MODELLING AND SIMULATION OF MODIFIED SKYHOOK CONTROL FOR SEMI-ACTIVE SUSPENSION

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CHAPTER 1

INTRODUCTION

1.0 Introduction

This chapter presents the project background as the motivation and starting point for the progress in this project. The problem statement and objectives of this project are then discussed. The chapter ends with the scopes of the project.

1.1 Project Background

Suspension system is a mechanism that physically separates the vehicles body with it tires. It is one of the most important parts of a vehicle. The roles of suspension system are to support the vehicle weight, isolate the vehicle body from road disturbance and also maintain the traction force between the tire and the road surface (Acker et al., 1991). Common problem when designing a passive vehicle suspension system is the criteria of the system whether it is for road holding or the passenger comfort (Simon, 1998). When the passive suspension system design is focusing on increasing the passenger comfort, it's automatically will decrease the handling abilities of the vehicle. This is a complex problem to solve and researches for solving this problem have been doing since 30 years ago. With continuous research and emerging of technology, scientists and engineers managed to create new approach in designing the vehicle suspension system. Although, this project focusing more on to increase the comfort of the vehicles passenger, the handling abilities will not be compromised as the design is following the new approach of designing the vehicle suspension. Alleyne et al., (1993) conclude that they are four important parameters that are associated with the comfort of the vehicles passenger. The parameters are suspension deflection, body (sprung mass, m_s) displacement, body (sprung mass, m_s) acceleration and tire assembly (unsprung mass, m_u) displacement. But the acceleration and displacement of vehicle's body (sprung mass, m_s) played the largest role in improving the comfort compared to other parameters (Alleyne et al., 1993). The approach of designing the vehicle suspension system for this project called semi-active suspension system that will be later fully explained in the next chapter.

1.2 Problem Statement

Passive suspension system is very common in the passenger's vehicles. The main problem for passive suspension system is it cannot give comfort to the passengers without sacrificing the traction force between the tire and the road. Figure 1.1 shows the relation of ride comfort and vehicle stability in a vehicle passive suspension system design. The passive suspension system performance also is variable subject to road profile and added passengers weight. It is because passive suspension system has fixed spring constant and damping coefficient thus its damping force is not adjustable. This project developed a vehicle suspension system that can adjust its damping force by replacing standard hydraulic damper with a continuously adjustable damper to overcome the problem. The main focus is to make the vehicle passenger feel more comfortable without sacrificing the vehicle handling abilities.

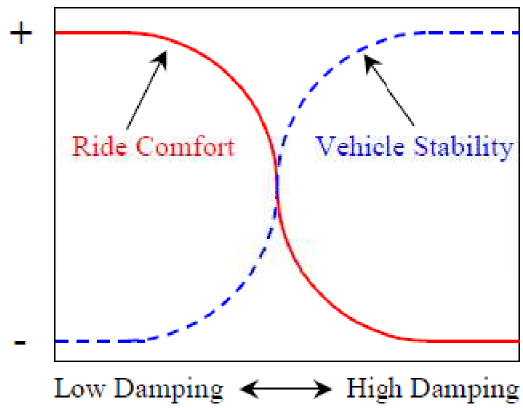


Figure 1.1: Passive Suspension Design Compromise

Source: Simon D.E (1998)

1.3 Objectives

There are three objectives of this project:

- To develop a two degree of freedom (2DOF) quarter car model passive suspension system.
- To develop Magneto Rheological (MR) damper using Bingham method.
- To develop modified skyhook controller to a semi-active quarter car suspension using MR damper.

1.4 Scopes

The scopes of this project are:

- Modeling two degree of freedom (2DOF) quarter car model passive suspension system block diagram in MATLAB.
- Modeling the modified skyhook controller block diagram in MATLAB.
- Modeling the Bingham Method MR damper block diagram in MATLAB.
- Connecting the block diagram and run the simulation.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter is conducted to investigate the past research done in any areas that are related in this project. This chapter starts with the meaning of each word in the project title. Previous researches are then reviewed and discussed briefly in order to understand more about the projects and also gathering useful information. Summary of the literature review ends this chapter.

2.1 Modeling and Simulation

Modeling and simulation within the engineering is well recognized and it is a discipline for developing a level of understanding of the interaction of the parts of a system, and of the system as a whole (Bellinger, 2004). A model is a simplified representation of a system at some particular point in time or space intended to promote understanding of the real system. A simulation is the manipulation of a model in such a way that it operates on time or space to compress it, thus enabling one to perceive the interactions that would not otherwise be apparent because of their separation in time or space.

2.2 Vehicle Suspension System

Suspension is a term that given for a system that contained spring, shock absorber and few linkages that connected the body o a vehicles to the tire. Suspension system can be divided into three categories which is passive, semi-active and fully active suspension system. This suspension system categorizing depends on the external power input and/or the control bandwidth into the system (Appleyard and Wellstead, 1995). A passive suspension system is conventional suspension system consist of non-controlled spring and shock-absorbing damper which means the damping criteria is fixed. Semi-active suspension system has equally same configuration as the passive suspension but with a controllable damping rate for the shock-absorbing damper. An active suspension is one in which the passive components are augmented by actuators that supply additional force.

2.2.1 Passive suspension system

Lot of common vehicles today uses passive suspension system to control the dynamics of a vehicle’s vertical motion as well as pitch and roll. Passive indicates that the suspension elements cannot supply energy to the suspension system. The passive suspension system controls the motion of the body and wheel by limiting their relative velocities to a rate that gives the desired ride characteristics. This is achieved by using some type of damping element placed between the body and the wheels of the vehicle, such as hydraulic shock absorber. Properties of the conventional shock absorber establish the tradeoff between minimizing the body vertical acceleration and maintaining good tire-road contact force. These parameters are coupled. That is, for a comfortable ride, it is desirable to limit the body acceleration by using a soft absorber, but this allows more variation in the tire-road contact force that in turn reduces the handling performance. Also, the suspension travel, commonly called the suspension displacement, limits allowable deflection, which in turn limits the amount of relative velocity of the absorber that can be permitted. By comparison, it is desirable to reduce the relative velocity to improve handling by designing a stiffer or higher rate shock absorber. This stiffness decreases the ride quality performance at the same time increases the body acceleration, detract what is considered being good ride characteristics.

An early design for automobile suspension systems focused on unconstrained optimizations for passive suspension system which indicate the desirability of low suspension stiffness, reduced unsprung mass, and an optimum damping ratio for the best controllability (Thompson, 1971). Thus the passive suspension systems, which approach optimal characteristics, had offered an attractive choice for a vehicle suspension system and had been widely used for car. However, the suspension spring and damper do not provide energy to the suspension system and control only the motion of the car body and wheel by limiting the suspension velocity according to the rate determined by the designer. Hence, the performance of a passive suspension system is variable subject to the road profiles. Passive suspension system representation diagram is shown in Figure 2.1.

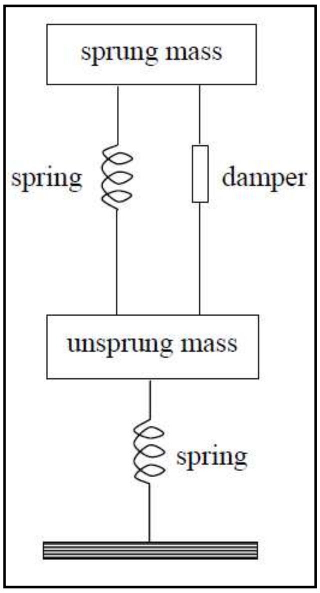
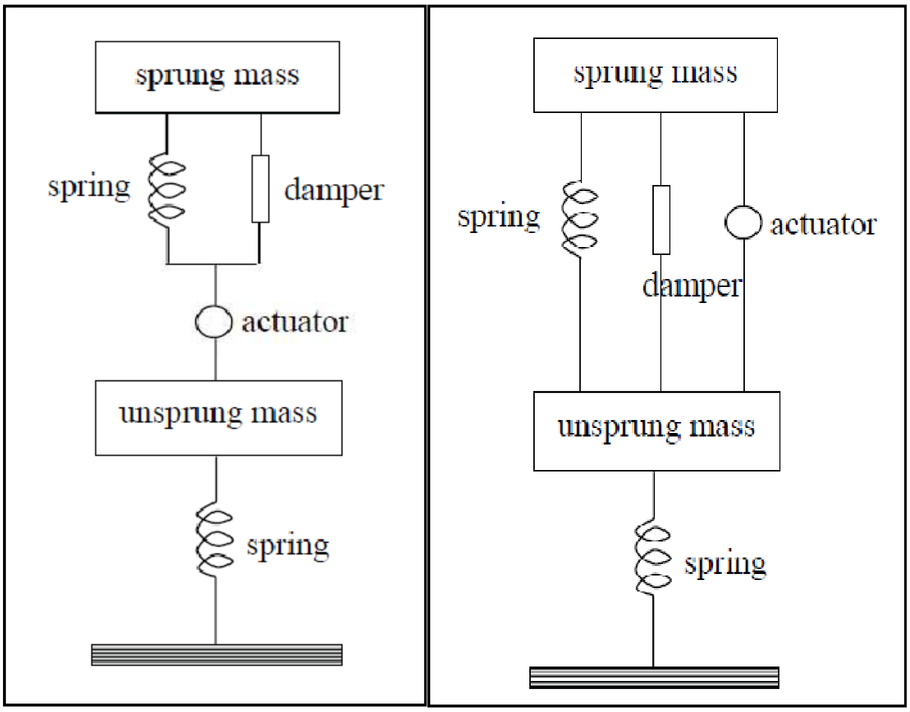


Figure 2.1: Passive suspension system

Source: Yahaya (2006)

2.2.2 Active suspension system

Active suspensions differ from the conventional passive suspensions in their ability to inject energy into the system, as well as store and dissipate it. Crolla (1988) has divided the active suspensions into two categories; the low-bandwidth or soft active suspension and the high-bandwidth or stiff active suspension. Low bandwidth or soft active suspensions are characterized by an actuator that is in series with a damper and the spring. Wheel hop motion is controlled passively by the damper, so that the active function of the suspension can be restricted to body motion. Therefore, such type of suspension can only improve the ride comfort. A high-bandwidth or stiff active suspension is characterized by an actuator placed in parallel with the damper and the spring. Since the actuator connects the unsprung mass to the body, it can control both the wheel hop motion as well as the body motion. The high-bandwidth active suspension now can improve both the ride comfort and ride handling simultaneously. Therefore, almost all studies on the active suspension system utilized the high-bandwidth type. Active suspension representation diagram is shown in Figure 2.2.



(a) **(b)**

Figure 2.2: Active Suspension System (a) Low-bandwidth (b) High-bandwidth

Source: Yahaya (2006)

2.2.3 Semi-active suspension system

Suspension system can be classified into two which is passive suspension and active suspension according to the existence of control input. The active suspension system can be further classified into two types which is a semi-active system and a fully active system according to the control input generation mechanism. 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 forces. An electro-rheological (ER) damper or a magneto-rheological (MR) damper applies various levels of electric field or magnetic field to cause various viscosities of the ER or MR fluids.

In early semi-active suspension system, the regulating of the damping force can be achieved by utilizing the controlled dampers under closed loop control, and such is only capable of dissipating energy (Williams, 1994). Two types of dampers are used in the semi-active suspension namely the two state dampers and the continuous variable dampers. The two state dampers switched rapidly between states under closed-loop control. In order to damp the body motion, it is necessary to apply a force that is proportional to the body velocity. Therefore, when the body velocity is in the same direction as the damper velocity, the damper is switched to the high state. When the body velocity is in the opposite direction to the damper velocity, it is switched to the low state as the damper is transmitting the input force rather than dissipating energy. The disadvantage of this system is that while it controls the body frequencies effectively, the rapid switching, particularly when there are high velocities across the dampers, generates high-frequency harmonics which makes the suspension feel harsh, and leads to the generation of unacceptable noise.

The continuous variable dampers have a characteristic that can be rapidly varied over a wide range. When the body velocity and damper velocity are in the same direction, the damper force is controlled to emulate the skyhook damper. When they are in the opposite directions, the damper is switched to its lower rate, this being the closest it can get to the ideal skyhook force. The disadvantage of the continuous variable damper is that it is difficult to find devices that are capable in generating a high force at low velocities and a low force at high velocities, and be able to move rapidly between the two. Karnopp (1990) has introduced the control strategy to control the skyhook damper. The control strategy utilized a fictitious damper that is inserted between the sprung mass and the stationary sky as a way to suppress the vibration motion of the spring mass and as a tool to compute the desired skyhook force. The skyhook damper can reduce the resonant peak of the spring mass quite significantly and thus achieves a good ride quality. But, in order to improve both the ride quality and handling performance of a vehicle, both resonant peaks of the spring mass and the unsprung mass need to be reduced. It is known, however, that the skyhook damper alone cannot reduce both resonant peaks at the same time (Hong et al., 2002). Figure 2.3 shows the representation diagram of semi-active suspension system.

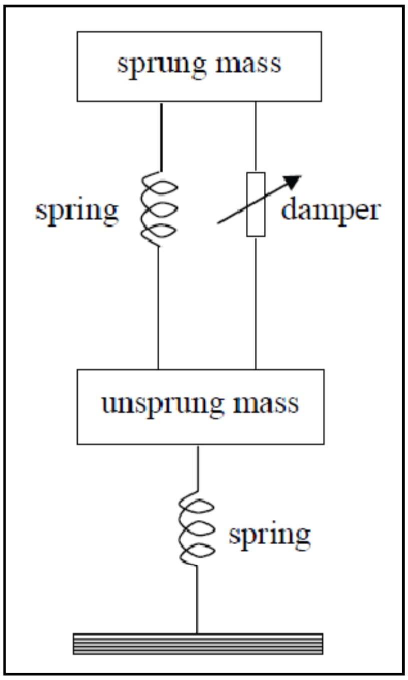


Figure 2.3: Semi-active Suspension Diagram with Controllable Damper.

Source: Yahaya (2006)

More recently, the possible applications of electro-rheological (ER) and magneto-rheological (MR) fluids in the controllable dampers were investigated by Yao et al. (2002) and Choi and Kim (2000). However, since MR damper cannot be treated as a viscous damper under high electric current, a suitable mathematical model is needed to be developed to describe the MR damper.

2.3 Magneto-Rheological (MR) Damper

Magneto-rheological (MR) dampers are semi-active control devices that use MR fluids to produce controllable dampers. They potentially offer highly reliable operation and can be viewed as fail-safe in that they become passive dampers should the control hardware malfunction. To develop control algorithms that take maximum advantage of the unique features of the MR damper, models must be developed that can adequately characterize the damper's intrinsic nonlinear behavior. Following a review of several idealized mechanical models for controllable fluid dampers, a new model is proposed that can effectively portray the behavior of a typical magneto-rheological damper. The Bingham method mathematical model is chosen for modeling the MR damper for this project. The schematic diagram of a MR damper is shown n Figure 2.4.

