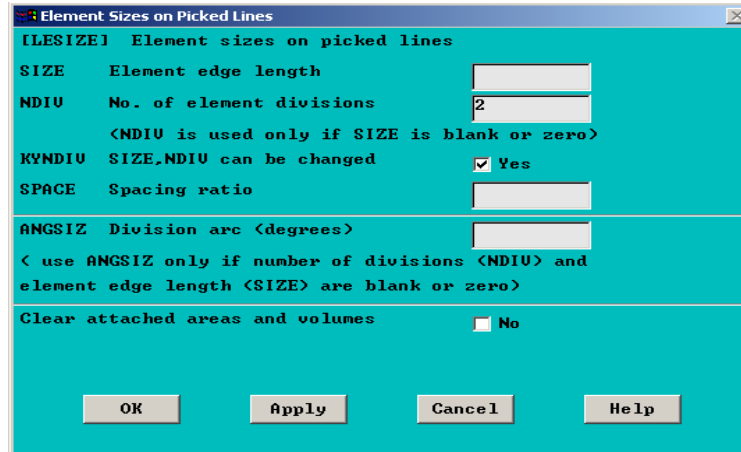
OK Apply Cancel Help

Step 8: Specify meshing-size controls on air gap

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

1. Choose Lines, Set for Size Controls.
2. Pick four vertical lines through air gap.
3. OK (in picking menu).
4. Enter 2 for No. of element divisions.
5. OK



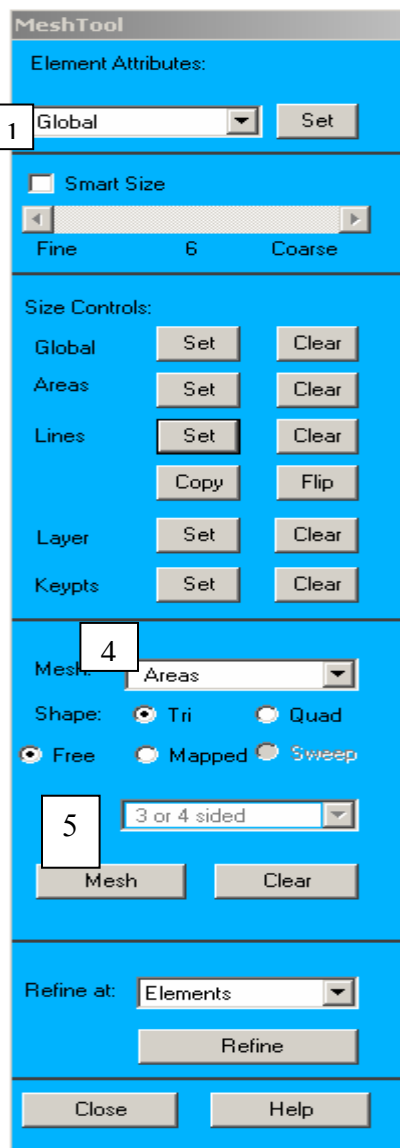


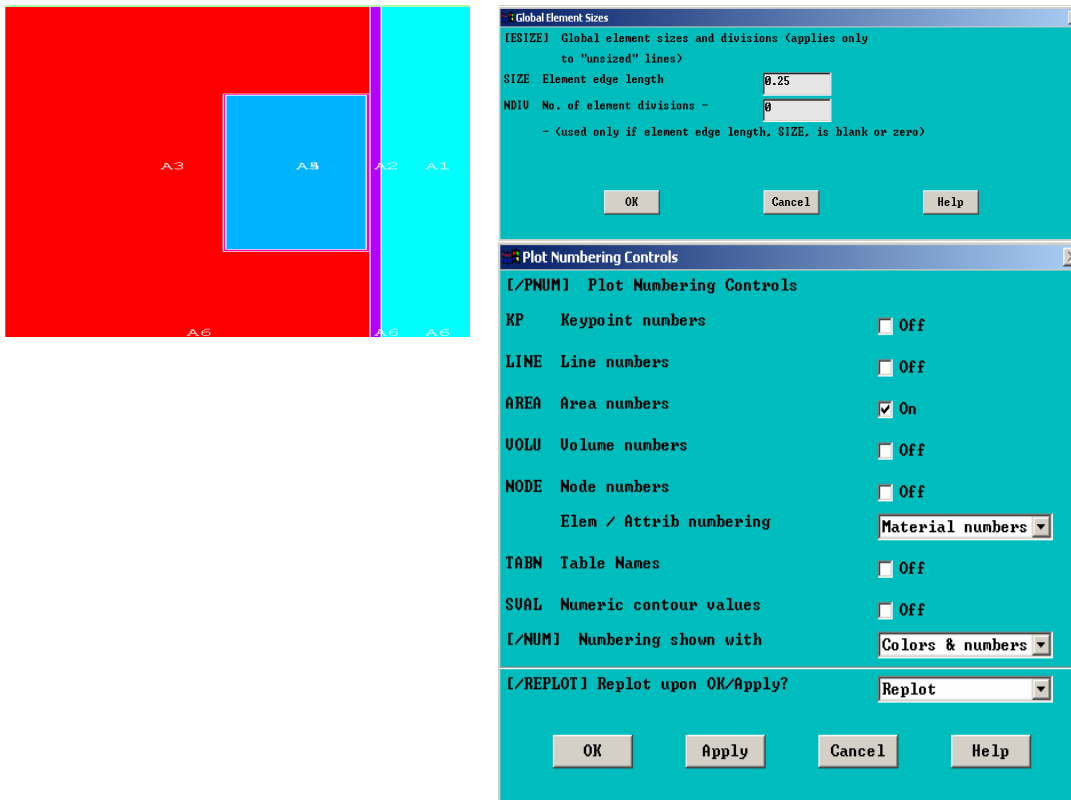
Step 9: Mesh the model using the MeshTool

1. Set Global Size Control.
2. Enter 0.25 for Element edge length.
3. OK.
4. Choose Areas.
5. Click on Mesh.
6. Pick All (in picking menu).
7. Close the MeshTool.

