# MODELING AND SIMULATION OF MODIFIED SKYHOOK CONTROLLER FOR ACTIVE SUSPENSION SYSTEM

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BACHELOR OF ENGINEERING
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MODELING AND SIMULATION OF MODIFIED SKYHOOK CONTROLLER FOR ACTIVE SUSPENSION SYSTEM

MUHAMAD RUSYDI BIN ALI

A 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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DECEMBER 2010

## SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Automotive.

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Date : 6 December 2010

**STUDENT'S DECLARATION**

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

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# DEDICATION

**Specially dedicated to**
**My beloved family, and those who have guided and inspired me**
**Throughout my journey of learning**

## ACKNOWLEDGEMENTS

In the name of ALLAH SWT, the most Gracious, who has given me the strength and ability to complete this study. All perfect praises belong to ALLAH SWT, lord of the universe. May His blessing upon the prophet Muhammad SAW and member of his family and companions.

I gratefully acknowledge the co-operation of Dr. Gigih Priyandoko who has provided me with the reference, guidance, encouragement and support in completing this thesis. All the regular discussion sessions that we had throughout the period of study have contributed to the completion of this project.

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## ABSTRACT

The purpose of this project is to model and simulate the modified skyhook controller for active suspension system a for a quarter car model. There are four parts have been developed in this study namely, the hydraulic actuator model, force tracking controller, quarter car for passive suspension system and modified skyhook for active suspension system. The simulation process of this system was carried out using MATLAB and SIMULINK toolbox. The data for the each parameter were obtained from the research that have done previously. Performance of active suspension system with modified skyhook controller is better than active suspension system with skyhook controller. The simulation results show that the 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 empat bahagian untuk dibangunkan dalam kajian ini iaitu, model actuator hidraulik, pengatur penjejak paksaan. Suku kereta untuk sistem suspensi pasif dan skyhook yang diubahsuai untuk sistem suspensi aktif. Simulasi sistem ini akan ditentukan oleh melakukan simulasi komputer dengan menggunakan MATLAB dan aturcara SIMULINK. Data untuk setiap parameter diperolehi dari kajian yang telah dilakukan dahulu. Prestasi sistem suspensi aktif dengan pengatur skyhook yang diubahsuai lebih baik daripada sistem suspensi aktif dengan pengatur skyhook biasa. Keputusan simulasi menunjukkan bahawa sistem suspensi aktif dapat memberikan perbaikan yang signifikan dalam kualiti pemanduan dan pengendalian jalan berbanding dengan sistem suspensi pasif.

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# CHAPTER 1

# INTRODUCTION

## 1.1 PROJECT BACKGROUND

Active suspensions systems have been widely studied over the last 30 years, with hundreds of papers published. Most of the published works focus on the outer-loop controller in computation of the desired control force as a function of vehicle states and the road disturbance. It is commonly assumed that the hydraulic actuator is an ideal force generator and able to carry out the commanded force accurately. Simulations of these outer-loop controllers were frequently done without considering actuator dynamics, or with highly simplified hydraulic actuator dynamics.

In real implementation, actuator dynamics can be quite complicated, and the interaction between the actuator and the vehicle suspension cannot be ignored. It is also difficult to produce the actuator force close to the target force without implementing inner-loop or force tracking controller. This is due to the fact that hydraulic actuator exhibits non-linear behavior resulted from servo-valve dynamics, residual structural damping, and the unwanted effects of back-pressure due to the interaction between the hydraulic actuator and vehicle suspension system.

This study focuses on the development of a hydraulic actuator model including its force tracking controller for an active suspension system. Force tracking control of the hydraulic actuator model is then performed using Proportional Integral (PI) controller for a variety of the functions of target forces namely step, sinusoidal, pulse, and repeating functions.

Then, this study continues with implementing the modified skyhook controller of active suspension system to the quarter car of passive suspension system to verify that active suspension system is better than passive suspension system. The performance of active suspension system also can be increase by the skyhook controller that will be discussed on the next chapter.

## 1.2 PROBLEM STATEMENT

The suspension system that commonly applied on the vehicle is a passive suspension system in which its spring stiffness and dumping value is constant. In the passive suspension system, it damping system has not yet gives a high performance where its vibration amplitude still high and the time required terminating the vibration is quite longer. To overcome this condition, it is then introduced a semi-active suspension and active suspension system. Unfortunately the semi-active systems can only change the viscous damping coefficient of the shock absorber, and do not add energy to the suspension system. So, the active suspension becomes a better choice to keep the quality of the car comfortable on any road condition.

## 1.3 OBJECTIVE

The objectives of this research are as follows:

a) To develop hydraulic model of the active suspension system
b) To develop force tracking controller for the system
c) To develop a quarter car model using passive suspension system
d) To develop modified skyhook controller for a active quarter car suspension using hydraulic actuator

## 1.4 SCOPE OF WORK

The scopes of work for this study are as follows:

a) Study on active suspension system for a quarter car model
b) Design the system by using MATLAB/SIMULINK
c) Simulate the system using MATLAB/SIMULINK

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 INTRODUCTION

With a reference from various source such as books, journal, notes, thesis and internet, literature review has been carry out to collect all information related to this project. This chapter discussed about active suspension system for a quarter car model that will be designed and simulated by using software Matlab/Simulink.

## 2.2 OVERVIEW OF VEHICLE SUSPENSION SYSTEM

Traditionally automotive suspension designs have been a compromise between the three conflicting criteria of road holding, load carrying and passenger comfort. The suspension system must support the vehicle, provide directional control during handling maneuvers and provide effective isolation of passenger or payload from road disturbances. Good ride comfort requires a soft suspension, whereas insensitivity to applied loads requires stiff suspension.

The primary functions of a suspension system are to provide vertical compliance so the wheels can follow the uneven road, isolating the chassis from roughness in the road. It can be maintain the wheels in the proper steer and camber attitudes to the road surface. The suspension also react to the control forces produced by the tires-longitudinal (acceleration and braking) forces, lateral (cornering) forces, braking and driving torques. It can be keep the tires contact with the road with minimal load variations and resist roll of the chassis.

The properties of a suspension important to the dynamics of the vehicle are primarily seen in the kinematic (motion) behavior and its response to the forces and moments that it must transmit from the tire chassis. In addition, other characteristic considered in design process are cost, weight, package space, manufacturability, ease of assembly, and others.

Therefore, each wheel is connected to a system of springs and dampers, which provide flexible but restrained wheel movement. The spring rate or stiffness, damper effects of the shock absorber and the ratio of the sprung mass to the unsprung mass are important parameters, which affect the ride qualities, as discussed earlier.

The following sub sections attempt to present a brief view on the key elements of available vehicle suspension system designs and describe their operating characteristics, ranging from the conventional system to the more advanced systems.

### 2.2.1 Passive Suspension System

The passive suspension has no means of adding external energy to the system because it contains only passive elements such as damper and a spring. Therefore its rates and forces can’t be varied by external signals. When we are using a passive suspension method by choosing a step unit, we will obtain the output in a second order system and would have an overshoot. It depends on the value that has been set. Passive suspension is divided into two parts. They are unsprung and sprung. The purpose is to reduce the wheel loading.

If the passive suspension model is observe it consists of two components. The components are a spring and a damper which are in a parallel position. The value of the spring and damper cannot be changed, as it is a constant. As a conclusion, it is difficult to control the movement of the car because it is impossible to load any controller to the model. The effects of the spring are to impart oscillatory force to the sprung mass with smooth changes in acceleration and velocity.

The amplitude of the motion of the mass depends upon the frequency and magnitude of the wheel motion. In technical form, they are velocity-sensitivity hydraulic damping devices. In other words, the faster they move, the more resistance there is to that movement. They work in conjunction with the spring. The spring allows movement of the wheel to allow the energy in the road shock to be transformed into kinetic energy of the unsprung mass. The force imparted by the wheel to the base of the spring will thus produce an acceleration of the sprung mass. Since this force is also related to the mass and acceleration of the unsprung mass.

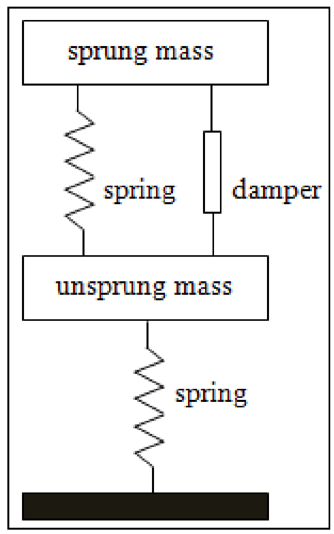


**Figure 2.1**: Passive suspension system

[Source: Prof. Dr. Yahaya Md. Sam, Robust Control Of Active Suspension System For A Quarter Car Model]

### 2.2.2 Semi Active Suspension System

As the passive suspension, semi active suspension has no force actuator. It is possible to continuously vary the rate of energy dissipation using a controller damper, but it is impossible to add energy. Semi-active suspension has the same concept with the passive suspension. It still consists of a spring and a damper. The value of the spring and damper cannot be changed, as it is a constant. Any type of controller can be loaded at the damper to control the movement of the car. The damper which has a modified value will be limited to a certain range but it still not able to regulate unless the damper is set to a setting value.

Semi active suspension has the potential to attain more widespread use in mass produced vehicles than fully active system because of their lower cost and their negligible demand for power. An important aspect, in which the performance of 'semi active' suspension is not satisfactory, is high frequency harshness that has been observed in road tests and reported in analytical studies of semi active suspension. More important for semi active suspensions the rapid variations of damping coefficients and consequently suspension forces will provide persistent excitation of the structural vibrations.

