UNIVERSITI MALAYSIA PAHANG

BORANG PENGESAHAN STATUS TESIS

JUDUL: **DESIGN SEMI –ACTIVE SUSPENSION USING MAGNETO-RHEOLOGICAL DAMPER**

SESI PENGAJIAN: **2010/2011**

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DESIGN SEMI-ACTIVE SUSPENSION USING MAGNETO-RHEOLOGICAL DAMPER

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BACHELOR OF ENGINEERING
UNIVERSITI MALAYSIA PAHANG

2010

DESIGN SEMI-ACTIVE SUSPENSION USING MAGNETO –RHEOLOGICAL DAMPER

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A report submitted in partial fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering With Automotive Engineering.

Faculty of Mechanical Engineering
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DECEMBER 2010

UNIVERSITI MALAYSIA PAHANG

FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled *"Design Semi-Active Suspension Using Magneto-Rheological Damper"* is written by *Muhamad AmzanSani Bin Abd Wahab.* I have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering with Automotive Engineering.

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I hereby declare that the work in this thesis is my own except for the quotations and summaries which have been duly acknowledged. The project has not been accept for any degree and is not concurrently submitted for any award of other degree.

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Name: MUHAMAD AMZANSANI BIN ABD WAHAB

I humbly dedicate this thesis to

My lovely mother and father, Noriati Mustafa Ismail and Abd Wahab Hashim

My dearest sister, Anis Syazwani, Amanina, and Asma Hanim

My dearest brother, Aizuddin

Who always trust me, love and had been a great source of support and the motivation.

ACKNOWLEDGEMENTS

Firstly, I would like to express my grateful to ALLAH s.w.t as for the blessing given so that I could finish my thesis.

I also would like to express my sincere gratitude to my supervisor Dr. Gigih Priyandoko for his germinal ideas, invaluable guidance, continuous encouragement and constant support in making this research possible. He has always impressed me with his outstanding professional conduct, his strong conviction for science, and his belief that a degree program is only a start of a life-long learning experience. I am truly grateful for his progressive vision about my training in engineering, his tolerance of my naïve mistakes, and his commitment to my thesis

My sincere thanks go to all my lab mates and members of the staff of the Mechanical Engineering Department, UMP, who helped me in many ways and made my stay at UMP pleasant and unforgettable.

I acknowledge my sincere indebtedness and gratitude to my parents for their love, dream and sacrifice throughout my life. I am also grateful to my brother, fellow friend for their support, patience, and understanding that were inevitable to make this work possible. I cannot find the appropriate words that could properly describe my appreciation for their devotion, support and faith in my ability to attain my goals. Special thanks should be given to my committee members. I would like to acknowledge their comments and suggestions, which was crucial for the successful completion of this study.

ABSTRACT

This thesis focused on the development of semi- active suspension by using magneto-rheological damper. The MR damper is a type of damper that used MR fluid as working fluid which enables us to change damping force and setting of suspension without need to setting manually damper itself. It can be achieve by changing the current flow on it magnetic circuit.This thesis first introduces MR technology through a discussion of MR fluid and then by giving a broad overview of MR devices that is being developed. After giving the reader an understanding of MR technology and devices, MR damper basics are presented. This section includes a discussion of MR damper types, mathematical fundamentals, and an approach to magnetic circuit design. With the necessary background information covered, MR dampers for automotive use are then discussed. Then come to design part. By using specification same as Proton Waja passive damper, the model was develop by using SOLIDWORK software. The design used twin tube damper with same size of outer tube of OEM damper. The parameter like number of turn, length and diameter of the wire, current induced, magnetic field generated, head piston velocity, and force produced by MR damper was be calculated and discussed. The result show the damper produced 6475.441 Newton of maximum force when 3 ampere of current being applied to the damper. The force generated by damper at 0.5, 1, 1.5, 2, 2.5 and 3 ampere was plotted in a single graph versus piston head velocity in order to give better view of result.

ABSTRAK

Tesis ini memokuskan pada pembangunan suspensi semi- aktif dengan menggunakan cecair magnetik yang dikenali sebagai cecair MR. Perendam MR adalah sejenis perendam yang menggunakan cecair MR sebagai medium operasinya dimana membenarkan kita mengubah daya perendeman dan ketetapan sesebuah suspensi dengan mudah. Ini dapat dicapai dengan mengubah arus elektrik yang mengalir pada litar magnetik yang terdapat dalam perendam.Dalam tesis ini, pertamanya diterangkan mengenai teknologi MR melalui penerangan tentang cecair MR dan secara am tentang alat MR yang sedang di bangunkan. Kemudian penerangan tentang perendam MR akan di terangkan. Dalam bahagian ini semua perbincangan tentang jenis perendam MR, teori mathematik, dan pengenalan pada rekaan litar magnetik. Dengan maklumat asas telah diterangkan, perendam MR untuk automotif dibincangkan. Kemudian kepada bahagian rekaan. Rekaan akan berdasarkan kepada perendam pasif Proton Waja. Dengan menggunakan spesifikasi sama seperti perendam Proton Waja, model perendam dibina dengan menggunakan perisian SOLIDWORK. Rekaan menggunakan tiub berkembar yang sama saiz dengan tiub luar perendam OEM. Semua parameter termasuk bilangan lilitan wayar, panjang dan diameter wayar yang digunakan, arus elektrik yang dikenakan, kekuatan medan magnet yang terjana, halaju piston perendam, dan daya yang terhasil akan dikira dan dibincangkan. Keputusan menunjukan yang perendam menghasilkan daya maksimum sebanyak 6475.441 Newton apabila dikenakan arus 3 ampere. Daya yang terhasil oleh perendam pada arus 0.5, 1, 1.5, 2, 2.5 dan 3 ampere di plotkan dalam satu graf bagi membolehkan keputusan dilihat dengan lebih baik.
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LIST OF SYMBOLS

α	Fluid efficiency
τ_y	Yield stress
η	Plastic viscosity
μ	Relative permeability of the material
μ_0	Free space permeability ($4\pi \times 10^{-7}$ Tm/A)
Φ	Magnetic flux

LIST OF ABBREVIATIONS

FYP	Final Year Project
MR	Magnetic-Rheological
OEM	Original Equipment Manufacturer
PTFE	Polyethylene

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Over the past decade, there has been a sustained interesting magneto rheological (MR) device due to the controllable interface provided by the MR fluid inside the devices that enables the mechanical device to interact with an electronic system, which can be used to continuously adjust the mechanical properties of the device. Some examples of devices in which MR fluids have been employed include dampers, clutches, brakes and transmissions. The most popular of these devices are MR dampers, especially as automotive shock absorbers. The automotive shock absorber has been shown to be a very important contributor to the ride comfort and road handling of a vehicle. For ride comfort, shock absorbers with a ‘soft’ setting are required to dissipate shock energy from the road, while a ‘hard’ setting is required for good vehicle handling. These conflicting characteristics of ride comfort and road-holding is a major challenge to automotive shock absorber designers. The tuning of conventional hydraulic shock absorbers normally involves the physical adjustments of the settings of various valves located inside the piston. Also, conventional absorbers will have a constant setting throughout their lifetime, and hence will not be able to operate satisfactorily in a wide range of road conditions. It is for these reasons that semi-active systems like MR dampers have attracted the attention of suspension designers and researchers. MR dampers are not only advantageous in their ability to provide variable damping forces to the suspension; they are inherently fail-safe devices from an electronic point of view. If there was a fault in the system, the MR damper can still operate as a passive damping system within certain performance parameters depending on the off-state characteristics of the MR fluid inside.

1.2 PROBLEM STATEMENT

Traditionally, automotive suspension designs have been a compromise between the two conflicting criteria of road holding and passenger comfort. The suspension system must support the weight of the vehicle, provide directional control during handling maneuvers, and provide effective isolation of passengers and payload from road disturbances .A passive suspension has the ability to store energy via a spring and to dissipate it via a damper. The parameters are generally fixed, being chosen to achieve a certain level of compromise between road holding and ride comfort. Once the spring has been selected based on the load-carrying capability of the suspension, the damper is the only variable remaining to specify. Low damping yields poor resonance control at the natural frequencies of the body (sprung mass) and axle (unsprung mass), but provides the necessary high frequency isolation required for a comfortable ride. Conversely, large damping results in good resonance control at the expense of high frequency isolation. Due to these conflicting demands, suspension design has had to be something of a compromise, largely determined by the type of use for which the vehicle is designed. The other solution is using active control. However this method is expensive for a standard car

1.3 OBJECTIVES

The primary objectives of this thesis is

i) To design MR damper geometry
ii) To develop MR damper about MR damper geometry and magnetic field
    - To determine the magnetic induction
    - To determine the magnetic field intensity
iii) To analyze the MR parameter.

1.4 Scope

The scope for this thesis is

i) Design a MR damper by using the same dimension of outer tube of Proton Waja

ii) To determine the diameter of wire that will use for the coil inside the MR damper

iii) To calculate the strength of magnetic induction and its field intensity

iv) To determine maximum force that MR damper can absorb

CHAPTER 2

LITERATURE REVIEW

2.1 BACKGROUND

The purpose of this chapter is to orient the reader with the topic of magneto rheological fluid technology. From this point forward, magneto rheological fluid will be referred to simply as MR fluid. MR fluid belongs to a class of materials that are known as "smart materials". The physical attributes of smart materials can be altered through the application of an electrical, magnetic, or thermal stimulus. Some smart materials, known as Piezoceramics, exhibit a change in physical size when an electric current is passed through them. Other materials, known as Shape Memory Alloys, can be deformed and then returned to their original dimensions through the application of heat. Still other materials, known as ER (electro rheological) fluids and MR fluids, exhibit a change in apparent viscosity when activated.

2.2 TYPES OF SUSPENSION

Suspension is the term given to the system of springs, shock absorbers and linkages that connects a vehicle to its wheels. Suspension systems serve a dual purpose – contributing to the car's road holding/handling and braking for good active safety and driving pleasure, and keeping vehicle occupants comfortable and reasonably well isolated from road noise, bumps, and vibrations. These goals are generally at odds, so the tuning of suspensions involves finding the right compromise. It is important for the suspension to keep the road wheel in contact with the road surface as much as possible, because all the forces acting on the vehicle do so through the contact patches of the tires. The suspension also protects the vehicle itself and any cargo or luggage from damage and wear. The design of front and rear suspension of a car may be different. Generally there are three type of suspension. There passive, semi active, and last one active.

2.2.1 PASSIVE SUSPENSION

The typical passive suspension system can be considered as a spring in parallel with a damper placed at each corner of the vehicle like Figure 2.1. The spring is chosen based solely on the weight of the vehicle, while the damper is the component that defines the suspensions placement on the compromise curve. Depending on the realistic condition of vehicle, a damper is chosen to make the vehicle perform best in its application. Ideally, the damper should isolate passengers from low-frequency road disturbances and absorb high-frequency road disturbances. Passengers are best isolated from low-frequency disturbances when the damping is high. However, high damping provides poor high frequency absorption. Conversely, when the damping is low, the damper offers sufficient high-frequency absorption, at the expense of low-frequency isolation.