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. **Utility Menu > PlotCtrls > Numbering**
9. Choose Material numbers.
10. OK



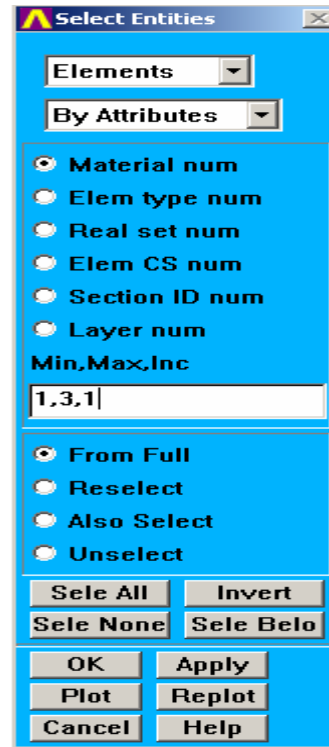


4. Apply Loads

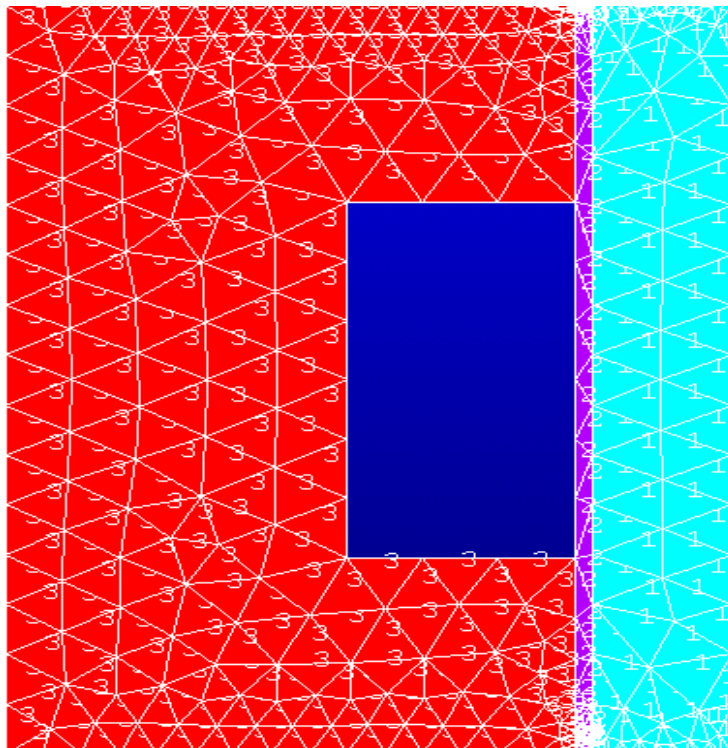
Step 11: Define the Engine, MR fluid gap and the Housing as a component

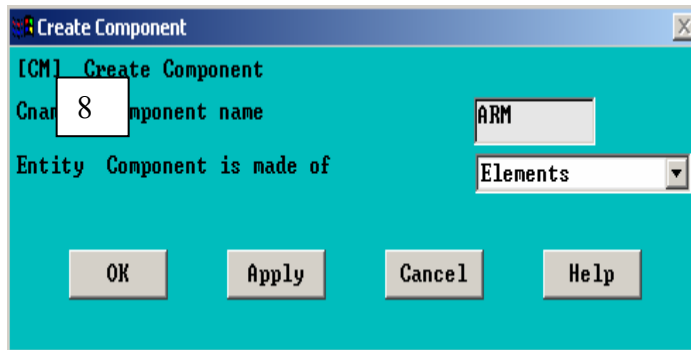
The system can conveniently be defined as a component by selecting its elements.

1. **Utility Menu > Select > Entities**
2. Choose Elements.
3. Choose By Attributes.
4. Enter 1,3,1 for Min, Max, Inc.
5. OK.
6. **Utility Menu > Plot > Elements**



7. **Utility Menu > Select
Comp/Assembly > Create Component**
8. Enter ARM for Component name.
9. Choose Elements.
10. OK.





Step 12: Apply force boundary conditions to armature

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

2. Choose ARM.

3. OK.

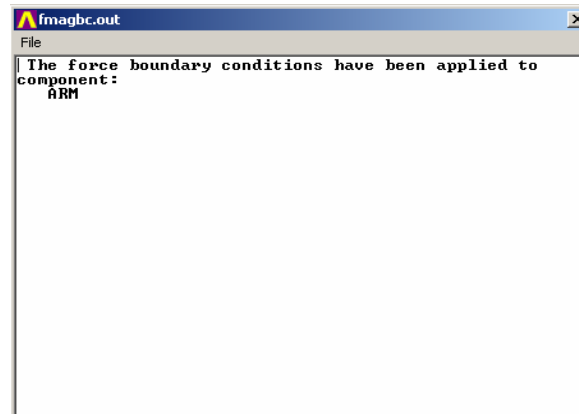
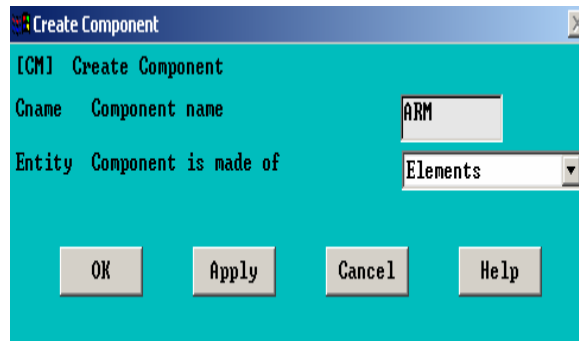
4. Review the information, then choose:

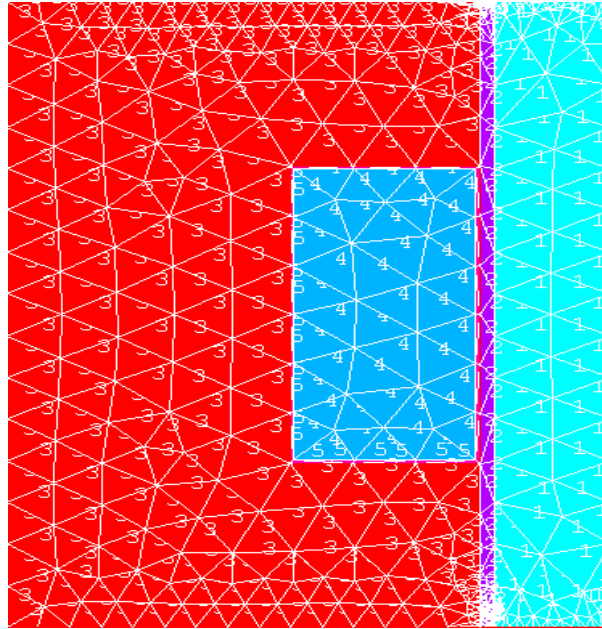
File > Close (Windows),

or

Close (X11/Motif), to close the window.