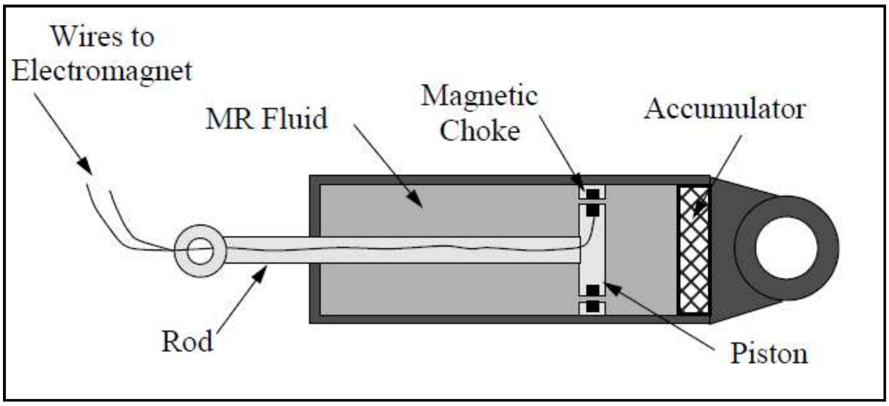


Figure 2.4: MR Damper Schematic Diagram

Source: Spencer et al., (1996)

2.3.1 Bingham mechanical model formulation

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, γ· the total stress is given by:

$$\tau = \tau_{y(field)} + \eta\dot{\gamma} \qquad (2.1)$$

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 2.5.

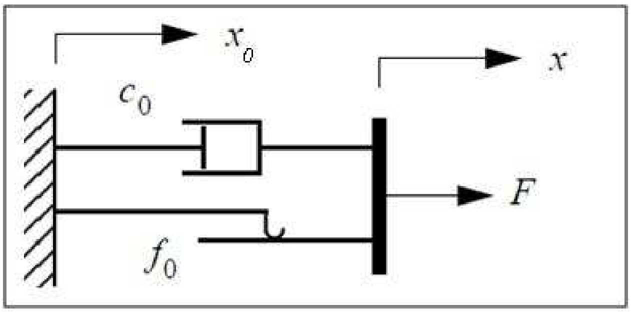


Figure 2.5: Bingham Model of a Controllable Fluid Damper

Source: Gongyu et al., (2000)

The force generated by the MR damper is given by;

$$f = f_o \operatorname{sgn}(\dot{x} - \dot{x}_0) + c_0(\dot{x} - \dot{x}_0) \tag{2.2}$$

Where c_0 is the damping coefficient and f_o is the frictional force, which is related to the fluid yield stress.

Considering that the increase in the damping force is approximately linear for a given increase in the applied voltage, the constants in (2.2) above also considered varying linearly with the applied voltage.

$$c_0 = c_a + c_h V, \qquad f_o = f_a + f_h V \tag{2.3}$$

Where c_a and f_a are constant values when there is no voltage on MR damper while c_h and f_h are the coefficients with voltage.

2.4 Skyhook Controller

Semi-active dampers allow for the damping coefficient, and therefore the damping force, to be varied between high and low levels of damping. Early semi-active dampers were mechanically adjustable by opening or closing a bypass valve. The only power required for the damper is the relatively small power to actuate the valve. For this research, a magneto-rheological damper which varies the damping by electrically changing the magnetic field applied to the magneto-rheological fluid is used. With a semi-active damper, the 2DOF model modifies to Figure 2.6, where the damping coefficient, $C_{ontrollable}$, can be varied in time. This configuration is referred to as a semi-active suspension.

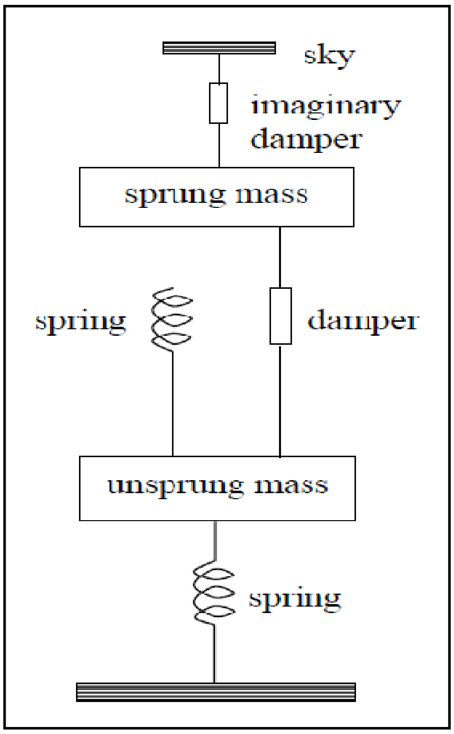


Figure 2.6: 2DOF Skyhook Damper Configuration

Source: Yahaya (2006)

Once it is decided that a semi-active damper is used, the means of modulating the damper such that it emulates a skyhook damper must be determined. We first define the velocity of the sprung mass relative to the unsprung mass, V_{12}, to be positive when the sprung mass and unsprung mass are separating (i.e., when V_1 is greater than V_2) for the systems. Now assume that for both systems, the sprung mass is moving upwards with a positive velocity V_1. If we consider the force that is applied by the skyhook damper to the sprung mass, we notice that it is in the negative X_1 direction, or

$$F_{sky} = -C_{sky}V_1 \tag{2.4}$$

Where, F_{sky} is the skyhook force and C_{sky} is the skyhook damping coefficient. Next, is to determine if the semi-active damper is able to provide the same force. If the sprung and unsprung masses in Fig. 3.1 are separating, then the semi-active damper is in tension. Thus, the force applied to the sprung mass is in the negative X_1 direction, or

$$F_{controllable} = -C_{controllable}V_{12} \tag{2.5}$$

Where $F_{controllable}$ is the force applied to the sprung mass. Since we are able to generate a force in the proper direction, the only requirement to match the skyhook suspension is

$$C_{controllable} = C_{sky}\frac{V_1}{V_{12}} \tag{2.6}$$

To summarize, if V_1 and V_{12} are positive, $C_{CONTROLLABLE}$ should be defined as in equation above. Now consider the case in which the sprung and unsprung masses are still separating, but the sprung mass is moving downwards with a negative velocity V_1. In the skyhook configuration, the damping force will now be applied in the upwards, or positive, X_1 direction. In the semi-active configuration, however, the semi-active damper is still in tension, and the damping force will still be applied in the downwards, or negative, direction. Since the semi-active damping force cannot possibly be applied in the same direction as the skyhook damping force, the best that can be achieved is to minimize the damping force. Ideally, the semi-active damper is desired to be set so that there is no damping force, but in reality there is some small damping force present and it is not in the same direction as the skyhook damping force. Thus, if V_{12} is positive and V_1 is negative, we need to minimize the semi-active damping force.

We can apply the same simple analysis to the other two combinations of V_1 and V_{12}, resulting in the well-known semi-active skyhook control policy:

$$\begin{cases} V_1 V_{12} > 0 & F_{SA} = C_{SKY} V_1 \\ V_1 V_{12} < 0 & F_{SA} = 0 \end{cases} \tag{2.7}$$

Where, F_{SA} is the semi-active skyhook damper force. Equation (4) implies that when the relative velocity across the suspension (V_{12}) and the sprung mass absolute velocity (V_1) have the same sign, a damping force proportional to V_1 is desired. Otherwise, the minimal amount of damping is desired. Further, Equation (4) provides a very simple method to emulate the ideal skyhook suspension system using only a semi-active damper.

The skyhook damper configuration attempts to eliminate the trade-off between resonance control and high frequency isolation common to passive suspensions (Alleyne et al., 1993). Consider the arrangement in Figure 2.6. The damper is connected to an inertial reference in the sky. Clearly, this arrangement is fictitious, since for this configuration to be implemented, the damper would have to be connected to a reference point which is fixed with respect to the ground but can translate with the vehicle. Such a suspension mounting point does not exist. The end goal of skyhook control is not to physically implement this system, but to command a controllable damper to cause the system to respond in a similar manner to this fictitious system.

In essence, this skyhook configuration is adding more damping to the sprung mass and taking away damping from the unsprung mass. The skyhook configuration is ideal if the primary goal is isolating the sprung mass from base excitations, even at the expense of excessive unsprung mass motion. An additional benefit is apparent in the frequency range between the two natural frequencies. With the skyhook configuration, isolation in this region actually increases with increasing C_{sky}.

2.5 Literature Review of Previous Research

This subchapter is conducted to investigate the past research done in any areas that are related to this project. The main interests are semi-active control, car suspension system, magneto-rheological dampers and skyhook controller. Figure 2.7 below show a flowchart of the literature search according to the keywords used.

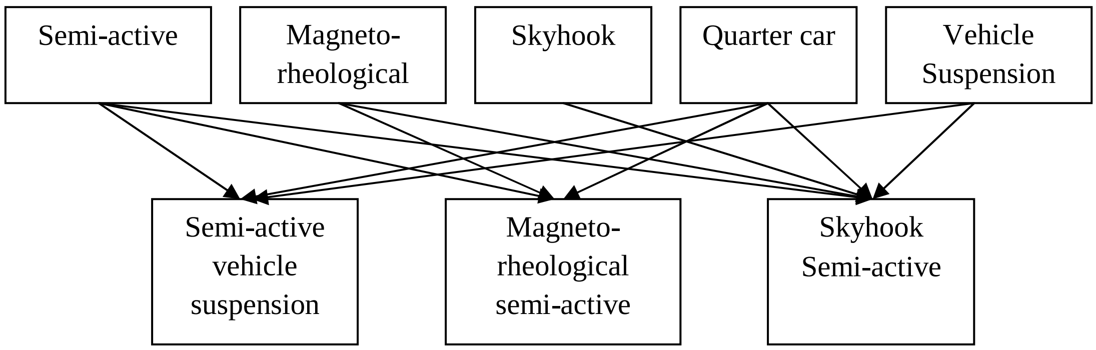


Figure 2.7: Flowcharts of the Literature Search

Keywords from the first tier of the flowchart give vast number of results but in order to avoid searching through large numbers of possibly unrelated papers, the keywords from second tier are used. In addition to the journal reviewed, many books and other papers related to the areas of vehicle dynamics, semi-active suspension control, and magneto-rheological dampers have been read and consulted over the course of this project.

A literature search was performed to investigate what others have done in areas relating to this work. The search included the areas of semi-active dampers, magneto-rheological fluid devices, and semi-active control.

2.5.1 Semi-active suspension

Searching under semi-active resulted in many papers that discussed the performance benefits of semi-active control on semi-active dampers. Lieh and Li (1997) discuss the benefits of an adaptive fuzzy control compared to simple on-off and variable semi-active suspensions. The intent of their work is to apply a fuzzy logic concept to control semi-active damping that is normally nonlinear with stochastic disturbances. A quarter-car model was used to implement the fuzzy control rule. A paper by Hennecke et al., (1990) discussed the development of a semi-active suspension for BMW's top models. Their work showcases BMW's latest advancement in their adaptive, frequency-dependent damper control. The system has three discrete, digressive damping characteristics, and varies the damping forces at the front and rear axles independently. In their work, the authors describe the frequency-selective and amplitude-dependent control strategy. The system shows potential for improving comfort and road safety.

The study by Ahmadian, (1993) examines the effects of semi-active damping on class 8 trucks. The truck was tested on both city streets and highway roads under different damper configurations. The study placed semi-active dampers on the front axle and passive dampers on the rear axles proved to be a better configuration than semi-active dampers on the rear axles and passive dampers on the front axle. The ride quality of the first configuration was shown to be nearly equal to that of semi-active dampers on all axles.

A preview estimation technique is used in studies performed by Hac and Youn (1992), and Huisman et al., (1993). The semi-active controller uses knowledge of approaching road disturbances from preview sensors to minimize the response to these disturbances. Giua et al., (1998), Lieh, J (1991), and Giua et al., (1999) use optimal control techniques for use in semi-active suspensions.

2.5.2 Magneto-Rheological damper (MR damper)

Searching under Magneto-Rheological damper resulted papers that discussed several different applications of MR dampers. The first by Lee and Choi (2000) presented the control characteristics of a full-car suspension with a MR damper. This study progressed into a full-car model where vertical, pitch, and roll motions were included. The control characteristics are evaluated through hardware-in-the-loop simulations. Sims et al., (1999) presented a less conventional use for MR fluid. Their work used a MR damper in the squeeze-flow mode. In squeeze-flow mode large, controllable forces can be generated over small displacement ranges. The authors describe a MR squeeze-flow device incorporated as the damping element in a vibration isolator.

MR dampers have reached into several other less conventional realms. Ahmadian (1999) discusses the development of MR dampers for use in bicycle suspensions. Results show that properly designed MR dampers can provide significant performance benefits over traditional passive bicycle dampers. Peel et al., (1996) present the benefits of using MR dampers to control the lateral vibrations of a modern rail vehicle. It is shown that a controllable MR damper can be designed to improve upon the specification for a conventional lateral railcar damper. Furthermore, Ahmadian et al., (1999) studied the advantages of using MR dampers for controlling shock loading. Their work shows that using a system that includes a 50-caliber rifle and a MR damper, the MR damper can be quiet effective in controlling the compromise that exists between shock forces and strokes across the shock absorber. This experimental study further shows that MR dampers can be used to adjust the shock loading characteristics in a manner that fits the dynamic system constraints and requirements. Choi et al., (2000) explore the use of MR fluid dampers in semi-active seat suspensions. A skyhook control scheme is employed to reduce the vibration level at the driver’s seat.

2.5.3 Skyhook control

The skyhook search resulted in several papers dealing directly with the implementation of skyhook control in vehicle applications. Shon et al., (2000) explore skyhook control for the semi-active Macpherson suspension system. The absolute velocity of the sprung mass and the relative velocity across the damper are estimated. The semi-active damper is included in the loop of computer simulations so as to incorporate the non-linearity, time-delay, and unmodeled dynamics of the continuously variable damper. Ikenaga et al., (2000) include skyhook damping in their study of suspension control of ground vehicles based on a full-vehicle model. Another study by Ikenaga et al., (2000) shows that motions of the sprung mass above and below the wheel hop mode can be diminished using skyhook damping plus active filtering of spring and damping coefficients.

Several other papers demonstrate the benefits of using skyhook damping for vehicle applications. Akatsu et al., (1990) developed an active suspension employing an electro hydraulic servo system. Their system features a skyhook damper which can reduce body vibration to less than one-half that of conventional suspensions at low frequencies. Hrovat and Hubbard (1981) explore using a skyhook spring as well as a skyhook damper in a simple single-degree-of-freedom vehicle model. Their performance index includes RMS jerk along with the more conventional RMS acceleration.

Finally, Ahmadian (1997) discusses the advantages of using skyhook dampers for secondary suspensions. It is shown that semi-active skyhook dampers provide a more favorable control of the dynamic resonance without decreasing the isolation effectiveness of the suspension. Furthermore, the study shows that the skyhook damper offer more control at one body at the expense of less control on the other body. In his study, Ahmadian also introduces an alternative semi-active control policy called hybrid control which can provide better control of both bodies.

2.5.4 Literature Review Summary

Of the previous studies mentioned in this literature review, the majority have been analytical studies. Model simulations and analytical studies have dominated the studies in this area. To date, few works have thoroughly investigated the commonly considered semi-active control policies, such as skyhook control. The research presented in the following chapters intends to contribute to the investigation of semi-active control. The extensive simulation analysis presented in this project aims to complement the analytical studies of the past.