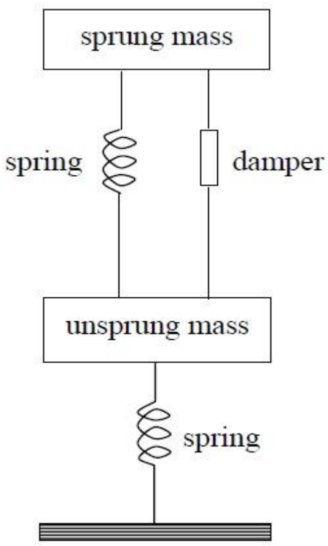

Figure 2.1 Passive suspension

2.2.2 SEMI – ACTIVE SUSPENSION

If the suspension is externally controlled then it is a semi-active or active suspension - the suspension is reacting to what are in effect "brain" signals like Figure 2.2. As electronics have become more sophisticated, the opportunities in this area have expanded. For example, a hydro pneumatic Citroën will "know" how far off the ground the car is supposed to be and constantly reset to achieve that level, regardless of load. It will not instantly compensate for body roll due to cornering however. Citroën's system adds about 1% to the cost of the car versus passive steel springs. Semi-active suspensions include devices such as air springs and switchable shock absorbers, various self-leveling solutions, as well as systems like Hydro pneumatic, Hydrolastic, and Hydragas suspensions. Mitsubishi developed the world's first production semi-active electronically controlled suspension system in passenger cars; the system was first incorporated in the 1987 Galant model. Delphi currently sells shock absorbers filled with a magneto-rheological fluid, whose viscosity can be changed electromagnetically, thereby giving variable control without switching valves, which is faster and thus more effective. The regulating of the damping force can be achieved by adjusting the orifice area in the damper, thus changing the resistance of fluid flow. Most recently the possible application of electrorheological and magnetorehological fluids to the development of controllable dampers has also attracted considerable interest

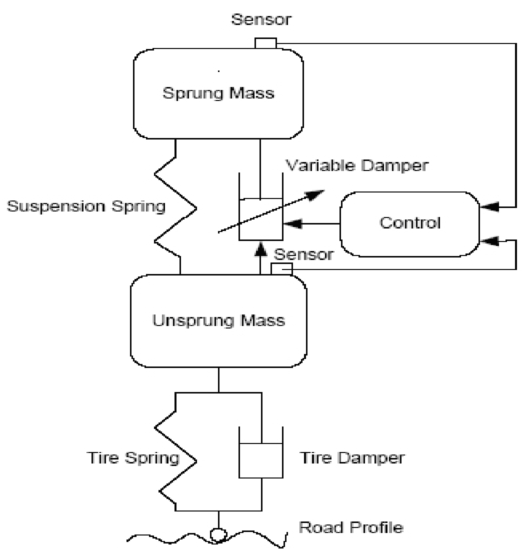

Figure 2.2 Semi-Active suspension

2.2.3 ACTIVE SUSPENSION

Active or adaptive suspension is an automotive technology that controls the vertical movement of the wheels via an onboard system rather than the movement being determined entirely by the surface on which the car is driving. The system therefore virtually eliminates body roll and pitch variation in many driving situations including cornering, accelerating, and braking. This technology allows car manufacturers to achieve a higher degree of both ride quality and car handling by keeping the tires perpendicular to the road in corners, allowing for much higher levels of grip and control.

An onboard computer detects body movement from sensors located throughout the vehicle and, using data calculated by opportune control techniques, controls the action of the suspension. Active suspensions, the first to be introduced, use separate actuators which can exert an independent force on the suspension which show in Figure 2.3 to improve the riding characteristics. The drawbacks of this design (at least today) are high cost, added complication/mass of the apparatus needed for its operation, and the need for rather frequent maintenance and repairs on some implementations. Maintenance can also be problematic, since only a factory-authorized dealer will have the tools and mechanics who know how to work on the system and, some issues can be difficult to diagnose reliably. It also require a huge power supply

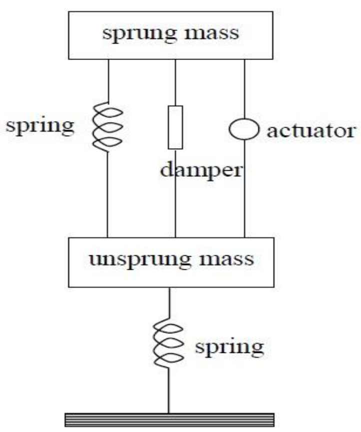

Figure 2.3 Model Active suspensions

2.3 MR FLUID PERFORMANCE

The capability of MR fluid lies in its ability to change the apparent viscosity proportional to an applied magnetic field due to the polarization of ferrous magnetic particles as seen in Figure 2.4. This apparent viscosity change is actually due to altering the yield stress of the MR fluid.. ER fluids are activated by exposure to an electric charge and MR fluids are activated by exposure to a magnetic field. When a magnetic field passes through MR fluid, it develops a yield stress which must be achieved before the material will flow. The piston is wrapped in magnet wire and generates magnetic flux in the piston, cylinder, and MR fluid. When subjected to intense magnetic fields (1 T), the yield stress of the MR material increases from less than 0.1 kPa to roughly 100 kPa. This change in material properties is sufficient to increase damping forces by a factor of 10 or more.

The iron particles are usually in a carrier fluid such as hydrocarbon oil, water, or silicone. The ferrous particles of iron may be from 1-20 microns in size .Many variations of the quantity of ferrous iron to fluid ratios exist for MR fluid. To retain a flowing fluid, the percentage of ferrous particles is typically limited to 20-40% in the composition of the MR fluid. Through magnetic activation at varied magnetic field intensities, MR fluid changes its apparent viscosity which is related to the content of ferrous particles. Therefore, this rheology behavior has enabled many passive devices to be operated with multifunctional capability to provide semi-active control. MR fluid has a very fast response time of less than 10 ms, when a magnetic field is applied. This extremely fast and adaptive behavior allows MR fluid to be controlled with an applied magnetic field. Moreover, the fast and reversible rheology helped MR fluid progress into automotive applications like the shock absorber. Since shock absorbers (dampers) dissipate energy based on the viscosity of the damper fluid, the viscosity is selected to offer either a comfortable ride or a responsive handling ride in the primary suspension of a vehicle. Moreover, with MR fluid in a damper, both of these ride characteristics can be achieved.

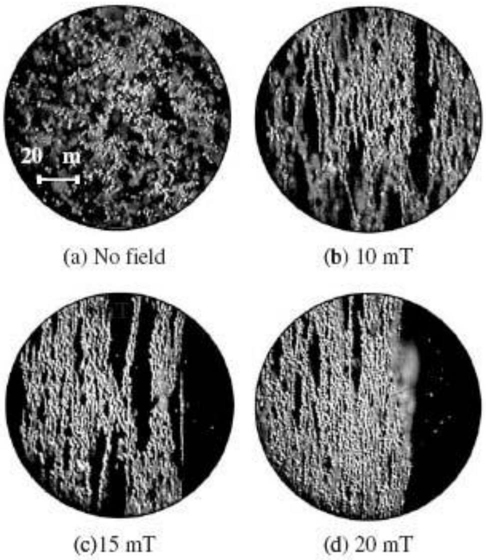

Figure 2.4 Polarization of ferrous magnetic particles

With the aforementioned magnetic particles suspended in a carrier fluid, several modes of operation can occur. Therefore, this section presents the operational modes of MR fluid. The primary mode of fluid operation for a damper is valve mode. Valve mode uses the flow of the fluid passing between magnetic poles, as seen in Figure 2.5, which is also referred to as pressure driven flow mode as described by Lord Materials Division .During valve mode, the applied magnetic field is varied across the fluid gap to cause an apparent viscosity change in the fluid. If used in a damper, the applied magnetic field through the fluid can alter the energy dissipated by the damper. Therefore, the damper may offer a soft ride or a stiff ride.

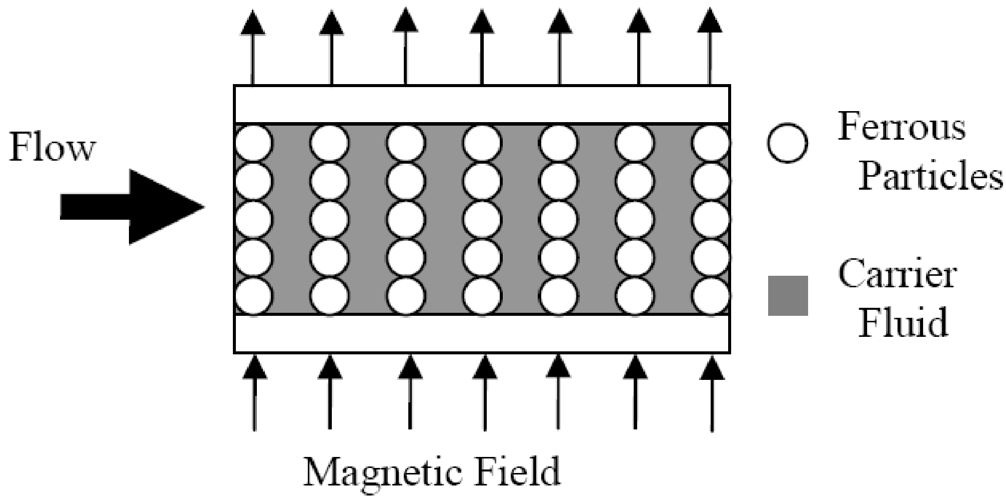

Figure 2.5 Valve mode model

Due to the ease of construction and the effectiveness of their magnetic configurations, most MR dampers are designed as fixed-pole valve mode devices, where the MR fluid is forced to flow through magnetically active annular gaps. In fixed-pole valve mode devices, the positions of both magnetic poles are stationary relative to one another during their operation, with the flow of the fluid generating the damping force provided by the device. This damping force can therefore be continuously regulated by controlling the strength of the applied magnetic field. Because the magnetically active gap is usually very small relative to the radius of the annulus, researchers have exploited this feature to approximate the flow of MR fluid through the annulus with fluid dynamics equations for flow through two infinitely wide parallel plates, a concept first introduced by Phillips for ER fluids and has been utilised widely in the design and modelling of MR dampers

The damper has a double-tube configuration consisting of two concentric cylinders. The piston, which is fixed onto the piston rod,moves up (rebound) and down (compression) along the inside of the inner tube. The piston divides the damper into two parts, namely: the rebound chamber, which is the space above the piston, and the compression chamber,which is the space below the piston. Holes at the bottom of the inner tube allow the compression chamber to be a continuous part of the outer tube.The gas phase on the outer cylinder is filled with pressurised air. Unlike single-tube configurations, this double-tube design does not require a purpose built accumulator to compensate for volumetric changes in the chamber sinduced by upward and downward motions of the piston.The stroke length of this type of double-tube design is also generally greater than an equivalent single-tube assembly. The MR fluid flows between the rebound and compression chambers through an annular gap in the piston. Inside the annular gap is a magnetic circuit that is driven by an electromagnet located in the piston head. The resistance to the flow of the MR fluid through this gap can be controlledby varying the strength of the magnetic field generatedby the coils. The force is considered to be positive if the rod moves out of the damper body, i.e. when it is in rebound stroke, and it is negative during compression. Continuity between the compression chamber and the gas phase requires that Pcom ¼ Pgas. Apart from the magnetic circuit inside the piston head, all the components of the damper are made from aluminium to minimise the loss of flux. Special low-friction, PTFE-based seals are used in the piston head, while wiper-type dynamic rod seals are used to ensure the fluid is contained inside the damper.