5. **Utility Menu > Select > Everything**
6. **Utility Menu > Plot > Elements**

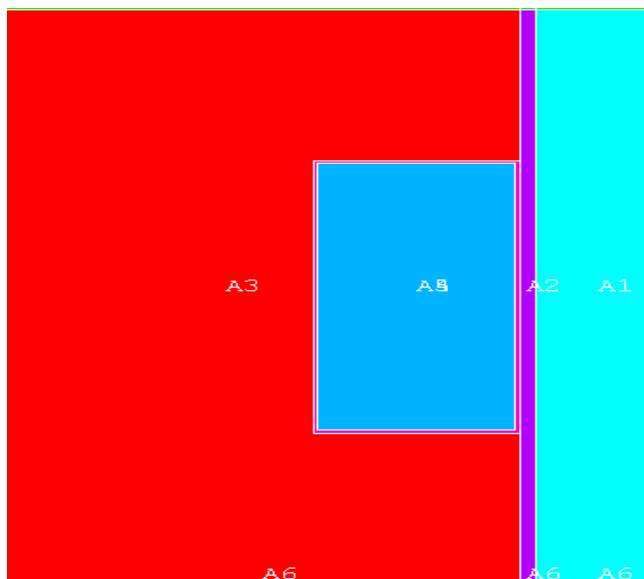




Step 13: Apply the current density

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

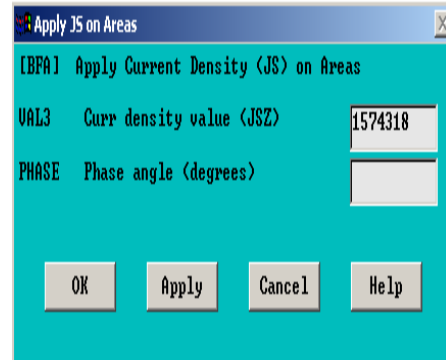
1. Utility Menu > Plot > Areas



2. **Main Menu > Preprocessor > Loads > - Loads- Apply > -Magnetic- Excitation > - Curr Density- On Areas**
3. Pick the coil area, which is the area in the

- center.
4. OK (in the picking menu).
5. Enter 1574318 for Current density value.

6. OK.



Step 14: Obtain a flux parallel field solution

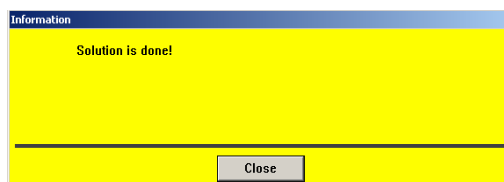
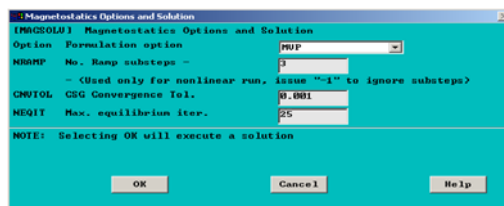
Apply a perimeter boundary condition to obtain a "flux parallel" field solution. This boundary condition assumes that the flux does not leak out of the iron at the perimeter of the model. Of course at the centerline this is true due to axisymmetry.

1. **Utility Menu > Plot > Lines >**
2. **Main Menu > Preprocessor > Loads > -Loads- Apply > -Magnetic-Boundary > -Vector Poten-Flux Par'l- On Lines**
3. Pick all lines around perimeter of model.
4. OK (in picking menu).
5. Toolbar: *SAVE_DB*.

5. Obtain Solution Step 15: Solve

1. **Main Menu > Solution > -Solve- Electromagnet > -Static Analysis- Opt & Solve**
2. OK to initiate the solution.

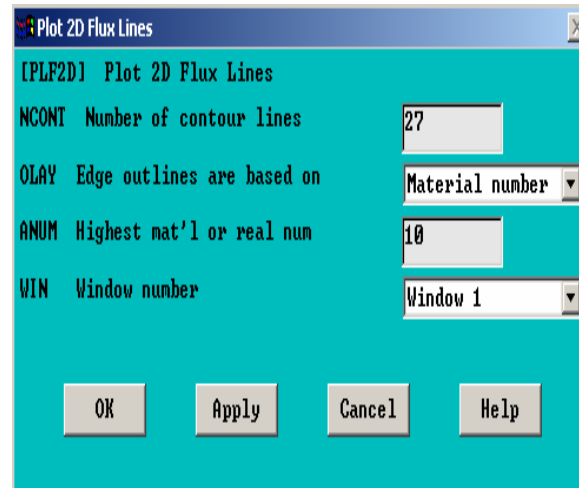
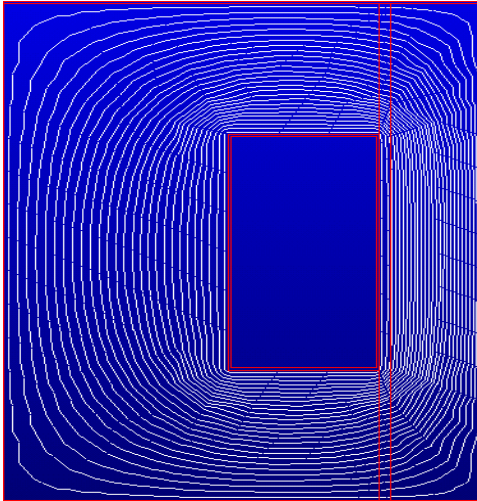
3. Close the information window when solution is done.