A good semi active system should provide high damping for low frequency inputs to achieve good body isolation, low damping in the mid -frequency range for good comfort, adequate damping to control the wheel hop, especially under conditions of motion that requires the development of lateral forces and finally increased damping of structural modes. Semi active suspension that use feedback of modal variables reduces structural vibrations in comparison to the corresponding systems with rigid body based controllers. The semi active suspension is shown in Figure 2.2.

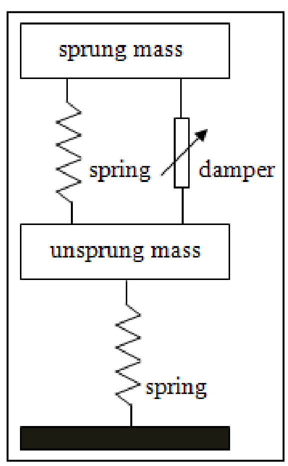


**Figure 2.2**: Semi Active Suspension System

[Source: Prof. Dr. Yahaya Md. Sam, Robust Control Of Active Suspension System For A Quarter Car Model]

### 2.2.3 Active Suspension system

The active suspension can supply energy from external source and generate force to achieve the desired performance. The ability to control the energy according to the environment provides the flexibility in control and better performance of suspension system. For this reason, the active suspension is widely investigated. Active suspension model is also similar to a passive suspension model. The difference between the two models is that the damper is replacing with an actuator. The function of the actuator is as a controller to the system and the advantage is that the system can be regulated at anytime.

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 as shown in Figure 2.3. 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 as illustrated in Figure 2.4. 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.

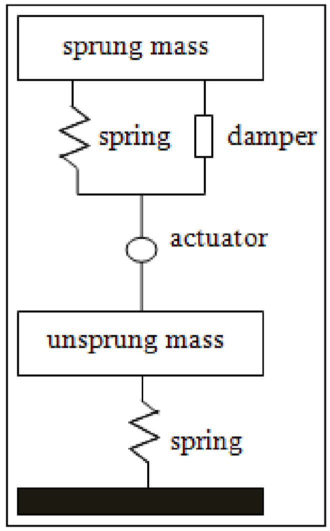


**Figure 2.3**: A low bandwidth or soft active suspension system

[Source: Prof. Dr. Yahaya Md. Sam, Robust Control Of Active Suspension System For A Quarter Car Model]

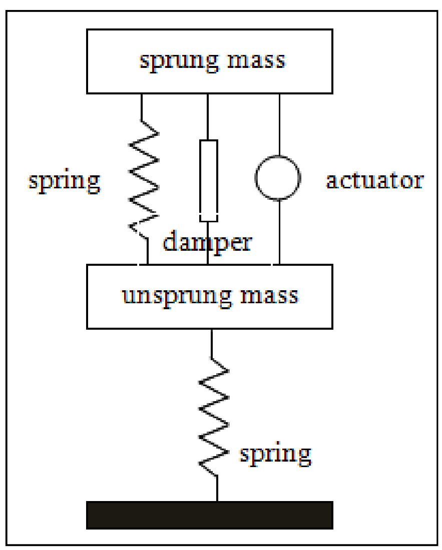


**Figure 2.4**: A high bandwidth or stiff active suspension system

[Source: Prof. Dr. Yahaya Md. Sam, Robust Control Of Active Suspension System For A Quarter Car Model]

Active suspension can overcome many limitations of passive system and eliminate or at least lessen, the need to compromise among a variety of operating conditions and among the generally conflicting goals of providing good isolation of the body (ride comfort), maintaining uninterrupted contact between the tires and the roads (road holding) and stability the vehicle body (handling).

## 2.3 CONTROL SYSTEM

A control system is a device or set of devices to manage, command, direct or regulate the behavior of other devices or systems.

There are two common classes of control systems, with many variations and combinations: logic or sequential controls, and feedback or linear controls. There is also fuzzy logic, which attempts to combine some of the design simplicity of logic with the utility of linear control. Some devices or systems are inherently not controllable.

The term "control system" may be applied to the essentially manual controls that allow an operator to, for example, close and open a hydraulic press, where the logic requires that it cannot be moved unless safety guards are in place.

An automatic sequential control system may trigger a series of mechanical actuators in the correct sequence to perform a task. For example various electric and pneumatic transducers may fold and glue a cardboard box, fill it with product and then seal it in an automatic packaging machine.

In the case of linear feedback systems, a control loop, including sensors, control algorithms and actuators, is arranged in such a fashion as to try to regulate a variable at a set point or reference value. An example of this may increase the fuel supply to a furnace when a measured temperature drops. Proportional Integral Derivative (PID) controllers are common and effective in cases such as this. Control systems that include some sensing of the results they are trying to achieve are making use of feedback and so can, to some extent, adapt to varying circumstances. Open-loop control systems do not directly make use of feedback, but run only in pre-arranged ways.

### 2.3.1 Proportional –Integral –Derivative (PID) Controller

The PID family controller (P, PD, PI, and PID) are widely used and successfully applied to many applications, for many years. The facts of their successful application, good performance, easiness of tuning are speaking for themselves and are sufficient rational for their use.

As well known PID control has been one of the most popular control methods for practical processes from 1940s when Ziegler and Nichols produced the parameter setting. This tuning method of PID control is to make a desired transient response and steady state by turning the three parameters (Proportional P, Integral I, and Derivative D) with scarce information about the controlled object. In 1960s the method of modern control theory was produced and if we comprehend control object accurately, we can modify the characteristic of control systems using the observed state, that is, we can design the control systems perfectly when it has controllability and observability.

However, in PID control strategy these structural properties were not be prescribed accurately in spite of having used the terminology about the controllability which is now popular term in modern control theory. For this reason, the PID control is seemed to be somewhat indistinct though having some advantages. However control equipment based on the structure of PID control has been practically implemented all over control equipment.

The operation of PID control is basically to control the process by using manipulated magnitude proportional to control error. Generally summing the integral value and the derivative one of the control error to it, we built the manipulated variable of PID control. Considering the time dependence of control error through the integral and derivative operation, the control error dynamically influences to the manipulated variable. Therefore PID control has an effective property indicating a physical relation between the control error and the manipulated variable. The transfer function of a PID controller is given as follows:

$$G_{PID} = K_P \left(1 + \frac{1}{T_i s} + T_d s\right) \quad [1]$$

where $T_i$=$K_p/K_i$, $T_d$=$K_d/K_p$ and $K_p$, $K_i$ and $K_d$ are proportional, integral and derivative gain respectively.

### 2.3.2 Force Tracking Control of Hydraulic Actuator Model

The structure of force tracking control of hydraulic actuator is shown in Figure 2.5. The hydraulic actuator model take two input namely spool valve position and real time piston speed. Proportional Integral control is implemented which takes force tracking error as the input and delivers control current to drive the spool valve. The target force is represented by step, sinusoidal, pulse and repeating functions.

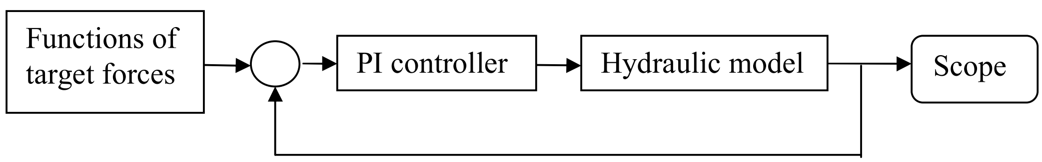


**Figure 2.5**: Force tracking control of hydraulic actuator

## 2.4 HYDRAULIC ACTUATOR MODEL

A complete set of a hydraulic actuator consists of five main components namely electro hydraulic powered spool valve, piston-cylinder, hydraulic pump, reservoir and piping system as shown in Figure 2.6. Power supply is needed to drive the hydraulic pump through AC motor and to control the spool valve position. The spool valve position will control the fluid to come-in or come-out to the piston-cylinder which determines the amount of force produced by the hydraulic actuator.

The hydraulic actuators are governed by electro hydraulic servo valve allowing for the generation of forces between the sprung and unsprung masses. The electro hydraulic system consists of an actuator, a primary power spool valve and a secondary bypass valve.

