MODELLING AND SIMULATION OF SKYHOOK CONTROLLER FOR SEMI-ACTIVE SUSPENSION SYSTEM

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MODELLING AND SIMULATION OF SKYHOOK CONTROLLER FOR SEMI-ACTIVE SUSPENSION SYSTEM

SAIFUL AMIN BIN KAMARUDDIN

Report submitted in partial fulfillment 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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FEBRUARY 2012

UNIVERSITI MALAYSIA PAHANG

FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "Modelling and Simulation of Skyhook Controller for Semi-Active Suspension System" is written by SAIFULAMIN BIN KAMARUDDIN. 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 declare that this thesis entitled Modeling and Simulation of Modified Skyhook Control for Semi-Active Suspension is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

The purpose of this project is to modeling and simulates the skyhook controller for semi-active suspension system for a quarter car model. There are two parts to be developed in this study namely, the hydraulic model and force tracking controller. The simulation of this system will be determined by performing computer simulations using the MATLAB and SIMULINK toolbox. The data for each parameter were obtained from the research that have done previously. The simulation results show that the semi-active suspension system could provide significant improvements in the ride quality and road handling compare with the passive suspension system.

ABSTRAK

Tujuan dari projek ini adalah untuk pemodelan dan simulasi pengatur skyhook yang diubahsuai untuk sistem suspensi aktif untuk model suku kereta. Ada dua bahagian untuk dikembangkan dalam kajian ini iaitu, model hidraulik dan pengatur penjejak paksaan. Simulasi sistem ini akan ditentukan dengan melakukan simulasi komputer dengan menggunakan MATLAB dan aturcara SIMULINK. Data untuk setiap parameter yang diperolehi dari kajian yang telah dilakukan dahulu. Keputusan simulasi menunjukkan bahawa sistem suspensi aktif dapat memberikan penambahbaikan yang signifikan dalam kualiti pemanduan dan pengendalian jalan berbanding dengan sistem suspensi pasif.

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ABBREVIATIONS

2DOF	Two degree of freedom
MR	Magneto-rheological
$\boldsymbol{C_{SKY}}$	Skyhook controller

CHAPTER 1

INTRODUCTION

1.1 Project background.

Suspension on the vehicle is a component equipment not only functions as a shock absorber of vibrations resulting from the burden of the vehicle and the wheel contact with the road surface, but also as a driving stability control made on a straight road driving, while taking turns, and driving on the road surface not smooth.

Nowadays many suspension manufacturers made their design from result of studies on the existing suspension and improvement have been made to the ability of suspension for passenger comfort in vehicles. Returning to the original purpose of the installation of suspension in a vehicle is to give comfortable to the passengers. When the vehicle is being driven wheel rotating in contact with the road surface and this depends on the type of surface. This phenomenon will result in vibration in direct proportion to the surface and the weight of the burden. Vibration is then absorbed by the suspension system consisting of a spring and damper. Spring will be oscillates when received vibrations from damper produced. Spring will return to the initial position so that oscillation will be smaller and smaller. In other words the resulting vibrations will be felt, but the amount is less than the actual vibration.

Various types of shock absorbers are sold in the market depend on the type of use such as Tanabe, Apex, HKS and many more. It's also equipped with a variable adjustment is made of alloys. It not only became one of the basic components of a vehicle but had to be madness on the user to modify their suspension systems for ride comfort.

Three types of suspensions that will be reviewed here are passive, fully active, and semi-active suspensions. A conventional passive suspension is composed of a spring and a damper. The suspension stores energy in the spring and dissipates energy through the damper. Both components are fixed at the design stage. For this reason, this type of suspension falls victim to the classic suspension compromise.

If the damper is replaced with a force actuator, the suspension becomes a fully active suspension. Hindered by its complexity and its power Consumption, fully active suspensions have yet to be accepted for conventional use. The idea behind fully active suspensions is that the force actuator is able to apply a force to the suspension in either jounce or Rebound. This force is actively governed by the control scheme employed in the suspension. Several different control schemes will be discussed later.

The third and final type of suspension that will be mentioned here is a semi-active suspension. In a semi-active suspension, the passive damper is replaced with a semi-active damper. A semi-active damper is capable of changing its tangent characteristics. Whether through mechanically changing orifices or fluid with adjustable viscosity a semi-active damper offers greater variation in close proximity. Again, the control algorithm used in the design governs the amount of damping

1.2 Problem Statement.

Vehicle suspension absorbs vibrations generated when the wheel in contact with the road surface is different and it gives effect to the vehicle passenger comfort. Control and vibration effects produced depend on the weight of the vehicle load and road surface if the amount of vibration generated can be controlled and reduced then this would increase passenger comfort.

1.3 Objective of the Research.

In this research focus on reduces of the vibration produced by road profile to the suspension and control the impact.

The objectives are:

1. To develop a two degree of freedom (2 DOF) quarter model passive suspension system diagram using Simulink software.
2. To develop Magneto-Rheological (MR) damper model using Bing-Ham method.
3. To develop skyhook controller to semi-active quarter car suspension with Magneto-Rheological (MR) damper using Simulink software.

1.4 Scope of Work.

Scopes of this project are:

1. Modelling 2DOF quarter car model for passive suspension system diagram using Simulink software.
2. Modelling Bingham method with MR damper diagram using Simulink software.
3. Modelling Skyhook controller for Bingham method with MR damper diagram using Simulink software.
4. Connect the entire diagram then run the simulation and compare the result between passive suspension system and semi-active suspension system using Bingham method.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction.

In this chapter will discuss on the suspension system including the types of suspension system. First of the system is passive, then the second one is semi-active suspension this kind of suspension is more cheep then the passive. The third system is active suspension system. Description of the MR damper and the Skyhook controller are also described in this chapter.

2.2 Overview of Vehicle Suspension system

The suspension system also includes shock and/or struts, and sway bars. Back in the earliest days of automobile development, when most of the car's weight (including the engine) was on the rear axle, steering was a simple matter of turning a tiller that pivoted the entire front axle. When the engine was moved to the front of the car, complex steering systems had to evolve. The modern automobile has come a long way since the days when "being self-propelled" been enough to satisfy the car owner. Improvements in suspension and steering, increased strength and durability of components, and advances in tire design and construction have made large contributions to riding comfort and to safe driving.

The suspension system has two basic functions, to keep the car's wheels in firm contact with the road and to provide a comfortable ride for the passengers. A lot of the system's work is done by the springs. Under normal conditions, the springs support the body of the car evenly by compressing and rebounding with every up-and-down movement. This up-and-down movement, however, causes bouncing and swaying after each bump and is very uncomfortable to the passenger. These undesirable effects are reduced by the shock absorbers.

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 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. 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.

2.3 Types of Suspension System

In generally suspension system can be dividing on two, passive and active system. The active suspension can be future classified into two types: a semi-active system and a fully active system according to the control input generation mechanism (Appleyard and Wellstead, 1995). The semi-active suspension system uses a varying damping force as a control force. For example, a hydraulic semi-active damper varies the size of an orifice in the hydraulic flow valve to generate desired damping force.

2.3.1 Passive Suspension System

The mass-spring-damper parameters are generally fixed, and they are chosen based on the design requirements of the vehicles. The suspension has ability to store energy in the spring and dissipate it through the damper. When springs support a load, it will compress until the force produced by the compression is equal to that of the load on it. If some other force then disturbs the load, then the load will oscillate up and down around its original position for some time.

Conventional or passive suspension systems are designed as a compromise between ride comfort and handling performance (Thompson, 1971). Ride is primarily associated with the ability of a suspension system to accommodate vertical inputs. Handling and attitude control relate more to horizontal forces acting through the centre of gravity and ground-level moments acting through the wheels. A low bounce frequency for maximum ride comfort normally leads to a low pitch frequency.

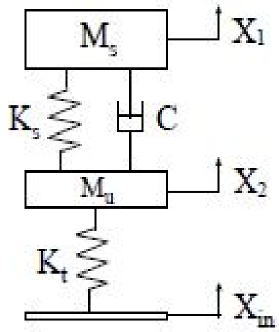


Figure 2.1: Passive Suspensionn system

Source: Cristoper A.P (1998)

2.3.2 Semi-Active Suspension System

Semi-active or adaptive systems are terms usually used to describe suspension systems that have some form of intelligence in the suspension dampers. Typically the damping curves can be altered such that the wheel control over the range of inputs is maximized. These systems also require fast-acting devices and complex control algorithms. A semi active suspension has the ability to change the damping characteristics of the shock absorbers without any use actuators. Previously, for semi-active suspension, by utilizing the controlled dampers under closed loop the regulating of the damping force can be achieved (Williams, 1994).

Semi-active suspension system using solenoid is the most economic and basic type of semi-active suspensions. They consist of a solenoid valve which alters the flow of the hydraulic medium inside the shock absorber, therefore changing the dampening characteristics of the suspension setup. The solenoids are wired to the controlling computer, which sends them commands depending on the control algorithm. This type usually called "Sky-Hook" technique.

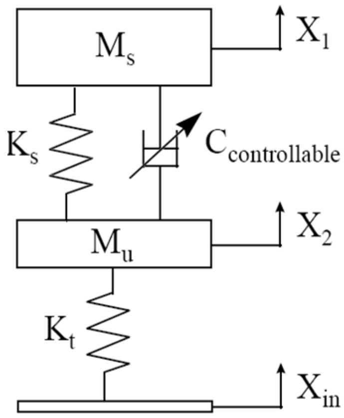


Figure 2.2: Semi-Active Suspension System
Source: Cristoper A.P (1998)

2.3.3 Active Suspension System

Active suspension system is one in which the passive components are augmented by hydraulic actuators that supply additional force. Theoretically this means that the compromise in conventional suspension systems can be eliminated. The active suspension is characterized by the hydraulic actuator that placed parallel to the damper and spring. It also can control both wheel hop motion as well as body motion. It can improve the ride comfort and ride handling simultaneously. (Sam, 2006).

The drawbacks of this design 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. Active suspension systems, however, usually involve a continuous power requirement, fast-acting devices, complex control algorithms, and closed-loop control systems. The cost of these systems has limited their application on mass-produced vehicles.

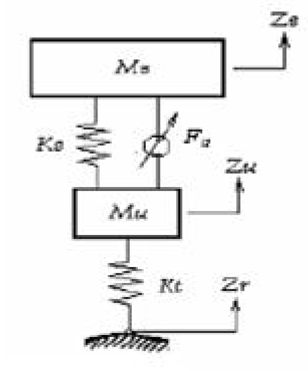


Figure 2.3: Active Suspension System
(Sam, Y.M and Huda, K. (2006))

2.4 Magneto-Rheological (MR) Damper

A magneto-rheological damper or magneto-rheological shock absorber is a damper filled with magneto-rheological fluid, which is controlled by a magnetic field, usually using an electromagnet. This allows the damping characteristics of the shock absorber to be continuously controlled by varying the power of the electromagnet. This type of shock absorber has several applications, most notably in semi-active vehicle suspensions which may adapt to road conditions, as they are monitored through sensors in the vehicle, and in prosthetic limbs.

MR dampers are much like conventional fluid dampers in basic construction, but the conventional damper valves are replaced with an electromagnetic coil to control the MR fluid behaviour.

Linear MR dampers can be of three primary designs: monotube, twintube, ordouble-ended (also known as through-tube). The three design types reflect methods of adjusting the fluid volume to account for the volume of the damper shaft. Monotube designs are the most common damper design; they exhibit simplicity and compactness of design and with the ability to be mounted in any orientation.

The monotube damper is composed of a main damper housing, a piston and piston rod assembly, and an accumulator, as shown in Figure. The main reservoir contains the piston and piston rod assembly submersed in the MR fluid, while the accumulator reservoir contains a compressed, non-oxidizing gas (usually nitrogen). As the piston rod moves into the damper housing, a volume of fluid equivalent to the volume of the intruding piston rod is displaced. The accumulator piston moves toward the bottom of the damper, compressing the nitrogen charge to account for the change in volume. As the piston rod retracts, the accumulator piston moves up the damper tube to counteract the loss of volume. The monotube damper design is the most versatile damper design since it can be mounted in any orientation without affecting the damper's performance.