2.4 TWIN TUBE DESIGN

A twin tube shock or the Twin tube shock absorber is a low pressure shock having tube inside the outer shock body which contains the piston assembly. In order to create damping force, different coil springs inside the shock body are used. The inner tube is known as pressure tube whereas the outer tube is known as the reserve tube. The reserve tube is used for storing different types of hydraulic fluid. The mounts used for the shock absorber are many but the most popularly used rubber mount is rubber bushings between the shock absorber and the suspension to minimizing the suspension vibration

The piston rod passes to the upper end of the pressure tube through rod guide and the seal. The rod guide assists the piston to move freely inside whereas the oil is kept inside by the seal. The movement of the fluid is controlled by the base valve which is located at the bottom of the pressure tube.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter describe in detail of flowchart, designing, designing parameter, OEM proton Waja twin tube dimension, designed MR damper, and the analysis of the system and parameter. The analysis is to determine the desire parameter and capability of designed damper.

Finally, overall process in this project will explain according to the flowchart in figure 3.2 and Gant chart in appendix 1.

3.2 DESIGN PARAMETER

The design that will be determined in this research will be divide into two categories which parameter at the core or piston and the electric magnetic properties. The Table 3.1 show all parameter in this design.

Table 3.1 Design parameter MR damper

Parameter classification	Design parameter
Core / piston	Number of stages Number of turn per layer Number of layer Length of the wire per stages (m) Wire gage
Electrical/magnetic properties	Current (amp) Coil resistance er stages (ohm) Inductance (mH) Voltage (v) Power (*watt*) Magnetic field at gap region (*Tesla*) Magnetic field at core region (*Tesla*) H_{gap}(*kA/m)*

3.3 OVERALL STRUCTURE OF THE DESIGNED MR DAMPER

The development of MR damper model is based on the original equipment (OE) shock absorber used in the passenger vehicle. In this study, an original shock absorber from Proton Waja model has been chosen as the benchmark in developing the MR damper model in terms of geometrical design and performance. The parameters such as the shock absorbers inner tube diameter, inner tube length and the stroke length have been taken into consideration in the design. These parameters will become the constraints in designing MR damper by assuming that the MR damper will be used as a retrofitting damper in Proton Waja model. Table 4.1 shows the parameters of the original shock absorber that were considered in this model.

Table 3.2 Proton Waja's Original Shock Absorber Measurement

Particulars	Measurement
Stroke	150 mm (± 75 mm)
Piston rod length	350 mm
Extension stroke stopper (from end valve)	65 mm
Inner tube thickness	2 mm
Inner tube diameter	35 mm
Inner tube height	302 mm
Gap between inner tube and outer tube	5 mm

A MR damper has been design according to Proton Waja's original shock absorber measurement where the diameter of the outer tube and inner tube remain the same. Figure 3.1 show MR damper for Proton Waja's.

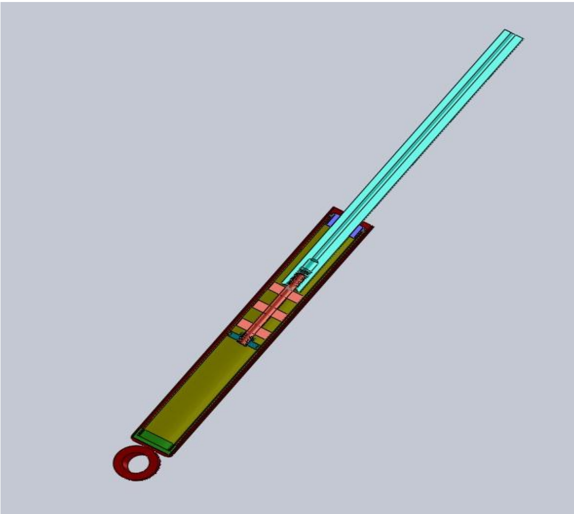

Figure 3.1: MR damper for Proton Waja's

3.4 FLOWCHART OF DEVELOPMENT

From the flow chart in figure 3.2, the project starts with literature review and research about the title. This consist a review of the concept of MR damper, type of suspension, and MR fluid performance. These tasks have been done through research from the internet, books, journals and other sources.

After gathering all the relevant information, the project undergoes for the modeling the damper through 2010 Solidwork software. In this step, from the knowledge and information gather from the literature review is use to design the damper according to OEM twin tube passive damper. After several designs have been chosen, model consideration has been made and one of the best models has been chosen.

After that, from models, the parameter analysis will be done to determine design parameter. After that, the equation of motion and other related equation will review. From the equation, then is transferred to transfer function for Excel process in FYP 2. The plots of MR dampers indicate that the high level of damping resulting from an applied current of three amps is greater than that of the original damper. They also show that the low state corresponding to zero applied current is lower than the original damper. In order for the MR dampers to successfully replace the original dampers, it was necessary that the MR damping range extend above and below the original dampers' force velocity curve

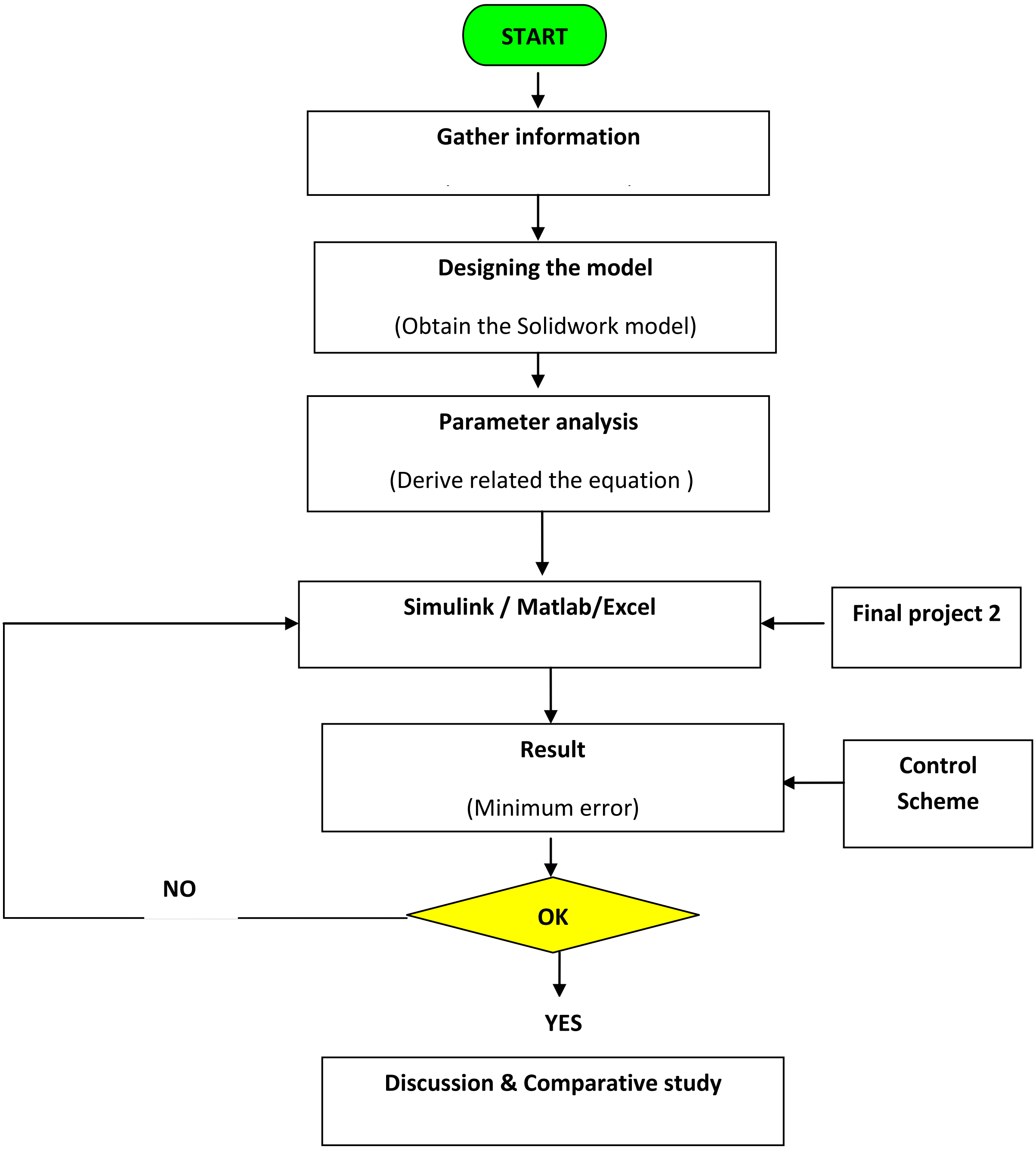

Figure 3.2: Research Flowchart.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

Magnetorheological (MR) damper is a popular choice among researchers and engineers to be employed as a damping system since Lord Corporation launch the world first damping system which utilizes MR fluid known as Motion Master System in 1990. The introduction of Motion Master System which is a damping system for passenger seat has shown the potential of MR technology in attenuating unwanted vibrations. Since then, the MR fluid technology has been widely applied not only in automotive applications but also in other applications such as in building control system, earthquake mitigation, gun recoil dampers and for managing the impact dynamics of the gun.

This chapter is dedicated to describe the fundamentals of MR damper. The chapter is also dedicated to describe on how to develop MR damper model based on the geometric constraints from a reference shock absorber. The principles of design of the MR dampers, and the mathematics involved with damper design will be discussed.

4.2 PROPERTIES OF MR FLUID

In order to choose the most appropriate MR fluid, a criterion to compare the nominal behavior of different MR fluids must first be established. Such an indicator is the figure of merit (Jolly *et al.*, 1998). The other parameters to be considered in the fluid choice are stability, durability, temperature range and compatibility with the other damper materials. Firstly the fluid efficiency α is defined as:

$$\alpha = \frac{\widehat{W}_{\mathrm{m}}}{\widehat{W}_{\mathrm{e}}}, \tag{4.1}$$

where $We = W/V$ is the power density, Wm the mechanical power density

In this design 132DG MR fluid from Lord Corporation was used as operation fluid. For the purpose of evaluating the different figures of merit the Lord Corporation132DG MR is chosen. The characteristics of this MR fluid are listed in Table 4.1 and in Figures 4.1, 4.2 and 4.3. The MR fluid dampers are usually designed such that, in normal conditions, the MR fluid is magnetically saturated. It is under this condition that the fluid will generate its maximum yield stress τ_y .