CHAPTER 3

METHODOLOGY

3.0 Introduction

This chapter discussed in detailed about the method used for modeling the suspension system and simulation process. This chapter begins with a brief explanation of the step involved in this project and followed by a methodology flowchart as the summary. The processes of each step that involved in this project are then is described and discussed thoroughly in this chapter. This chapter is important in ensuring the objective of this project achieved successfully.

3.1 Methodology Process

This project starts with title confirmation with the supervisor of the project. Then the project background, problem statement, objectives and the scopes of the project is discussed with supervisor in order to understand what the overall project is about. Literature review is then conducted in order to investigate past researches in the areas related to this project. Literature review is important as it helps to understand more about the project as well as to get more information about the data and results that can help or used in this project.

After getting enough information about the project, the modeling of the Simulink diagram is started. Firstly is to model the 2DOF passive suspension system Simulink diagram in MATLAB. The modeling is done by following the equation of motion for the 2DOF passive suspension system. The next process is modeling the skyhook controller Simulink diagram according to the equation that is sourced from the journal. The Simulink diagram of MR damper then is developed and modeled. The MR damper is developed by following the mechanical model formulation of the Bingham method.

The next step is creating the Simulink diagram of semi-active suspension system with skyhook controller. This is achieved by replacing the hydraulic damper in passive suspension system with the MR damper and attached the skyhook controller. Simulink diagram of semi-active suspension system with modified skyhook controller is created after that by adding the modified skyhook controller Simulink diagram to the previous semi-active suspension system with skyhook controller.

After completing all the Simulink diagrams needed for this project, the simulation processes are done in the MATLAB. The results of the simulation then are analyzed and discussed briefly. The final step is writing the final report of the project which includes all five chapters starting from introduction, literature review, methodology, results analysis and the conclusion. The summary of all the methodology above can be summarized into a methodology flowchart which is shown in Figure 3.1 at the next page. All the methodology processes are following the timeline in the Gantt chart which is attached in the appendix.

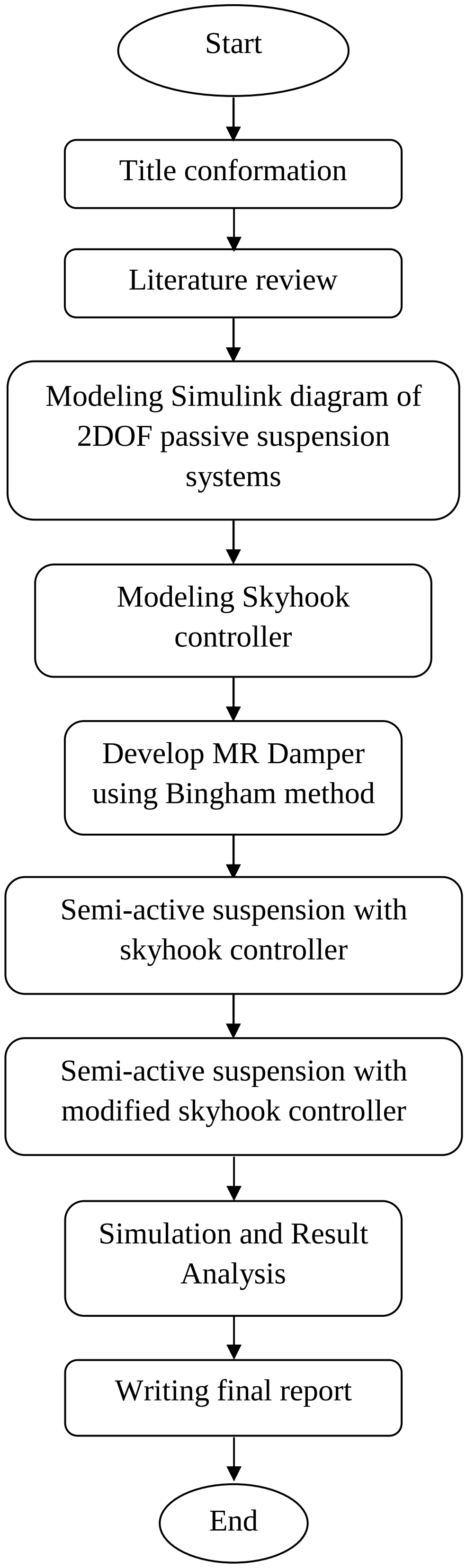


Figure 3.1: Methodology Flowchart

3.2 Modeling and 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 of the suspension system. 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. For simulation, the complete Simulink diagram must modeled first in order to represent the real suspension system configuration. Figure 3.2 shows the MATLAB interface and Figure 3.3 shows the MATLAB Simulink Library.

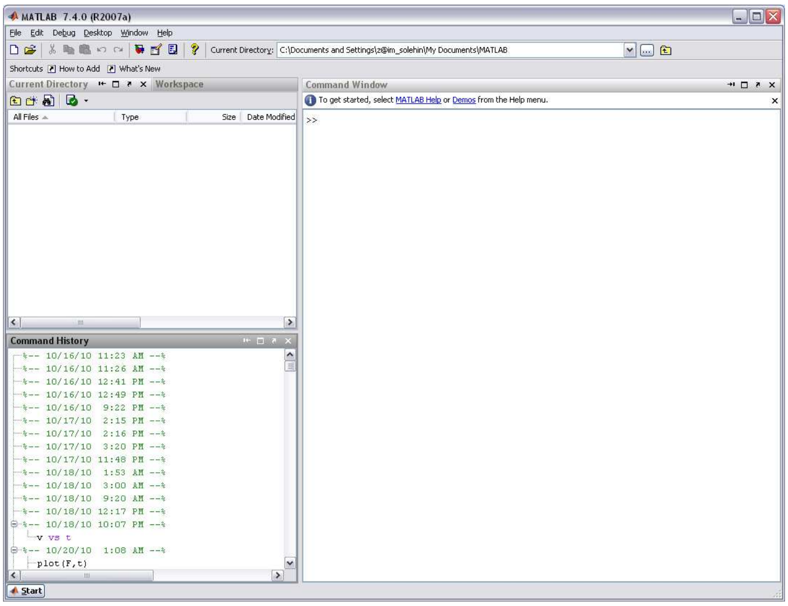


Figure 3.2: MATLAB Interface

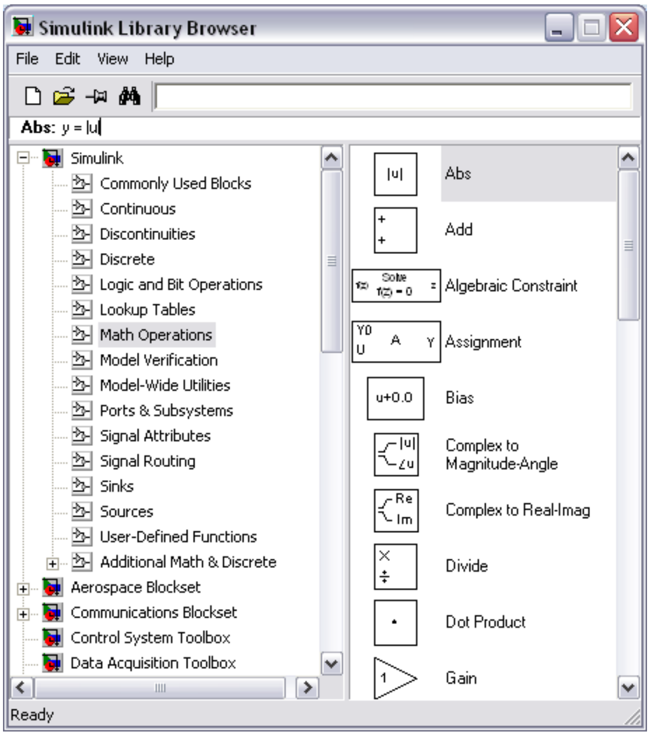


Figure 3.3: MATLAB Simulink Library

3.3 2DOF Quarter Car Passive Suspension System Modeling

The passive quarter car was design as a representation of a classic two degree of freedom (2DOF) suspension system. In the physical implementation of the 2DOF model, each component of the quarter-car was chosen to closely resemble the characteristics of one quarter of a passenger vehicle. Figure 3.4 below shows the 2DOF quarter car passive suspension system representation.

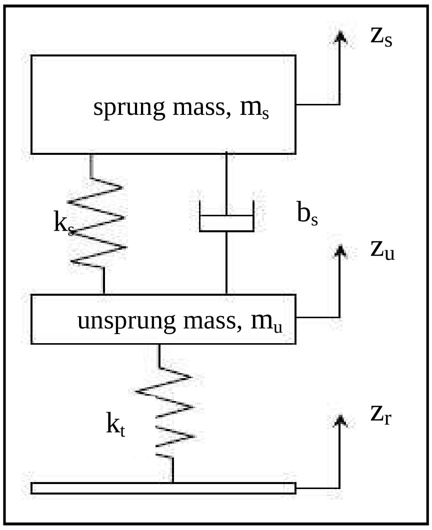


Figure 3.4: 2DOF Quarter Car Representation System

The Simulink modeling is done by following the mathematical representation of the passive suspension system which is its equation of motion. For 2DOF quarter car passive suspension system, the mathematical representations are below:

$$m_s\ddot{z}_s = -k_s(z_s - z_u) - b_s(\dot{z}_s - \dot{z}_u) \quad (3.1)$$

$$m_u\ddot{z}_u = k_s(z_s - z_u) + b_s(\dot{z}_s - \dot{z}_u) - k_t(z_u - z_r) \quad (3.2)$$

Where;

m_s = sprung mass

m_u = unsprung mass

b_s	= damping coefficient
k_s	= spring stiffness coefficient
k_t	= tire stiffness coefficient
z_u	= displacement of unsprung mass
z_r	= displacement of road
$z_s - z_u$	= suspension deflection
$z_u - z_r$	= tyre deflection
z_s	= sprung mass displacement
$\ddot{z}_s$	= sprung mass acceleration

The equation (3.1) is for the sprung mass, m_s and equation (3.2) is for the unsprung mass, m_u. Therefore, from the equations above, the Simulink diagram of 2DOF quarter car passive suspension system is developed. Although there are two equations involved in modeling this Simulink diagram, it can be simplified to get only one Simulink diagram representation of the 2DOF quarter car passive suspension system. The Simulink diagram of 2DOF quarter car passive suspension system is shown as in Figure 3.5.

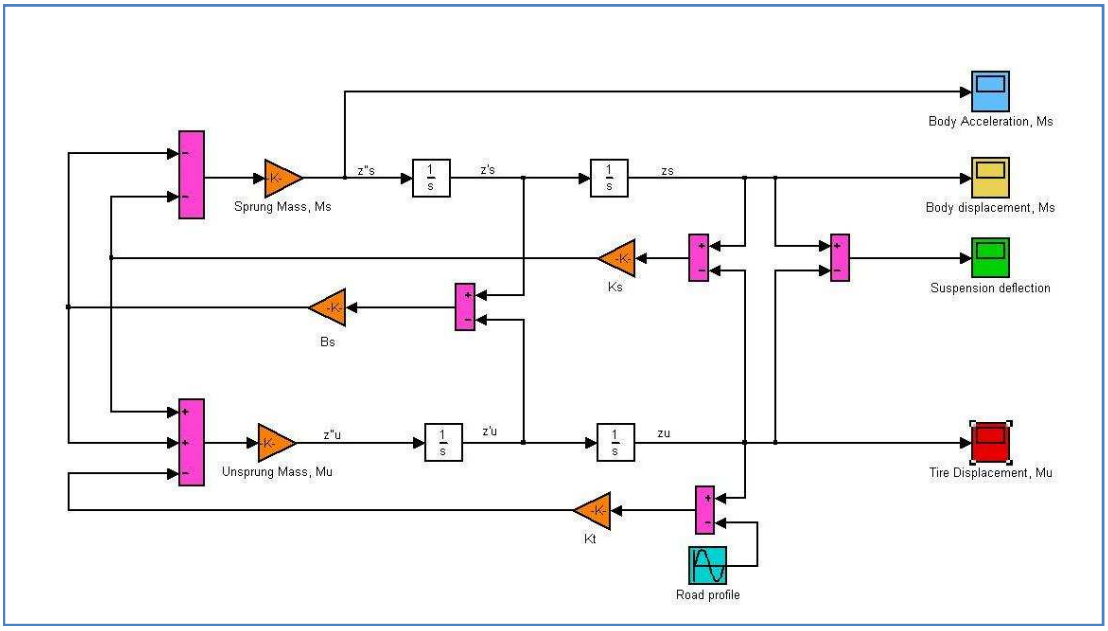


Figure 3.5: Simulink of 2DOF Quarter Car Passive Suspension System

Scope is a block diagram in Simulink that is used to display the results of the simulation in graph. The input for the scope is taken from specific placed according to what parameters that the scope is set to displayed. As explained in the early chapter, the important parameter that is associated with passengers comfort are sprung mass (m_s) acceleration. But the other three parameters also important which are sprung mass (m_s) displacement, usprung mass (m_u) displacement and suspension deflection. This is to ensure that the traction force between the tire and the road is maintained while the comfort is increased.

A set of data for the quarter car must be put into the Simulink diagram in order to represent the suspension system and to run the simulation. There are two ways for inserting data into the Simulink diagram which is by using M-file function or directly key in the data into the specific block in the Simulink diagram according to the part of the suspension that the block represented. For this project, the second way is chosen as it is much simpler and consumed less time. The data is inserted into the Gain block which is triangular in shape and orange colored.

Table 3.1 2DOF quarter car passive suspension system data

Source: Lin and Kanellakopoulos (1997)

Data	**Value**
Sprung mass, m_s	290kg
Unsprung mass, m_u	59kg
Spring stiffness, k_s	16 812 N/m
Damping Coefficient, b_s	1000 N.s/m
Tire Stiffness, k_t	190 000 N/m

3.4 Modified Skyhook Controller Modeling

The modified skyhook controller position in the quarter car system is shown by Figure 3.6. The ideal concept of skyhook control is by attaching an imaginary damper to the sprung mass and fixed sky. In reality it is not possible hence a realization model is developed.