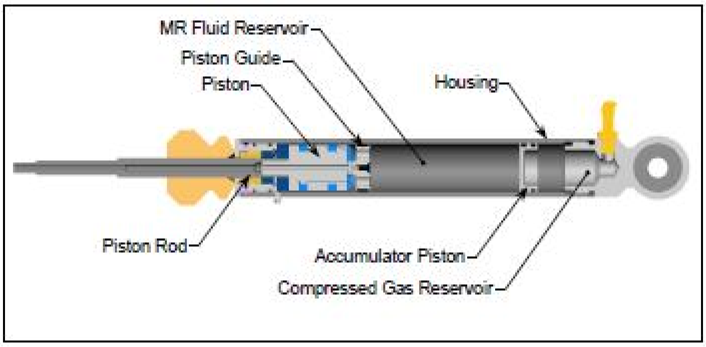


Figure 2.4: Sectional view of MR damper built by James Poynor (2001).

The twintube damper uses inner and outer cartridges to negotiate the changing volume of MR fluid, as shown in Figure 2.8. As the piston rod enters the inner housing, the extra volume of MR fluid displaced by the piston rod is forced from the inner housing to the outer housing via the foot valve. When the piston rod retracts, MR fluid flows back into the inner housing, therefore preventing the creation of vacuum in the inner housing and cavitations of the damper. Drawbacks of this design include size and orientation – this damper must be mounted with the foot valve at the bottom to ensure no cavitation.

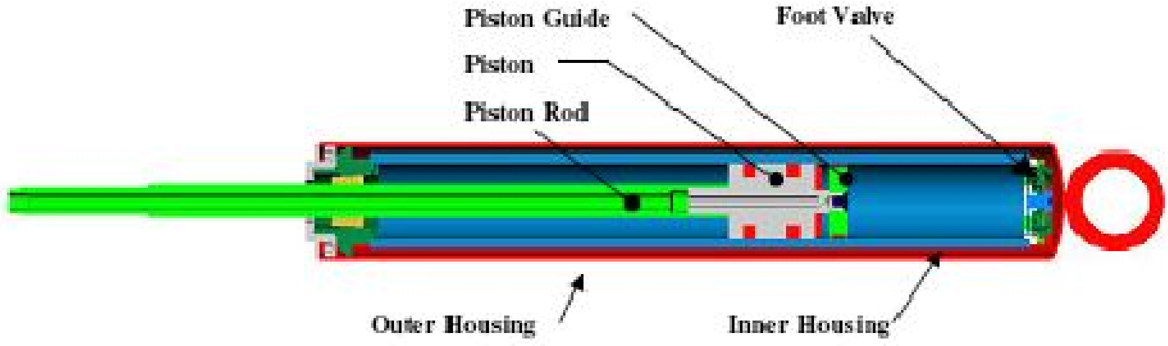


Figure 2.5: Twintube MR Damper, Section View (Poynor J. C, 2001)

Double-ended (through-tube) dampers use a third method to account for the piston rod volume. Fully extended, the piston rod protrudes through both sides of the damper housing, as shown in Figure. This method of damper design retains a constant piston rod and fluid volume within the housing, thereby eliminating the need for a second housing or accumulator.

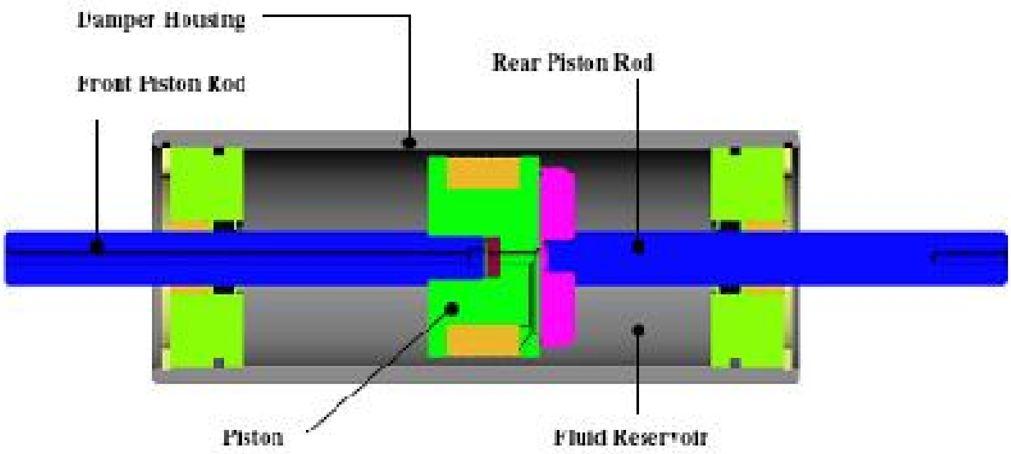


Figure 2.6: Double-Ended (Through-Tube) MR Damper, Section View (Poynor J. C, 2001)

The twintube and double-ended damper provide a significant advantage over the monotube design. The pressurized charge in the accumulator of the monotube design adds a spring force to the damping rod, so not only does the damper have force vs. velocity characteristics, it also has a spring rate. The twintube and double-ended damper, however, do not demonstrate this trait, showing only force vs. velocity characteristics.

2.4.1 Magneto-Rheological Fluid

In recent year, a family of fluids known as magneto-rheological fluids has gained increased recognition for its many applications. Magneto-rheological fluid or as known as MR fluids, demonstrate a change in apparent viscosity when exposed to the magnetic field. Jacob Rainbow, an inventor at the US National Bureau of Standards, developed the first MR fluids in the late 1940s.

Upon introduction, there was keen interest in technology for the devices like automatic transmissions and clutches, but the activity dropped off shortly thereafter. Resurgence in interest in MR fluids occurred in the early 1990s when Dave Carlson of Lord Corporation began to experiment with the fluids for the variety of devices, including vehicle suspensions.

Jacob Rainbow’s original MR fluids consisted of nine parts by weight of carbonyl iron to one part of carrier fluid, namely silicon oil hydrocarbon-based oil. To increase the fluid stability and reduce settling, grease or another thixotropic solution was added. This original solution proved to be as strong as modern day MR fluids. Modern fluids use micron sized iron particles coated with an anticoagulant in a carrier fluid of hydrocarbon-based oil, silicon-based, or water. The fluids also contain a number of anti-settling agents to prevent the fluid from hardening.

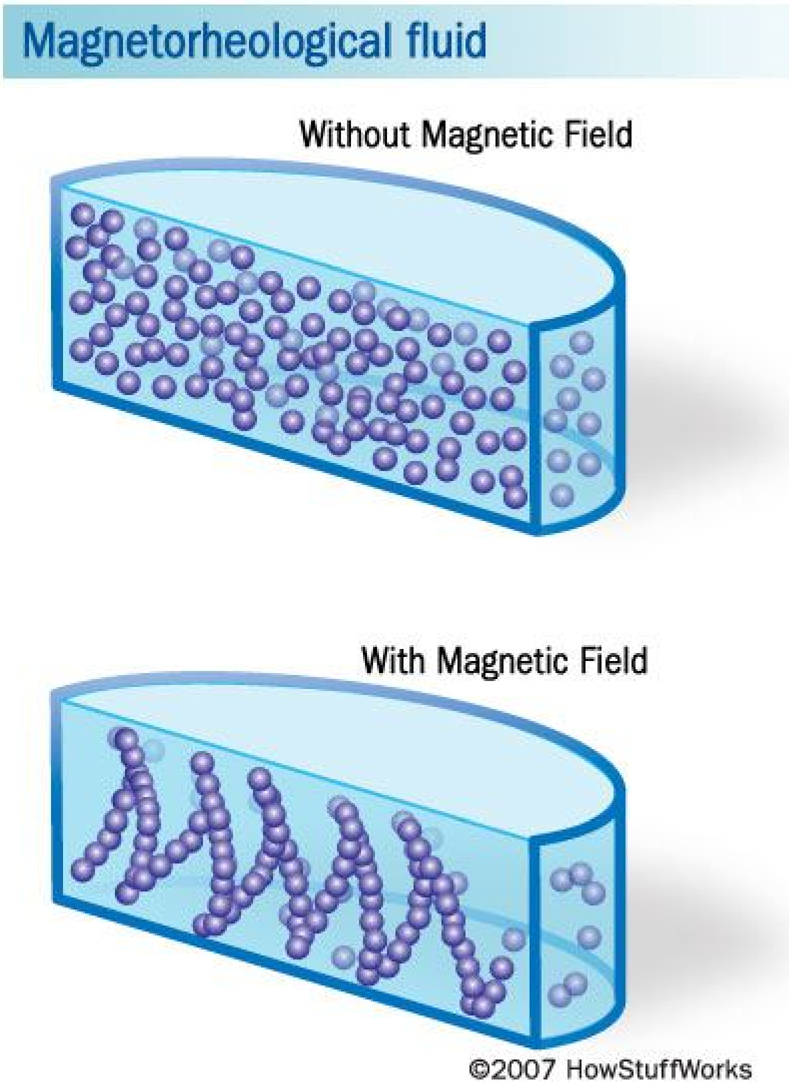


Figure 2.7: Magneto-Rheological Fluid (How Stuff Works 2007)

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. There are, however, many drawbacks to ER fluids, including relatively small rheological changes and extreme property changes with temperature.

Although power requirements are approximately the same, MR fluids only require 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. However, in the area of vibration control, the MR effect is most interesting since 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.

2.5 Skyhook Control

As the name implies, the skyhook configuration shown in the Figure below has a damper connected to the some inertial reference in the sky. With the skyhook configuration, the tradeoff between resonance control and high-frequency isolation, common in passive suspensions, is eliminated. Notice that skyhook control focuses on the sprung mass, as c_{sky} increases, the sprung mass motion decrease. This, of cause, comes with cost. The skyhook configuration excels at isolating the sprung mass from base excitations, at the expense of increased unsprung mass motion.

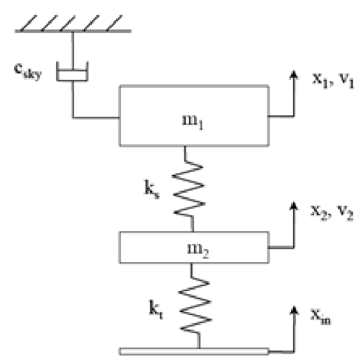


Figure 2.8: Skyhook controller diagram

Source: Goncalves. D.F (2001)

2.6 Bingham.

The stress-strain behavior of the Bingham viscoplastic model (Shames and Cozzarelli, 1992) is often used to describe the behavior of MR (and ER) fluids. In this model, the plastic viscosity is defined as the slope of the measured shear stress versus shear strain rate data. Thus, for positive values of the shear rate, $\gamma^{\cdot}$ the total stress is given by:

Where $\tau_{y(field)}$, is the yield stress induced by the magnetic (or electric) field and η is the viscosity of the fluid. Based on this model of the rheological behavior of ER fluids, Stanway, *et al.* (1985, 1987) proposed an idealized mechanical model, denoted the Bingham model, for the behavior of an MR damper. The model consists of a Coulomb friction element placed in parallel with viscous damper as shown in Figure 2.9.