Table 4.1: Rheological properties of MR fluid 132DG

Properties	Value/Limits	Properties	Value/Limits
Base Fluid	Synthetic Oil	Density	3.055 kg/m³
System	Open or Closed	Color	Dark gray
Operating Temperature	40÷150°C	Weight Percent Solids	80.74%
Viscosity [Pa·s] Shear Rate 10 s⁻¹ Shear Rate 80 s⁻¹	 0,94 Pa·s 0,33 Pa·s	Coefficient of Thermal Expansion 0 to 50°C 50 to 100°C 100 to 150°C	Unit Volume/°C 0.55×10⁻³ 0.61×10⁻³ 0.67×10⁻³
Settling (dependent on device design)	The fluid is developed to settle softly, will remix with a 2-3 cycles of the device	Thermal Conductivity @ 25°C	0,25÷1,06W/m·°C
Specific Heat @ 25°C	800 J/kg·°C	Flash Point	>150°C

(http://www.lordfulfillment.com/upload/DS7015.pdf)

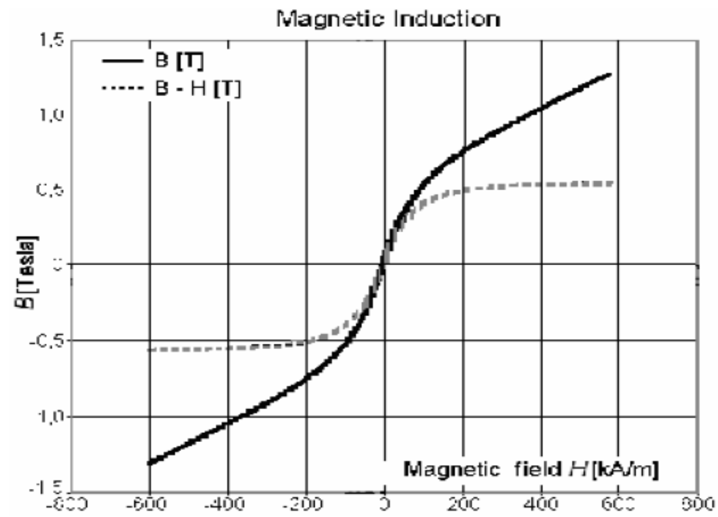

Figure 4.1 Magnetic flux versus magnetic field for MR fluid 132DG

(http://www.lordfulfillment.com/upload/DS7015.pdf)

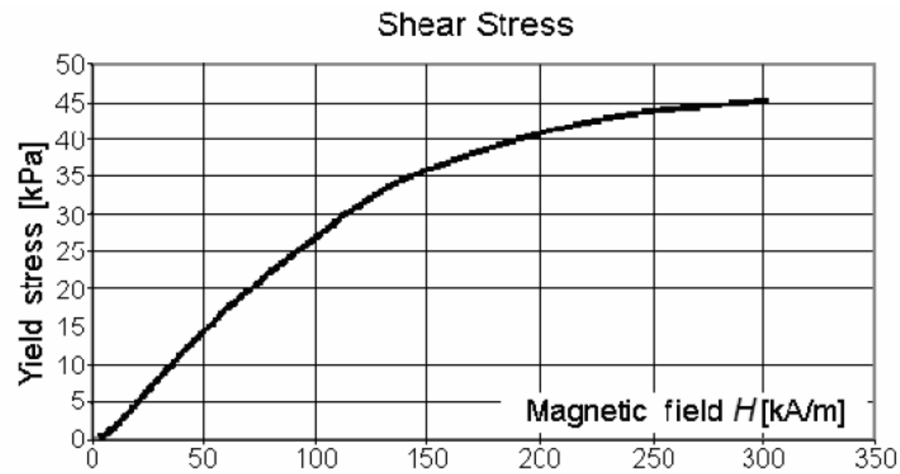

Figure 4.2 Yield stress versus magnetic field for MR fluid 132DG

(http://www.lordfulfillment.com/upload/DS7015.pdf)

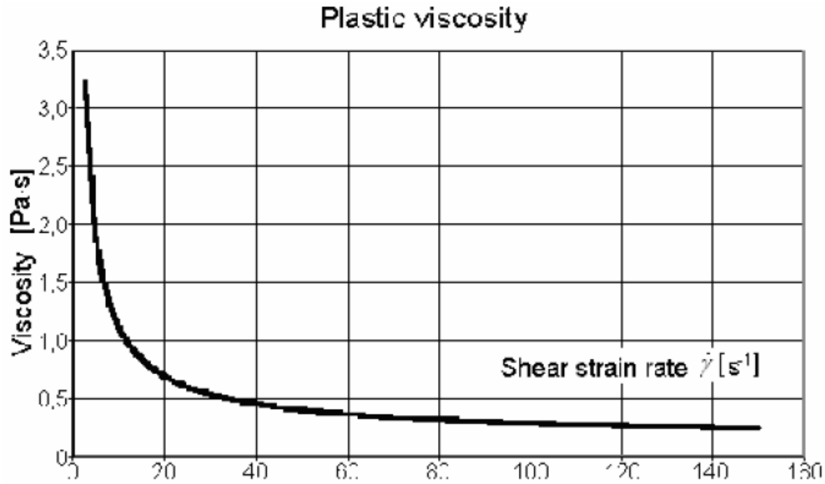

Figure 4.3 Viscosity versus shear strain rate for MR fluid 132DG

(http://www.lordfulfillment.com/upload/DS7015.pdf)

4.3 FUNDAMENTAL OF MR DAMPER

MR damper uses magneto rheological fluid, which is considered as a smart fluid. It has a lot of potentials to be explored in control-based application. The MR fluid that consists of micro or nano size iron particles in a carrier fluid, when subjected to magnetic field will change its viscosity into a semi-solid state. The behavior of MR fluid is manipulated by researchers and engineers to provide controllable damping resisting force.

The key design of MR damper is the design of the piston inside the damper. There are two types of piston that can be used; valve mode and direct shear mode and this design are using valve mode. In valve mode as shown in Figure 4.1, the flow of MR fluid will be restricted by the chain-like iron particles, which are subjected by the magnetic field between two fixed plates.

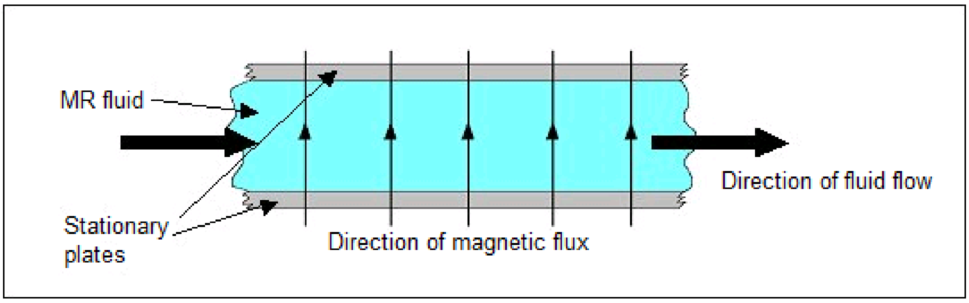

Figure 4.4 MR fluid in valve mode

The pressure drops that exist for this mode can be represented by (Guglielmino, 2008)

$$\Delta p = \Delta p_{\eta} + \Delta p_{\tau} \tag{4.2}$$

$$\Delta p_{\eta} = \frac{12\eta A_{R_m} v_p}{A_g h^2} L \tag{4.2a}$$

$$\Delta p_{\tau} = \frac{c}{h} \tau_y(H) L \tag{4.2b}$$

$$\Delta p = \frac{6v_p\left(A_p + \pi R_m h\right)}{\pi R_m h^3}\eta L + \frac{c}{h}\tau_y(H)L \tag{4.2c}$$

In equation (4.1), the pressure drop (ΔP) is assumed to be the sum of viscous component (ΔP_n)(4.1a) and a field dependant induced yield stress component (ΔP_τ)(4.1b) where represents the pressure driven MR fluid flow, η represents the plastic viscosity of MR fluid, τ_y represents field dependent yield stress of MR fluid, L represents the length of magnetic pole, h represent the fluid gap. The variable c ranges from a minimum value of 2 (for $\Delta P\tau / \Delta P\eta < 1$) to a maximum value of 3 (for $\Delta P\tau / \Delta P\eta > 100$). Ag represents is the cross-sectional area of the piston head and $v_p = v_o$ is the piston head velocity. A_p is the piston area, while A_{Rm} is gap average area which given by:

$$A_{R_m} = \pi R_m^2 \tag{4.3}$$

And gap average radius Rm represents by:

$$2\pi R_m h = A_g \tag{4.3a}$$

The equation of damping resistant force for this design mode is (Guglielmino, 2008):

$$F = F_\eta + F_\tau \tag{4.4}$$

$$F = \Delta p A_p = \Delta p_\eta A_p + \Delta p_\tau A_p \tag{4.4a}$$

Therefore ,

$$F_\eta = \frac{12\eta A_{R_m} v_p}{A_g h^2} A_p L \text{ and } F_\tau = \frac{c\tau_y(H) A_p}{h} L \tag{4.4b}$$

In general, equations (4.1) and (4.4) can be further manipulated to give the volume of activated MR fluid, V which can be represented by:

$$V = k\left(\frac{\eta}{\tau_y{}^2}\right)\lambda W_m \tag{4.5}$$

where λ is the desired control ratio and W_m is the mechanical power dissipation. The parameters in equation (4.5) for valve mode design can be calculated as

$$k = \frac{12}{c} \tag{4.6a}$$

$$\lambda = \frac{\Delta P_\tau}{\Delta P_\eta} \tag{4.6b}$$

$$W_m = Q\Delta P_\tau \tag{4.6c}$$

In terms of magnetic circuit design, the main purpose of designing the magnetic coil is to design a flux conduit that will guide and focus the magnetic flux into the region of active magnetic fluid, which is at the fluid gap. The magnetic circuit can be analyzed using a magnetic Kirchhoff Law and is given by:

$$\sum H\ l = Ni \tag{4.7}$$

where H is the magnetic field and l is the length of the wire. The number of coil turn is given by N and i am the amount of current supplied to the coil. The magnetic field has units of Amp. Turn/meter. The relation of the magnetic field and the magnetic strength (Tesla) is given by

$$B = \mu\mu_o H \tag{4.8}$$

where μ is relative permeability of the material and μ_0 is the free space permeability ($4\pi\times10^{-7}$ Tm/A). The magnetic flux density of the magnetic strength for the core, B_c and the wall B_w are found from the conservation of magnetic flux that exist in the fluid gap, Φ with B_g is the magnetic flux density at fluid gap.

$$\Phi = B_g A_g \tag{4.9a}$$

$$B_c = \frac{\Phi}{A_c} \tag{4.9b}$$

$$B_w = \frac{\Phi}{A_w} \tag{4.9c}$$

where A_g , A_c and A_w are the cross sectional areas of the fluid gap, the core, and the cylinder wall respectively. The flux density for each component needs to be computed in order to ensure that no part of the system will becomes magnetically saturated or causing a 'bottleneck' to the flux lines. The current required can be obtained from the magnetic circuit equation and is given by

$$i = \frac{1}{N}(H_g h + H_c l_c + H_w l_w) \quad (4.10)$$

where N is the number of turns, h is the fluid gap, l_c is the core length and l_w is the wall length.