6. Review Results

Step 16: Plot the flux lines in the model

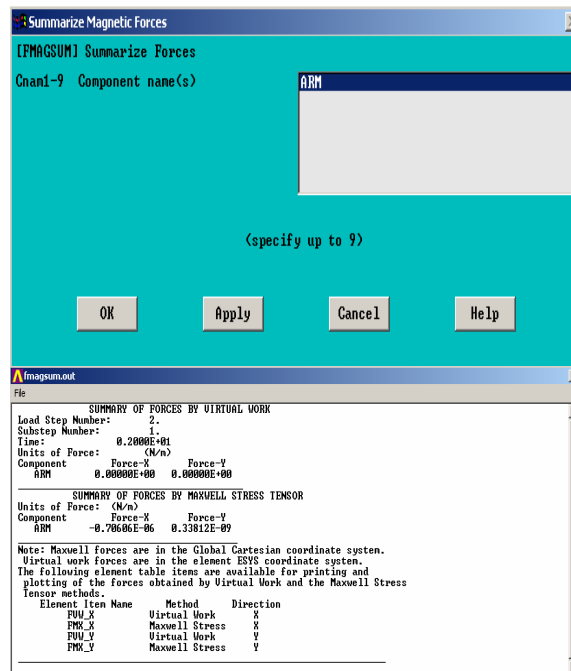
1. Main Menu > General
Postproc > Plot Results > -
Contour Plot- 2D Flux Lines.
2. OK



Step 17: Summarize magnetic forces

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

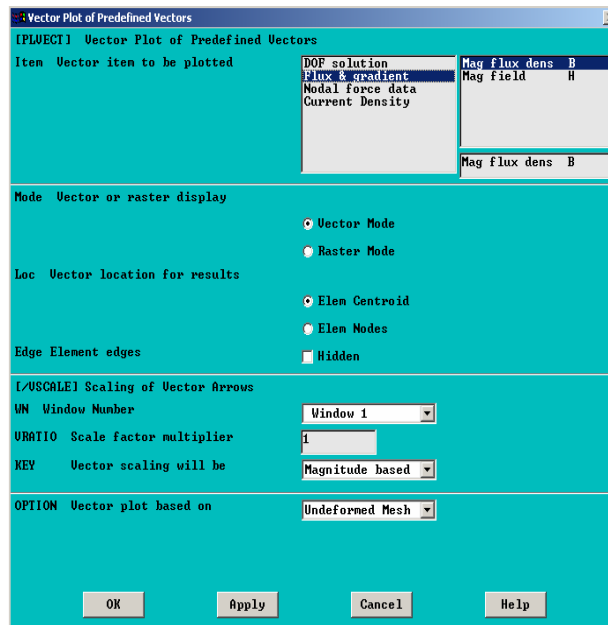
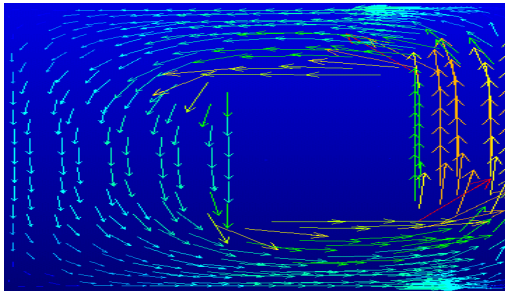
File > Close
(Windows).



Step 18: Plot the flux density as vectors

1. **Main Menu > General Postproc > Plot Results > - Vector Plot- Predefined**
2. Choose Flux & gradient.
3. Choose Mag flux dens B.

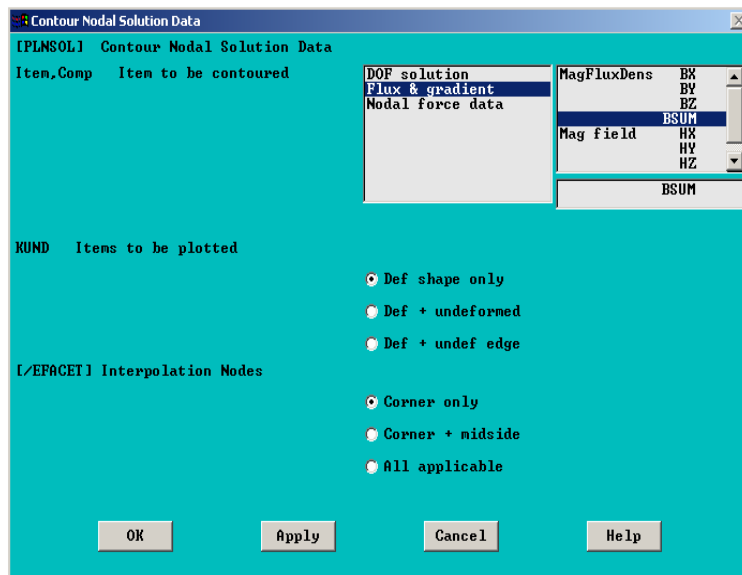
OK.

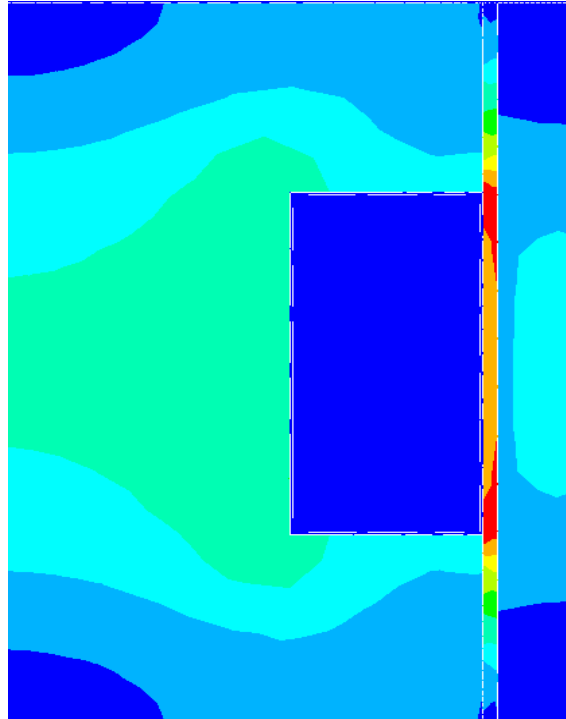


Step 19: Plot the magnitude of the flux density

Plot the magnitude of the flux density without averaging the results across material discontinuities.