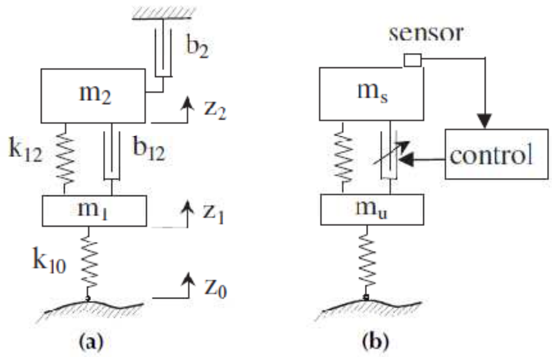


Figure 3.6: Skyhook Control (a) Ideal concept (b) Skyhook controller realization

Source: Karnopp et al., (1974)

The equation of the modified skyhook controller is given as below:

Modified Skyhook: $C_{sky}\,[\alpha\,(\dot{z}_u\; - \;\dot{z}_s) + \,(1 - \,\alpha)\dot{z}_s]$ (3.1)

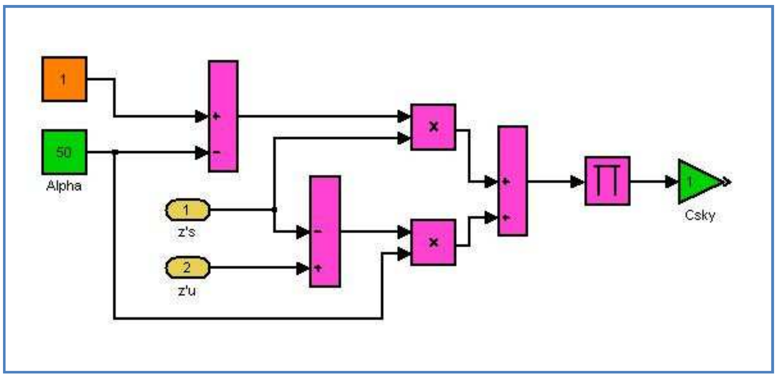


Figure 3.7: Simulink of Modified Skyhook Controller

Figure 3.7 in the previous page shows the Simulink diagram of the modified skyhook controller. Modified skyhook controller has two inputs which are sprung mass (m_s) velocity and unsprung mass (m_u) velocity. The yellow blocks in the Simulink diagram are the input blocks and it is connected to the quarter car suspension system to get the desired input. Modified skyhook controller has two manipulated parameters which is C_{sky} and α. Both parameters are represented by the green colored blocks and are manipulated to get the best skyhook damping in order to increased passengers comfort.

3.5 MR Damper Modeling

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

$$f = f_o \text{ sgn } (\dot{x} - \dot{x}_0) + c_0(\dot{x} - \dot{x}_0) \tag{3.2}$$

Where,

$$c_0 = c_a + c_h V, \qquad f_o = f_a + f_h V \tag{3.3}$$

The data for Bingham method MR 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 et al., (2000)

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

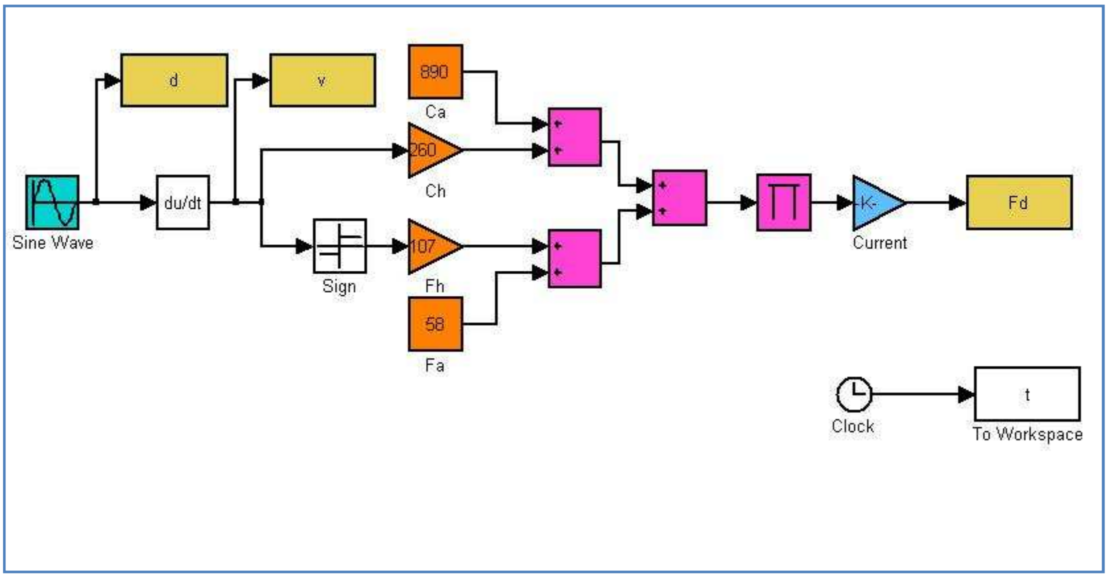


Figure 3.8: Simulink of Bingham Method MR Damper

The data of MR damper are inserted in the orange blocks. The sine wave block and current block is inserted for the checking purposed. Those blocks are removed when the MR damper is replacing the hydraulic damper in the passive suspension system. The input for the MR damper actually is the sprung mass (m_s) velocity minus unsprung mass (m_u) velocity.

The Simulink diagram 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 thus producing accurate results in the end of the project. The Simulink diagram of MR damper must produce damping forced according to the predicted characteristic shown in Figure 3.9.

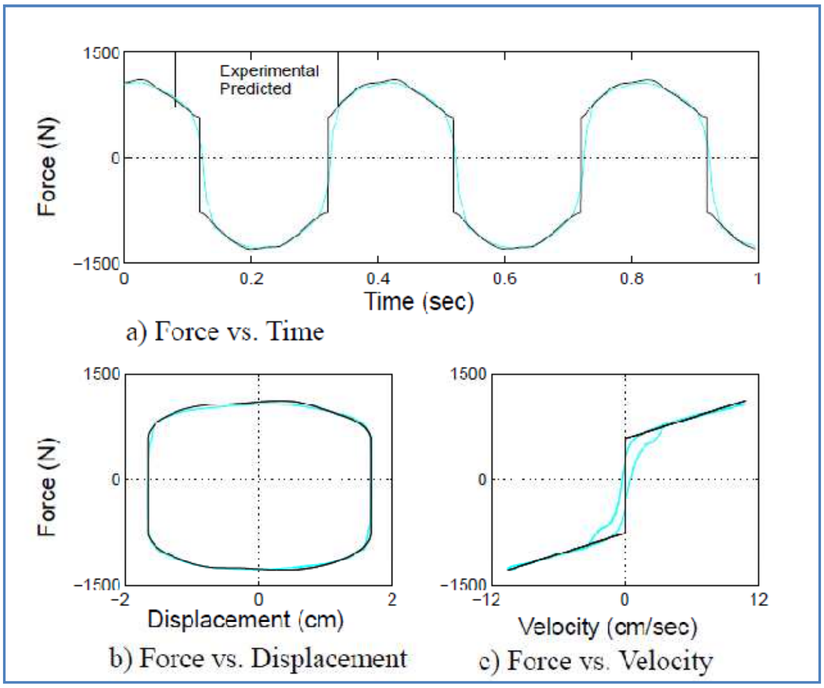


Figure 3.9 Predicted Characteristic of Bingham Method MR Damper

Source: Spencer et al., (1996)

3.6 Semi-Active Suspension Analysis

The semi-active suspension analysis is divided to two parts as this project also compared the different controller configuration. The first controller is the basic skyhook controller and the second controller is the modified skyhook controller.

3.6.1 Semi-active suspension with skyhook controller

To create a semi-active suspension representation model in Simulink, 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 a 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.

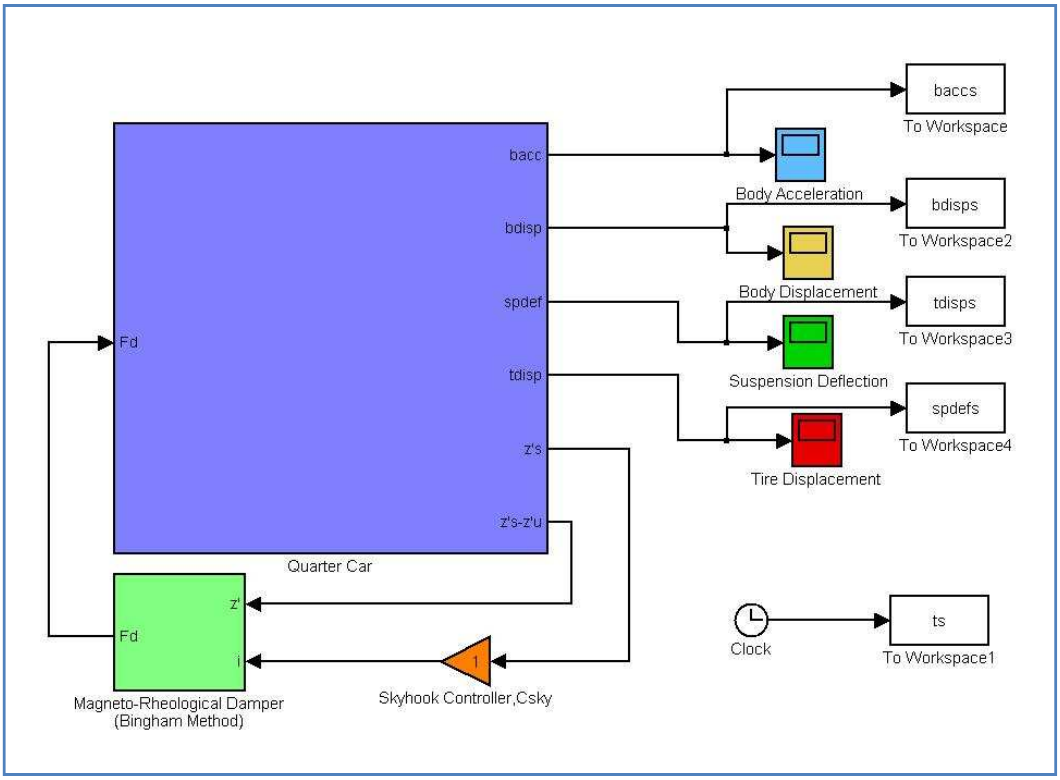


Figure 3.10: Simulink of Semi-active Suspension with Skyhook Controller

Figure 3.10 above shows the complete Simulink diagram of the semi-active suspension with skyhook controller. The skyhook controller is represented by the Gain block and the value of C_{sky} is manipulated to get the best damping force that can improve comfort. The actual skyhook control value, C_{sky} is automatically configured by a computer box but for this project it is enough to represent it with a Gain block.

As in Simulink of passive suspension system, the scopes are placed also to shows the results of the simulation in graph. The input for each scope is exactly the same as in the passive suspension system as the scopes are showing the same parameters results.

3.6.2 Semi-active suspension with modified skyhook controller

Figure 3.11 shows the complete Simulink diagram of semi-active suspension system with modified skyhook controller. The difference of this Simulink diagram is the controller for the suspension system. The modified skyhook controller that has been developed before is added to the semi-active suspension Simulink diagram. For the simulation, the best value of C_{sky} from semi-active suspension with skyhook controller is retained. The only parameter that is manipulated is the value of α in order to improve the previous simulation result.

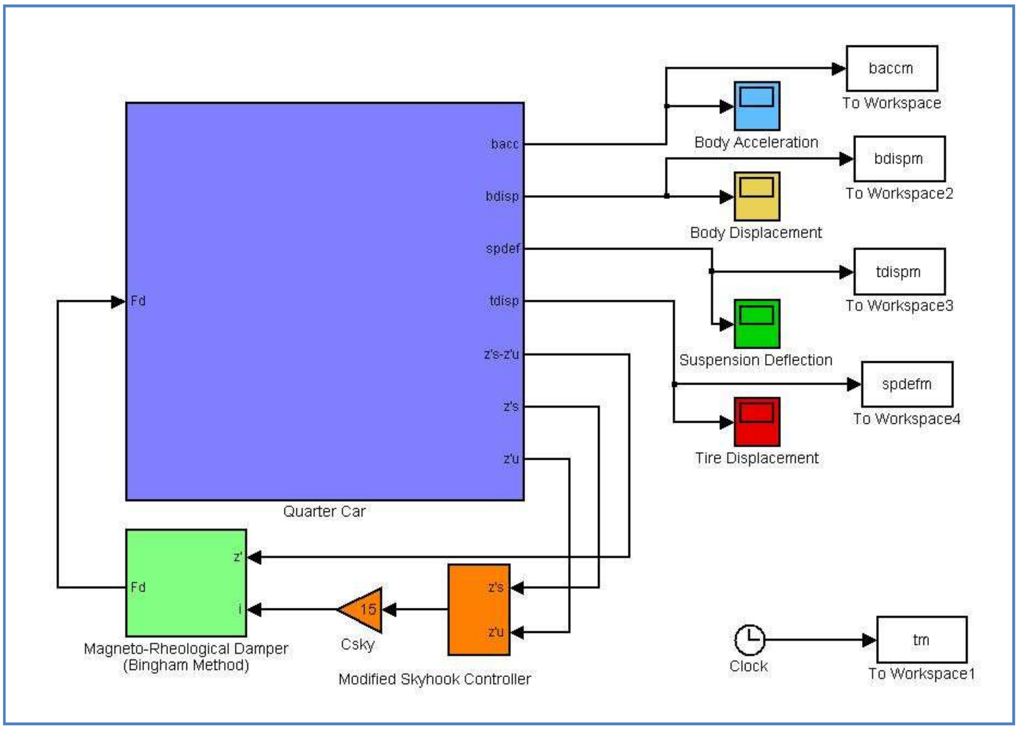


Figure 3.11: Simulink of Semi-active Suspension with Modified Skyhook Controller

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

In this chapter, all the findings and results are showed and discussed briefly. For all the simulations, the road profile given is a sin wave with amplitude of 0.05m and frequency is 1 Hz. This is to ensure all suspension configurations are tested on the same road profile. The results of passive suspension system is showed first and discussed accordingly. The results of MR damper simulation then are previewed to see whether the response of the damper is similar to the predicted results. Next are the simulation results of semi-active suspension with skyhook controller and then followed by simulation results of semi-active suspension with modified skyhook controller. The results then are compared to see which suspension system configuration gives best comfort to the passengers.

4.1 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 is the sprung mass (m_s) acceleration of the system. The acceleration pattern is quite random in early 5 seconds before it becomes a constant sine wave graph with the maximum acceleration is 0.35 m/s^2 average acceleration of 0.05 m/s^2. The random acceleration pattern makes the passengers feel uncomfortable.

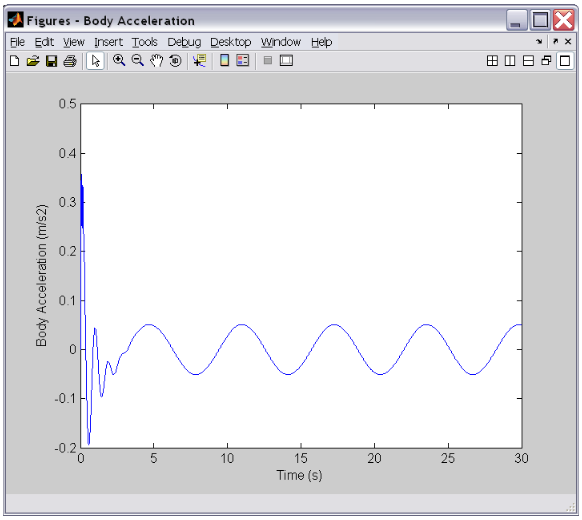


Figure 4.1: Passive suspension sprung mass (m_s) acceleration

Figure 4.2 shows the sprung mass (m_s) displacement of the passive suspension system. As mention in the introduction for this chapter, the amplitude of road profile is 0.05m. The result shows no decrement of amplitude of the sprung mass (m_s) displacement which means that the vehicles body is displaced in the same amount of the road profile. In reality, the passengers absolutely feel the bump on the road hence it can be describe as uncomfortable.