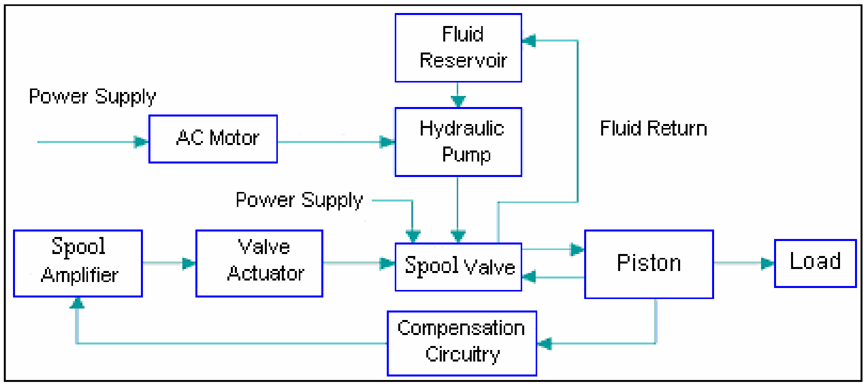


**Figure 2.6**: Diagram of a complete set of hydraulic actuator.

[Source: Y. M. Sam and K. Hudha, Modeling and Force Tracking Control of Hydraulic Actuator for an Active Suspension System]

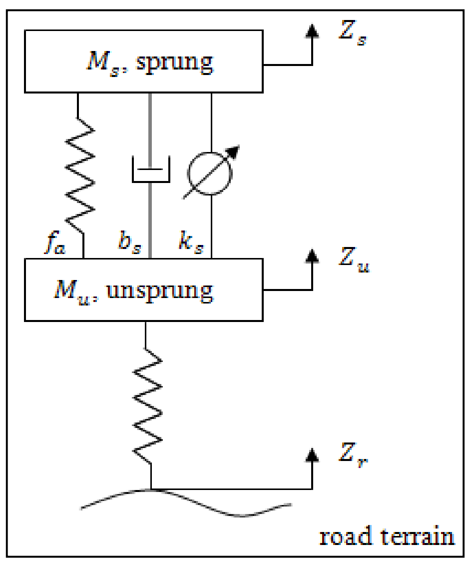


**Figure 2.7**: Active suspension system

[Source: G. Priyandoko, M. Mailah and H. Jamaluddin, Vehicle Active Suspension System Using Skyhook Adaptive Neuro Active Force Control]

## 2.5 SKYHOOK CONTROLLER

As the name implies, the skyhook configuration shown in the Figure 2.8 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.

The controller responds to the pitch and roll motions of the vehicle, as well as the vertical motion of the wheels. The results in an actual vehicle showed marked improvements over the passive suspension.

Modified skyhook = $C[\alpha(\dot{Z}_u - \dot{Z}_s) + (1-\alpha)\dot{Z}_s]$ [2]

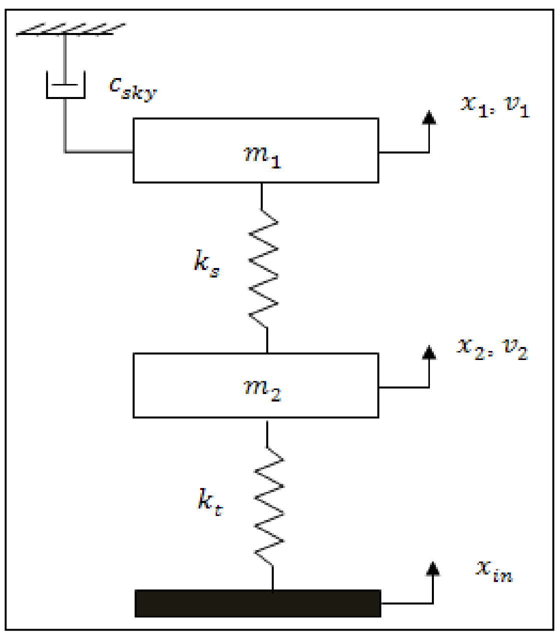


**Figure 2.8**: Skyhook model

[Source: Supavut Chantranuwathana , Practical Adaptive Robust Controllers For Active Suspensions]

## 2.6 QUARTER-CAR ACTIVE SUSPENSION MODEL WITH A HYDRAULIC ACTUATOR

In this section, it will present the model of a quarter-car AS system equipped with a hydraulic actuator. The governing equations of the quarter-car active suspension system (Figure 2.7) are presented. The two degrees of freedom (DOF) are the vertical motions of the sprung mass ( $m_s$ ) and unsprung mass ( $m_{us}$ ), respectively. This 2 DOF system has one external input, $\dot{z}_0$, which is the rate of change of road surface elevation. A force (*f*) is applied by the active suspension actuator on $m_s$ and $m_{us}$ .

The transfer function from actuator force to suspension stroke is then:

$$G_p = \frac{Z_s}{Z_{us}}$$

$$= \frac{(m_s + m_{us})s^2 + c_{us}s + k_{us}}{m_s m_{us} s^4 + (c_s m_{us} + m_s c_s + m_s c_{us})s^3 + (m_{us}k_s + c_s c_{us} + k_s m_s + m_s k_{us})s^2 + (k_{us}c_s + k_s c_{us})s + k_s k_{us}} \quad [3]$$

By using standard servo-valve dynamic equations, the hydraulic system is described by:

$$f = \frac{\sqrt{2}A_p.\beta.k_{xd}}{V}.x_{sp}.signsqrt\left(P_s - \frac{sign(x_{sp})f}{A_p}\right) + \frac{2.A_p^2.\beta}{V}.(\dot{z}_{us} - \dot{z}_s) \quad [4]$$

$$\dot{x}_{sp} = \frac{1}{\tau}(-x_{sp} + k_{sv}i_{sv}) \quad [5]$$

## 2.7 QUARTER-CAR FOR PASSIVE SUSPENSION SYSTEM

The vehicle model considered in this study is a quarter car model. 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 2.9.

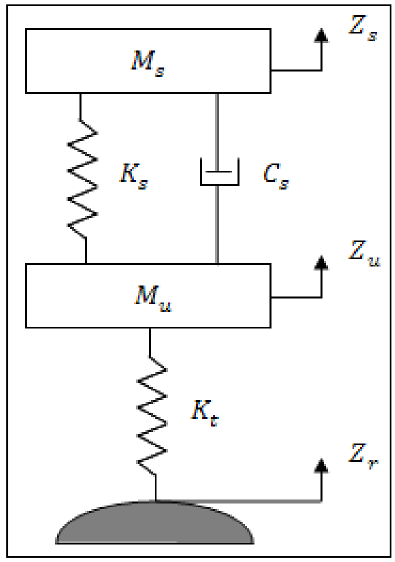


**Figure 2.9**: Passive quarter car model

[Source: Y. M. Sam and K. Hudha. Modelling and Force Tracking Control of Hydraulic Actuator for an Active Suspension System]

The assumptions of a quarter car modeling are as follows: the tire is modeled as a linear spring without damping, there is no rotational motion in wheel and body, the behavior of spring and damper are linear, the tire 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 modeling. The equations of motion for the sprung and unsprung masses of the passive quarter car model are given by

$$M_s\ddot{Z}_s + K_s(Z_s - Z_u) + C_s(\dot{Z}_s - \dot{Z}_u) = 0 \quad [6]$$

$$M_u\ddot{Z}_u + K_t(Z_u - Z_r) + K_s(Z_u - Z_s) + C_s(\dot{Z}_u - \dot{Z}_s) = 0 \quad [7]$$

## 2.8 SIMULATION DATA

In this section, we will examine the effect of modified suspension parameters on the characteristics of the hydraulic equation model. In particular, we will focus on their effect on the output from simulation. We assume that the sprung mass is given and cannot be assigned. The nominal values of the suspension parameters are shown in Table 3.1.

**Table 3.1**: Parameter value

| Parameter | | Value |
|---|---|---|
| $V$ | cylinder chamber volume | $1.16e^{-4}\ m^2$ |
| $K_{sv}$ | valve gain | 0.0157 m/A |
| $K_{xd}$ | orifice flow coefficient | 0011 $m^3$/sec/$N^{1/2}$ |
| $Ap$ | piston area | 0.0011 $m^2$ |
| $\tau$ | time constant for servo valve | 0 .0046 sec |
| $Ps$ | supply pressure | 1000 Psi |
| β | fluid bulk modulus | 4.4e7 N/$m^2$ |
| $M_s$ | sprung mass (body) | 282 kg |
| $M_u$ | unsprung mass (tire) | 45kg |
| $K_s$ | spring stiffness | 17900 N/m |
| $K_t$ | tire stiffness | 165790 N/m |
| $C_s$ | damping constant | 1500 Nsec/m |

[Source: Y. M. Sam and K. Hudha. Modelling and Force Tracking Control of Hydraulic Actuator for an Active Suspension System]

# CHAPTER 3

# METHODOLOGY

## 3.1 INTRODUCTION

The methodology applied in this study is briefly shown in Figure 3.1. Literature study was done in the early stage of study to have a better understanding on the project. Active suspension system was designed and run in the simulation to acquire the result. The design and simulation will be done by using MATLAB/SIMULINK. The result from the simulation will be analysis decision will make based on the observation of results.