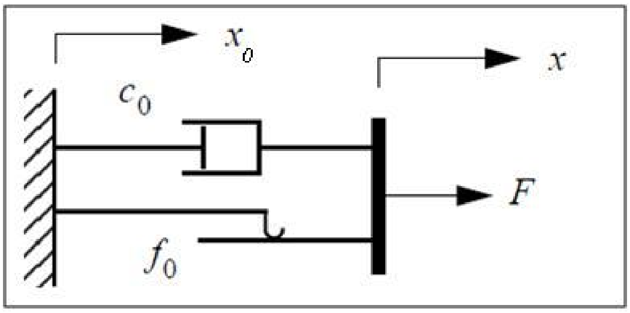


Figure 2.9: Bingham Model of a Controllable Fluid Damper

Source: Gongyu, Hiroshi and Yoshihisa (2000)

2.7 2DOF Quarter Car Model

The vehicle model considered in this study is a quarter car models. The quarter car model for passive suspension system consists of one-fourth of the body mass, suspension components and one wheel as shown in Figure 8 (a). The quarter car model for active suspension system, where the hydraulic actuator is installed in parallel with the spring, is shown in Figure 8 (b).

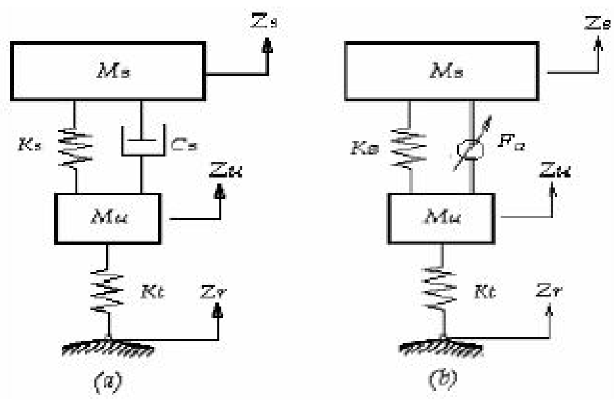


Figure 2.10: Passive and Active Quarter Car Model.
(Sam, Y.M and Huda, K. (2006))

The assumptions of a quarter car modelling are as follows: the tyre is modelled as a linear spring without damping, there is no rotational motion in wheel and body, the behaviour of spring and damper are linear, the tyre is always in contact with the road surface and effect of friction is neglected so that the residual structural damping is not considered into vehicle modelling. The equations of motion for the sprung and unsprung masses of the passive quarter car model are given by:

$$M_s\ddot{Z}_s + K_s(Z_s - Z_u) + C_s(\dot{Z}_s - \dot{Z}_u) = 0 \quad (2.1)$$

$$M_u\ddot{Z}_u + K_t(Z_u - Z_r) + K_s(Z_u - Z_s) + C_s(\dot{Z}_u - \dot{Z}_s) = 0 \quad (2.2)$$

Whereas, the equations of motion for the sprung and unsprung masses of the semi-active quarter-car model are given by: (Sam, Y.M and Huda, K. (2006))

$$M_u\ddot{Z}_u + K_t(Z_u - Z_r) + K_s(Z_u - Z_s) - F_a = 0 \quad (2.3)$$

$$M_s\ddot{Z}_s + K_s(Z_s - Z_u) + F_a = 0 \quad (2.4)$$

Where,

Ms = sprung mass

Ks = spring stiffness

Mu = unsprung mass

Cs = damping constant

Zr = road profile

Kt = tyre stiffness

Zu = unsprung mass displacement

Zs = sprung mass displacement

Fa = actuator force

Due to the tyre stiffness, vertical force acting on the contact point between tyre and the road will be created when the tyre hits a certain road profile. Then, the vertical force is transferred to the wheel resulting in vertical acceleration of the wheel. Part of the vertical force is damped out by the suspension elements, whereas, the rest is transferred to the vehicle body via the suspension elements. The vehicle body will move vertically in response to the vertical force of the suspension elements. The performance criteria of the suspension system to be investigated in this study are body acceleration ($\ddot{Z}s$), body displacement (*Zs*), suspension working space (*Zu* – *Zs*) and wheel displacement (*Zu*). Performance of the suspension system is characterized by the ability of the suspension system in reducing those four performance criteria effectively.

2.8 Conclusion

In this chapter discuss details related to the type of suspension system suspension system, consisting of three systems of passive, active and semi-active suspension. This chapter also describes the Magneto-rheological damper and the MR fluid. Skyhook control is also discussed at the end of this chapter.

CHAPTER 3

METHODOLOGY

3.1 Introduction.

Chapter 3 will discuss about process and methodology for this research. Methodology is very important for doing analysis. Every process that will be discusses has their own importance according to the research. Start from find the article, journal, thesis, and books, the idea of thesis or another research which is related or same with this research will be use. The idea from that literature review will be compare the make the best conclusion for the research get the successfully result.

3.2 Project Methodology Flow Chart

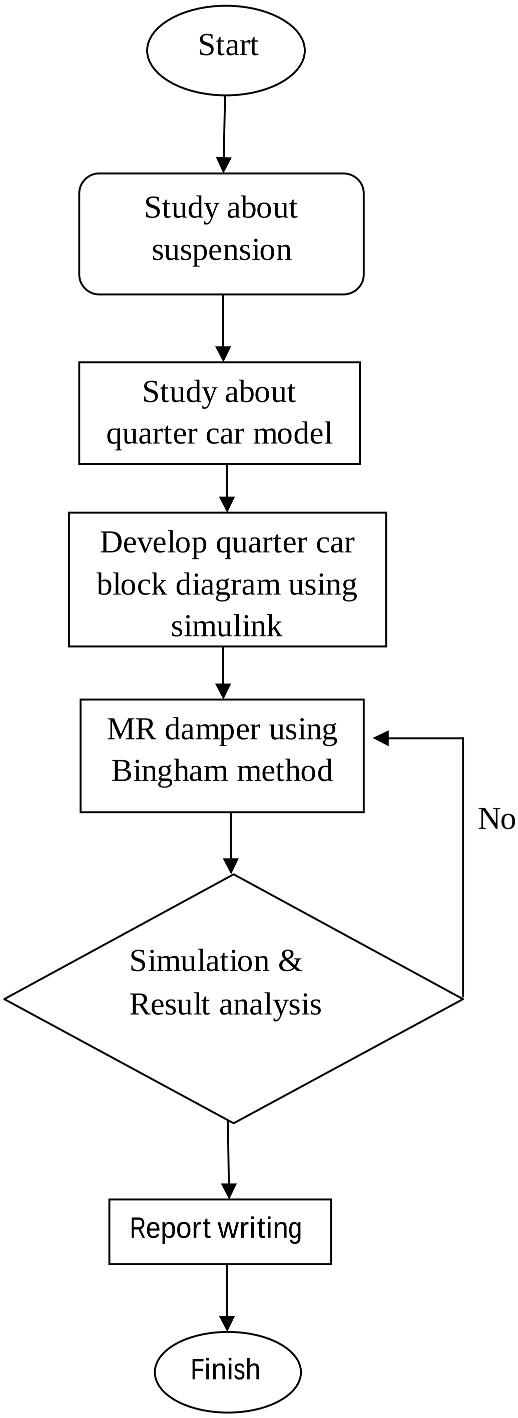


Figure 3.1: Methodology Flow Chart

3.3 Simulation Software

The software that is used to create the Simulink diagram and running the simulation is MATLAB. MATLAB stands for Matrix Laboratory. The very first version of MATLAB, written at the University of New Mexico and Stanford University in the late 1970s was intended for use in Matrix theory, Linear algebra and Numerical analysis. Later and with the addition of several toolboxes the capabilities of MATLAB were expanded and today it is a very powerful tool at the hands of an engineer. Typical uses of MATLAB include:

- Math and Computation
- Algorithm development
- Modeling, simulation and prototyping
- Data analysis, exploration and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building.

For the project, Simulink from MATLAB is used to model the block diagram. The equations will be converted into block diagram by using MATLAB Simulink Library block function. Modeling must be precisely following the required equations in order to avoid error thus giving the correct results during the simulation.

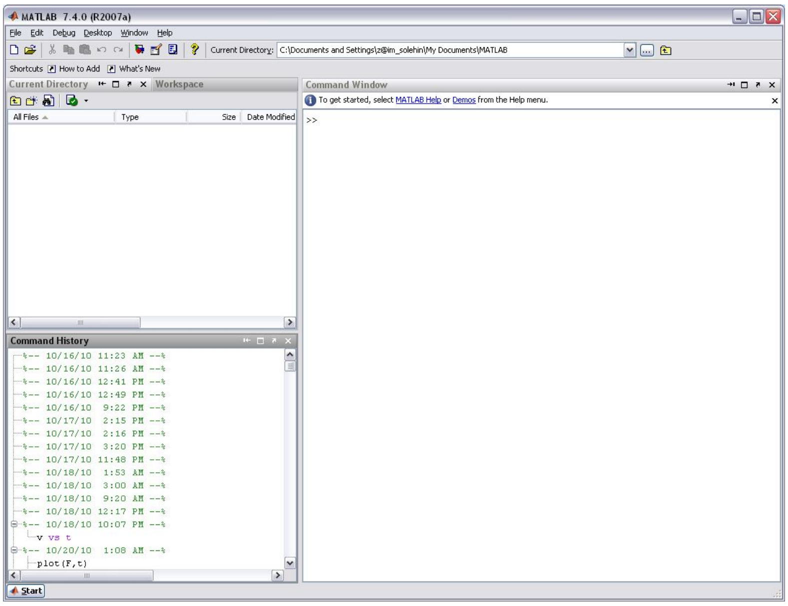


Figure 3.2: MATLAB interface

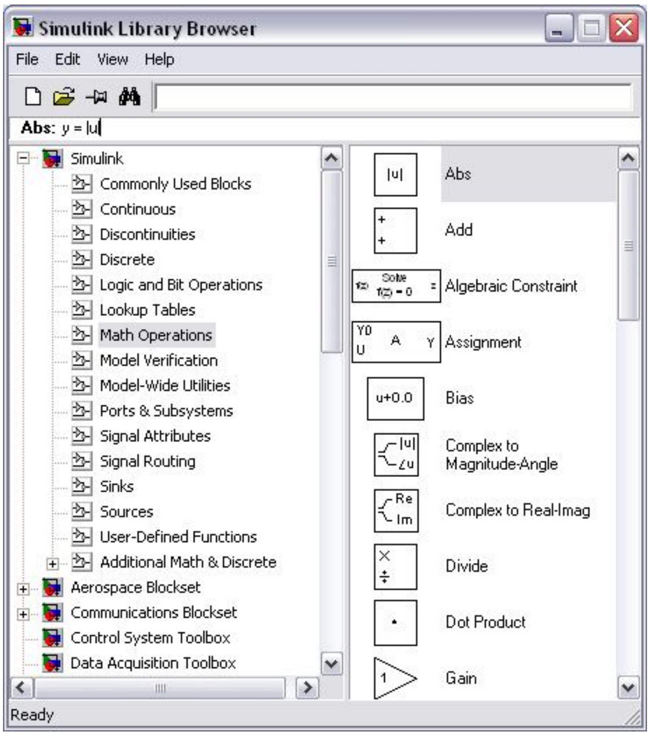


Figure 3.3: MATLAB Simulink Library

3.4 Quarter Car Passive Model & Equation.

From two degree of freedom free body diagram, we can generate equation to find the acceleration ($\ddot{x}$), velocity ($\dot{x}$) and displacement (x).

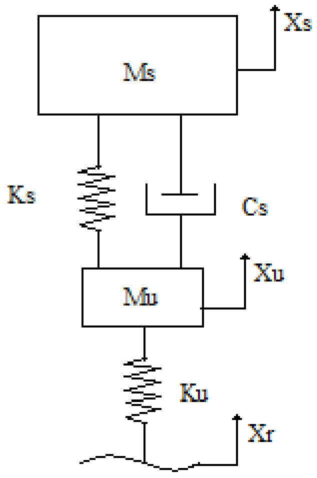


Figure 3.4: 2DOF quarter car free body diagram (FBD).