1. **Main Menu > General Postproc > Plot Results > - Contour Plot- Nodal Solu**
2. Choose Flux & gradient.
3. Choose BSUM.
4. OK.

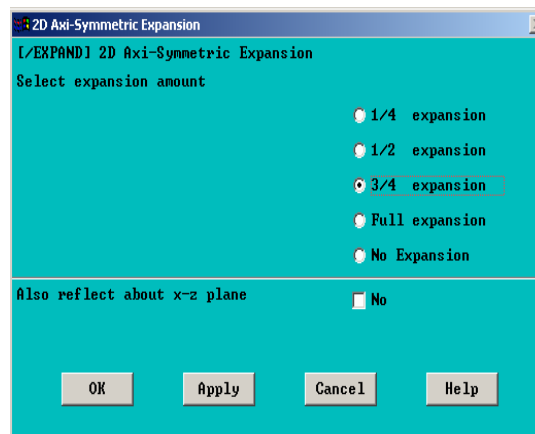




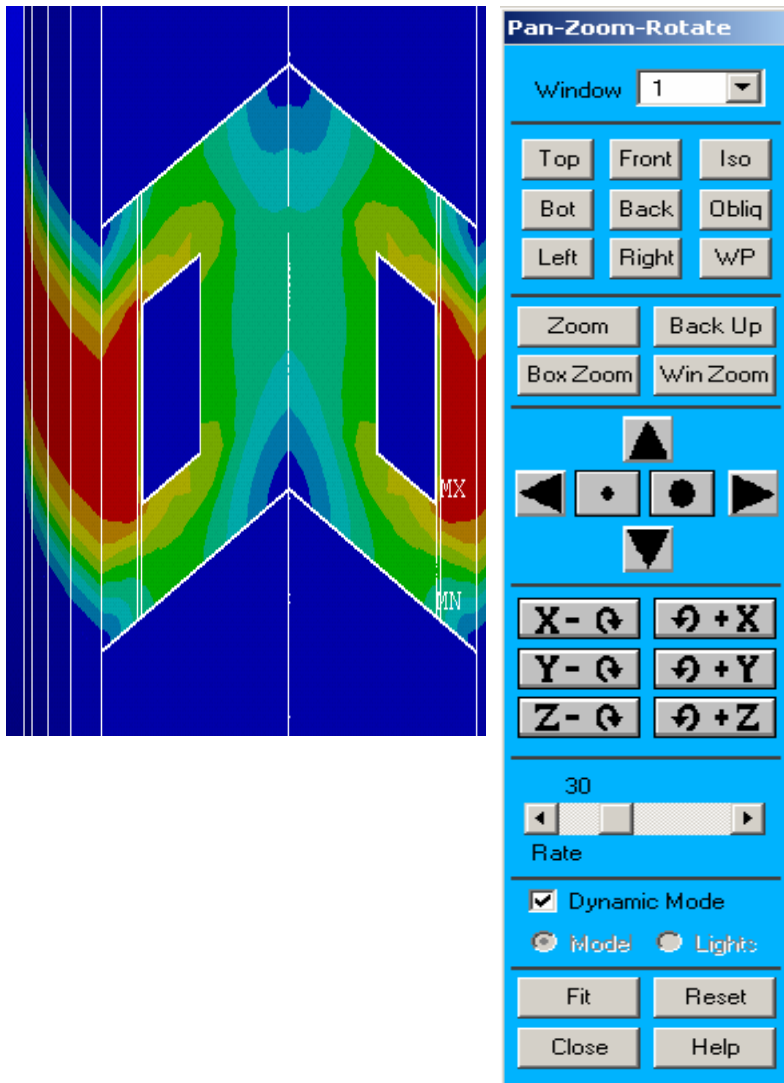
1. **Utility Menu > PlotCtrls > Style > Symmetry Expansion > 2D Axi-Symmetric**

2. Choose 3/4 expansion.
3. OK.

Obtain an isometric view for a more meaningful representation.

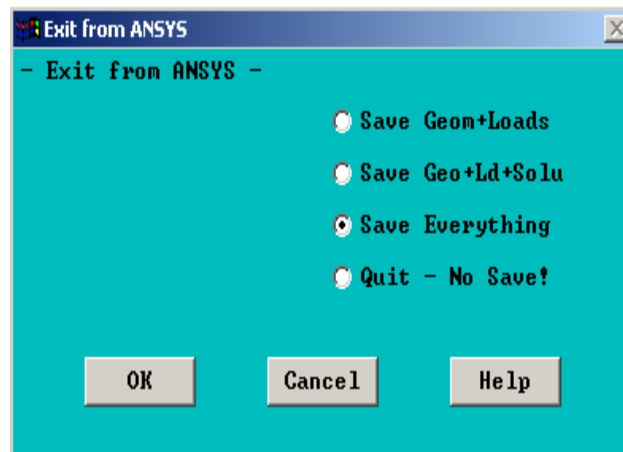


4. **Utility Menu > PlotCtrls > Pan,Zoom,Rotate**
5. Iso.
6. Close.