4.4 THE DEVELOPMENT OF MR DAMPER MODEL

The development of MR damper model is based on the original equipment (OE) shock absorber used in the passenger vehicle. In this study, an original shock absorber from Proton Waja model has been chosen as the benchmark in developing the MR damper model in terms of geometrical design and performance. The parameters such as the shock absorbers inner tube diameter, inner tube length and the stroke length have been taken into consideration in the design. These parameters will become the constraints in designing MR damper by assuming that the MR damper will be used as a retrofitting damper in Proton Waja model. Table 4.1 shows the parameters of the original shock absorber that were considered in this model. The performance of the OE shock absorber was also investigated and taken as the benchmark in designing the MR damper.

The development and modeling of MR damper was done by considering the geometric design and magnetic circuit design. In order to assist the development of the MR damper, an excel spreadsheet such as in Figure 4.4 was developed.

The design was started by determining several parameters that are known or desired by the designer.

Table 4.1 Proton Waja's Original Shock Absorber Measurement

Particulars	Measurement
Stroke	150 mm (± 75 mm)
Piston rod length	350 mm
Extension stroke stopper (from end valve)	65 mm
Inner tube thickness	2 mm
Inner tube diameter	35 mm
Inner tube height	302 mm
Gap between inner tube and outer tube	5 mm

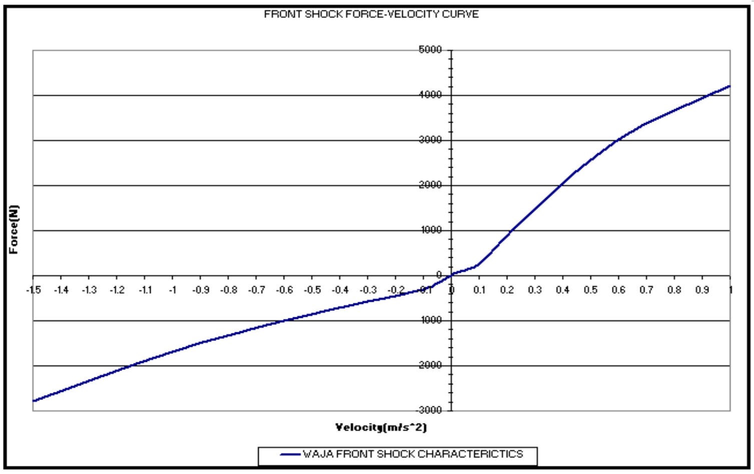

Figure 4.5 Force-velocity curve of original shock absorber for Proton Waja

In order to maintain good damper adjustability, not only should the aspect ratios be considered, but the electromagnet design should also be examined. The electromagnet circuit creates the magnetic field lines that are responsible for activating the MR fluid, so proper operation of this circuit is essential. The goal of the electromagnet design is to channel the field lines in a manner that makes them cross the fluid gap in a perpendicular fashion, as well as making sure that the fluid gap is the point of highest reluctance in the path of the field lines. Therefore, an efficient magnetic circuit must be designed to have no bottlenecks. In order to do so, the areas perpendicular to the field lines must be equal, namely the piston cross-sectional area (Ap), and the housing cross-sectional area (AC).

The Excel spread sheet shown in Table 4.3a, 4.3b and 4.3c has been used as an aid for the piston design and magnetic circuit while Figure 4.4 show the parameter of MR damper

Table 4.3a Data of various wire properties (Poynor, 2001)

Wire Gage	Wire Diameter (mm)	Total Turn	Length(m)	Resistance(Ohm)	Amperage(Amp)
25	0.455	2780	7.19	0.76	15.71
26	0.404	3526	8.1	1.09	11.01
27	0.361	4416	9.06	1.53	7.85
28	0.32	5619	10.23	2.19	5.48
29	0.287	6986	11.4	3.04	3.95
30	0.254	8919	12.88	4.38	2.74
31	0.226	11266	14.48	6.22	1.93
32	0.203	13964	16.12	8.57	1.4
33	0.18	17760	18.18	12.27	0.98
34	0.16	22478	20.45	17.53	0.68
35	0.142	28538	23.04	25	0.48

Table 4.3b Input parameter of MR damper

Input Parameter	Column2
Conduit Diameter (Dc)	1 mm
Bore Diameter (Db)	32 mm
Piston Minor Diameter	8.80mm
Coil Gap	0.5 mm
Coil Recess Length(L)	30 mm
Coil Connector Groove Width	1 mm
Coil Connector Groove Depth	1 mm
System Voltage (V)	12 V
Copper Wire Resistivity (rho)	%.64E-08 Ohm*ft

Table 4.3c Output parameter of MR damper

Output parameter	Column2
Piston Cross Sectional Area (Ap)	536.546 mm^2
Housing Cross Sectional Area (Ac)	106.814mm
Gap Area (Ag)	51.05 mm
Housing Outer Diameter (Dh)	35 mm
Piston Major Diameter (Dma)	32 mm
Piston Flange Width (W)	10mm

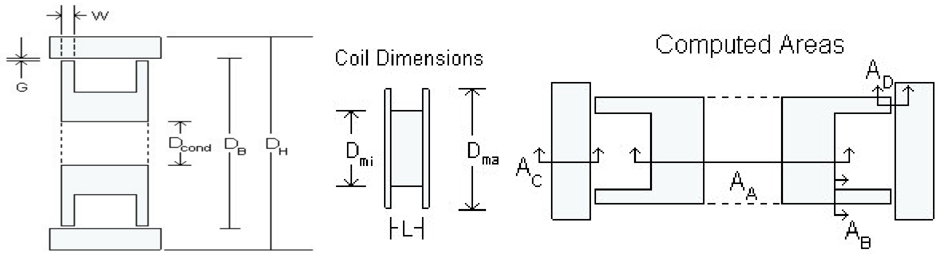

Figure 4.6 MR damper parameter design

(John W. Gravatt, 2003)

When designing a MR damper, usually a few of the design's dimensions are known or can be determined. Some of these dimensions include the wire conduit diameter *Dc*, the bore diameter D_b, the fluid gap *h*, the coil recess length *L*, and the coil, connector groove width and depth. The piston minor diameter, D_{mi}, must be solved for iteratively until a desired housing outer diameter or total piston length is determined. Choosing the wire size to use is dependent on multiple items: magnetic field required, power dissipation, and the feasibility of hand-winding the chosen number of turns. While the highest magnetic field possible is usually desirable (more adjustability), power dissipation and coil turns have a major effect on the size of the wire chosen

The most important aspect in designing the magnetic circuit is to focus on the region where the MR fluid will be activated. The activation region is the region where the highest reluctance exists. The efficiency of the generated reluctance depends on the fluid gap, *h* value chosen. The fluid gap, *h* should be minimized to give the highest reluctance effect when the MR damper is activated. However, it also needs to be compromised so that the damping force generated during the off-state condition is not too low. Also, to have an efficient magnetic circuit, the piston cross-sectional area, *A* the piston ring cross sectional area, *C* and the piston radial root area, *B* should be the same. This is to avoid 'bottleneck' of MR fluid flow during on-state condition.

To have good magnetic circuit, the number of turn and the amount of current that injected the damper must be have good combination. If the wire of diameter is too small then the number of turn will increase. These also cause high resistance in the circuit thus lower current flow through the coil which leads to low electromagnetic flux density. When the wire diameter is too big, it will decrease the number of the turn but increase the current output. That means much higher current needed to generate magnetic field. In this design, wire gage size 30 with 0.254 mm wire diameter are the best since its operated at 0 to 3 Ampere as operating current.

The overall performance of the designed MR damper should envelope the performance of OE shock absorber by making sure that the damping force during maximum supplied current are at least 150% more than the OE shock absorber performance during the on-state condition and at least 50% less than the OE shock absorber performance during off-state condition. The advantage from this general rule (Poynor, 2001) is, the MR damper will have the capability to provide any value of resisting force including the resisting force value from the OE shock absorber.

The characteristic was plotted for current that varies from 0 to 3 Ampere. It is very interesting to observe from this model that having a large amount of current supplied to the MR damper model does not necessarily promise a higher damping resisting force. There will be a time when the magnetic circuit will become fully saturated and any higher supplied current will only be a waste of power source. The plotted characteristic in Figure 4.5 also shows the current operating range which is very useful information needed when the MR damper is in a control system.

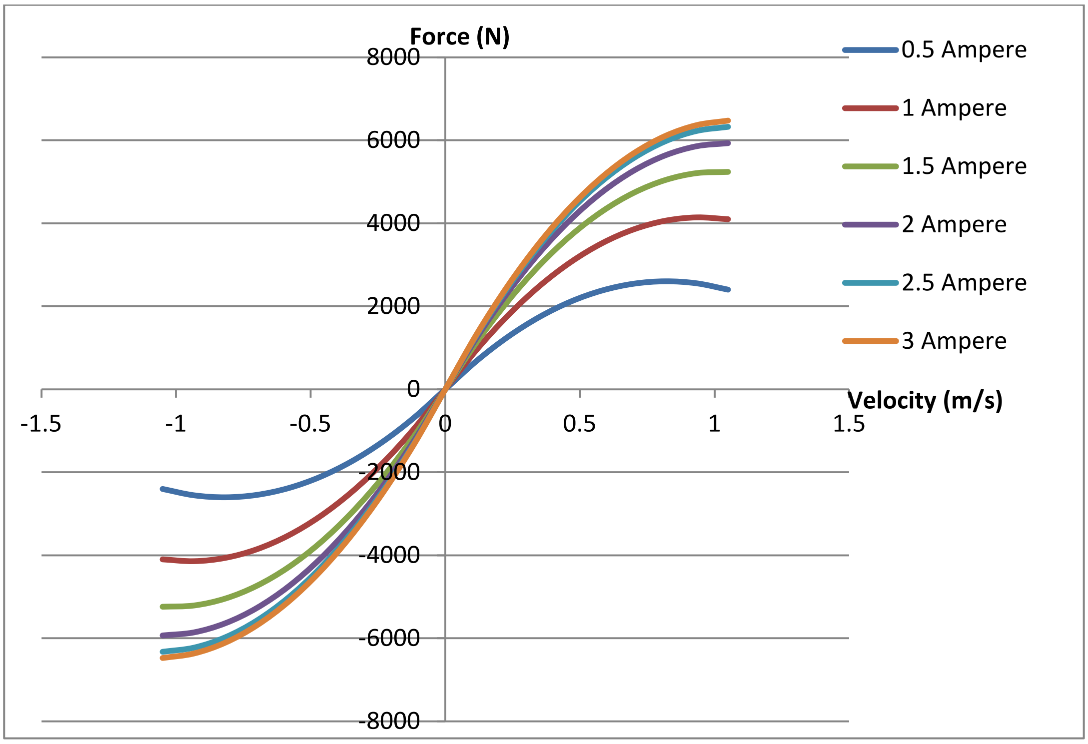

Figure 4.5 MR damper characteristic based on the designed parameters

4.5 A 3D MR DAMPER MODEL

There are three types of MR damper design usually in practice. There are monotube MR damper, twin tube MR damper and doubled ended MR damper. For the 3D model of the developed MR damper model, twin tube type has been chosen to be modeled using the parameters that were designed previously (refer Figure 4.4). The selection of this type of MR damper was made due to its compactness and can be installed in any orientation and fit with the OEM passive win tube damper. Figure 4.6 shows a 3D view of MR damper model based on the parameters stated previously in Figure 4.4.