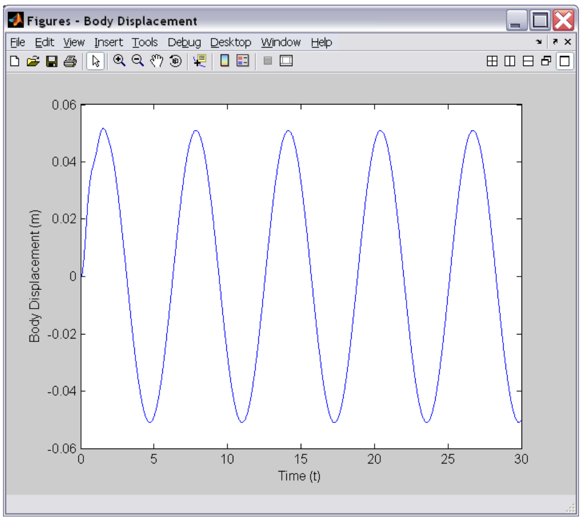


Figure 4.2: Passive suspension sprung mass (m_s) displacement

Figure 4.3 is the suspension deflection that occurs during the simulation process. The pattern of the graph is similar with sprung mass (m_s) acceleration but the amplitude is different. The same pattern occurs because suspension deflection is directly proportional with the sprung mass (m_s) acceleration. The maximum deflection of the suspension is 0.008m.

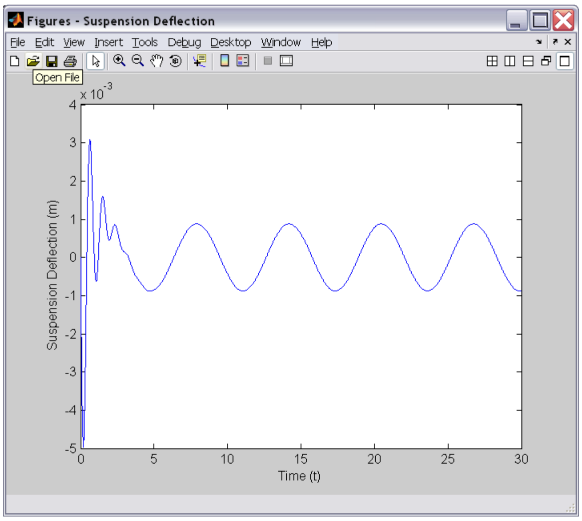


Figure 4.3: Passive suspension deflection

Figure 4.4 is the unsprung mass (m_u) displacement. The amplitude and graph pattern is similar to the road profile which means that the traction force is good.

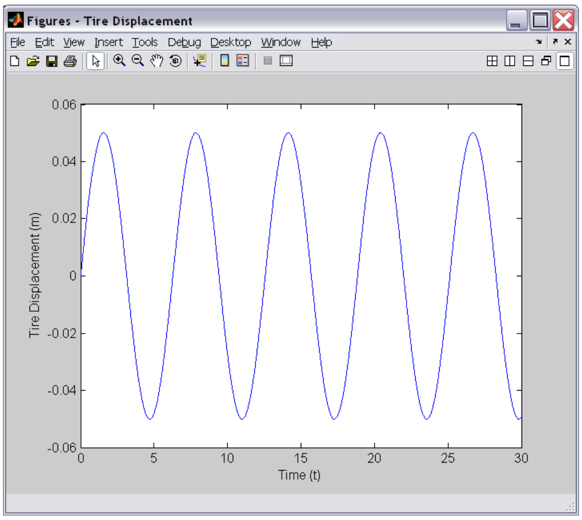


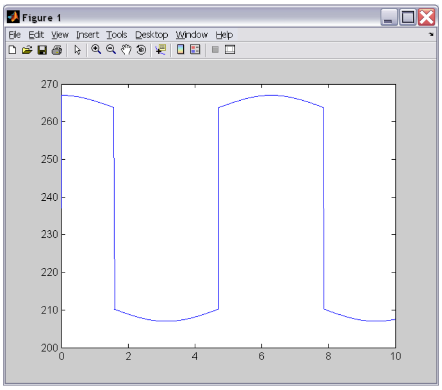
Figure 4.4: Passive suspension unsprung mass (m_u) displacement

In overall, although this passive suspension system configuration has good traction force between the tire and the road, it is very uncomfortable to the vehicle passengers. This passive suspension system is very stiff and not absorbing the disturbance from the road profile. The passengers definitely can feel the disturbance as the suspension system did not isolate vehicle body from road disturbance very well.

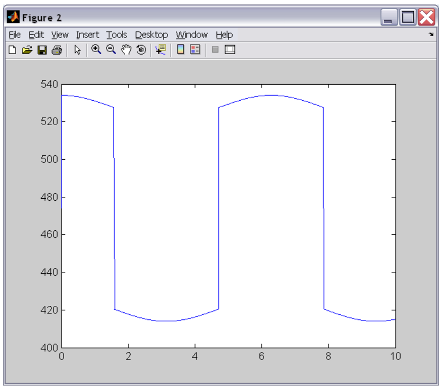
4.2 Bingham Method MR Damper Response and Characteristic Results

The result from this simulation process shows the characteristic of the Magneto-Rheological damper that is developed by using Bingham method. The result from this 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 (m_s) 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 Chapter 3. Based from the comparison of the graph pattern, it can be concluded that this Simulink diagram of MR damper is correct and can be used as a representation model of the real MR damper.

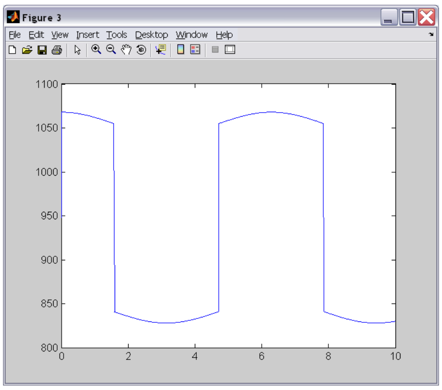
For this simulation process, the MR damper is also tested with different current values just to show how it increased the damping force. The damping force is directly proportional with the current given to the MR damper. The current given to the MR damper starts from 0.25A, 0.5A, 1.0A, 1.5A and ends with 2.0A. Figure 4.5 shows the graph of force vs. time. The graph pattern looks like a sine wave but with boxy edge. This is because the mathematical model that is used for modeling is the simplest one.



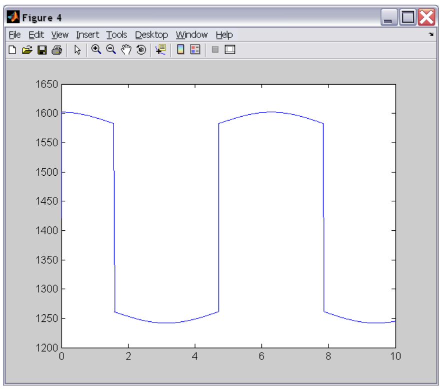
(a) I = 0.25A



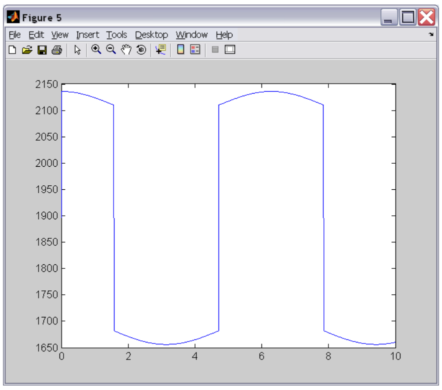
(b) I = 0.5A



(c) I = 1.0A



(d) I = 1.5A



(e) I = 2.0A

Figure 4.5: Graph of Force vs. Time

Figure 4.6 in the next page shows the displacement vs. time graph. Although the current given is increasing but the displacement is equally the same for all current. The amplitude of the displacement is equal to the input signal which is 0.05m.

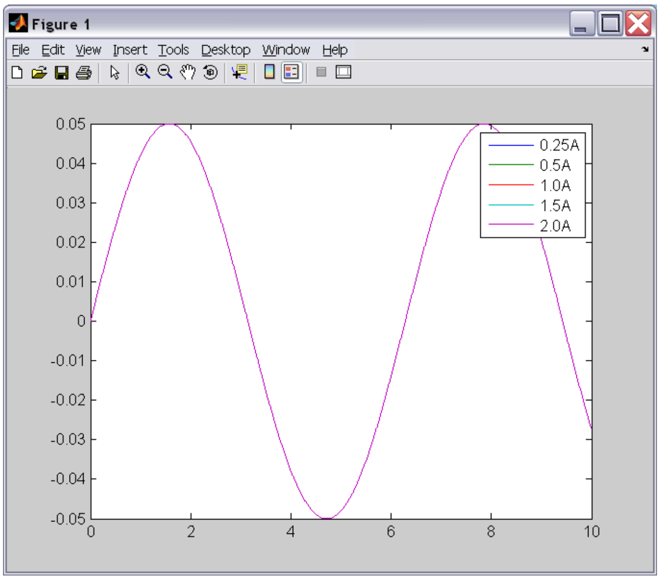


Figure 4.6: Graph of Displacement vs. Time

Figure 4.7 below shows the velocity vs. time graph. For this graph, the amplitude is equal for all current given as in Figure 4.6 but the graph pattern is in opposite direction.

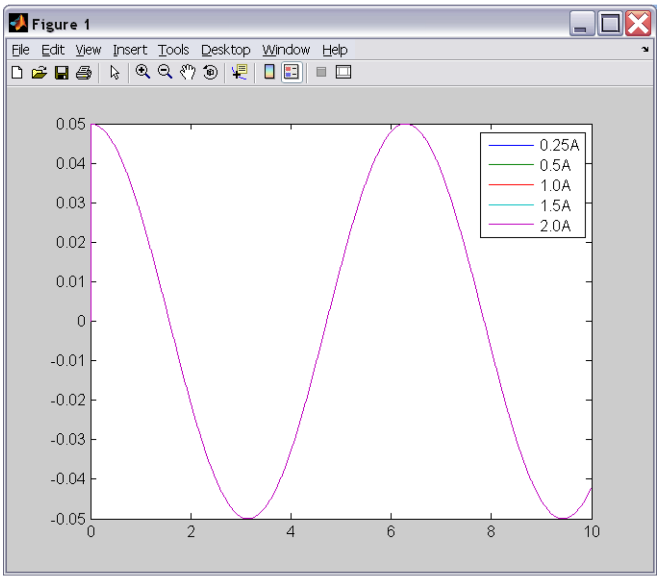
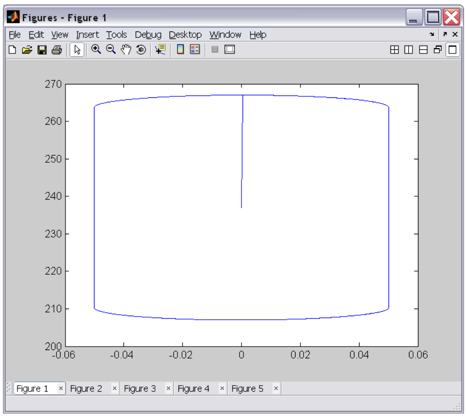
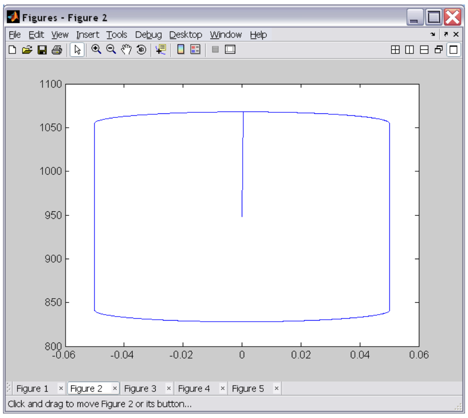


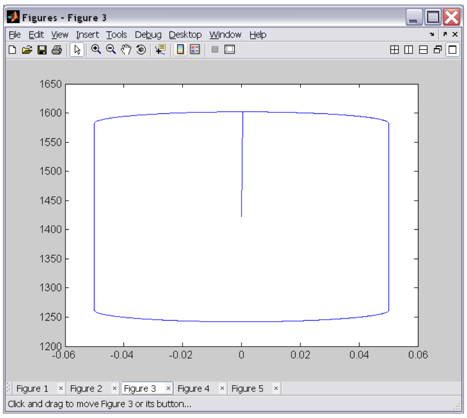
Figure 4.7: Graph of Velocity vs. Time



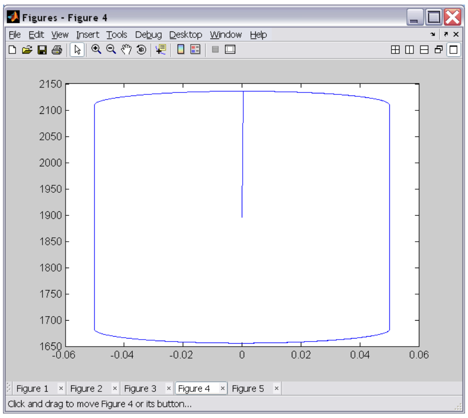
(a) I = 0.25A



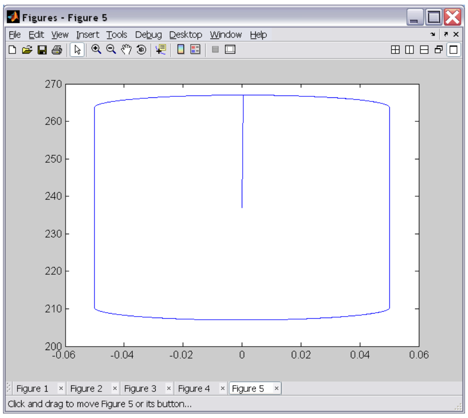
(b) I = 0.5A



(c) I = 1.0A



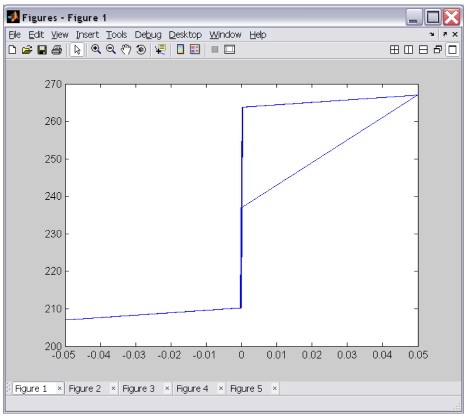
(d) I = 1.5A

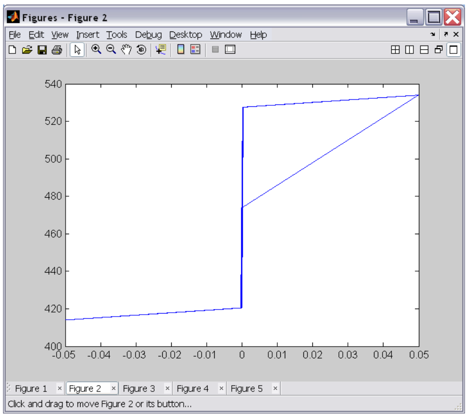


(d) I = 2.0A

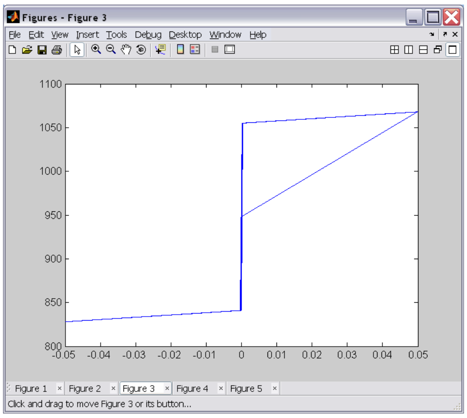
Figure 4.8: Graph of Force vs. displacement

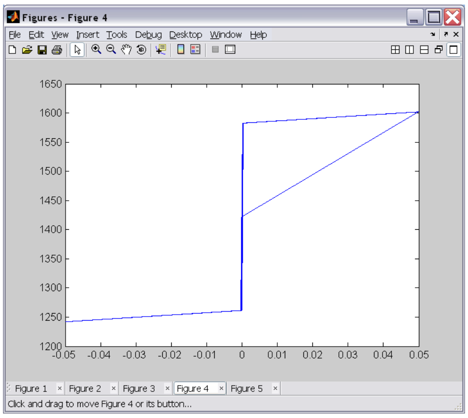
Figure 4.8 above shows the force vs. displacement graph of the MR damper. The graph is in a loop similar to its predicted characteristic that is shown in Chapter 3. The loop is quite boxy in shape as this model used simple mathematical model.