Step 20: Exit the ANSYS program

1. Toolbar: *QUIT*.
2. Choose Quit – Save everything
3. OK.

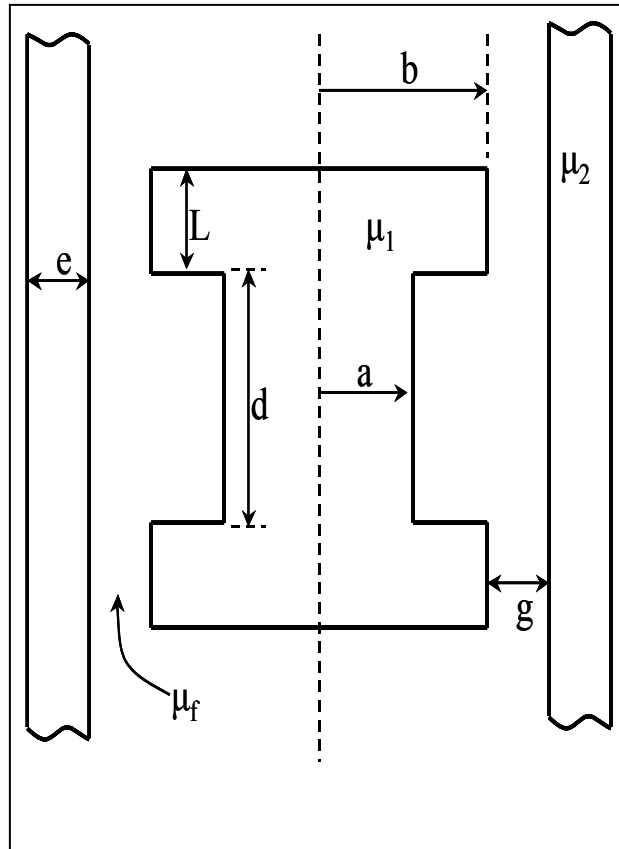


Appendix – B

Microsoft Excel Worksheet

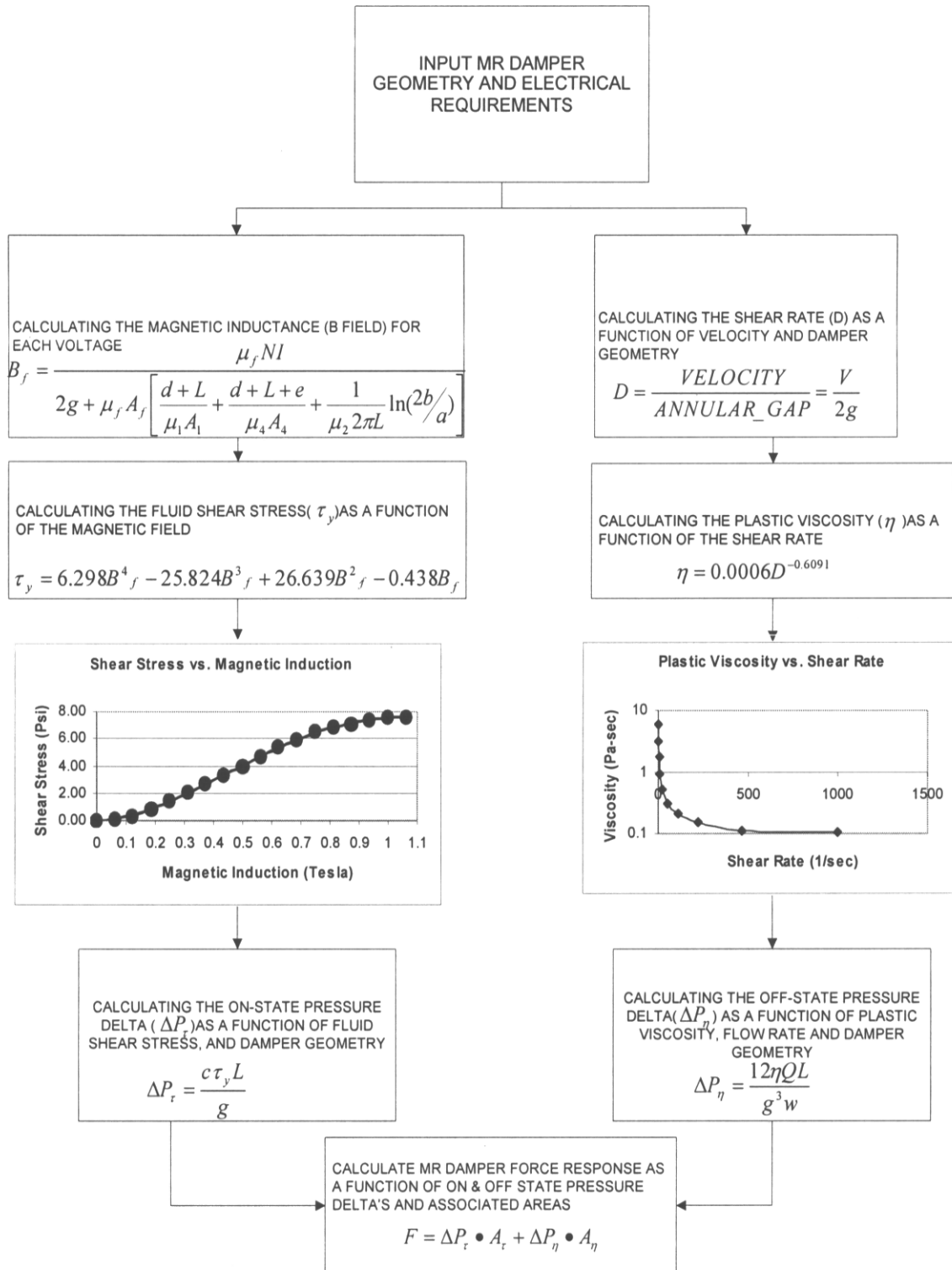
In this section, we will show the worksheets that were generated in Microsoft excel 2000 for calculating the force – velocity plot for all models. We will first define the geometry of the MR damper and shows a flow diagram to lead the reader through the steps that must be taken in excel models. Using the equations in Chapters 2 and 4, we can plot the Force – Velocity characteristics of the MR dampers for different currents.