## 3.2 METHODOLOGY OF FLOW CHART

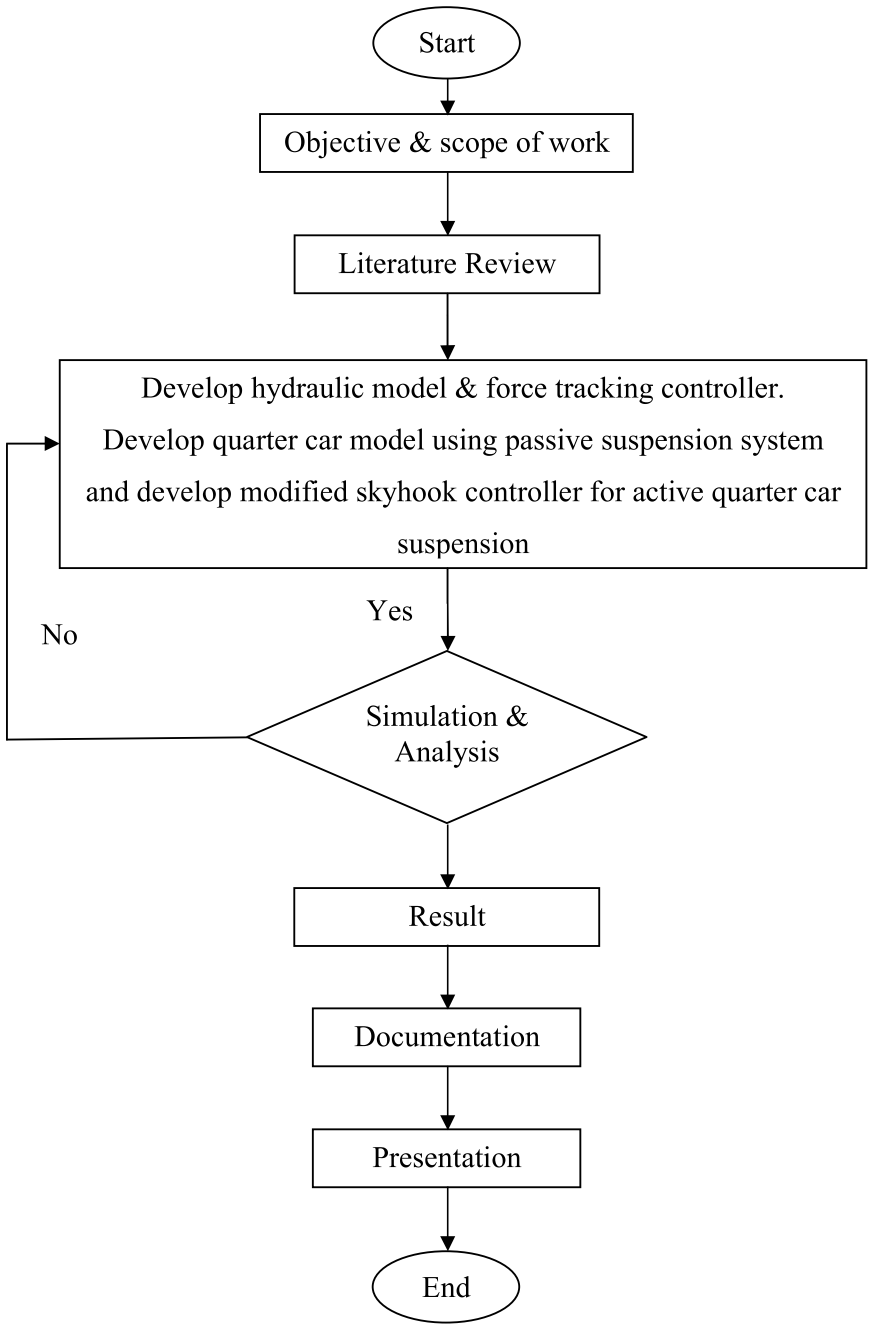


**Figure 3.1:** Flow Chart

According to the diagram as shown before, the project starts with discussion with supervisor of the objective and scope of work about the title. After that, following with the literature review, this consist a review of the concept of active suspension system. These tasks have been done through research on the internet, theses, journal and others sources.

After gathering all the relevant information, the project undergoes design process. In this step, from the knowledge gather from the review is use to develop hydraulic model and force tracking controller for the active suspension system with the guidance from supervisor. This step is done based on the hydraulic equation that has been obtained from the trusted sources.

Then, simulate the hydraulic model in Matlab/Simulink with the actual data to get the right hydraulic model diagram. This followed by developing the force tracking controller to the hydraulic model in Matlab/Simulink. The graph that appear from the simulation is the result that required in this project.

The project continues with developing the quarter car of passive suspension system and developing the modified skyhook controller for active suspension system. Then, all the block diagram will be combined together and simulate by using Matlab/Simulink with data that been taken from reference journal.

All the information that has been gathered during the project is collected to make a thesis for the given title. This thesis is using the format that has been specified by the university.

After the thesis is been completed, slide presentation is prepared for the presentation day. This slide presentation contains the information about the title to be described to the presentation panel.

Finally, this thesis is submitted to the university for review and further action.

## 3.3 SIMULATION

### 3.3.1 Simulation of Hydraulic Model and Force Tracking Controller

The simulation of hydraulic model and force tracking controller for active suspension system were simulated using MATLAB/SIMULINK. To gain the result of the controller, the step input with the value of 1000 were transferred to the block parameter.

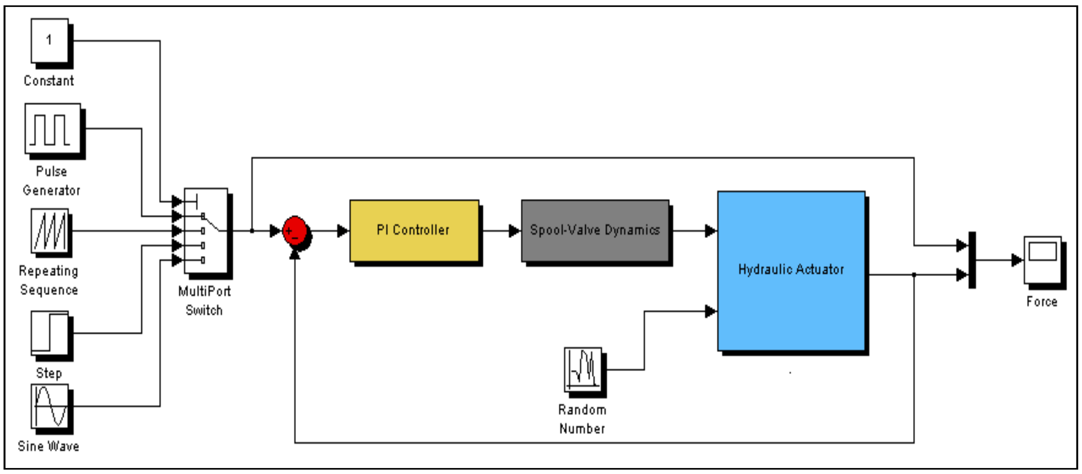


**Figure 3.2**: Diagram for hydraulic model and force tracking controller

### 3.3.2 Simulation of Quarter Car

The simulation of quarter for passive suspension system was simulated using MATLAB/SIMULINK. To gain the result of quarter car for passive suspension system, the step input with the height of 0.1 m at t=0sec were transferred to the block parameter.

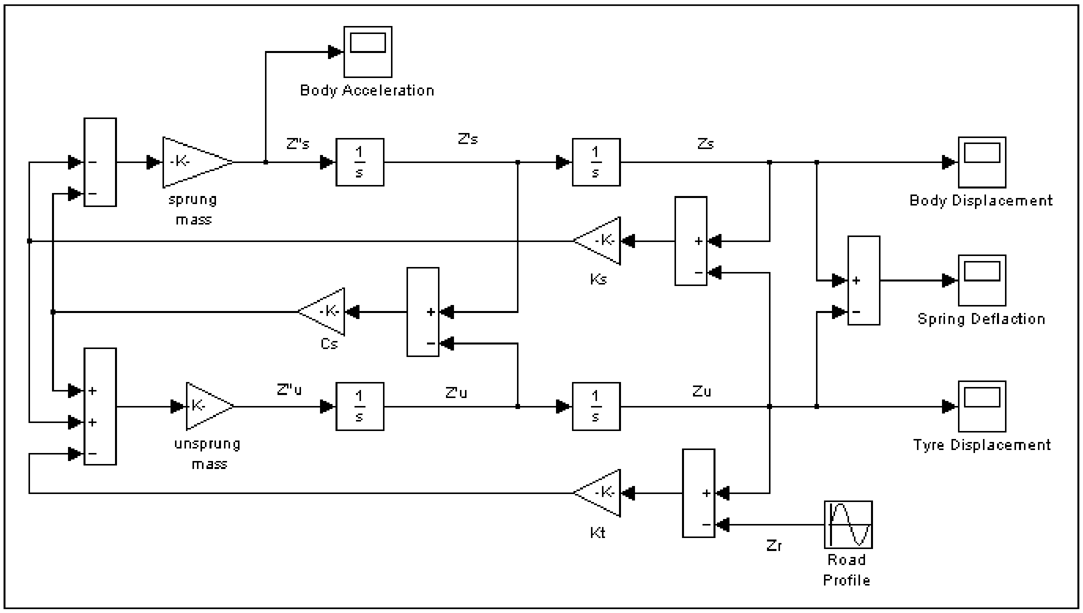


**Figure 3.3**: Diagram for quarter car

### 3.3.3 Simulation of Quarter Car and Modified Skyhook Controller

The simulation of quarter car and modified skyhook controller for active suspension system were simulated using MATLAB/SIMULINK. To gain the result of quarter car and modified skyhook controller for active suspension system, the step input with the height of 0.1 m at t=0sec were transferred to the software.