Where,

Ms	Sprung Mass
Mu	Unsprung Mass
$\ddot{X}s$	Acceleration
Xs	Displacement
$\dot{X}s$	Velocity
Xr	Road Profile
Ks	Sprung Spring
Ku	Unsprung Spring
Cs	Sprung Damper
Cu	Unsprung Damper

Equation of motion from the diagram:

$$Ms\ddot{X}s + KsXs + Cs\dot{X}s - KsXu - Cs\dot{X}s = 0 \quad (3\ 1)$$

$$Mu\ddot{X}u + KsXu + KuXu + Cs\dot{X}u - KsXs - Cs\dot{X}s - KuXr = 0 \quad (3\ 2)$$

From that equation, take out the $\ddot{X}$ as a subject.

$$\ddot{X}s = \frac{1}{Ms}(Cs\ddot{X}s + KsXu - Cs\dot{X}s - KsXs) \quad (3\ 3)$$

$$\ddot{X}u = \frac{1}{Ms}(Cs\dot{X}s + KsXs + KuXr - KsXu - KuXu - Cs\dot{X}u) \quad (3\ 4)$$

Use the equation above, generate block diagram by using simulik from Matlab software.

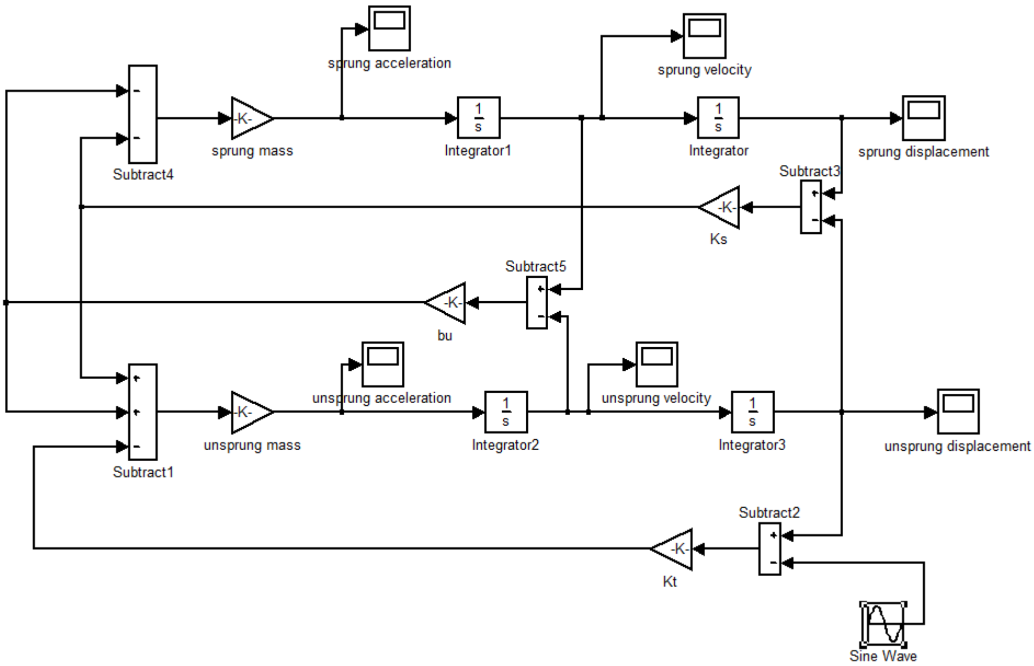


Figure 3.5: Quarter Car Block Diagram

A Quarter Car Data

Ms	290 kg
Mu	59 kg
Xr	5
Ks	16,812 N/m
Ku	190,000 N/m
Cs	1000 N/m/sec

Source: Lin, J., and Kanellakopoulos, I (1997)

Table 3.1: Parameter Value

3.5 MR damper modeling

The MR damper was developed by following the mechanical model formulation of Bingham method. The Bingham method mathematical expression is below:

$$f = f_o \, \text{sgn}\,(\dot{x} - \dot{x}_0) + c_0(\dot{x} - \dot{x}_0) \qquad (3\ 5)$$

Where,

$$c_0 = c_a + c_h V, \qquad f_o = f_a + f_h V \qquad (3\ 6)$$

The Simulink of the MR damper must behave as the predicted characteristic of Bingham model MR damper. This is important as the Simulink diagram of the MR damper must produced the correct response as the real MR damper. The Simulink diagram of MR damper must produce damping forced according to the predicted characteristic or otherwise the simulation results are wrong.

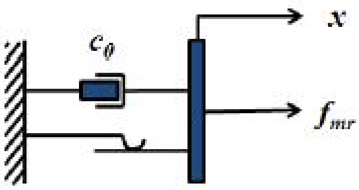


Figure 3.6: Bingham mechanical model

(Fabian, 2009)

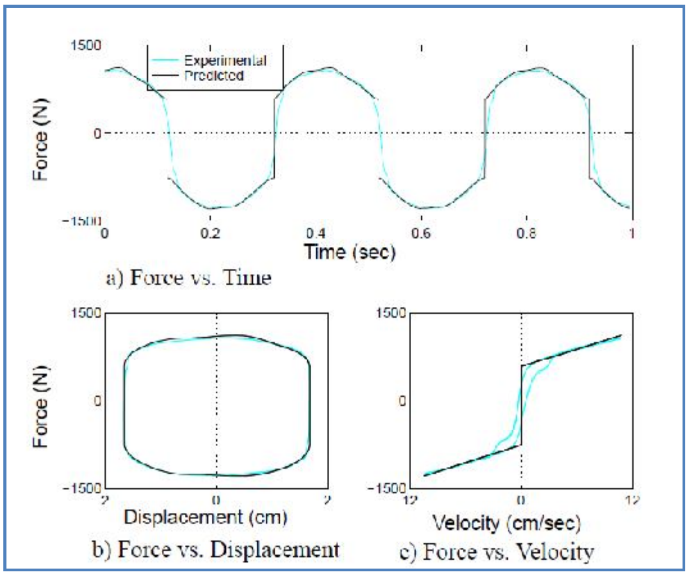


Figure 3.7: Predicted characteristic of Bingham method MR damper

Source: Spencer, Dyke, Sain & Carlson (1996)

The Simulink diagram of Bingham method Magneto-Rheological damper is modelled and is shown in Figure 3.8 below:

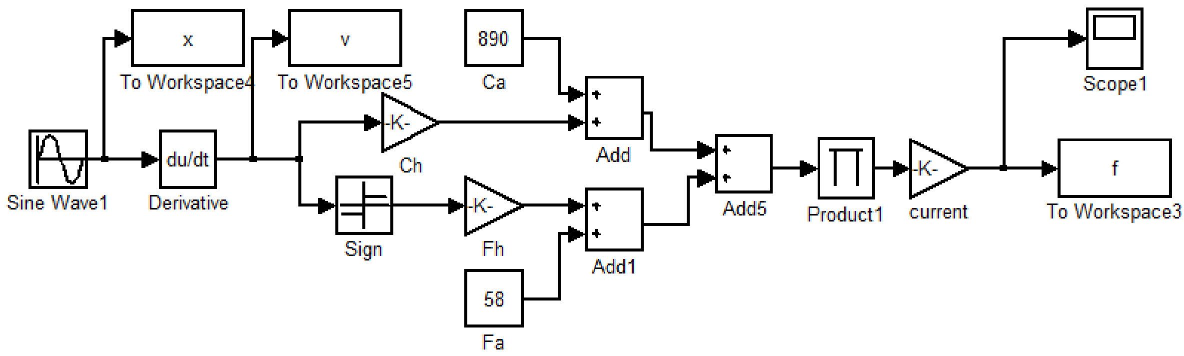


Figure 3.8: Simulink of Bingham method

The data for Bingham method magneto-rheological damper is shown in Table below:

Table 3.2: Data for Simulink diagram of MR damper

Damping Coefficient, c_0	**Frictional force, f_o**
c_a = 890 N.s/m	f_a = 58N
c_h = 560 N.s/mV	f_h = 107N/V

Source: Gongyu, Hiroshi and Yoshihisa (2000)

3.6 Simulink Analysis Developments

3.6.1 Semi-active suspension with skyhook controller

To create a semi-active suspension model, the original damping element is removed and replaced by the MR damper that is developed before. By replacing the damping element with MR damper, it becomes suspension system with adjustable damping coefficient. Skyhook controller is added to the system in order to make the damping coefficient can be controlled and adjusted according to the input thus giving the best damping force to the system.

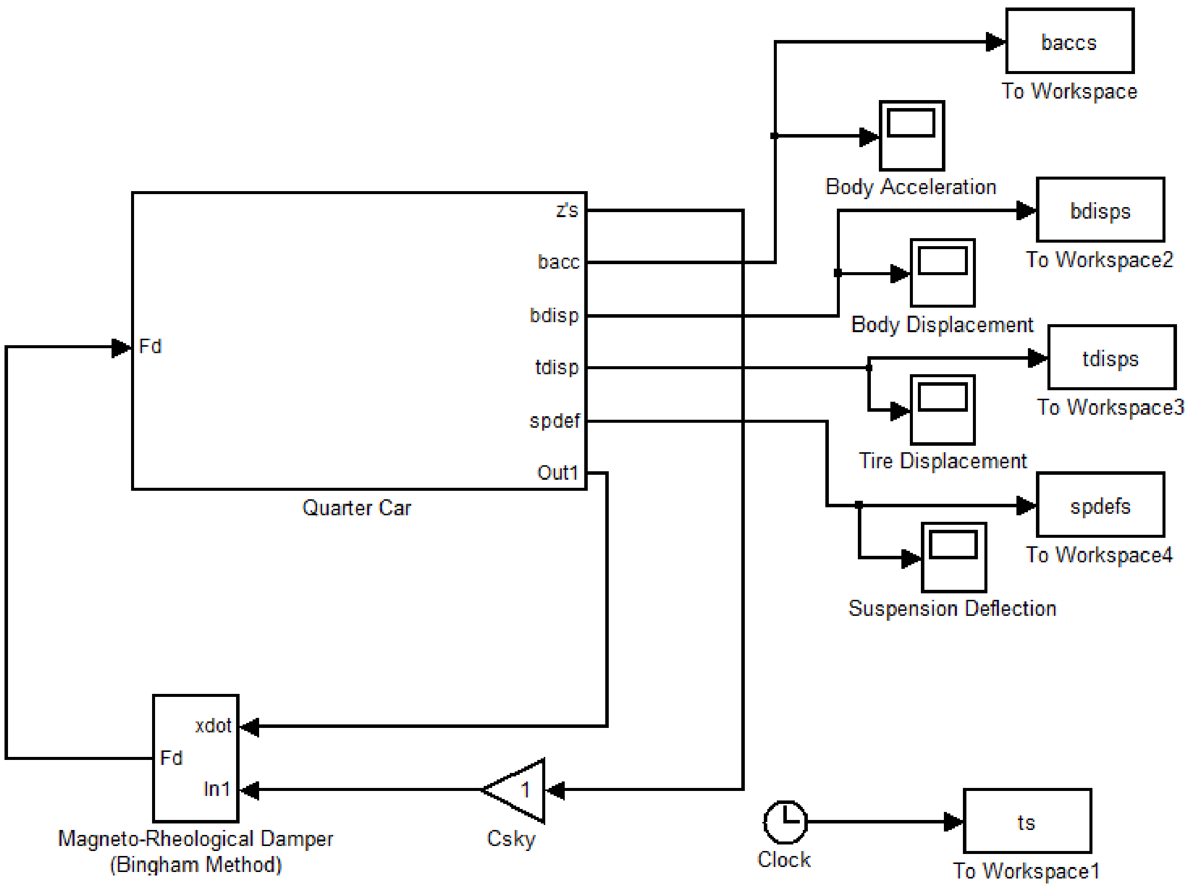


Figure 3.9: Simulink of 2DOF quarter car semi-active suspension with skyhook controller

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, all the findings and results will be showed and discussed briefly. The results are divided into several stages according to the simulation staging. The results mainly in graph representation as it are the best way to show how the sprung mass, m_s and unsprung mass, m_u behave when given specific road signal. Graph representation also better when to show comparison between the results for different simulation staging.