symbol	Description	Value	Units
a	inner radius of engine	0.009665	meters
b	outer radius of engine	0.016167	meters
d	spool length	0.0127	meters
e	housing thickness	0.002692	meters
g	annular gap	0.000495	meters
L	length of contact area	0.00701	meters
μ_f	permeability of MR fluid	0.0008	H/m
μ_1	permeability of engine material	75	H/m
μ_2	permeability of housing material	75	H/m
	conversion from inches to meter	0.0254	m/in
N	number of turns of wires	650	
I	current	0	Amps
I	current	0.2	Amps
I	current	0.4	Amps
I	current	0.6	Amps
I	current	0.8	Amps
I	current	1	Amps
I	current	1.2	Amps
I	current	1.4	Amps
I	current	1.6	Amps
I	current	1.8	Amps
I	current	2	Amps
r	mean radius	0.016415	m
w	width	0.103137	m
A(f)	Active fluid area	0.002899	m ²
A(1)	Active area through engine	0.000293	m ²
A(4)	Active area through housing	0.000593	m ²



Supplied Current (Amps)	B(f) - Tesla				
	ANSYS	first model	second model	third model	fourth model
0.0	0	0	0	0	0
0.2	0.465	0.466	0.444	0.454	0.53
0.4	0.679	0.684	0.674	0.647	0.725
0.6	0.721	0.73	0.717	0.747	0.787
0.8	0.768	0.777	0.76	0.801	0.857
1.0	0.812	0.827	0.805	0.849	0.924
1.2	0.859	0.878	0.854	0.896	1
1.4	0.91	0.93	0.904	0.944	1.09
1.6	0.96	0.98	0.958	0.995	1.22
1.8	1.02	1.04	1.02	1.05	1.32
2.0	1.09	1.11	1.08	1.09	1.43

The following flow chart describes the process that the model undergoes to simulate the force – velocity characteristics of an MR Damper.



The next two tables are the results obtained after using the equations from chapter 2 and 4 to generate the force – velocity plots.

First, we have the Off-State factors, where the condition is defined as the response of the damper when no current is applied.

Off-State Factors				
Velocity (m/sec)	Fluid Shear Rate (1/sec)	Plastic Viscosity (Pa-sec)	Flow Rate (m³/sec)	Off-State Pressure (Pa)
-0.635	641	0.087	-0.00051	-591211
-0.6096	615	0.089	-0.00049	-581851
-0.5842	590	0.091	-0.00047	-572251
-0.5588	564	0.094	-0.00045	-562394
-0.5334	538	0.096	-0.00043	-552259
-0.508	513	0.099	-0.00041	-541826
-0.4826	487	0.102	-0.00039	-531071
-0.4572	462	0.106	-0.00037	-519964
-0.4318	436	0.110	-0.00035	-508475
-0.4064	410	0.114	-0.00033	-496567
-0.381	385	0.118	-0.00031	-484196
-0.3556	359	0.123	-0.00028	-471312
-0.3302	333	0.129	-0.00026	-457855
-0.3048	308	0.135	-0.00024	-443751
-0.2794	282	0.143	-0.00022	-428912
-0.254	256	0.151	-0.00020	-413226
-0.2286	231	0.161	-0.00018	-396553
-0.2032	205	0.173	-0.00016	-378709
-0.1778	179	0.188	-0.00014	-359448
-0.1524	154	0.207	-0.00012	-338428
-0.127	128	0.231	-0.00010	-315148
-0.1016	103	0.264	-0.00008	-288824
-0.0762	77	0.315	-0.00006	-258104
-0.0508	51	0.403	-0.00004	-220272
-0.0254	26	0.615	-0.00002	-167992
0	0	1211.963	0.00000	0
0.0254	26	0.615	0.00002	167992
0.0508	51	0.403	0.00004	220272
0.0762	77	0.315	0.00006	258104
0.1016	103	0.264	0.00008	288824
0.127	128	0.231	0.00010	315148
0.1524	154	0.207	0.00012	338428
0.1778	179	0.188	0.00014	359448
0.2032	205	0.173	0.00016	378709
0.2286	231	0.161	0.00018	396553

0.254	256	0.151	0.00020	413226
0.2794	282	0.143	0.00022	428912
0.3048	308	0.135	0.00024	443751
0.3302	333	0.129	0.00026	457855
0.3556	359	0.123	0.00028	471312
0.381	385	0.118	0.00031	484196
0.4064	410	0.114	0.00033	496567
0.4318	436	0.110	0.00035	508475
0.4572	462	0.106	0.00037	519964
0.4826	487	0.102	0.00039	531071
0.508	513	0.099	0.00041	541826
0.5334	538	0.096	0.00043	552259
0.5588	564	0.094	0.00045	562394
0.5842	590	0.091	0.00047	572251
0.6096	615	0.089	0.00049	581851
0.635	641	0.087	0.00051	591211