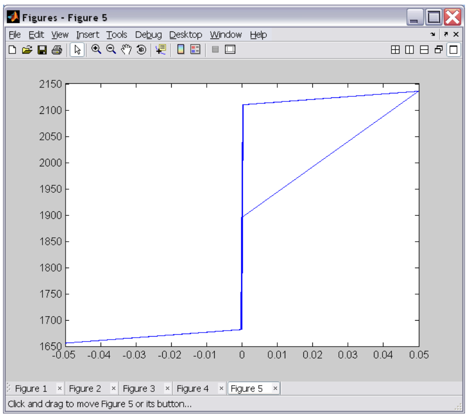


(a) I = 0.25A (b) I = 0.5A





(c) I = 1.0A (d) I = 1.5A



(d) I = 2.0A

Figure 4.9: Graph of Force vs. velocity

Figure 4.9 above shows the graph of force vs. velocity. The force increased dramatically when the velocity is equal to zero. But the force then increased slowly at some point. As mentioned before, the graph is boxy in the edge as the Simulink of MR damper used simple mathematical model.

4.3 Semi-Active Suspension with Skyhook Controller Results

The results of semi-active suspension with skyhook controller are shown in this subchapter. 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 the vehicle.

4.3.1 Finding the best value of C_{sky}

In the reality, 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 manually manipulated in order to get the best results. 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 4.10 to Figure 4.13 shows the results for each parameter for semi-active suspension with skyhook controller.

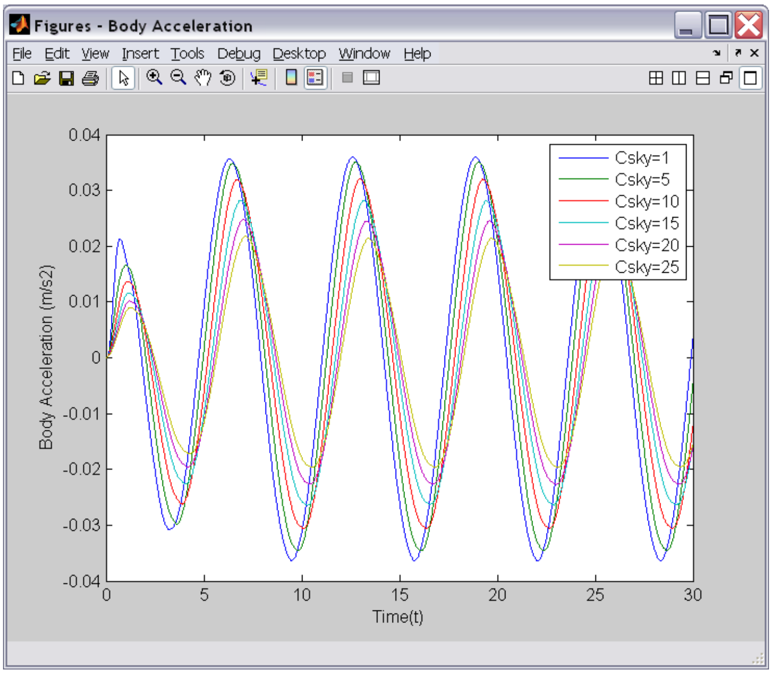


Figure 4.10: Graph of Sprung Mass (m_s) Acceleration vs. Time

Figure 4.10 in the previous pages shows the sprung mass (m_s) acceleration when the system given the specific C_{sky} value. The values of C_{sky} that are shown in the graph are 1, 5, 10, 15, 20 and 25. From the graph, the acceleration of the sprung mass (m_s) is decreasing with each increment of the C_{sky} value. As discussed in the previous chapter, passengers are more comfortable in a vehicle that has low sprung mass (m_s) acceleration.

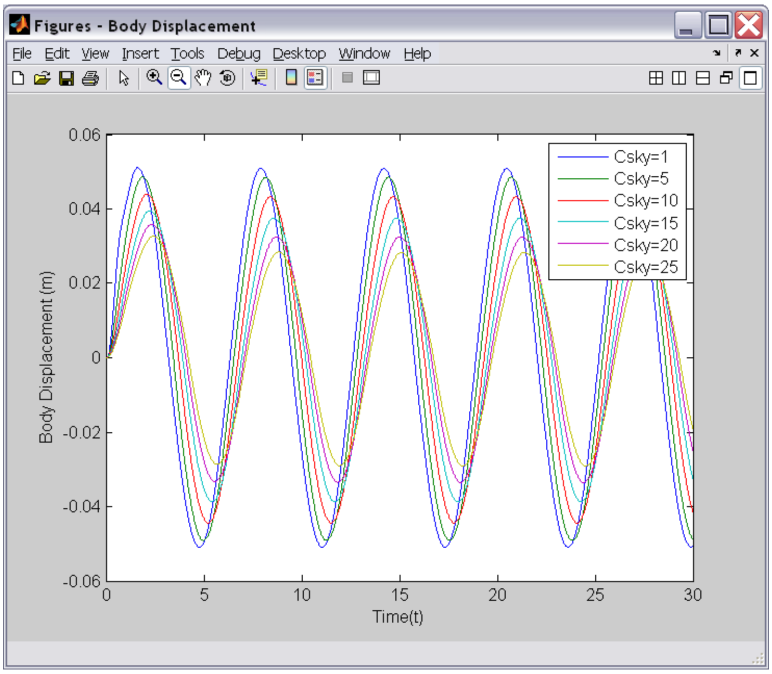


Figure 4.11: Graph of Sprung Mass (m_s) Displacement vs. Time

Figure 4.11 is the sprung mass (m_s) displacement and the amplitude of the graph is decreasing with the increment of C_{sky} value. The decreasing of sprung mass (m_s) displacement means that the comfort of the vehicle passengers is increased. The skyhook controller gives best damping force that can absorb the road disturbance hence isolate the disturbance from the vehicle body.

Figure 4.12 in the next page is the suspension deflection. Suspension deflection reacts in the opposite of sprung mass (m_s) acceleration and displacement. It increased proportionally with the C_{sky} value. This is the drawback of focusing more on comfort when designing vehicle suspension system.

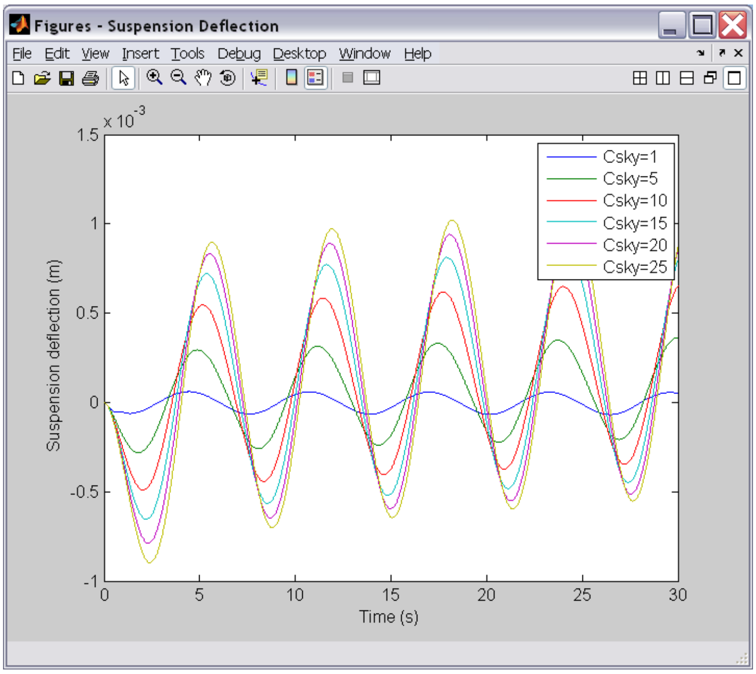


Figure 4.12: Graph of Suspension Deflection vs. Time

Figure 4.13 below is the unsprung mass (m_s) displacement. The graph shows that the pattern is still similar with passive suspension system. Small amount of noise occurs in the negative displacement but it can be neglected.

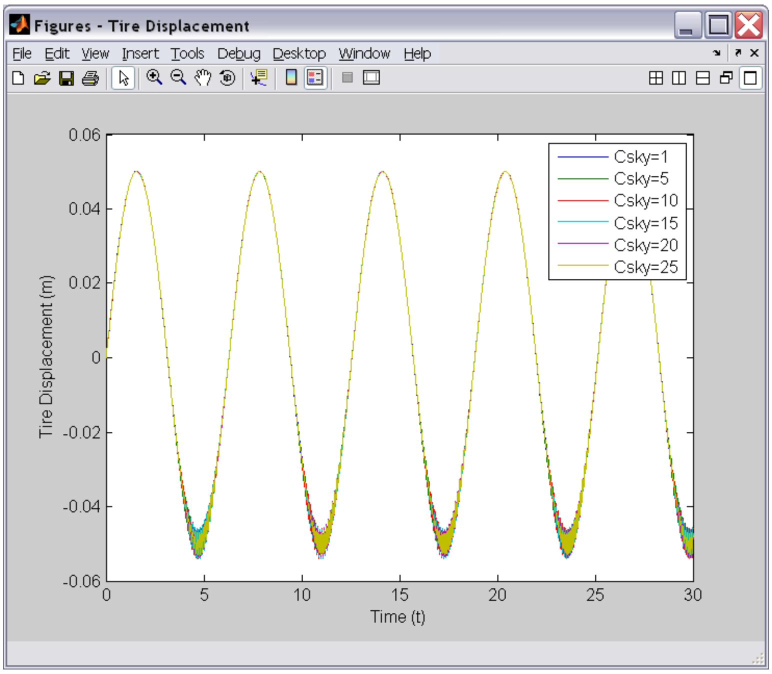


Figure 4.13: Graph of Unsprung Mass (m_u) vs Time

4.3.2 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}. This project objective is to increase passengers comfort without sacrificing the traction force. Hence it is important to select the C_{sky} value that can achieve the desired objectives. The C_{sky} value selected must produced lower sprung mass (m_s) acceleration and displacement but also produce an equal amount of suspension deflection. After a few graphical comparison, the best value of C_{sky} = 15 is chosen. The value provided the semi-active suspension a much lower sprung mass (m_s) acceleration and displacement compared to passive suspension without affecting the handling characteristic. The suspension deflection shows improvement as the average deflection is slightly 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 4.14 to Figure 4.17 below shows the comparison between passive suspension system and the semi-active suspension with skyhook controller where C_{sky} = 15.

Figure 4.14 in the next page is the comparison of sprung mass (m_s) acceleration. The sprung mass (m_s) acceleration for semi-active suspension with skyhook controller is much lower compared to passive suspension system. The graph pattern for semi-active suspension did not have random pattern as the passive suspension system. The average amplitude of the semi-active suspension is 0.028 m/s^2 compared to passive suspension system which is 0.05 m/s^2.

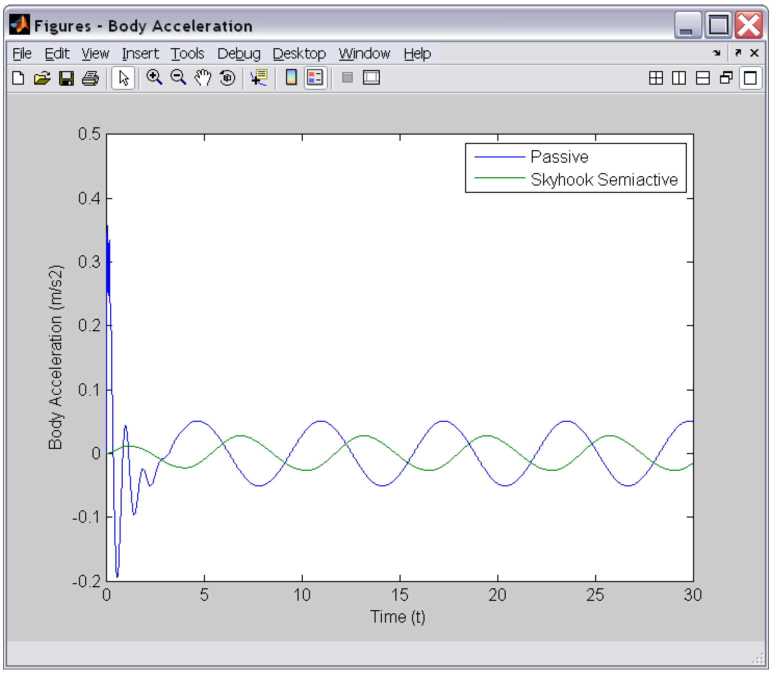


Figure 4.14: Graph of Sprung Mass (m_s) Acceleration vs. Time

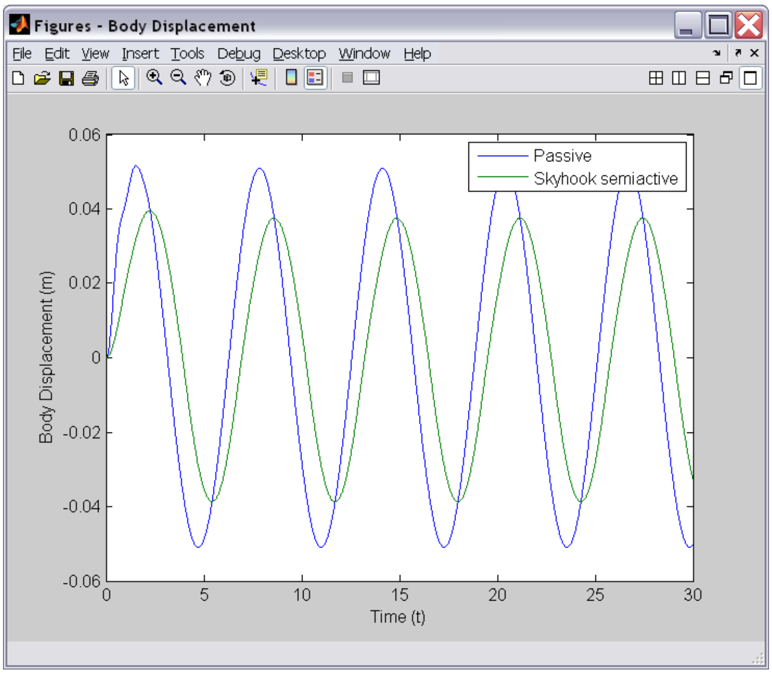


Figure 4.15: Graph of Sprung Mass (m_s) Displacement vs. Time

Figure 4.15 shows the sprung mass (m_s) displacement comparison. The semi-active suspension amplitude is 0.04m compared to passive suspension which is 0.05m.