4.2 A quarter car passive suspension system simulation results

The results of simulation for 2DOF quarter car passive suspension system are shown in Figure 4.1 to Figure 4.4.

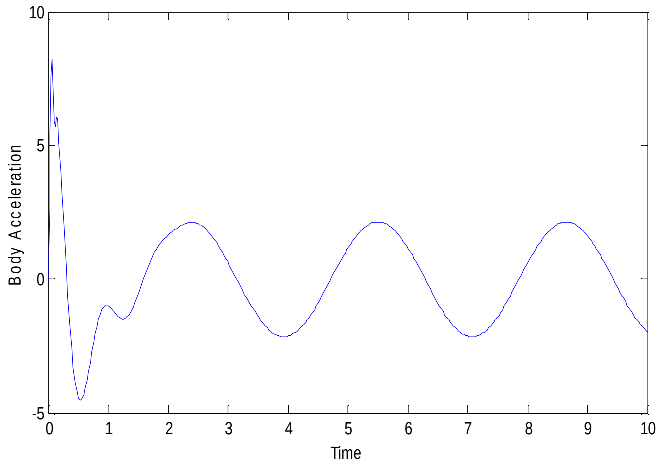


Figure 4.1: Body Acceleration

Figure 4.1 shows the sprung mass acceleration (Body Acceleration) and from the graph, the early acceleration is quite high and not constant. That means that the car body will accelerate randomly thus provide un-comfortable situation for the passenger for the first few second riding.

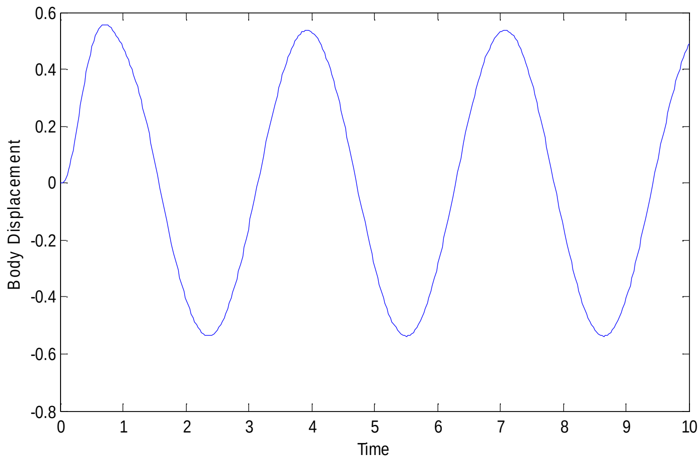


Figure 4.2: Body displacement

Figure 4.2, the sprung mass displacement (Body Displacement) is exactly same with the road signal input amplitude which is 0.05m. In real situation, it means that when the vehicles passing through 0.05m high bump on the road surface, the body of the car also displaced exactly as the bump high. The passenger inside the vehicles will definitely feel the bump hence it can be conclude that the passenger is not comfortable riding this vehicles.

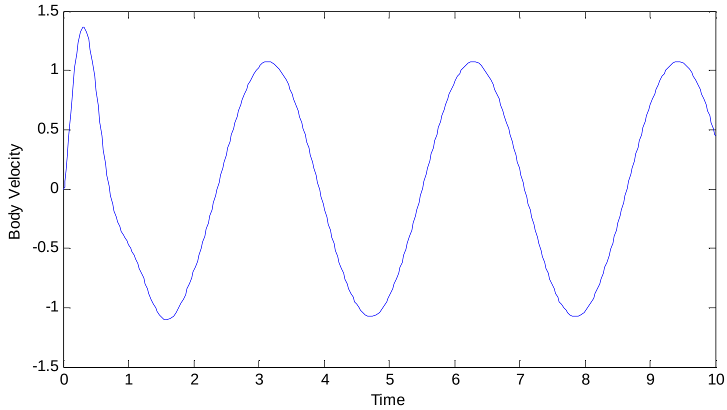


Figure 4.3: Body Velocity

Figure 4.3 is the body velocity that occurs. The pattern of the graph shows some similarity with the body velocity graph. In the early 2 second, the line is random before it's become a sinus wave graph.

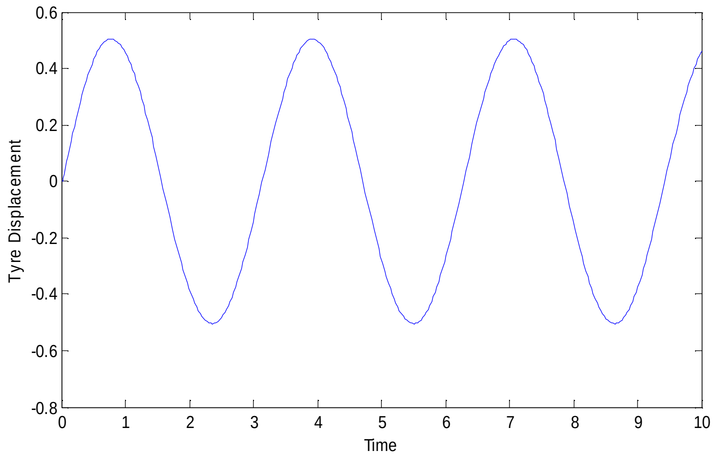
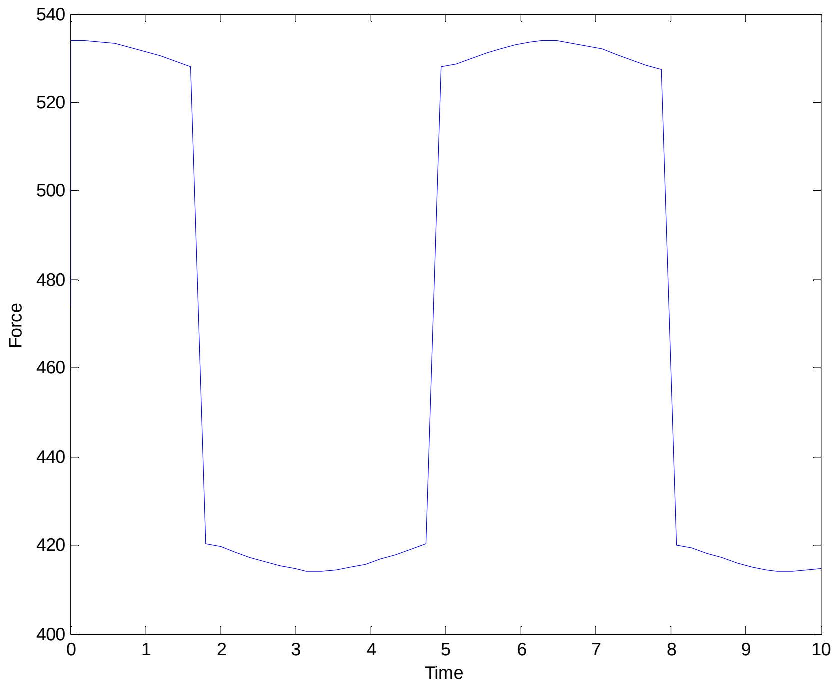


Figure 4.4: Tire Displacement.

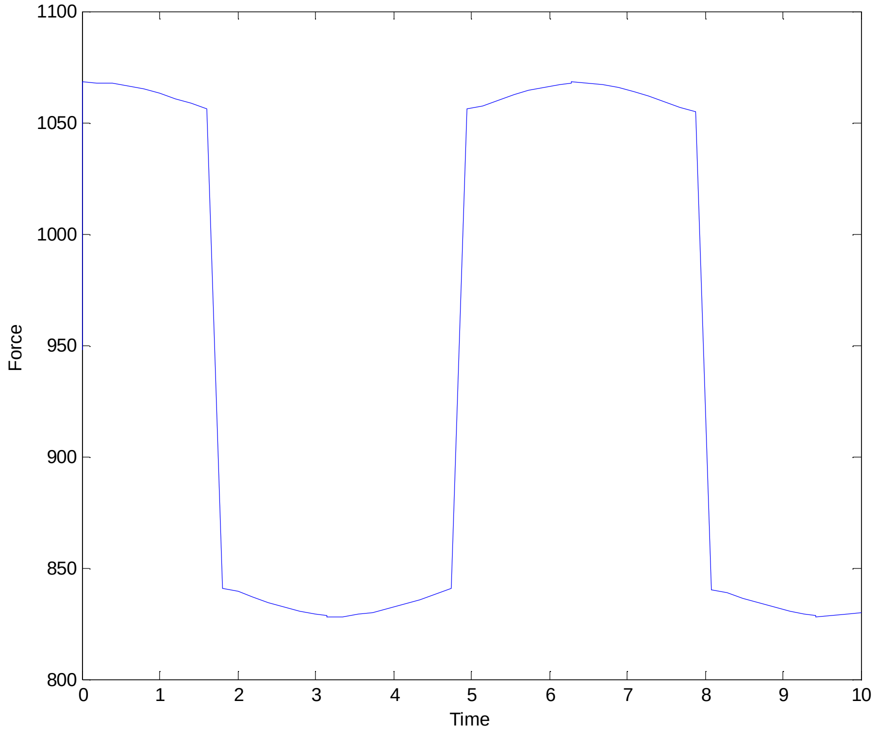
Tire displacement is shown by Figure 4.4 and it can concluded that the passive suspension system offers good amount of tire traction force as the patterns of the graph is equal to the road signal given.

4.3 Bingham method MR damper characteristic results

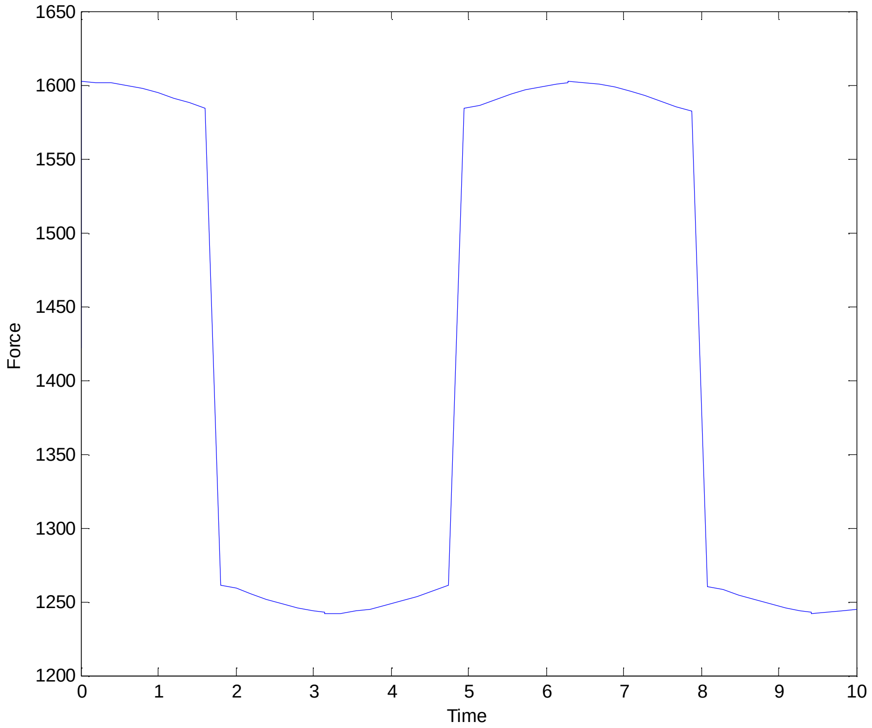
The result from this stage of simulation shows the characteristic of the Magneto-Rheological damper that is developed by using Bingham method. The result from this sub chapter as shown in Figure 4.5 to Figure 4.9 is important as it can prove that the Simulink diagram of the Magneto-Rheological damper is correct and behave as predicted. The actual input for MR damper is the sprung mass velocity but for this simulation, the input is given as a sinus wave. It is because this simulation is run to check the characteristic and behavior of MR damper. The input given to the Simulink diagram is a sinus waves with amplitude of 0.05m and 1Hz frequency. The results of the simulation then are compared to the characteristic of the MR damper that is shown in previous researches and journals to make sure the behavior and characteristic is similar.