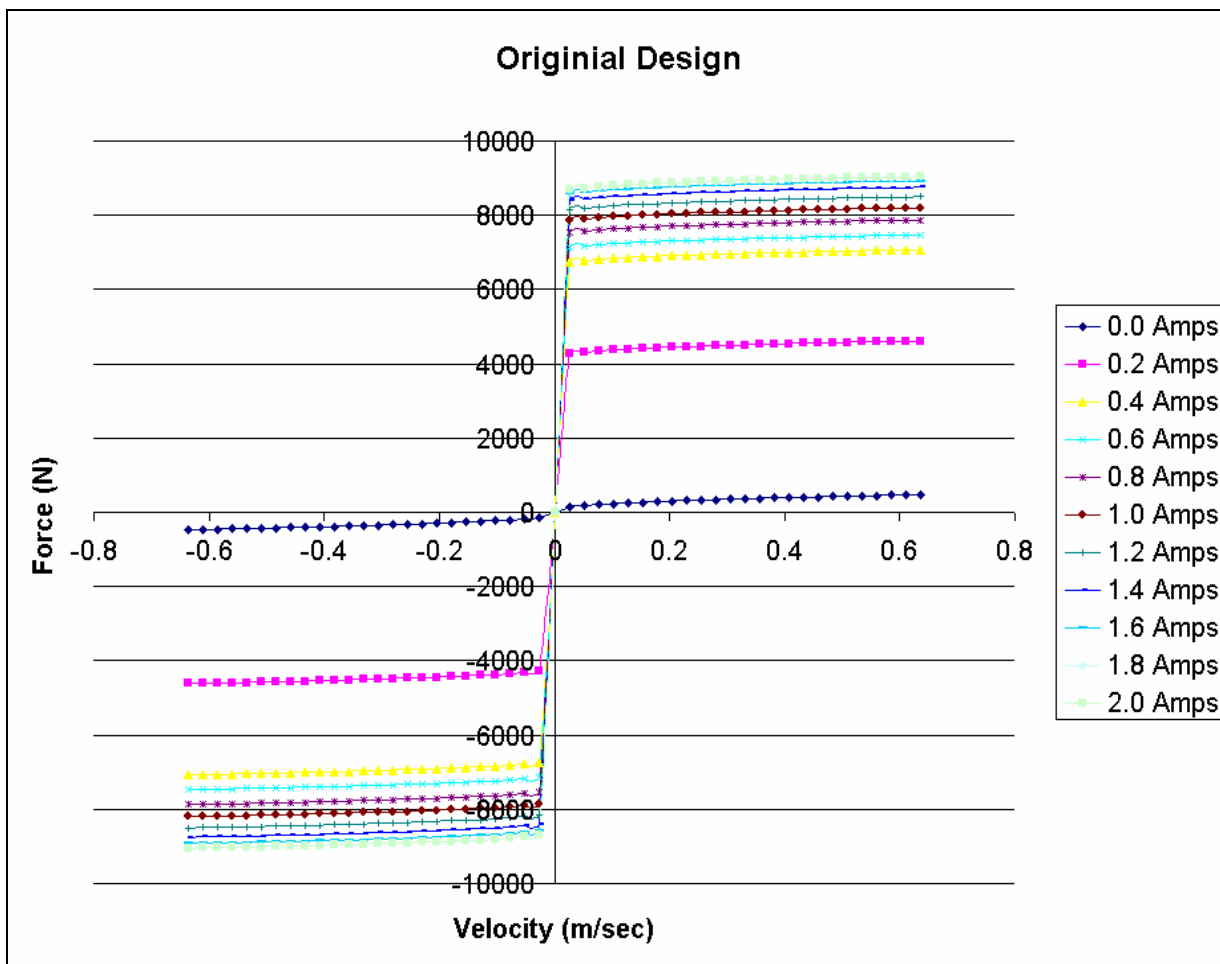
Second, we have the On-State factors, where the condition is defined as the response of the damper when a current greater than zero is applied. This table shows the output of the damper force at 0.2 and 0.4 Amps.

On-State Factors

	0.2 Amps			0.4 Amps		
Damper Force (N)	On-State Pressure (Pa)	Fluid Shear Stress (Pa)		Damper Force (N)	On-State Pressure (Pa)	Fluid Shear Stress (Pa)
-4617	-1429358	25247		-7075	-2277227	40223
-4609	-1429358	25247		-7067	-2277227	40223
-4602	-1429358	25247		-7060	-2277227	40223
-4594	-1429358	25247		-7052	-2277227	40223
-4586	-1429358	25247		-7044	-2277227	40223
-4577	-1429358	25247		-7035	-2277227	40223
-4569	-1429358	25247		-7027	-2277227	40223
-4560	-1429358	25247		-7018	-2277227	40223
-4551	-1429358	25247		-7009	-2277227	40223
-4541	-1429358	25247		-6999	-2277227	40223
-4531	-1429358	25247		-6989	-2277227	40223
-4521	-1429358	25247		-6979	-2277227	40223
-4510	-1429358	25247		-6968	-2277227	40223
-4499	-1429358	25247		-6957	-2277227	40223
-4487	-1429358	25247		-6945	-2277227	40223
-4474	-1429358	25247		-6932	-2277227	40223

-4461	-1429358	25247		-6919	-2277227	40223
-4447	-1429358	25247		-6905	-2277227	40223
-4431	-1429358	25247		-6889	-2277227	40223
-4414	-1429358	25247		-6872	-2277227	40223
-4396	-1429358	25247		-6854	-2277227	40223
-4375	-1429358	25247		-6833	-2277227	40223
-4350	-1429358	25247		-6808	-2277227	40223
-4320	-1429358	25247		-6778	-2277227	40223
-4278	-1429358	25247		-6736	-2277227	40223
0	0	0		0	0	0
4278	1429358	25247		6736	2277227	40223
4320	1429358	25247		6778	2277227	40223
4350	1429358	25247		6808	2277227	40223
4375	1429358	25247		6833	2277227	40223
4396	1429358	25247		6854	2277227	40223
4414	1429358	25247		6872	2277227	40223
4431	1429358	25247		6889	2277227	40223
4447	1429358	25247		6905	2277227	40223
4461	1429358	25247		6919	2277227	40223
4474	1429358	25247		6932	2277227	40223
4487	1429358	25247		6945	2277227	40223
4499	1429358	25247		6957	2277227	40223
4510	1429358	25247		6968	2277227	40223
4521	1429358	25247		6979	2277227	40223
4531	1429358	25247		6989	2277227	40223
4541	1429358	25247		6999	2277227	40223
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4577	1429358	25247		7035	2277227	40223
4586	1429358	25247		7044	2277227	40223
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4602	1429358	25247		7060	2277227	40223
4609	1429358	25247		7067	2277227	40223
4617	1429358	25247		7075	2277227	40223

From these tables, we can set a plot between the damper force and the input velocity, as shown in the figure below.



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Vita

Walid El-Aouar was born on July 7, 1975 in Kornayel, Lebanon. At an early age, he developed a keen interest in how things worked. After completing High school in Hammana, Lebanon; he went on to pursue an Associate degree in Applied Science with a major in J. Sargeant Reynolds Community College in Richmond, Virginia.

After completing the Associates degree, Walid transferred to Virginia Tech where he earned a Bachelor of Science degree in Mechanical Engineering.

After completing a Bachelor of Science degree, Walid went to pursue a Masters of Science degree in Mechanical Engineering, also at Virginia Tech. He graduated in December 2002. In the near future, he will move to work in California where he hopes to continue participating in his favorite hobbies.