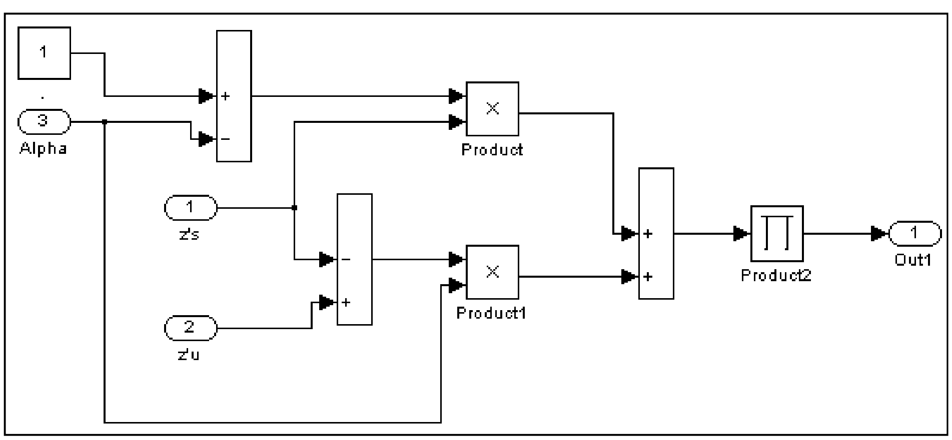


**Figure 3.4**: Diagram for modified skyhook controller

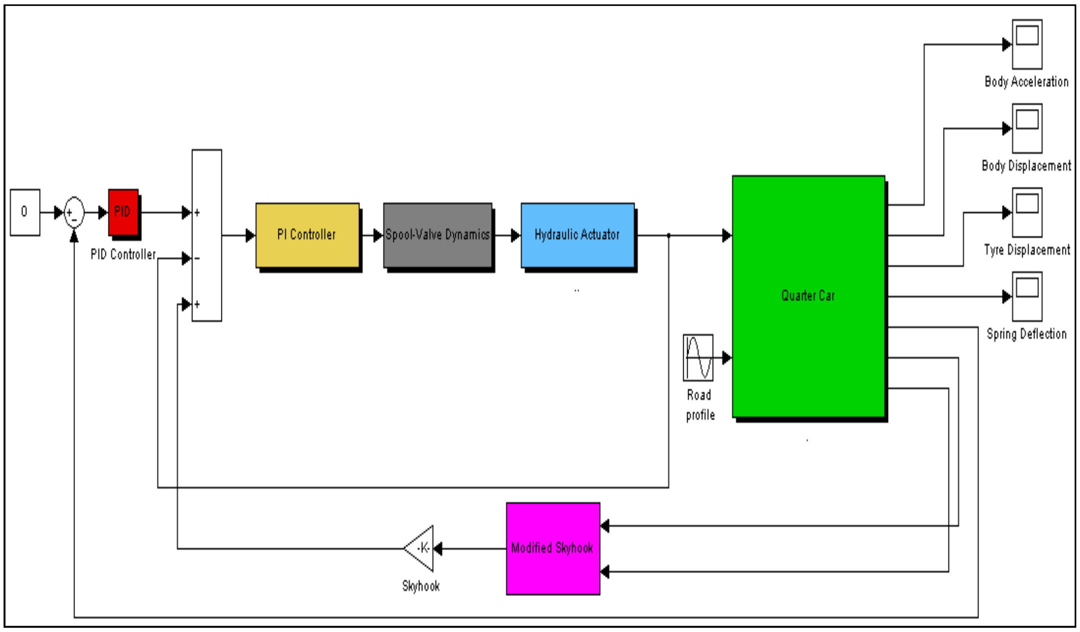


**Figure 3.5**: Diagram for quarter car with modified skyhook controller

# CHAPTER 4

# RESULTS & DISCUSSIONS

## 4.1 INTRODUCTION

The main objective of this project is about to analyze the active suspension system by the modified skyhook controller. The comparison will be done between the difference frequency in order to analyze the effect at the body acceleration, body displacement, tire displacement and spring deflection by using Matlab/Simulink.

## 4.2 DATA ANALYSIS

### 4.2.1 Analysis of Hydraulic Actuator and Force Tracking Controller

Based on the equation of hydraulic actuator in Chapter 2, the simulation had been done for the force tracking controller in Matlab/Simulink. The simulation was done by a step input of 1000 for block parameter's value of pulse generator, repeating sequence, step and sine wave.