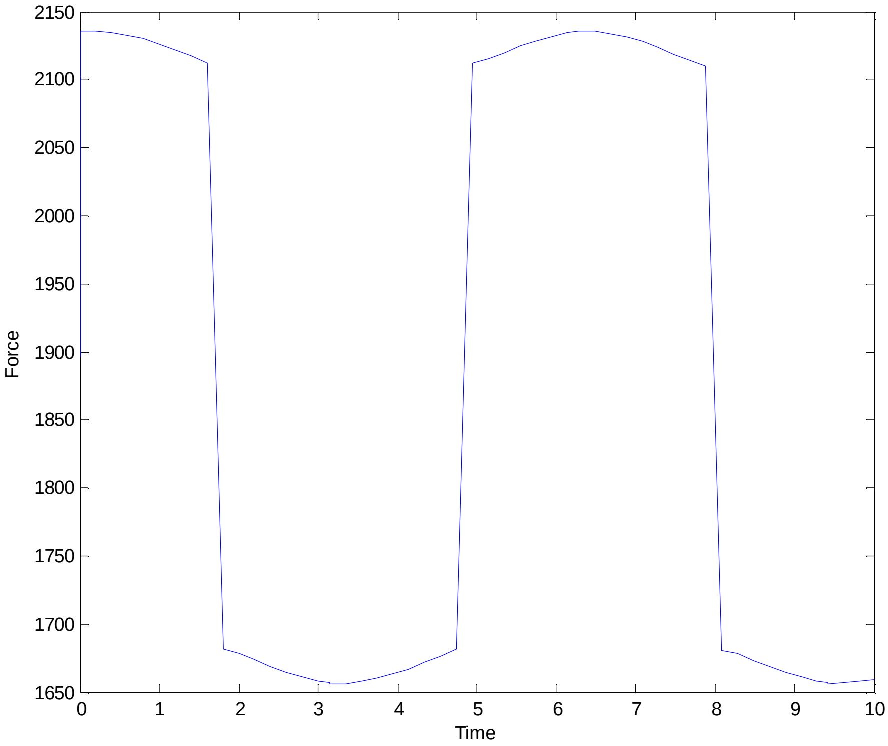
(a) I = 0.5A


1100
1050
1000
950
900
850
800
Force
0
1
2
3
4
5
6
7
8
9
10
Time

(b) I = 1A

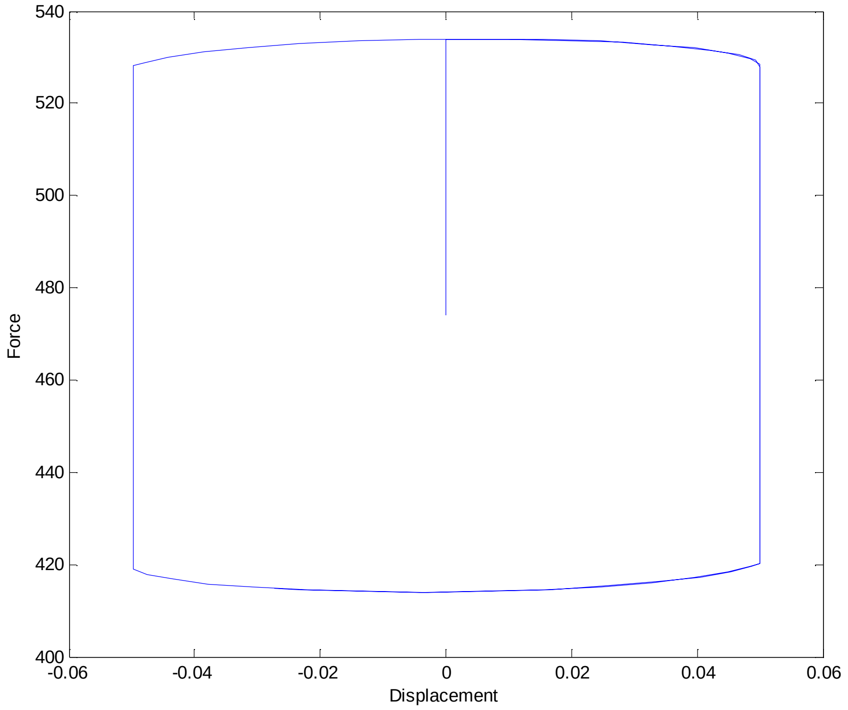

1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
Force
0
1
2
3
4
5
6
7
8
9
10
Time

(c) I = 1.5A

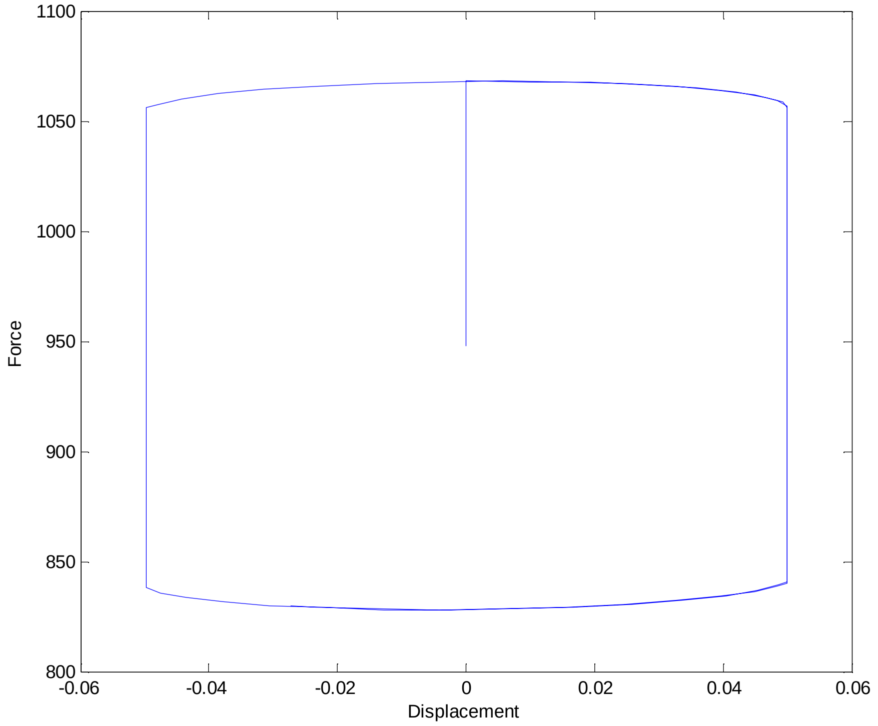


(d) I = 2.0A

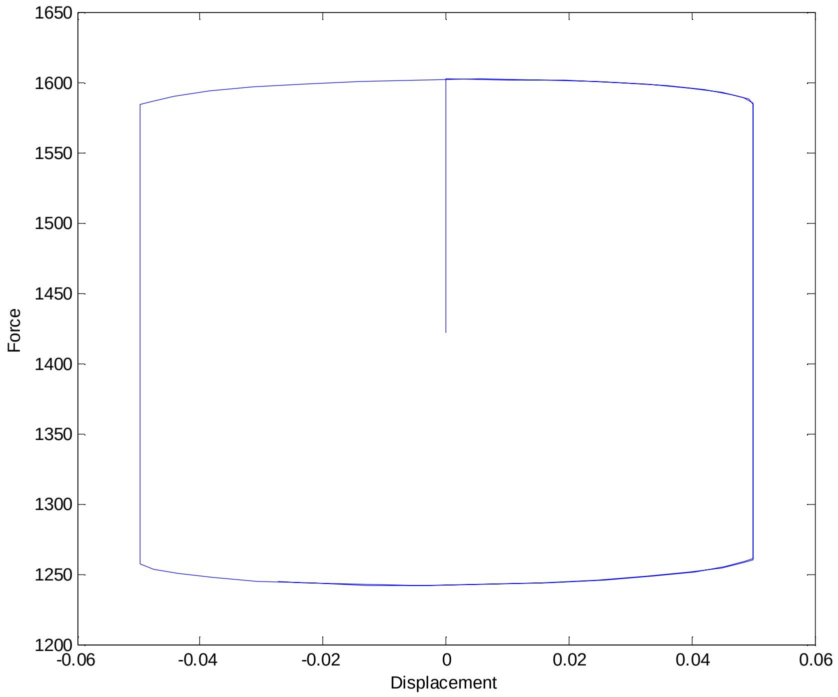
Figure 4.5: Graph of Force vs. Time


540
520
500
480
460
440
420
400
Force
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
Displacement

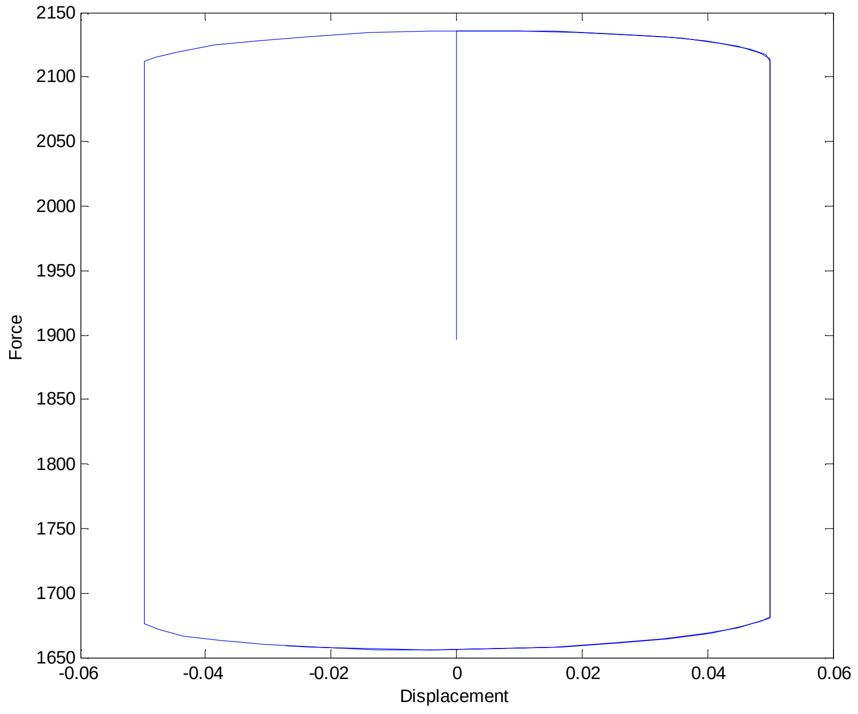
(a) I = 0. 5A


1100
1050
1000
950
900
850
800
Force
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
Displacement