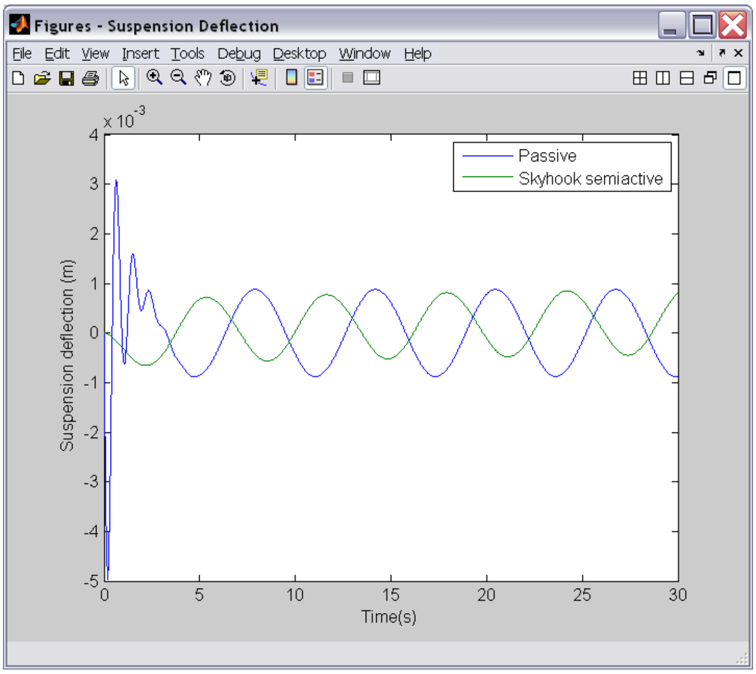


Figure 4.16: Graph of Suspension deflection vs. Time

Figure 4.16 shows the suspension deflection comparison. The semi-active suspension did not show random pattern in the early 5 seconds and amplitude shows a little improvement compared to passive suspension system.

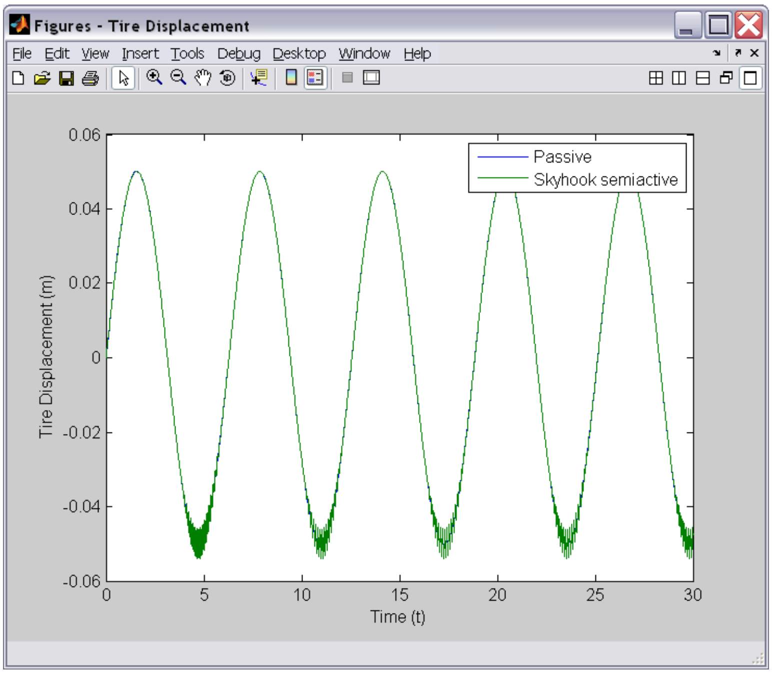


Figure 4.17: Graph of Unsprung Mass (m_u) Displacement vs. Time

Figure 4.7 in the previous pages shows the comparison of the unsprung mass (m_u) displacement. Both of the suspension system shows the same graph pattern but semi-active suspension has small amount of noise in the negative displacement area.

In summary, the semi-active suspension with skyhook controller can improved the comfort of the vehicle passengers. For C_{sky} = 15, it reduce the sprung mass (m_s) acceleration to 0.028 m/s^2 which greatly increased the passengers comfort. The sprung mass (m_s) also reduces by 0.01m to 0.04m although the road profile given is 0.05m. In real situation, although the vehicles pass through 0.05m high bumper, the vehicles body is displaced by only 0.04m. The suspension deflection shows little improvement in terms of average amplitude hence improving the traction force between the tire and the road.

4.4 Semi-Active Suspension with Modified Skyhook Controller Results

The result in this stage of simulation is for the semi-active suspension with modified skyhook controller. From literature review, it is known that the modified skyhook controller can improve the semi-active suspension further more compared to the original skyhook controller.

4.4.1 Finding the best α value

From the Simulink diagram, it is known that the modified skyhook controller is an addition to the original skyhook controller. Hence, the C_{sky} value used in the modified skyhook controller is retained as it already gives the best result for the suspension configuration. The only parameter that needs to be fine tune is α. The value of α is manually manipulated like the C_{sky} value as in the reality the value is automatically determined by the computer box. Figure 4.18 to Figure 4.21 below will shows some of the value tries for α in the modified skyhook controller.

Figure 4.18 in the next pages shows the sprung mass (m_s) acceleration reaction when α value is manipulated. The acceleration shows decrement when α value is smaller.

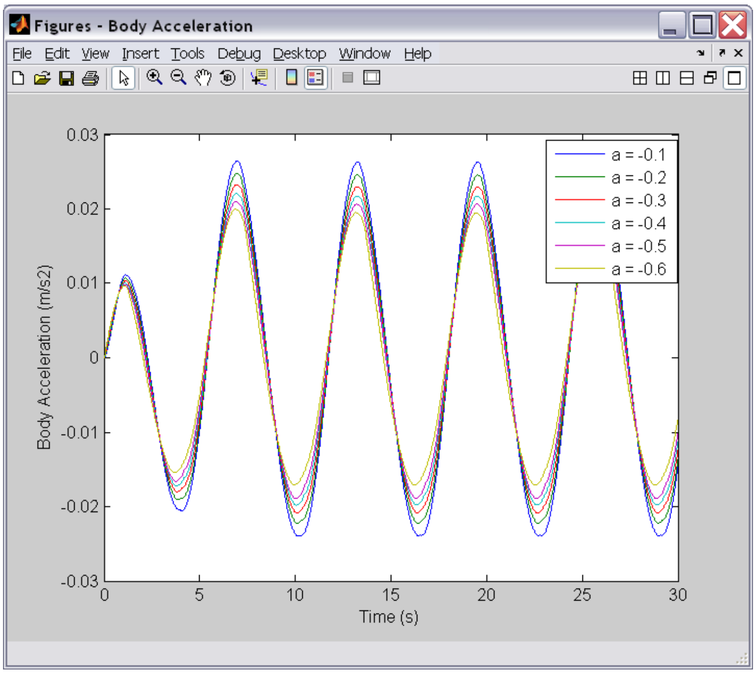


Figure 4.18: Graph of Sprung Mass (m_s) Acceleration vs. Time

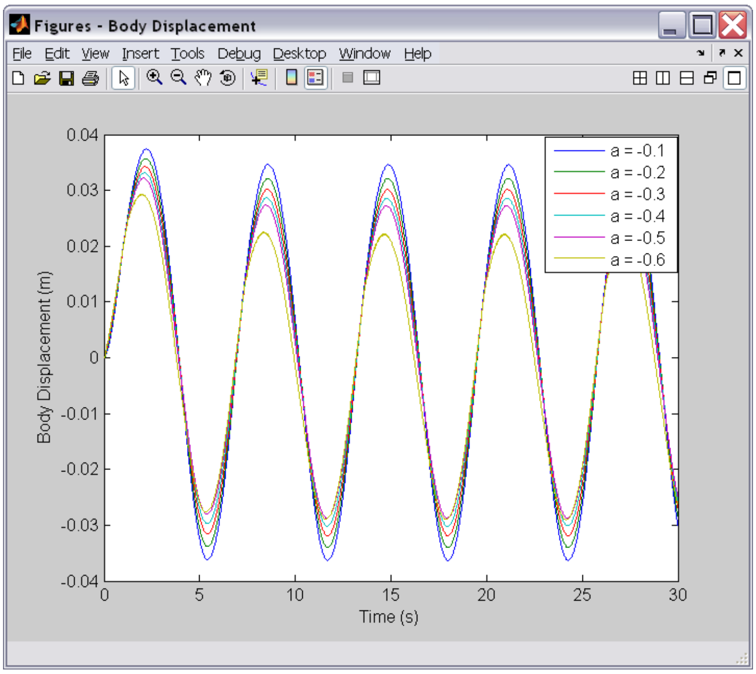


Figure 4.19: Graph of Sprung Mass (m_s) Displacement vs. Time

Figure 4.19 above shows the sprung mass (m_s) displacement reaction towards α value. The sprung mass (m_s) displacement showed an improvement when α value is smaller.

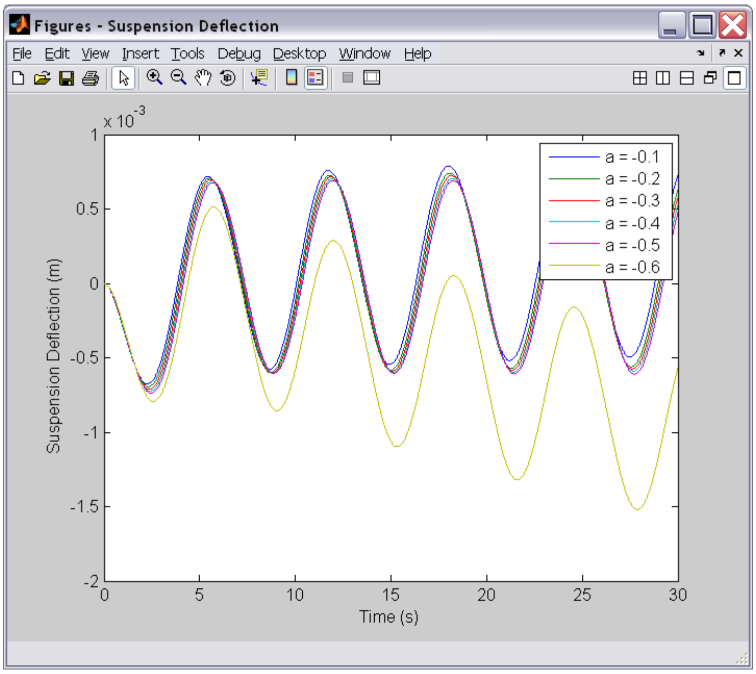


Figure 4.20: Graph of Suspension Deflection vs. Time

The result of suspension deflection is shown in Figure 4.20 above. The suspension deflection shows very little improvement with the decrement of α value except for α = -0.6. The suspension deflection shows improvement but the graph pattern slowly descends to negative area. Therefore, α = -0.6 cannot be selected as the suspension failed to maintain its deflection.

Figure 4.21 in the next page shows the unsprung mass (m_u) displacement simulation result. The displacement is similar to the passive suspension system. The tire is still holding the road well although the sprung mass (m_s) acceleration and displacement is improved. There also less noise in the graph pattern compare to the semi-active suspension with skyhook controller.

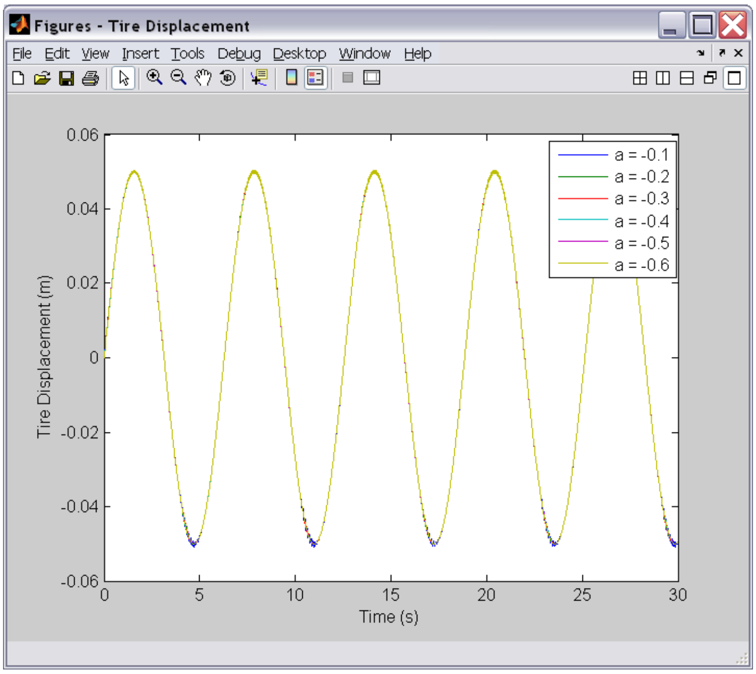


Figure 4.21: Graph of Unsprung Mass (m_u) Displacement vs. Time

As stated before, the modified skyhook can further improve the semi-active suspension system. The sprung mass (m_s) acceleration and displacement is decrease further more with each decrement of α value. The smaller α value gives better result of sprung mass (m_s) acceleration and displacement. For suspension deflection, the suspension system is failed when α = -0.6. The unsprung mass (m_u) displacement shows the similar result as the passive suspension system which is good. Because the suspension encounter failure when α = -0.6, α = -0.5 is chosen as the best value.

4.4.2 Comparison between Passive suspension, Semi-active suspension with skyhook controller and Semi-active suspension with modified skyhook controller

The semi-active suspension with modified skyhook control results is then compared to the passive suspension and semi-active suspension with skyhook controller. As mention above, the best value for α = -0.5. Figure 4.22 to Figure 4.25 shows the comparison of the passive suspension system, semi-active suspension with skyhook controller and semi-active suspension with modified skyhook controller.