It can be seen in Figure 4.6 that the 3D-MR damper model has 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 change that occurs when the piston rod enters the housing.

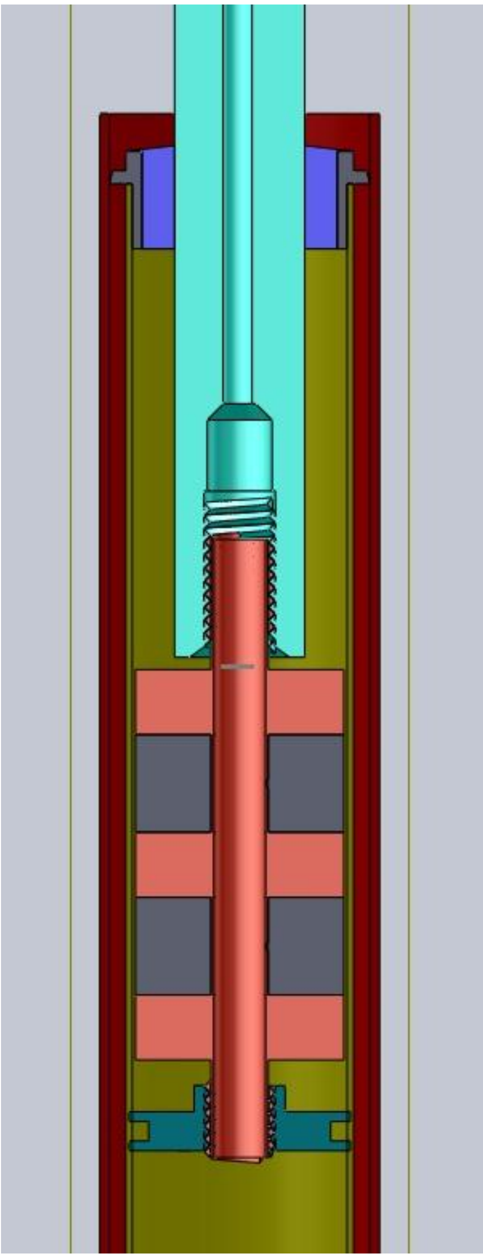

Figure 4.6 A 3D view of MR damper model

As for the piston design, a valve mode type was chosen as it can reduce the number of components inside the MR tube. Commonly, in conventional twin tube damper, a piston guide is installed at the end of the piston rod in order to guide the piston during its reciprocation motion. The valve mode type does not require this as the piston outer ring will guide the piston reciprocation motion while at the same time maintaining the piston's eccentricity with the damper's tube housing.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 CONCLUSION

The primary objective of this thesis was to design MR damper its geometry. By using the specification of Proton Waja passive damper, a MR damper has been developed. The goal of the use of MR dampers was to allow both comfort and performance with the same suspension package in OEM Proton Waja. After success developing the model, the second objective which require to calculating and determine the magnetic induction and magnetic field was been achieve. The work continue on last objective to analyze the MR parameter like number of turn, length and diameter of the wire, current induced, magnetic field generated, head piston velocity, and force produced by MR damper was be calculated and discussed. The work that has been done for this thesis involved research, modeling, and design. Testing and solid-modeling the OEM dampers provided a design envelope for the retrofit MR dampers.

The MR damper design proved to be an arduous task, as it required a very slim package with relatively high damping rates, as well as a new system for accumulator charging. MR damper designs were studied and modeled to provide size data and force versus velocity data to facilitate comparison of both OEM and MR dampers. Providing a background of magneto-rheological technologies and vehicle suspension history, this paper showed that MR dampers for Proton Waja would be a perfect application of the technology.

5.2 RECOMMENDATIONS

5.2.1 SUGGESTION

This research still has to carry forward to improve the accuracy of the result when using the correlation that being developed. During the analysis several factor not being considered in the scope and for the further work strongly recommended:

i. Parameter – need to consider more parameter other than just have two parameters which are magnetic field and current in order to get the precise value. The other parameter such as plastic viscosity and velocity also should be analyzed when generated the data.
ii. MR fluid – there are several brand and type of MR fluid in market. They vary according to their properties and maximum yield stress generate. Right choose of MR fluid will make a different in design.

5.2.2 PROBLEM OF THE RESEARCH

In this project, there are some problems that have been encounter from started until finish the research. So there are some suggestions to improvement this for the future research:

i. Lack of data – there a main problem with the data needed to develop the equation. It is because, many researchers just using correlation that been done by previous experiments.
ii. Other method – need to use another equation to develop the result because of not enough data.
iii. Lack of material and equipment – there are some lack of equipment such as no measuring device for testing the OEM suspension such as, braces and the damper itself.
iv. Time limitation – period of time is an important thing in ensured the research is complete with perfectly. So there should continued by the next final year student

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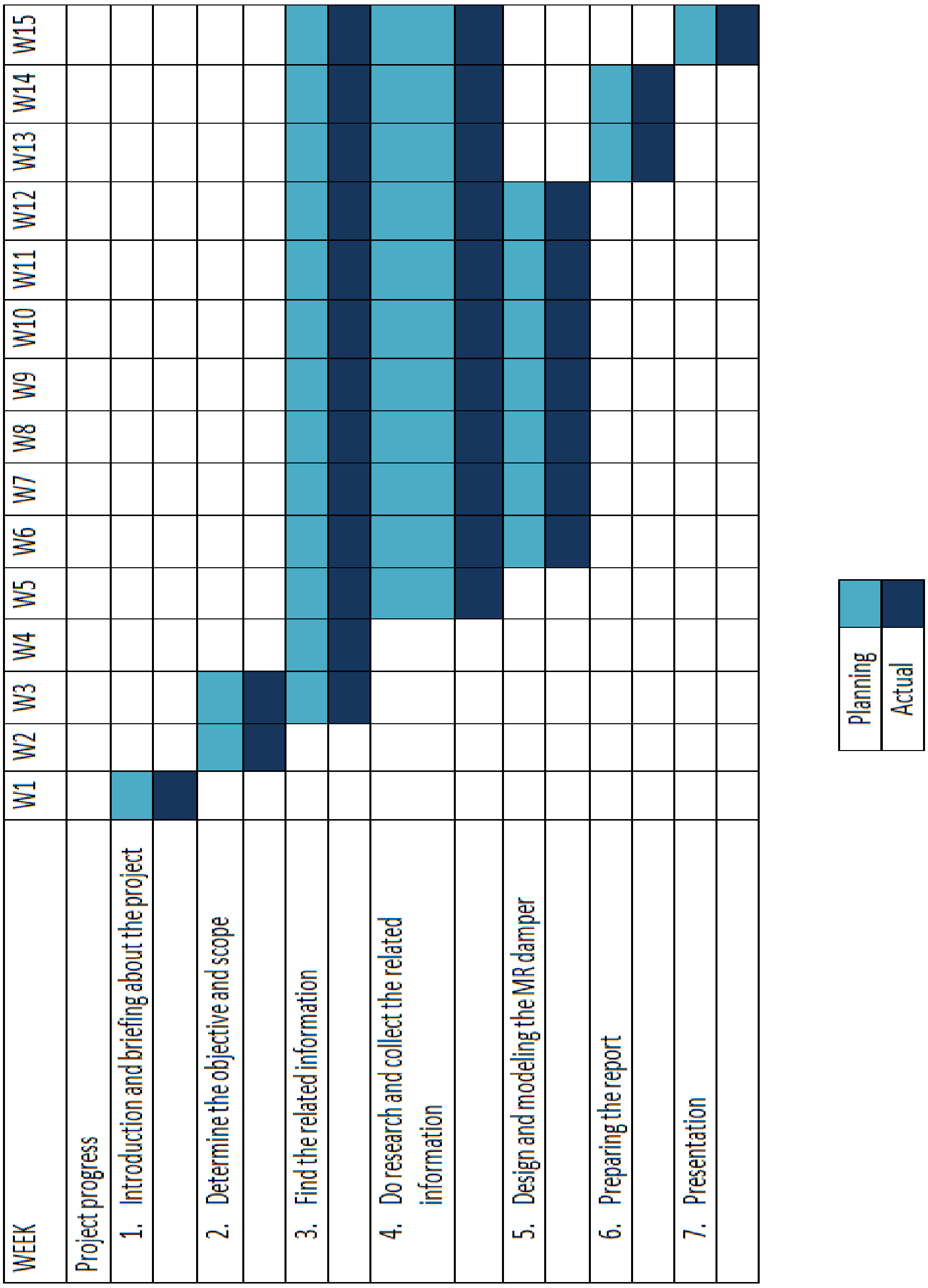
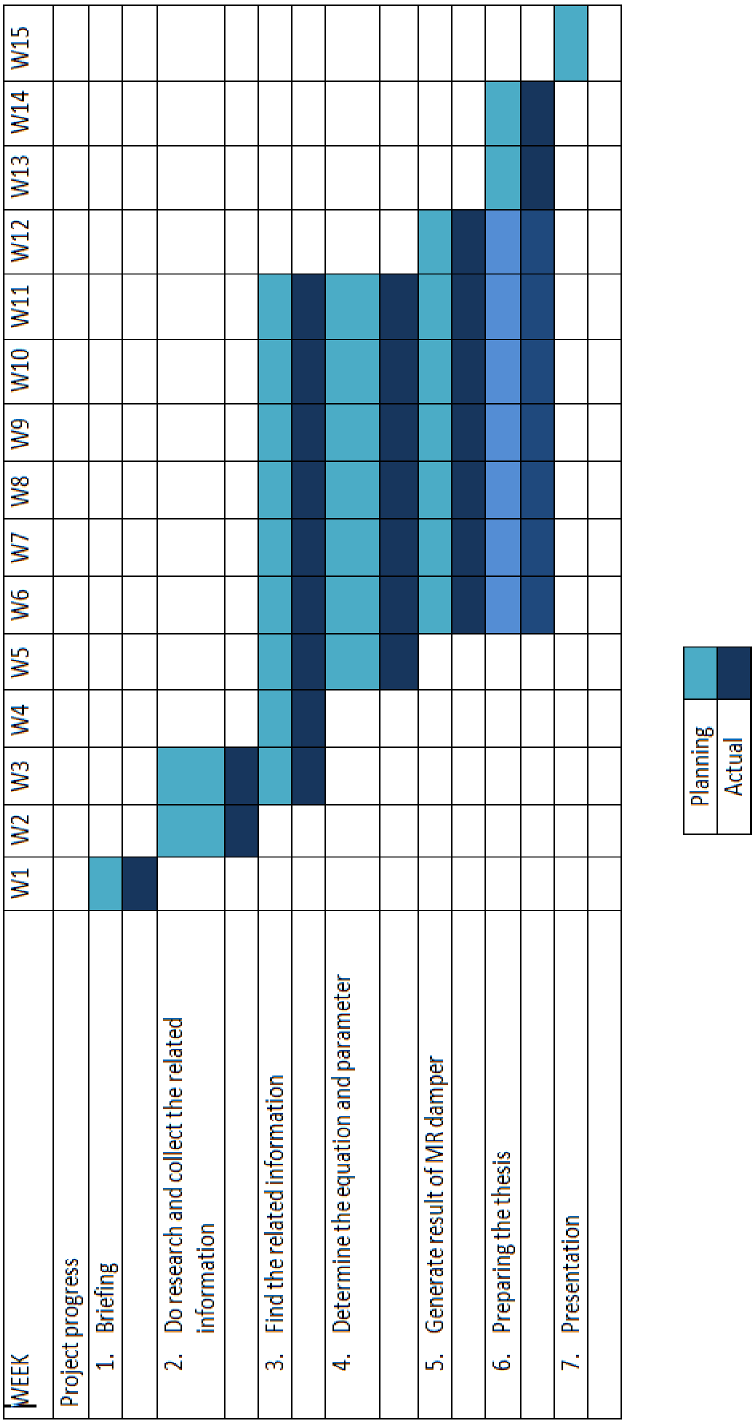
APPENDIX A1