(b) I = 1A

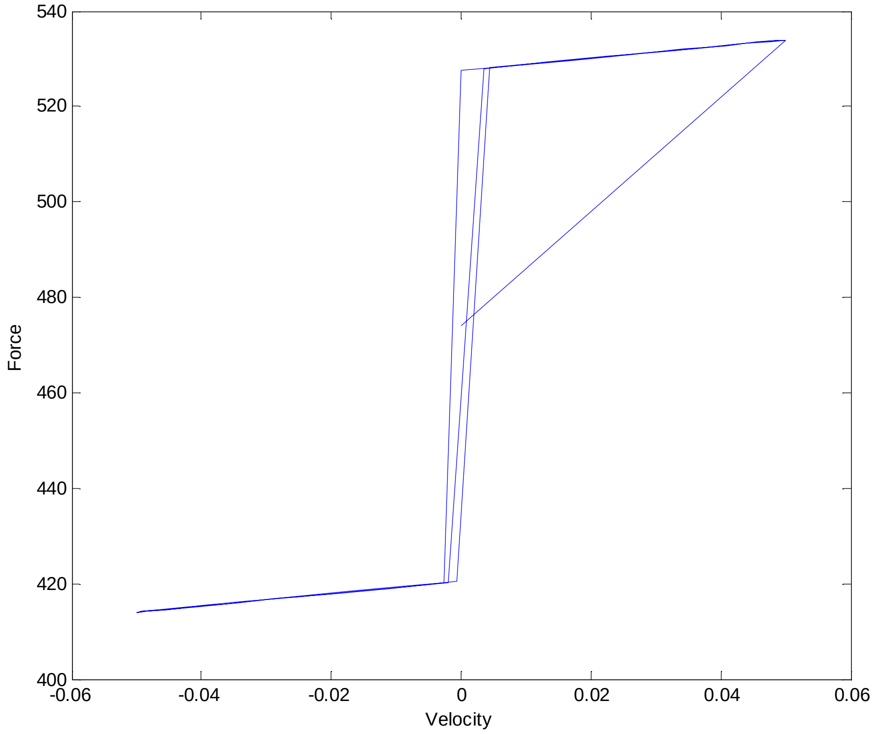


(c) I = 1.5A

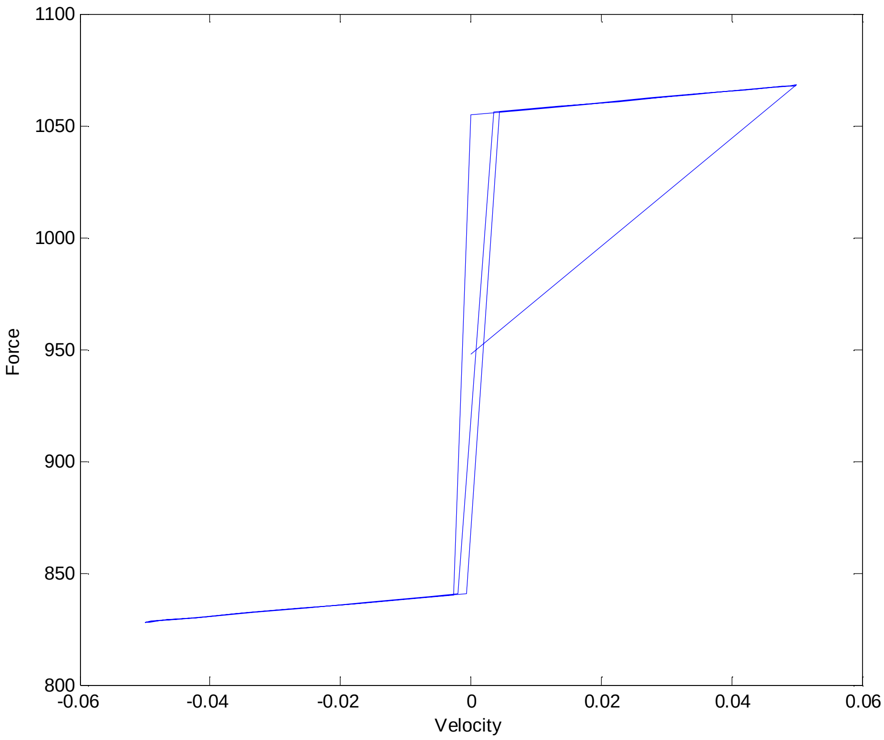


(d) I = 2A

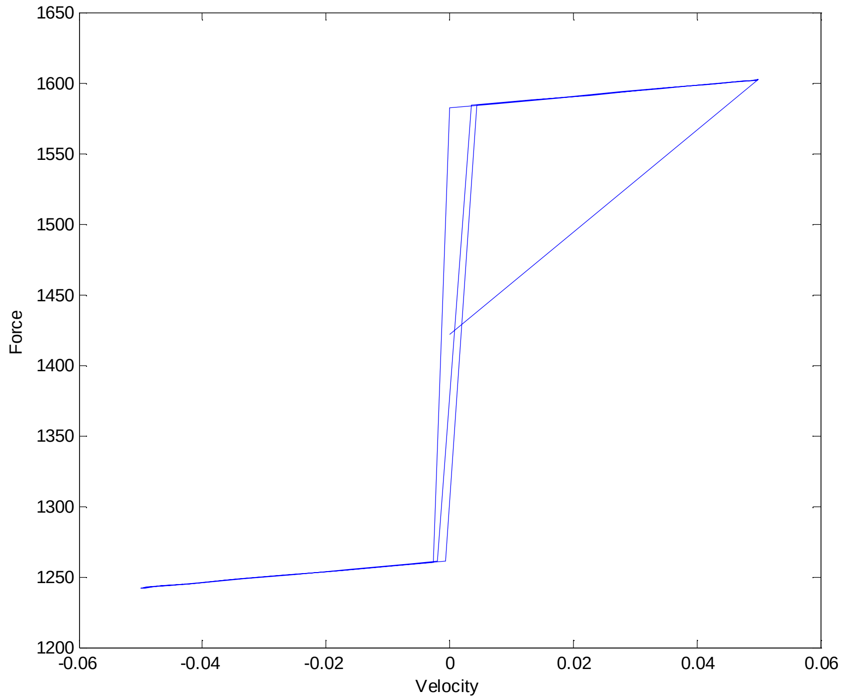
Figure 4.6: Graph of Force vs. Displacemen


540
520
500
480
460
440
420
400
Force
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
Velocity

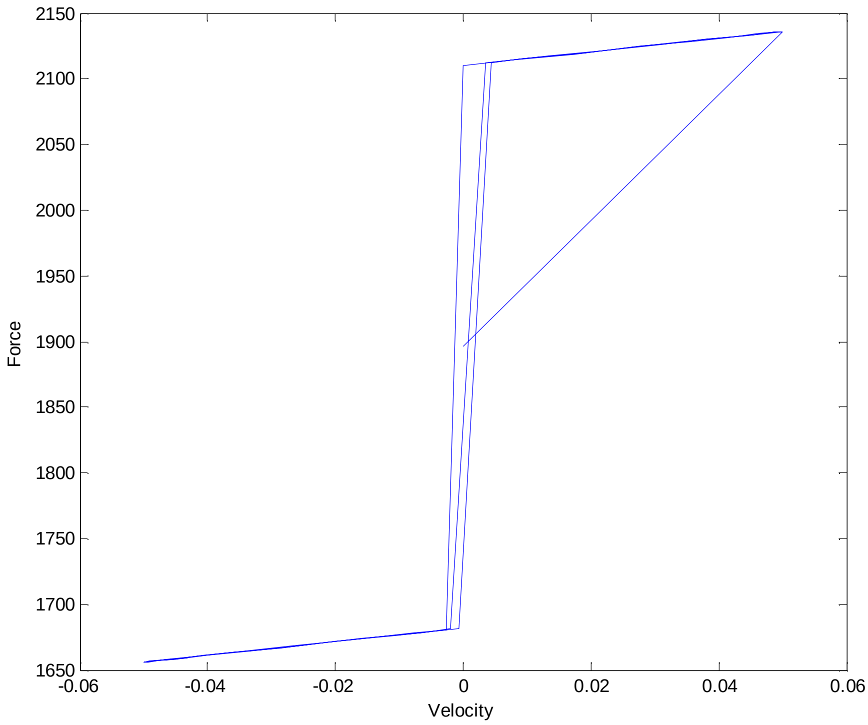
(a) I = 0.5A


1100
1050
1000
950
900
850
800
Force
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
Velocity

(b) I = 1.0A



(c) I = 1.5A



(d) I = 2.0A

Figure 4.7: Graph of Force vs. Velocity

4.4 Semi-active suspension with skyhook controller results

The results in this stage of simulation will show the semi-active suspension with skyhook controller is run together. It is expected that the results of semi-active suspension with skyhook controller can improve the ride quality of a vehicles thus giving passengers comfort when riding vehicle.

4.4.1 Finding the best possible value of C_{sky}

In the real semi-active suspension configuration, the C_{sky} value is decided by a controller box or the computer. The controller box or the computer will calculate the best C_{sky} base from the input of the sensors that can provide the best damping force to the suspension system. For this modeling and simulation project, the C_{sky} best value is computed by try and error process. The range of C_{sky} value is varying and big and it is impossible to fit all the value tries in this report. Hence, only a few selected C_{sky} value is shown in order to give a clear view of how skyhook controller controlled the suspension system. Figure 4.8 to Figure 4.9 shows the results for body acceleration, body displacement, suspension deflection and tire displacement for each C_{sky} value tries.

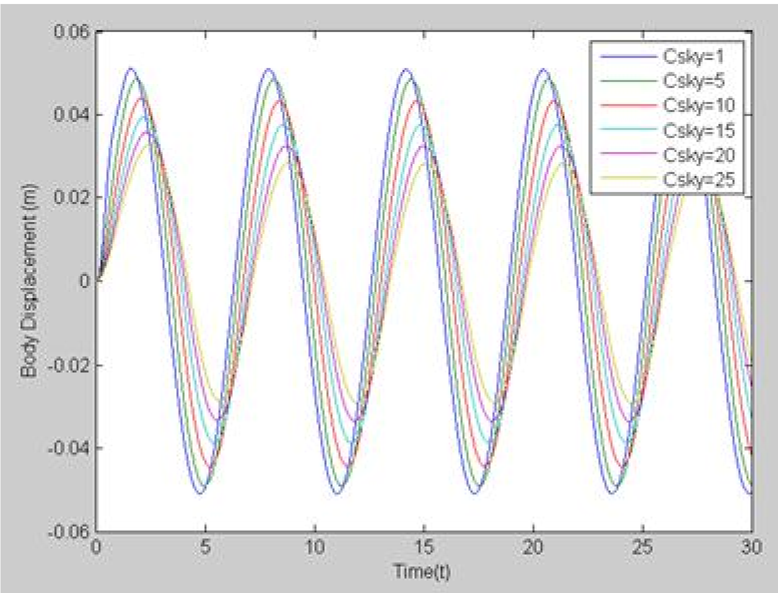


Figure 4.8: Graph of Body Displacement vs. Time

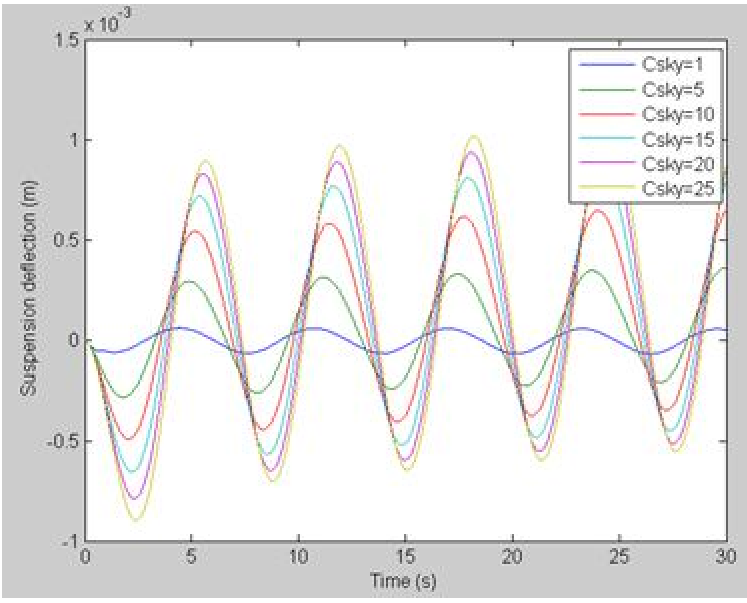


Figure 4.9: Graph of Suspension Deflection vs. Time

From Figure 4.8 and Figure 4.9 shows decrement in each increment of the C_{sky} value that is given. This decrement of both parameters means that the ride quality of the vehicles is improving but, there are two other parameters that must be considered before selecting the best C_{sky} value which is suspension deflection and tire displacement. The suspension is deflecting much more with the increment of C_{sky} value. If the suspension deflecting too much compared to the passive suspension system, the handling characteristic of the car become worse. Hence, the selected value of C_{sky} must provide good quality ride but without affecting the vehicles handling characteristic. So that the best value have been choose is $C_{sky} = 15$.