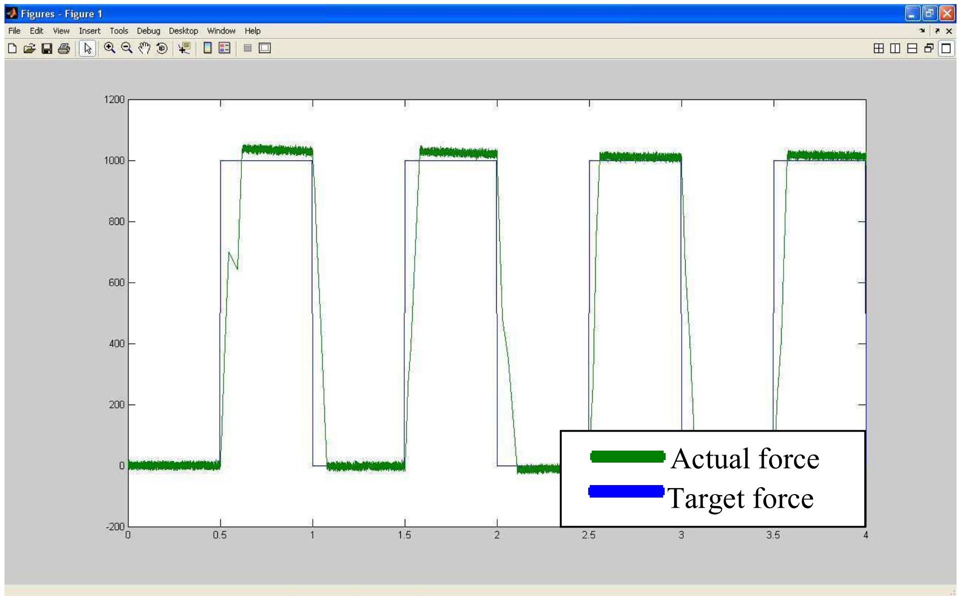


**Figure 4.1**: Pulse generator graph

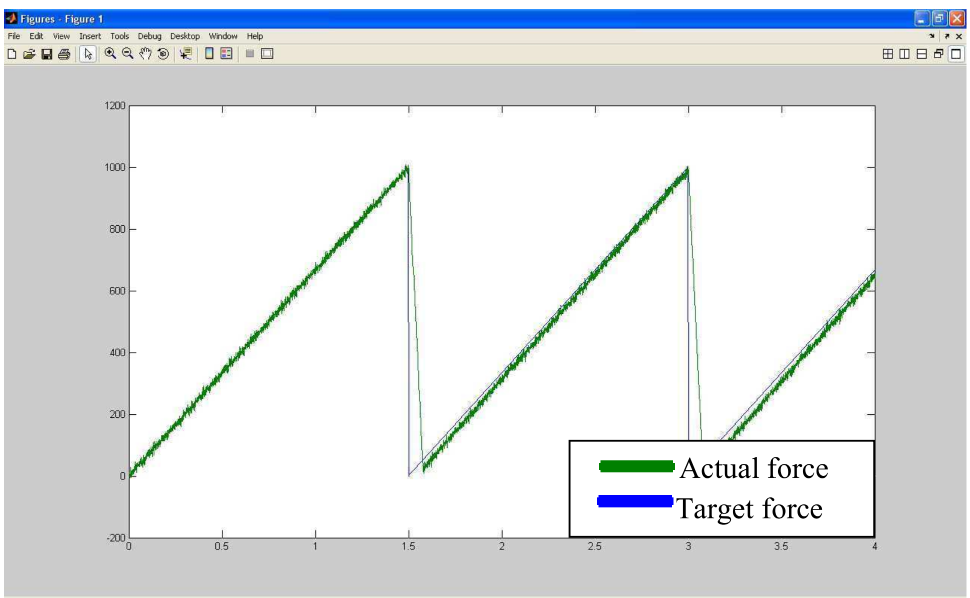


**Figure 4.2**: Repeating sequence graph

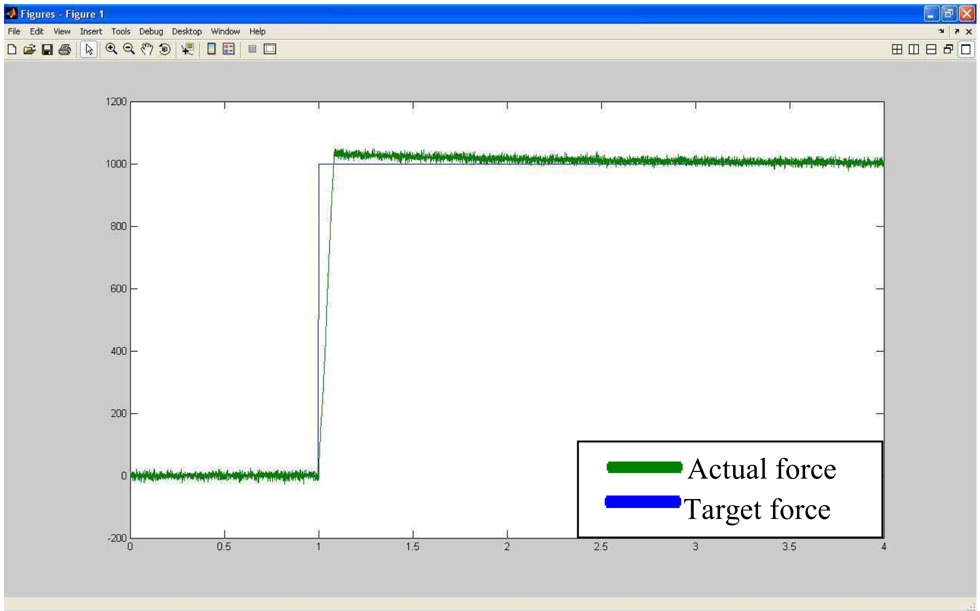


**Figure 4.3**: Step graph

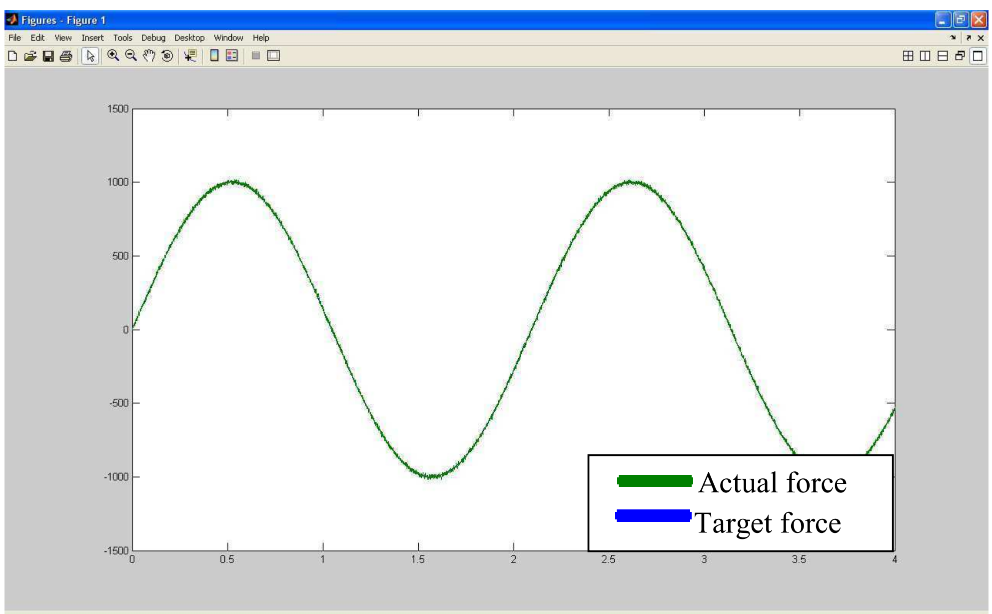


**Figure 4.4**: Sine wave graph

As seen on Figure 4.1, 4.2, 4.3 and 4.4, all the output value were same as the input value that had been transferred to the block parameter. These values give an exact data to continue this project. The simulation results of the force tracking control are shown in figures which clearly show that the actual trajectories are capable in tracking the desired ones. This signifies that the appropriate controller setting enables the hydraulic actuator to operate satisfactorily.

### 4.2.2 Analysis of Skyhook Controller

From the equation of motion in Chapter 2, the system was designed and simulated in Matlab/Simulink. The simulation was excited by a step input with the height of 0.1 m at t=0sec. Figure 4.5 show the response of systems by mean of sprung mass (body) acceleration by using parameters in Table 3.1.

From the simulation, a graph of sprung mass (body) acceleration was produced. There are three lines in the graphs, blue (100), green (500) and red (1000). The line represents the skyhook values that changed to get the best value.

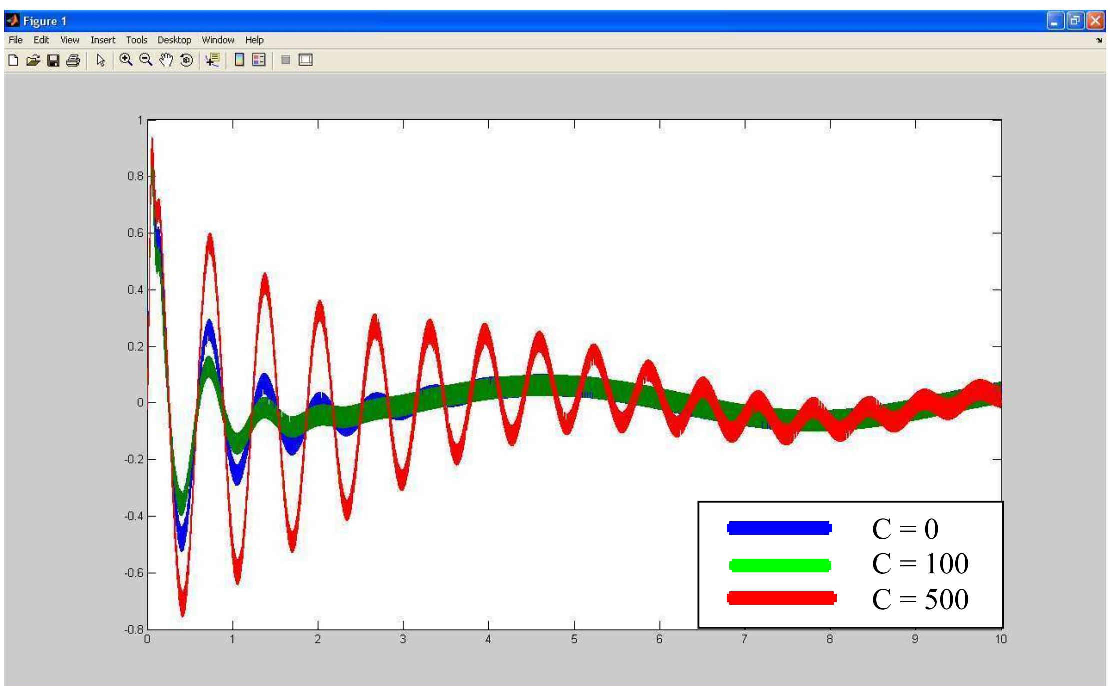


**Figure 4.5**: Sprung mass (body) acceleration

In Figure 4.5, the sprung mass (body) acceleration for skyhook's value of 100 is improved rather than skyhook's value of 0 and 500 as the vibration amplitude for sprung mass (body) is lower than other values and the time taken to terminate the vibration is much faster.

The time taken to terminate the vibration is slower and the oscillation become more rapidly as the skyhook's value increased and decreased. So, the best value for skyhook controller is 100 based on the simulation that had been done.

### 4.2.3 Analysis of Modified Skyhook Controller

From the equation of modified skyhook controller in Chapter 2, the system was designed and simulated in Matlab/Simulink. The simulation was excited by a step input with the height of 0.1 m at t=0sec.

Modified skyhook = $C[\alpha(\dot{Z}_u - \dot{Z}_s) + (1-\alpha)\dot{Z}_s]$ [2]

From the simulation, a graph of sprung mass (body) acceleration was produced. There are four lines in the graphs, blue (-10), light blue (0), green (10) and red (100). The line represents the modified skyhook's values that changed to get the best value.

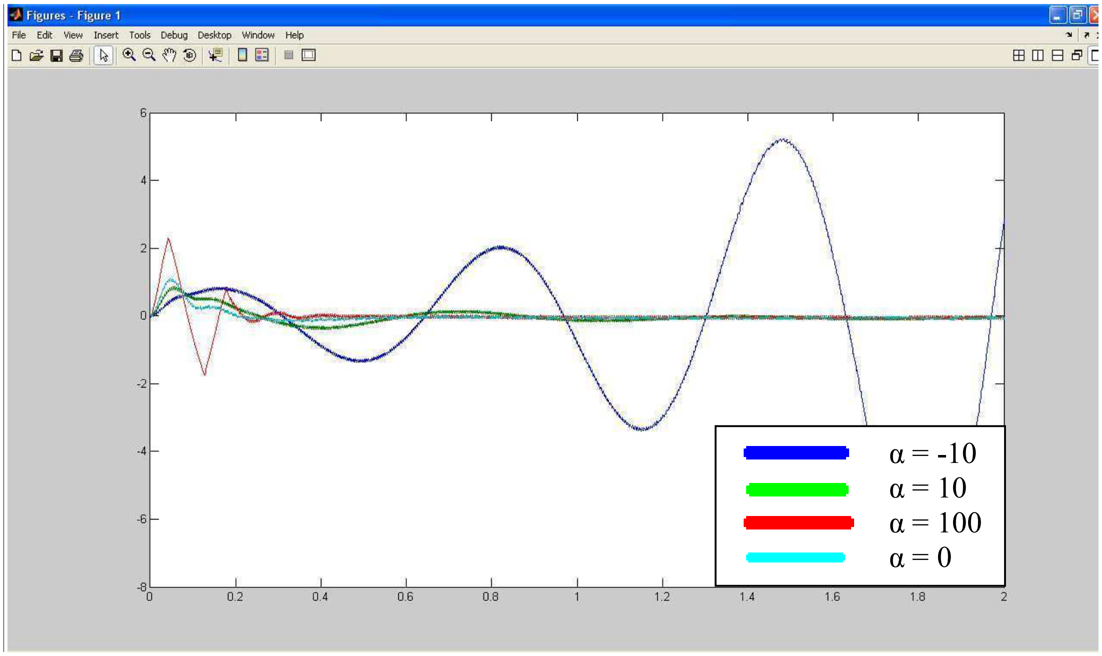


**Figure 4.6**: Sprung mass (body) acceleration

In Figure 4.6, the sprung mass (body) acceleration for modified skyhook's value of 10 is improved rather than modified skyhook's value of -10, 0 and 100 as the vibration amplitude for sprung mass (body) is lower than other values.

The time taken to terminate the vibration is longer and the oscillation become more rapidly as the modified skyhook's value increased and decreased. In Figure 4.6, the value of 0 represent of the normal skyhook controller. From the simulation, it proved that the modified skyhook controller give a better performance than normal skyhook controller. So, the best value for modified skyhook controller is 10 based on the simulation that had been done.

### 4.2.4 Analysis of Passive Suspension System Vs Active Suspension System

The block diagram was built by referring the equation of passive suspension system and active suspension system with modified skyhook controller that been stated in Chapter 2. The system was designed and simulated in Matlab/Simulink. The simulation was excited by a step input with the height of 0.1 m at t=0sec.