FYP 1 GANTT CHART



APPENDIX A2

FYP 2 GANTT CHART



APPENDIX B

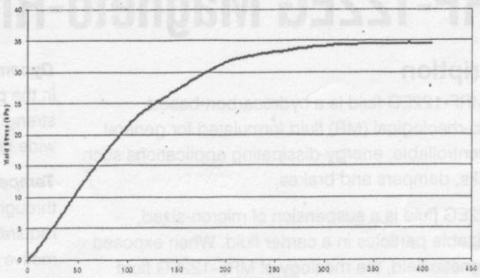
MR SHEET PROPERTIES

Cautionary Information

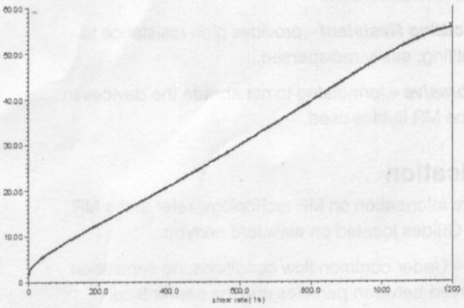
Before using this or any LORD product, refer to the Material Safety Data Sheet (MSDS) and label for safe use and handling instructions.

For industrial/commercial use only. Not to be used in household applications. Not for consumer use.

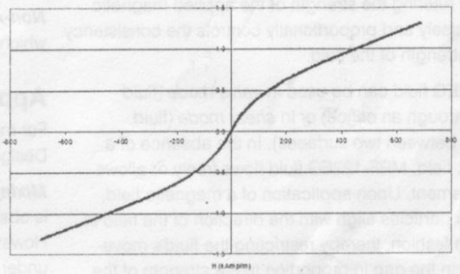
Yield Stress vs. Magnetic Field Strength



Shear Stress as a function of Shear Rate with no Magnetic Field applied at 40°C (104°F)



Typical Magnetic Properties



Values stated in this technical data sheet represent typical values as not all tests are run on each lot of material produced. For formalized product specifications for specific product end uses, contact the Customer Support Center.

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APPENDIX C1

EXCEL SHEET FOR DAMPING FORCE AT 0.5 AMPERE

Ty	Wm	Q	Vp	Pn	Pt	Fn	Ft	Ftotal	N	L	I	H		
-15000	80	-0.00012	-1.04994	-681107	-3799980	-365.074	-2036.79	-2401.86	1288	12.88	0.5	50		-2401.86
-13333.3	80	-6.6E-05	-0.93328	-1210858	-3555522	-649.02	-1905.76	-2554.78	1144.877	12.88	0.5	44.444		-2554.78
-11666.7	80	-5E-05	-0.81663	-1589262	-3266621	-851.845	-1750.91	-2602.75	1001.69	12.88	0.5	38.8855		-2602.75
-10000	80	-4.4E-05	-0.69997	-1815076	-2933280	-972.881	-1572.24	-2545.12	858.5937	12.88	0.5	33.3305		-2545.12
-8333.35	80	-4.2E-05	-0.5833	-1890603	-2555505	-1013.36	-1369.75	-2383.11	715.484	12.88	0.5	27.775		-2383.11
-6666.67	80	-4.4E-05	-0.46646	-1814224	-2133280	-972.424	-1143.44	-2115.86	572.3872	12.88	0.5	22.22		-2115.86
-5000	80	-5E-05	-0.34999	-1588052	-1666620	-851.196	-893.308	-1744.5	429.3162	12.88	0.5	16.666		-1744.5
-3333.33	80	-6.6E-05	-0.23326	-1209593	-1155520	-648.342	-619.359	-1267.7	286.2065	12.88	0.5	11.1105		-1267.7
-1666.67	80	-0.00012	-0.1166	-680212	-599800	-364.594	-321.493	-686.087	143.1097	12.88	0.5	5.5555		-686.087
0	0	0	0	0	0	0	0	0	0	12.88	0.5	0		0
1666.667	80	0.000118	0.1166	680212.5	599980	364.5939	321.5893	686.1832	143.0968	12.88	0.5	5.555		686.1823
3333.334	80	6.61E-05	0.23326	1209593	1155520	648.3418	619.3588	1267.701	286.2065	12.88	0.5	11.1105		1267.701
5000	80	5.04E-05	0.349986	1588052	1666620	851.1958	893.3083	1744.504	429.3162	12.88	0.5	16.666		1744.504
6666.667	80	4.41E-05	0.46646	1814224	2133280	972.4241	1143.438	2115.862	572.3872	12.88	0.5	22.22		2115.862
8333.335	80	4.23E-05	0.5833	1890603	2555501	1013.363	1369.748	2383.111	715.484	12.88	0.5	27.775		2383.111
10000	80	4.41E-05	0.699966	1815076	2933280	972.8807	1572.238	2545.119	858.5937	12.88	0.5	33.3305		2545.119
11666.67	80	5.03E-05	0.816626	1589262	3266620	851.8446	1750.909	2602.753	1001.69	12.88	0.5	38.8855		2602.753
13333.34	80	6.61E-05	0.93328	1210858	3555520	649.0197	1905.759	2554.779	1144.877	12.88	0.5	44.444		2554.779
15000	80	0.000117	1.04994	681107.5	3799981	365.0736	2036.79	2401.863	1288	12.88	0.5	50		2401.863

APPENDIX C2

EXCEL SHEET FOR DAMPING FORCE AT 1.0 AMPERE

Ty	Wm	Q	Vp	Pn	Pt	Fn	Ft	Ftotal	N	L	I	H		
-27500	80	-0.00012	-1.04994	-681107	-6966630	-365.074	-3734.11	-4099.19	1288	12.88	1	100		-4099.19
-24444.4	80	-6.6E-05	-0.93328	-1210858	-6518444	-649.02	-3493.89	-4142.91	1159.2	12.88	1	90		-4142.91
-21388.9	80	-5E-05	-0.81663	-1589262	-5988795	-851.845	-3209.99	-4061.84	1030.4	12.88	1	80		-4061.84
-18333.3	80	-4.4E-05	-0.69997	-1815076	-5377673	-972.881	-2882.43	-3855.31	901.6	12.88	1	70		-3855.31
-15277.8	80	-4.2E-05	-0.5833	-1890603	-4685078	-1013.36	-2511.2	-3524.56	772.8	12.88	1	60		-3524.56
-12222.2	80	-4.4E-05	-0.46646	-1814224	-3911009	-972.424	-2096.3	-3068.73	644	12.88	1	50		-3068.73
-9166.66	80	-5E-05	-0.34999	-1588052	-3055466	-851.196	-1637.73	-2488.93	515.2	12.88	1	40		-2488.93
-6111.11	80	-6.6E-05	-0.23326	-1209593	-2118451	-648.342	-1135.49	-1783.83	386.4	12.88	1	30		-1783.83
-3055.56	80	-0.00012	-0.1166	-680212	-1099633	-364.594	-589.403	-953.997	257.6	12.88	1	20		-953.997
0	0	0	0	0	0	0	0	0	0	12.88	0	0		0
3055.555	80	0.000118	0.1166	680212.5	1099963	364.5939	589.5802	954.1741	257.6	12.88	1	20		954.1741
6111.105	80	6.61E-05	0.23326	1209593	2118451	648.3418	1135.49	1783.832	386.4	12.88	1	30		1783.832
9166.655	80	5.04E-05	0.349986	1588052	3055466	851.1958	1637.73	2488.926	515.2	12.88	1	40		2488.926
12222.21	80	4.41E-05	0.46646	1814224	3911008	972.4241	2096.3	3068.724	644	12.88	1	50		3068.724
15277.76	80	4.23E-05	0.5833	1890603	4685076	1013.363	2511.201	3524.564	772.8	12.88	1	60		3524.564
18333.31	80	4.41E-05	0.699966	1815076	5377672	972.8807	2882.432	3855.313	901.6	12.88	1	70		3855.313
21388.86	80	5.03E-05	0.816626	1589262	5988794	851.8446	3209.994	4061.838	1030.4	12.88	1	80		4061.838
24444.41	80	6.61E-05	0.93328	1210858	6518443	649.0197	3493.885	4142.905	1159.2	12.88	1	90		4142.905
27500	80	0.000117	1.04994	681107.5	6966630	365.0736	3734.114	4099.187	1288	12.88	1	100		4099.187