4.4.2 Comparison between passive suspension and semi-active suspension with skyhook controller

The semi-active suspension with skyhook controller results is then compared with the passive suspension system results in order to get the best value of C_{sky}. After a few comparison, the best value of $C_{sky} = 15$. The value provided the semi-active suspension a much lower body acceleration and displacement compared to passive suspension without affecting the handling characteristic. The suspension deflection also shows some improvement as the average deflection is lower than the deflection of passive suspension system. Although the suspension deflection is decreased, the comparison of the tire displacement shows the same pattern which means the traction forces is the not affected by the new suspension configuration. Figure 4.10 to Figure 4.11 below will show the comparison between passive suspension system and the semi-active suspension with skyhook controller where $C_{sky} = 15$.

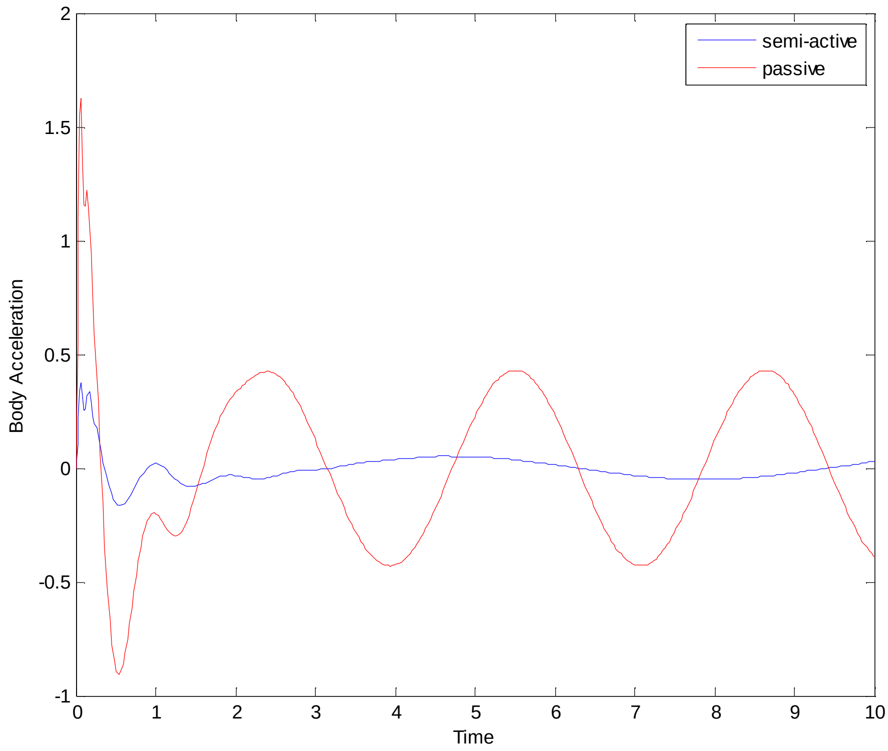


Figure 4.10: Graph of Body Acceleration vs. Time

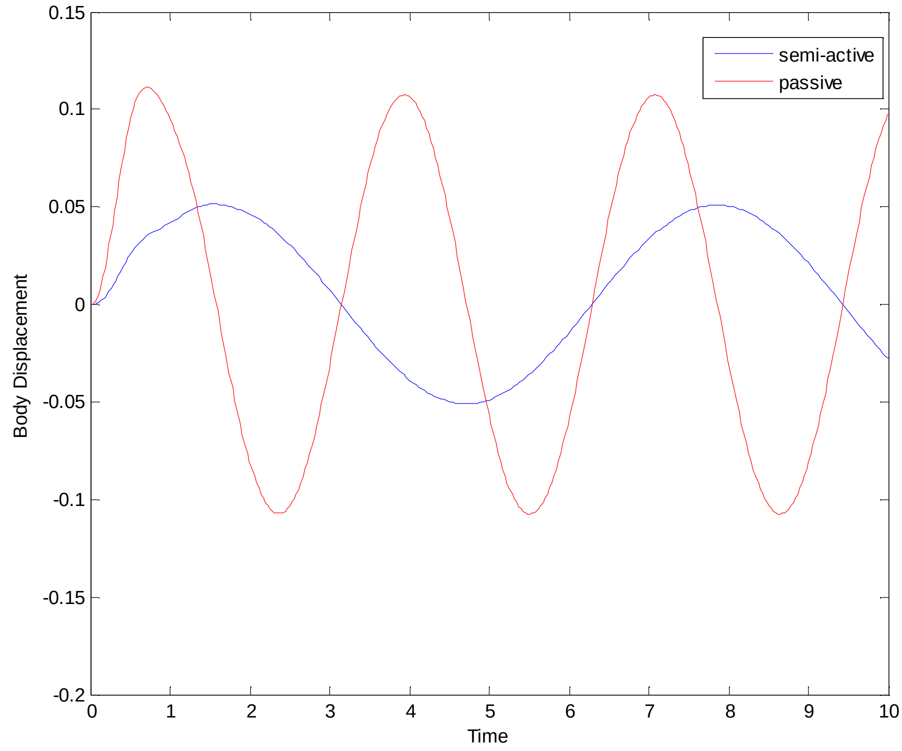


Figure 4.11: Graph of Body displacement vs. Time

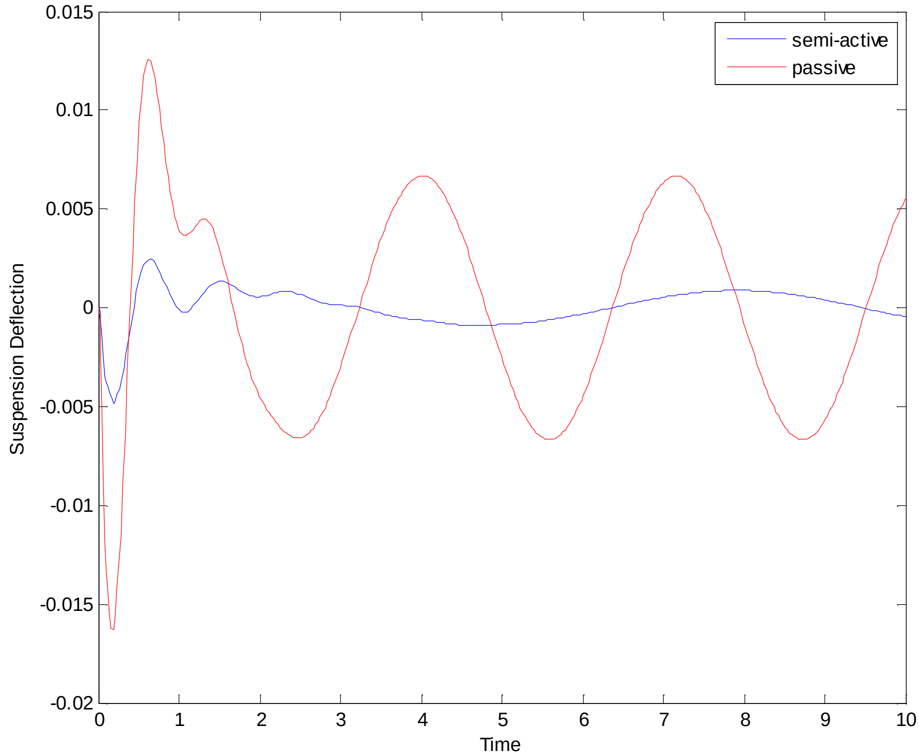


Figure 4.12: Graph of Suspension deflection vs. Time

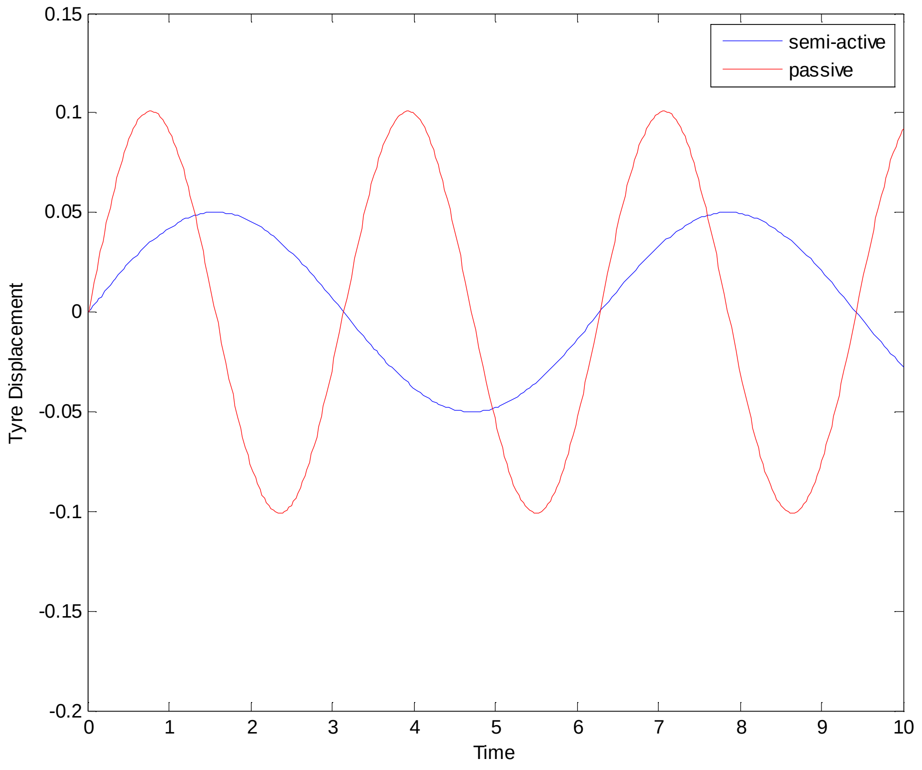


Figure 4.13: Graph of Tire Displacement vs. Time

The comparison between passive suspension and semi-active suspension system with skyhook controller.

Figure 4.10 to Figure 4.13 above, it is clear that semi-active suspension to improve ride quality which in turn provides the passengers a feeling of comfort. With the skyhook controller, body acceleration and body displacement increase significantly. This is because the vibration control using semi-active suspension is better and the rate of absorption higher than the passive suspension. Acceleration is reduced and the amplitude of the body becomes more frequent as compared with passive suspension. The displacement body is reduced from 0.12m to 0.05m to make more passenger comfort in vehicles. It almost to the tire displacement, the value reduces from 0.1m to 0.05m. For the deflection of the suspension, it was very fortunate because the deflection shows drop some time comparing the semi-active suspension with skyhook controller.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter is summarizing of the tasks that has been completed for this thesis. The results will be discussed with respect to the research objectives. This chapter will conclude with several suggestions for future work that should be to improve.

5.2 Summary

The objective of this project is achieved successfully where the semi-active suspension with skyhook controller has better result from passive suspension and improves the quality of comfort when riding and handling vehicle. Parameters have been subjected in this project are body acceleration, body displacement, suspension deflection and tire displacement.

1. Two degree of freedom (2DOF) quarter model passive suspension system diagram has been successfully developed using Simulink software.
2. Magneto-Rheological (MR) damper model using Bingham method has been developed using Simulink software for semi-active with skyhook suspension.

From all the graph of Magneto-Rheological damper using Bingham method for semi-active suspension system shown that the value more decreasing rather than passive suspension system.

5.3 Future recommendations

This project has a lot more to improve because this only part of developing the diagram for comparing the passive and semi-active suspension. More study about semi-active suspension system also study about MR damper. Expanding the car modeling from 2DOF to full car, the vibration behavior of the car becomes more accurate as the suspension system modeling is much more complicated. The mechanical model formulation used for this project is the basic of Bingham Method. As can be seen in the MR damper characteristic graph, the force, displacement and velocity is not reasonably expressed.

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