The frequency of amplitude was changed to 1Hz, 2Hz and 4Hz. From the simulation, four graphs were produced. The first one is sprung mass (body) acceleration versus time, the second is sprung mass (body) displacement versus time, the third is unsprung mass (tire) displacement versus time and the fourth is spring deflection versus time.

### 4.2.5 Analysis of Passive Suspension System Vs Active Suspension System for 1Hz

The comparison between the passive suspension system and active suspension system were determined and the frequency of the damping rate was set to 1Hz. Passive suspension system represented with line of blue and active suspension system represented with line of green. From the simulation, four graphs were produced. The first one is sprung mass (body) acceleration versus time, the second one is sprung mass (body) displacement versus time, the third one is unsprung mass (tire) displacement versus time and the fourth one is spring deflection versus time.

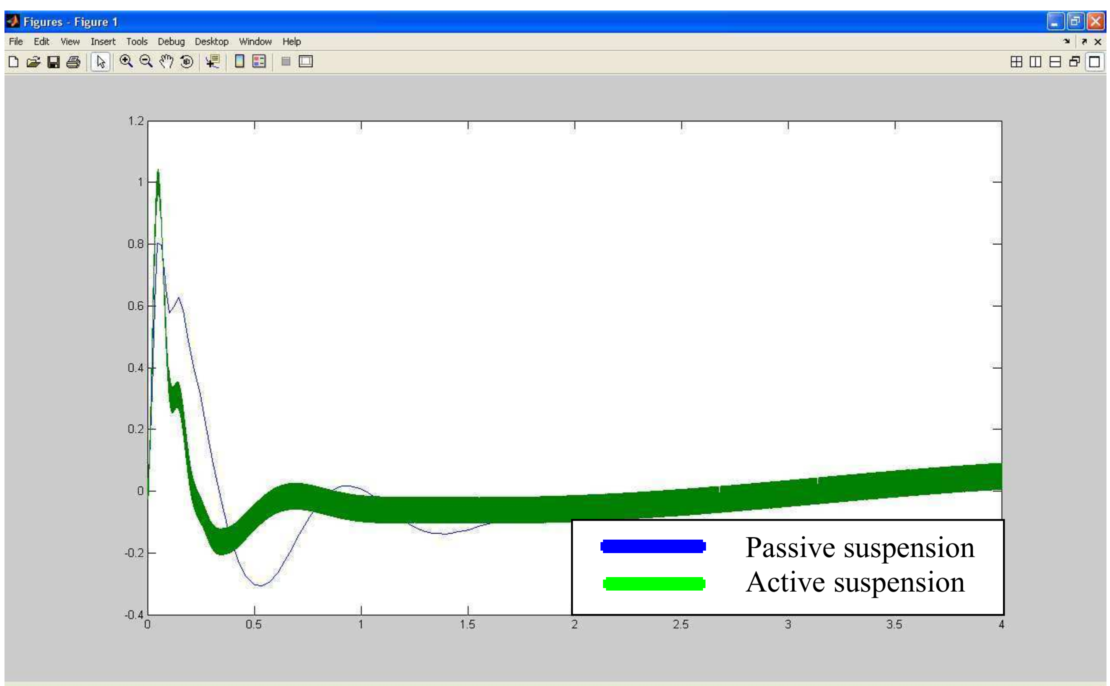


**Figure 4.7**: Sprung mass (body) acceleration

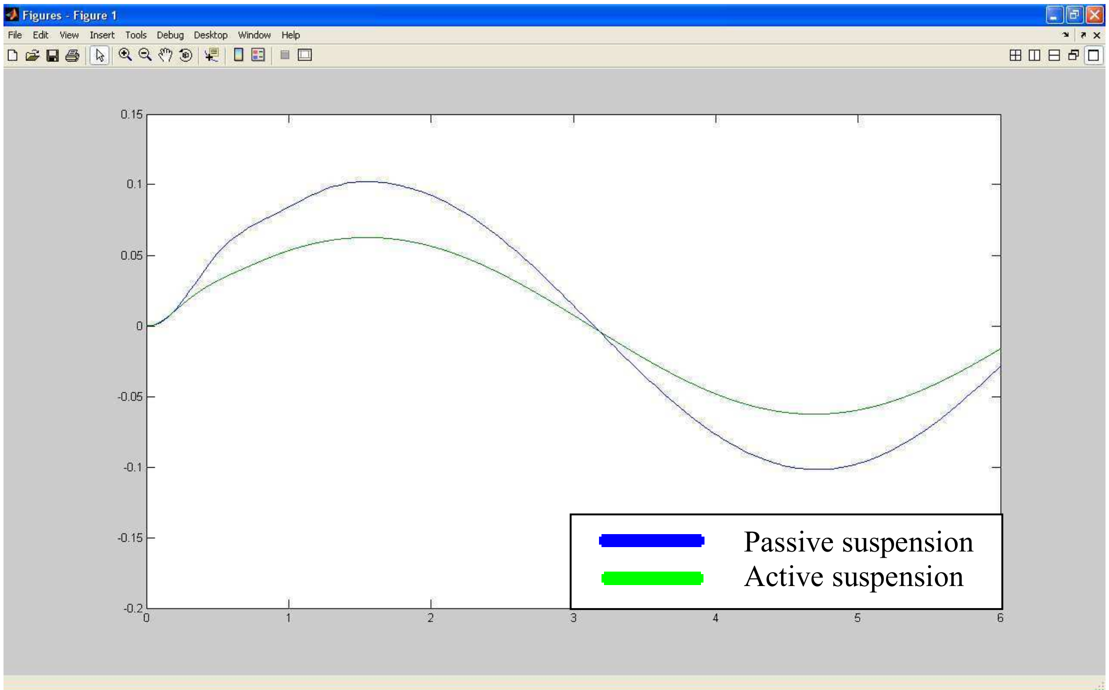