APPENDIX C3

EXCEL SHEET FOR DAMPING FORCE AT 1.5 AMPERE

Ty	Wm	Q	Vp	Pn	Pt	Fn	Ft	Ftotal	N	L	I	H		
-35900	80	-0.00012	-1.04994	-681107	-9094619	-365.074	-4874.72	-5239.79	1288	12.88	1.5	150		-5239.79
-31911.1	80	-6.6E-05	-0.93328	-1210858	-8509542	-649.02	-4561.11	-5210.13	1144.884	12.88	1.5	133.3328		-5210.13
-27922.2	80	-5E-05	-0.81663	-1589262	-7818110	-851.845	-4190.51	-5042.35	1001.721	12.88	1.5	116.66		-5042.35
-23933.3	80	-4.4E-05	-0.69997	-1815076	-7020316	-972.881	-3762.89	-4735.77	858.6581	12.88	1.5	99.999		-4735.77
-19944.4	80	-4.2E-05	-0.5833	-1890603	-6116162	-1013.36	-3278.26	-4291.63	715.5527	12.88	1.5	83.333		-4291.63
-15955.6	80	-4.4E-05	-0.46646	-1814224	-5105648	-972.424	-2736.63	-3709.05	572.4387	12.88	1.5	66.666		-3709.05
-11966.7	80	-5E-05	-0.34999	-1588052	-3988775	-851.196	-2137.98	-2989.18	429.3247	12.88	1.5	49.999		-2989.18
-7977.79	80	-6.6E-05	-0.23326	-1209593	-2765549	-648.342	-1482.33	-2130.68	286.2194	12.88	1.5	33.333		-2130.68
-3988.89	80	-0.00012	-0.1166	-680212	-1435521	-364.594	-769.439	-1134.03	143.1054	12.88	1.5	16.666		-1134.03
0	0	0	0	0	0	0	0	0	0	12.88	0	0		0
3988.888	80	0.000118	0.1166	680212.5	1435952	364.5939	769.6702	1134.264	143.1054	12.88	1.5	16.666		1134.264
7977.777	80	6.61E-05	0.23326	1209593	2765544	648.3418	1482.332	2130.673	286.2194	12.88	1.5	33.333		2130.673
11966.66	80	5.04E-05	0.349986	1588052	3988777	851.1958	2137.984	2989.18	429.3247	12.88	1.5	49.999		2989.18
15955.55	80	4.41E-05	0.46646	1814224	5105649	972.4241	2736.628	3709.052	572.4387	12.88	1.5	66.666		3709.052
19944.44	80	4.23E-05	0.5833	1890603	6116162	1013.363	3278.263	4291.626	715.5527	12.88	1.5	83.333		4291.626
23933.33	80	4.41E-05	0.699966	1815076	7020315	972.8807	3762.889	4735.77	858.6581	12.88	1.5	99.999		4735.77
27922.22	80	5.03E-05	0.816626	1589262	7818109	851.8446	4190.506	5042.351	1001.772	12.88	1.5	116.666		5042.351
31911.1	80	6.61E-05	0.93328	1210858	8509543	649.0197	4561.115	5210.135	1144.884	12.88	1.5	133.3328		5210.135
35900	80	0.000117	1.04994	681107.5	9094619	365.0736	4874.716	5239.789	1287.991	12.88	1.5	149.999		5239.789

APPENDIX C4

EXCEL SHEET FOR DAMPING FORCE AT 2.0 AMPERE

Ty	Wm	Q	Vp	Pn	Pt	Fn	Ft	Ftotal	N	L	I	H		
-41000	80	-0.00012	-1.04994	-681107	-10386612	-365.074	-5567.22	-5932.3	1288	12.88	2	200		-5932.3
-36444.4	80	-6.6E-05	-0.93328	-1210858	-9718420	-649.02	-5209.07	-5858.09	858.667	12.88	2	133.3334		-5858.09
-31888.9	80	-5E-05	-0.81663	-1589262	-8928762	-851.845	-4785.82	-5637.66	644	12.88	2	100		-5637.66
-27333.3	80	-4.4E-05	-0.69997	-1815076	-8017631	-972.881	-4297.45	-5270.33	515.2	12.88	2	80		-5270.33
-22777.8	80	-4.2E-05	-0.5833	-1890603	-6985034	-1013.36	-3743.98	-4757.34	364.933	12.88	2	56.66661		-4757.34
-18222.2	80	-4.4E-05	-0.46646	-1814224	-5830965	-972.424	-3125.4	-4097.82	322	12.88	2	50		-4097.82
-13666.7	80	-5E-05	-0.34999	-1588052	-4555429	-851.196	-2441.71	-3292.91	257.6	12.88	2	40		-3292.91
-9111.11	80	-6.6E-05	-0.23326	-1209593	-3158421	-648.342	-1692.91	-2341.26	171.7333	12.88	2	26.66666		-2341.26
-4555.56	80	-0.00012	-0.1166	-680212	-1639453	-364.594	-878.747	-1243.34	107.3333	12.88	2	16.66666		-1243.34
0	0	0	0	0	0	0	0	0	0	12.88	0	0		0
4555.555	80	0.000118	0.1166	680212.5	1639945	364.5939	879.0106	1243.604	107.333	12.88	2	16.66661		1243.604
9111.11	80	6.61E-05	0.23326	1209593	3158421	648.3418	1692.914	2341.255	171.7333	12.88	2	26.66666		2341.255
13666.67	80	5.04E-05	0.349986	1588052	4555428	851.1958	2441.709	3292.905	257.6	12.88	2	40		3292.905
18222.22	80	4.41E-05	0.46646	1814224	5830965	972.4241	3125.397	4097.821	322	12.88	2	50		4097.821
22777.78	80	4.23E-05	0.5833	1890603	6985032	1013.363	3743.977	4757.341	364.9333	12.88	2	56.66666		4757.341
27333.33	80	4.41E-05	0.699966	1815076	8017631	972.8807	4297.45	5270.331	515.2	12.88	2	80		5270.331
31888.89	80	5.03E-05	0.816626	1589262	8928760	851.8446	4785.815	5637.66	644	12.88	2	100		5637.66
36444.44	80	6.61E-05	0.93328	1210858	9718420	649.0197	5209.073	5858.093	858.667	12.88	2	133.3334		5858.093
41000	80	0.000117	1.04994	681107.5	10386612	365.0736	5567.224	5932.298	1288	12.88	2	200		5932.298

APPENDIX C5

EXCEL SHEET FOR DAMPING FORCE AT 2.5 AMPERE

Ty	Wm	Q	Vp	Pn	Pt	Fn	Ft	Ftotal	N	L	I	H		
-43900	80	-0.00012	-1.04994	-681107	-1.1E+07	-365.074	-5961	-6326.08	2146.667	12.88	1.5	250		-6326.08
-39022.2	80	-6.6E-05	-0.93328	-1210858	-1E+07	-649.02	-5577.52	-6226.54	1908.148	12.88	1.5	222.2222		-6226.54
-34144.4	80	-5E-05	-0.81663	-1589262	-9560307	-851.845	-5124.32	-5976.17	1669.629	12.88	1.5	194.4444		-5976.17
-29266.7	80	-4.4E-05	-0.69997	-1815076	-8584731	-972.881	-4601.42	-5574.3	1431.105	12.88	1.5	166.666		-5574.3
-24388.9	80	-4.2E-05	-0.5833	-1890603	-7479097	-1013.36	-4008.8	-5022.16	1192.59	12.88	1.5	138.8886		-5022.16
-19511.1	80	-4.4E-05	-0.46646	-1814224	-6243399	-972.424	-3346.46	-4318.89	572.4444	12.88	2.5	111.1111		-4318.89
-14633.3	80	-5E-05	-0.34999	-1588052	-4877641	-851.196	-2614.42	-3465.61	429.3325	12.88	2.5	83.33318		-3465.61
-9755.56	80	-6.6E-05	-0.23326	-1209593	-3381822	-648.342	-1812.66	-2461	286.2214	12.88	2.5	55.5554		-2461
-4877.78	80	-0.00012	-0.1166	-680212	-1755415	-364.594	-940.902	-1305.5	143.1107	12.88	2.5	27.7777		-1305.5
0	0	0	0	0	0	0	0	0	0	12.88	0	0		0
4877.778	80	0.000118	0.1166	680212.5	1755941	364.5939	941.1846	1305.779	143.1107	12.88	2.5	27.7777		1305.779
9755.555	80	6.61E-05	0.23326	1209593	3381822	648.3418	1812.656	2460.998	286.2214	12.88	2.5	55.5554		2460.998
14633.33	80	5.04E-05	0.349986	1588052	4877640	851.1958	2614.415	3465.611	429.3325	12.88	2.5	83.33318		3465.611
19511.11	80	4.41E-05	0.46646	1814224	6243399	972.4241	3346.462	4318.886	572.4443	12.88	2.5	111.1111		4318.886
24388.89	80	4.23E-05	0.5833	1890603	7479096	1013.363	4008.796	5022.159	715.554	12.88	2.5	138.8886		5022.159
29266.66	80	4.41E-05	0.699966	1815076	8584731	972.8807	4601.416	5574.297	858.6632	12.88	2.5	166.666		5574.297
34144.44	80	5.03E-05	0.816626	1589262	9560308	851.8446	5124.325	5976.17	1001.778	12.88	2.5	194.4444		5976.17
39022.22	80	6.61E-05	0.93328	1210858	10405822	649.0197	5577.52	6226.54	1144.889	12.88	2.5	222.2222		6226.54
43900	80	0.000117	1.04994	681107.5	11121275	365.0736	5961.003	6326.077	1288	12.88	2.5	250		6326.077

APPENDIX C6

EXCEL SHEET FOR DAMPING FORCE AT 3.0 AMPERE

Ty	Wm	Q	Vp	Pn	Pt	Fn	Ft	Ftotal	N	L	I	H
-45000	80	-0.00011746	-1.04994	-681107.4515	-1.1E+07	-365.074	-6110.37	-6475.44	1288	12.88	3	300
-40000	80	-6.6069E-05	-0.93328	-1210857.692	-1.1E+07	-649.02	-5717.28	-6366.3	858.6667	12.88	3	200
-35000	80	-5.0338E-05	-0.81663	-1589262.397	-9799860	-851.845	-5252.72	-6104.57	644	12.88	3	150
-30000	80	-4.4075E-05	-0.69997	-1815075.98	-8799840	-972.881	-4716.71	-5689.59	515.2	12.88	3	120
-25000	80	-4.2315E-05	-0.5833	-1890602.792	-7666500	-1013.36	-4109.24	-5122.61	364.9333	12.88	3	85
-20000	80	-4.4096E-05	-0.46646	-1814224.104	-6399840	-972.424	-3430.31	-4402.74	322	12.88	3	75
-15000	80	-5.0376E-05	-0.34999	-1588051.829	-4999860	-851.196	-2679.92	-3531.12	257.6	12.88	3	60
-10000	80	-6.6138E-05	-0.23326	-1209592.91	-3466560	-648.342	-1858.08	-2506.42	171.7333	12.88	3	40
-5000	80	-0.00011761	-0.1166	-680212.4875	-1799400	-364.594	-964.478	-1329.07	107.3333	12.88	3	25
0	0	0	0	0	0	0	0	0	0	12.88	0	0
5000	80	0.00011761	0.1166	680212.4875	1799940	364.5939	964.7678	1329.362	107.3333	12.88	3	25
10000	80	6.6138E-05	0.23326	1209592.91	3466560	648.3418	1858.076	2506.418	171.7333	12.88	3	40
15000	80	5.03762E-05	0.349986	1588051.829	4999860	851.1958	2679.925	3531.121	257.6	12.88	3	60
20000	80	4.4096E-05	0.46646	1814224.104	6399840	972.4241	3430.314	4402.738	322	12.88	3	75
25000	80	4.23145E-05	0.5833	1890602.792	7666500	1013.363	4109.244	5122.607	364.9333	12.88	3	85
30000	80	4.40753E-05	0.699966	1815075.98	8799840	972.8807	4716.714	5689.595	515.2	12.88	3	120
35000	80	5.03378E-05	0.816626	1589262.397	9799860	851.8446	5252.725	6104.57	644	12.88	3	150
40000	80	6.60689E-05	0.93328	1210857.692	10666560	649.0197	5717.276	6366.296	858.6667	12.88	3	200
45000	80	0.000117456	1.04994	681107.4515	11399940	365.0736	6110.368	6475.441	1288	12.88	3	300