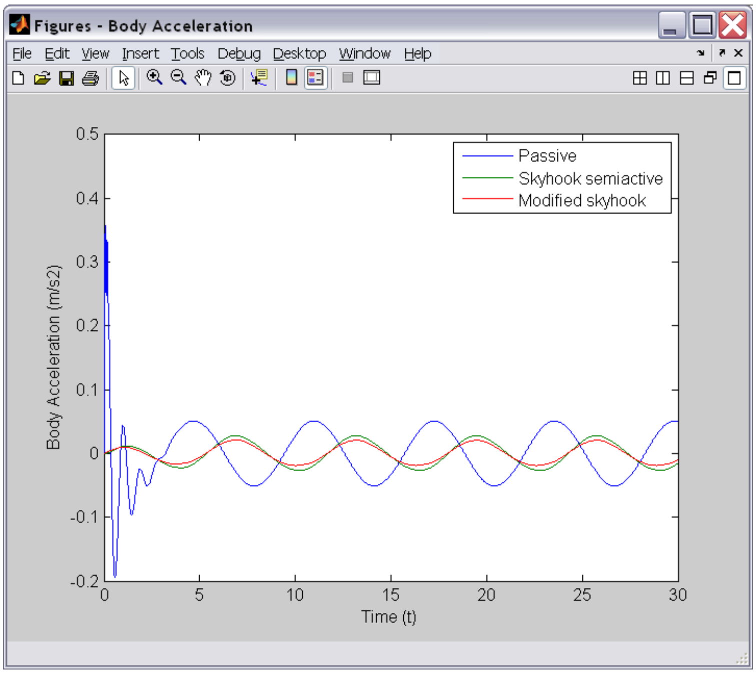


Figure 4.22: Graph of Sprung Mass (m_s) Acceleration vs. Time

Figure 4.22 shows the sprung mass (m_s) acceleration comparison between the three suspension configurations. As in the figure, the modified skyhook controller only improved the sprung mass (m_s) acceleration a little bit compared to skyhook controller. However the small improvement is very much accepted as it still making the suspension system better compared to passive suspension system. The sprung mass (m_s) acceleration for semi-active suspension with modified skyhook controller now is 0.02 m/s^2. The improvement of sprung mass (m_s) acceleration in term of percent is 60%.

Figure 4.23 shows in the next page is the sprung mass (m_s) displacement comparison. From the graph pattern, it can be seen that modified skyhook controller improved the sprung mass (m_s) displacement furthermore. The sprung mass (m_s) displacement for semi-active suspension with modified skyhook control now is 0.027m. It is a big improvement compared to sprung mass (m_s) displacement for passive suspension system which is 0.05m. In term of percent, the sprung mass (m_s) displacement is improved by 46%. In other words, the passengers only feel 54% of the height of the bumper that the vehicle travels through.

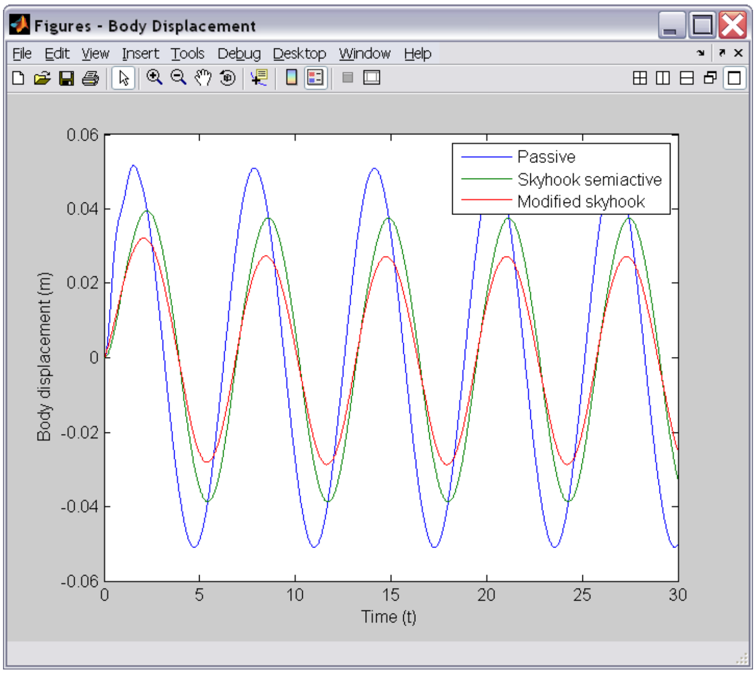


Figure 4.23: Graph of Sprung Mass (m_s) Displacement vs. Time

Figure 4.24 is the comparison of suspension deflection between the three suspension configurations. The skyhook controller and the modified skyhook controller eliminate the random pattern that occurs in passive suspension system.

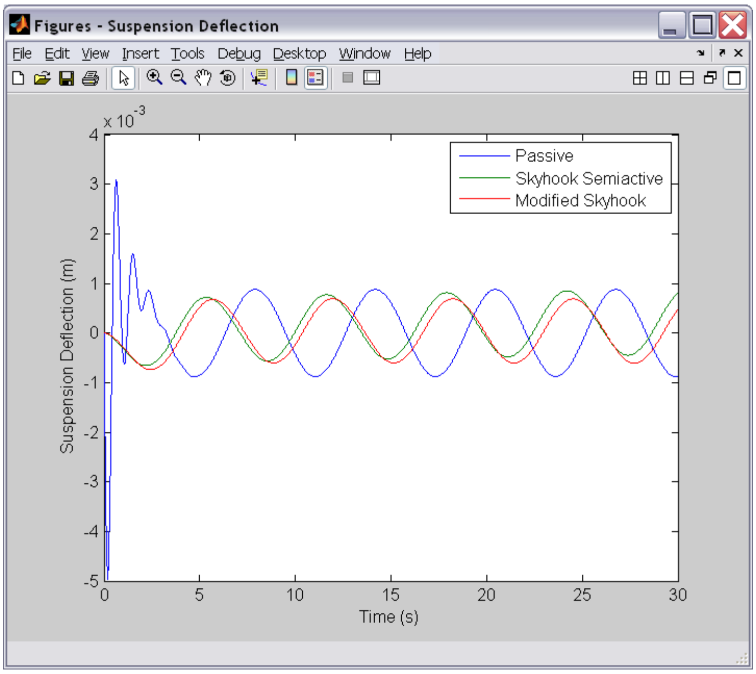


Figure 4.24: Graph of Suspension deflection vs. Time

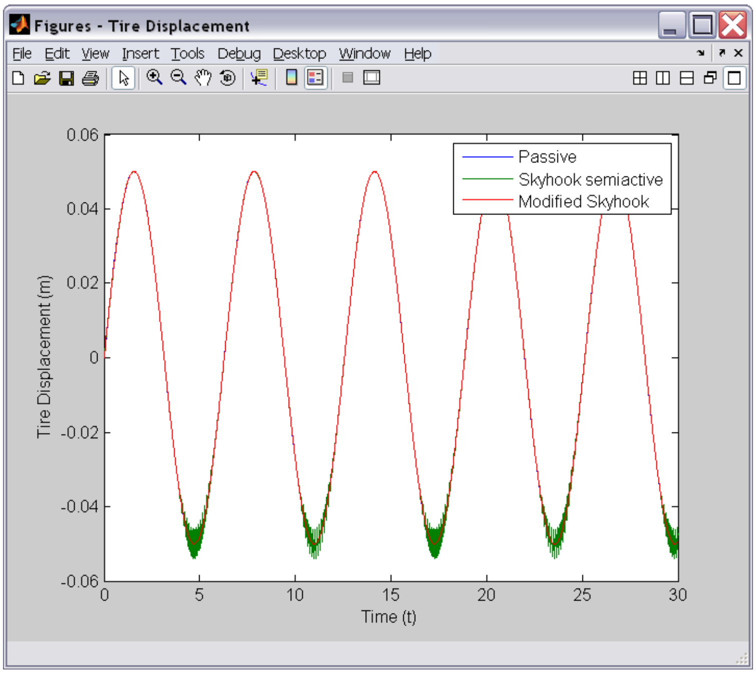


Figure 4.25: Graph of Unsprung Mass (m_u) Displacement vs. Time

Figure 4.25 above shows the unsprung mass (m_u) displacement comparison. The patterns of the graph are basically similar with each other. The only different is the semi-active suspension with skyhook controller produce noise in the negative area. The semi-active suspension with modified skyhook controller later improved the pattern with eliminating the noise back.

In summary, semi-active suspension with modified skyhook controller greatly improved the passengers comfort without compromising the traction force of the tire and the road. The sprung mass (m_s) acceleration and displacement is greatly improved compared to passive suspension system thus providing greater comfort to the vehicle passengers. The handling characteristic is receiving small improvement as the suspension deflection is also decreased while the unsprung mass (m_u) displacement is maintained.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

The purpose of this chapter is to summarize the work that has been completed for this thesis. In addition, the results of testing will be discussed with respect to the research objectives set forth in Chapter 1. The chapter will conclude with several suggestions for future work that should be pursued in this area of research.

5.1 Conclusions

The objective of this project is achieved successfully where the semi-active suspension with modified skyhook controller has improved the passengers comfort significantly. As discussed in previous chapter, sprung mass (m_s) acceleration and displacement parameters played large role in passengers comfort. The sprung mass (m_s) acceleration now is 60% improved and sprung mass (m_s) displacement improved by 46%. The sprung mass (m_s) acceleration now is 0.02 m/s^2 compared to the passive suspension system sprung mass (m_s) acceleration which is 0.05 m/s^2. The sprung mass (m_s) displacement now is 0.027m compared to the passive suspension system sprung mass (m_s) displacement which is 0.05m. The traction is not being compromised as the suspension deflection shows some improvement while maintaining the unsprung mass (m_s) displacement.

5.2 Future recommendations

This project has a lot more potential as there lot of improvements that can be done in order to improved the ride quality of a vehicle. The recommendations for improvement as below:

5.2.1 Expand the car modeling from 2DOF quarter car to full car modeling

With 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 behavior of a car and suspension can be modeled by thoroughly followed the actual configuration of the vehicle suspension.

5.2.2 Suspension configuration

The suspension configuration in this project is a very simple and not considered any angle or other moving part such as lower arm. In order to improve the results, the suspension configuration is modeled by following the real suspension configuration such as Mc-Pherson suspension or Double-Wishbone suspension.

5.2.3 Mechanical model formulation of MR damper.

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. Thus, to get a more accurate expression a more complicated mechanical formulation must be used such as the Bingham method that proposed by Gamota and Filisco (1991).

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APPENDIX

APPENDIX A1

GANTT CHART/PROJECT SCHEDULE FOR FYP 1

PROJECT ACTIVITIES	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16
Title conformation, project background, objectives and scopes																
Literature review study																
Methodology																
Modeling of 2DOF passive suspension system																
FYP 1 draft report writing																
FYP 1 Presentation																

Planning

Actual Progress

APPENDIX A2

GANTT CHART/PROJECT SCHEDULE FOR FYP 2

PROJECT ACTIVITIES	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16
Modeling the MR damper and skyhook controller																
Modeling semi-active suspension with both controller																
Simulation and result analysis																
Writing final report																
FYP 2 Presentation																
1st and 2nd draft to supervisor																
1st and 2nd draft to examiner																
Final report submit																

Planning

Actual Progress

SUPERVISOR'S DECLARATION

"I hereby declare that I have read this thesis and in my opinion this thesis sufficient in terms of scope and quality for the award the degree of Bachelor of Mechanical Engineering with Automotive Engineering"

Signature	: ……………………………………………
Name of Supervisor	: DR. GIGIH PRIYANDOKO
Date	: 30 MAY 2011

STUDENT'S DECLARATION

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.

Signature : ……………………………….
Name of Candidate : AHMAD ZAIM SOLEHIN BIN CHE HASAN
ID Number : MH 07046
Date : 30 MAY 2011

This work is sincerely dedicated to my beloved and precious one,

My father Che Hasan bin Che Daud,

My mother Norrafida bt Ibrahim,

My siblings Adibah Solehah bt Che Hasan,

Huda Husna bt Che Hasan,

Ahmad Mawardi bin Che Hasan,

Aminatul Mardhiah bt Che Hasan,

Ezzatul Aliyah bt Che Hasan,

Ahmad Muhaimin bin Che Hasan,

Ahmad Fawwaz bin Che Hasan,

Ahmad Imtiyaz bin Che Hasan,

And

All of my allies..

Thank you for all the supports and encouragements through the process of finishing this work,

May Allah bless all of you.

ACKNOWLEDGEMENT

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Last but not least, I acknowledge my sincere indebtedness and gratitude to my father Che Hasan bin Che Daud and my mother Norrafida binti Ibrahim for their endless love, support and sacrifice.

ABSTRACT

The objective of this project is to increase comfort of the vehicle's passenger. In order to improve comfort and ride quality of a vehicles, there are four parameters need to be acknowledge. The four parameters are sprung mass acceleration, sprung mass displacement, unsprung displacement and suspension deflection. This project used a new approach in designing the suspension system which is semi-active suspension. The hydraulic damper is replaced by a magneto-rheological damper. A controller is developed for controlling the damping force of the suspension system. The actual concept of the controller is fictitious hence the realization model developed. The controller is called skyhook control. A modified skyhook controller also developed to further improve the suspension system. The semi-active suspension with modified skyhook controller reduces the sprung mass acceleration and displacement hence improving the passengers comfort.

ABSTRAK

Tujuan dari projek ini adalah untuk meningkatkan keselesaan penumpang kenderaan. Dalam rangka meningkatkan keselesaan penumpang kenderaan, terdapat empat parameter yang harus diambil kira semasa kajian. Empat parameter tersebut adalah pecutan badan kenderaan, sesaran badan kenderaan, sesaran tayar kenderaan dan disfleksi suspensi. Projek ini menggunak kaedah baru dalam mereka sistem suspensi kenderaan iaitu suspensi semi-aktif. Penyerap hentak hidraulik diganti dengan penyerap hentak dengan bendalir bermagnetik. Satu sistem kawalan direka untuk mengawal kekuatan redaman sistem suspensi tersebut. Konsep sebenar untuk sistem kawalan tersebut adalah mustahil, oleh itu satu realisasi model direka. Sistem kawalan tersebut dinamakan sistem kawalan "skyhook". Suatu sistem kawalan yang diubahsuai turut direka bagi menambah baik sistem suspensi tersebut. Sistem suspensi semi-aktif dengan sistem kawalan yang diubahsuai ini mengurangkan pecutan dan sesaran badan kenderaan. Oleh itu, tahap keselesaan penumpang kenderaan meningkat.

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LIST OF SYMBOLS

m_s	sprung mass
m_u	unsprung mass
b_s	damping coefficient
k_s	spring stiffness coefficient
k_t	tire stiffness coefficient
z_u	displacement of unsprung mass
z_r	displacement of road
$z_s - z_u$	suspension deflection
$z_u - z_r$	tyre deflection
z_s	sprung mass displacement
$\ddot{z}_s$	sprung mass acceleration

LIST OF FIGURES

ABBREVIATIONS

2DOF	Two degree of freedom
MR	Magneto-rheological

LIST OF APPENDICES

UNIVERSITI MALAYSIA PAHANG

BORANG PENGESAHAN STATUS TESIS

JUDUL: **MODELING AND SIMULATION OF MODIFIED SKYHOOK CONTROL FOR SEMI-ACTIVE SUSPENSION**

SESI PENGAJIAN: **2010/2011**

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Tesis dimaksudkan sebagai tesis bagi Ijazah doktor Falsafah dan Sarjana secara Penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM).

UNIVERSITI MALAYSIA PAHANG

FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "Modeling and Simulation of Modified Skyhook Controller for Semi-Active Suspension System" is written by Ahmad Zaim Solehin bin Che Hasan. 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.

MR. HADI BIN ABDUL SALAAM ……………….

Examiner Signature