**Figure 4.8**: Sprung mass (body) displacement

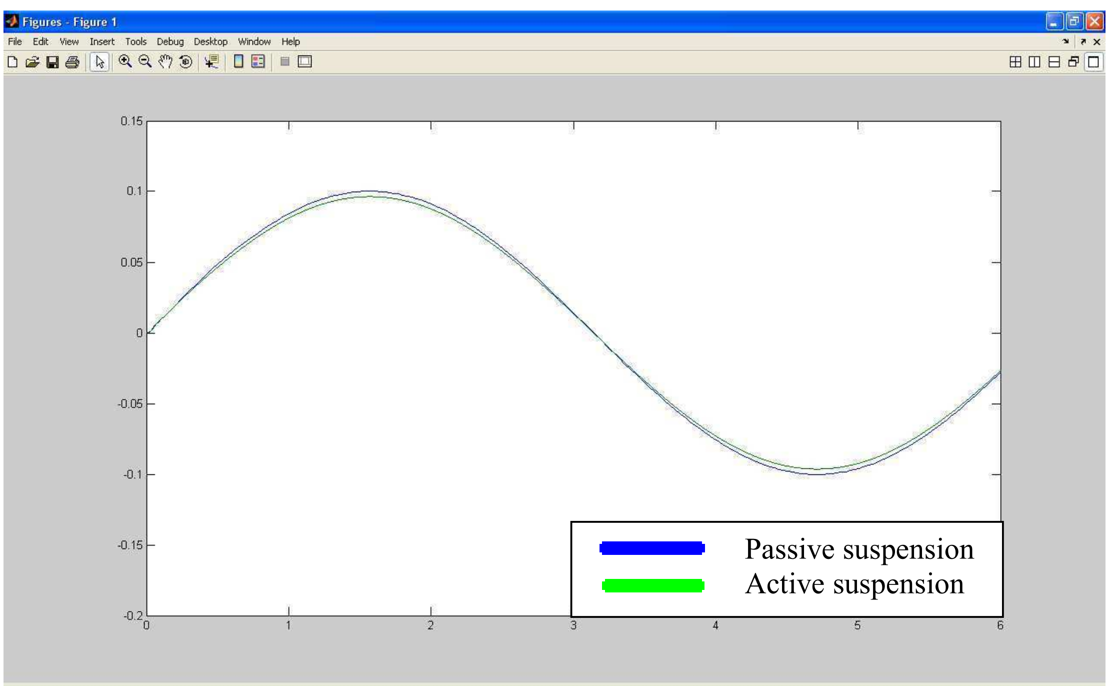


**Figure 4.9**: Unsprung mass (tire) displacement

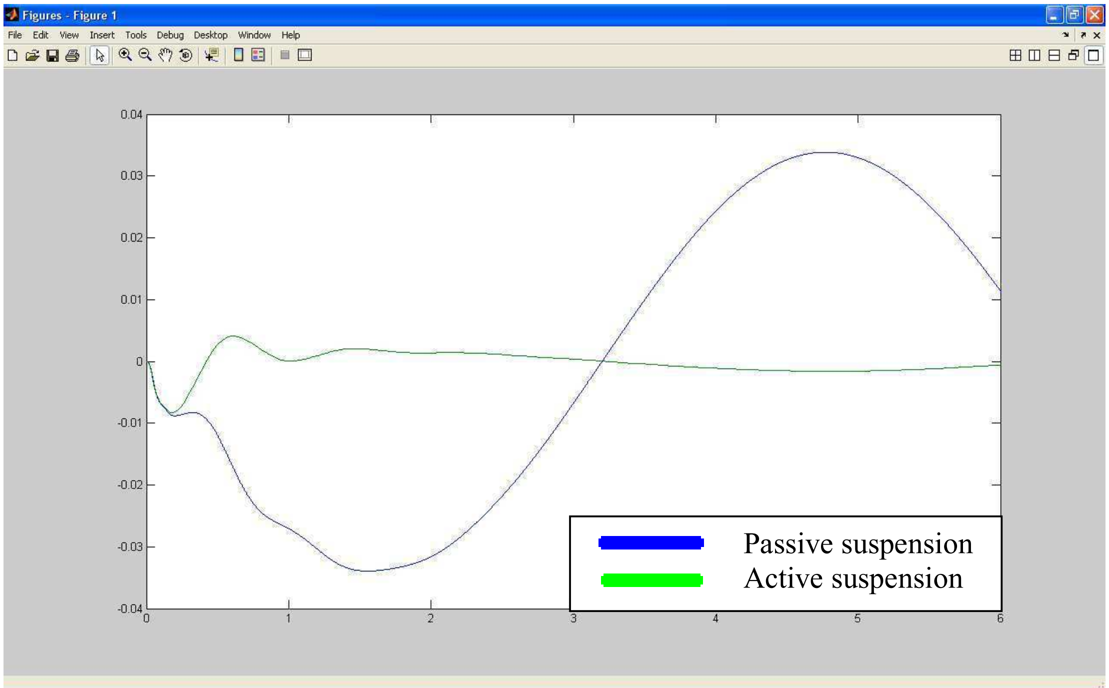


**Figure 4.10**: Spring deflection

### 4.2.6 Analysis of Passive Suspension System Vs Active Suspension System for 2Hz

The comparison between the passive suspension system and active suspension system were determined and the frequency of the damping rate was set to 2Hz. Passive suspension system represented with line of blue and active suspension system represented with line of green. From the simulation, four graphs were produced. The first one is sprung mass (body) acceleration versus time, the second one is sprung mass (body) displacement versus time, the third one is unsprung mass (tire) displacement versus time and the fourth one is spring deflection versus time.

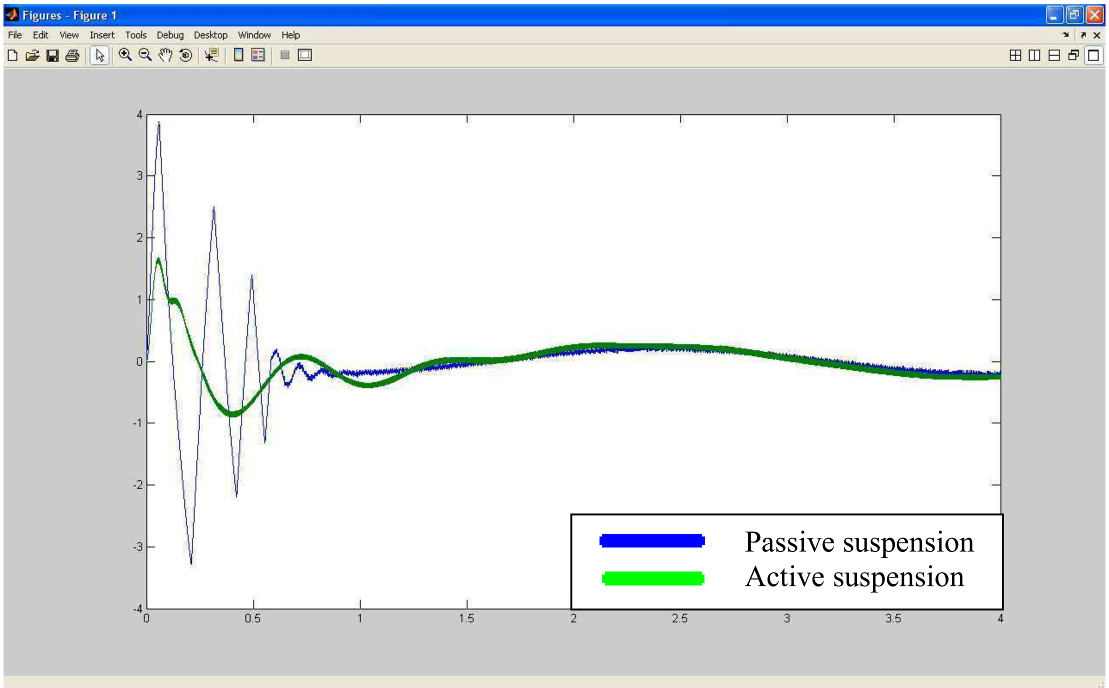


**Figure 4.11**: Sprung mass (body) acceleration

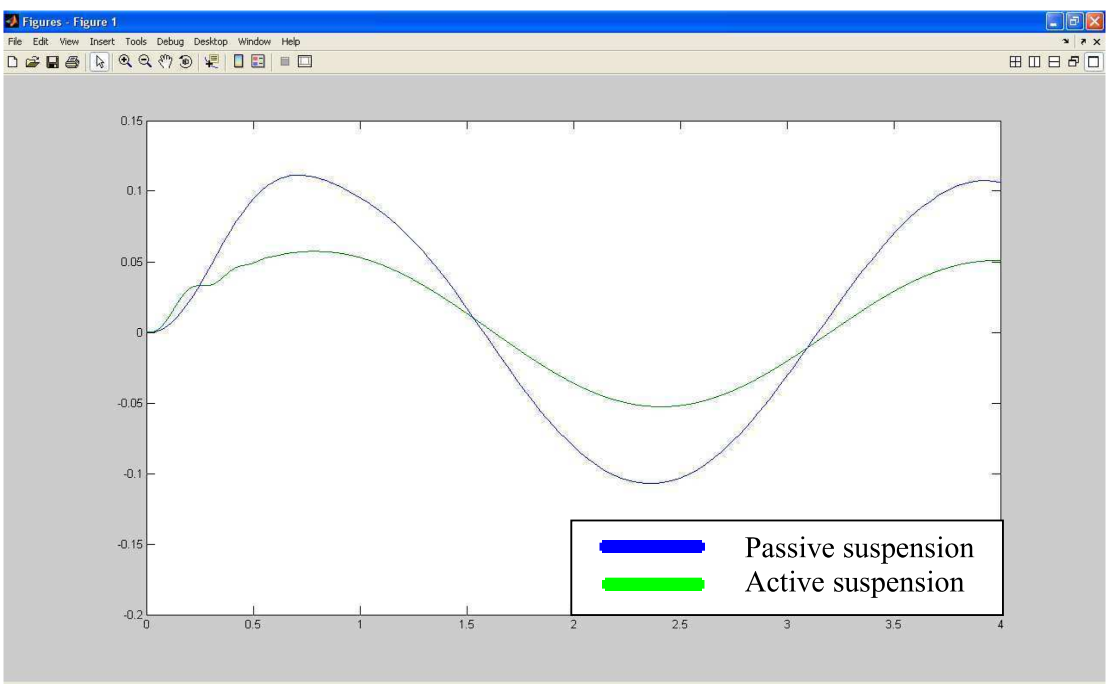


**Figure 4.12**: Sprung mass (body) displacement

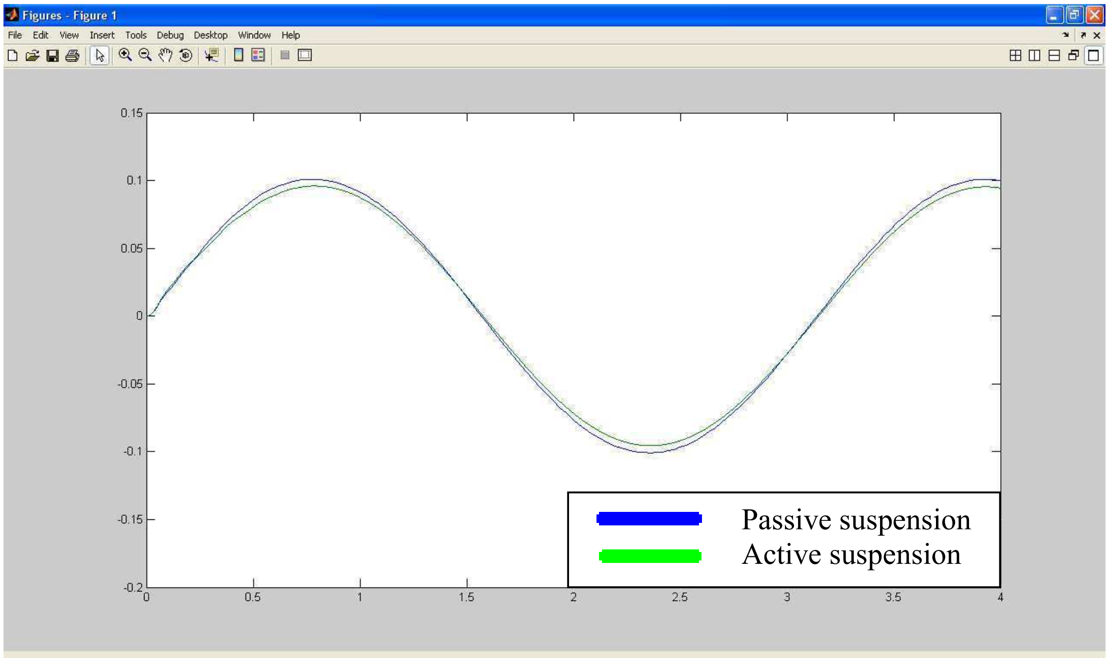


**Figure 4.13**: Unsprung mass (tire) displacement

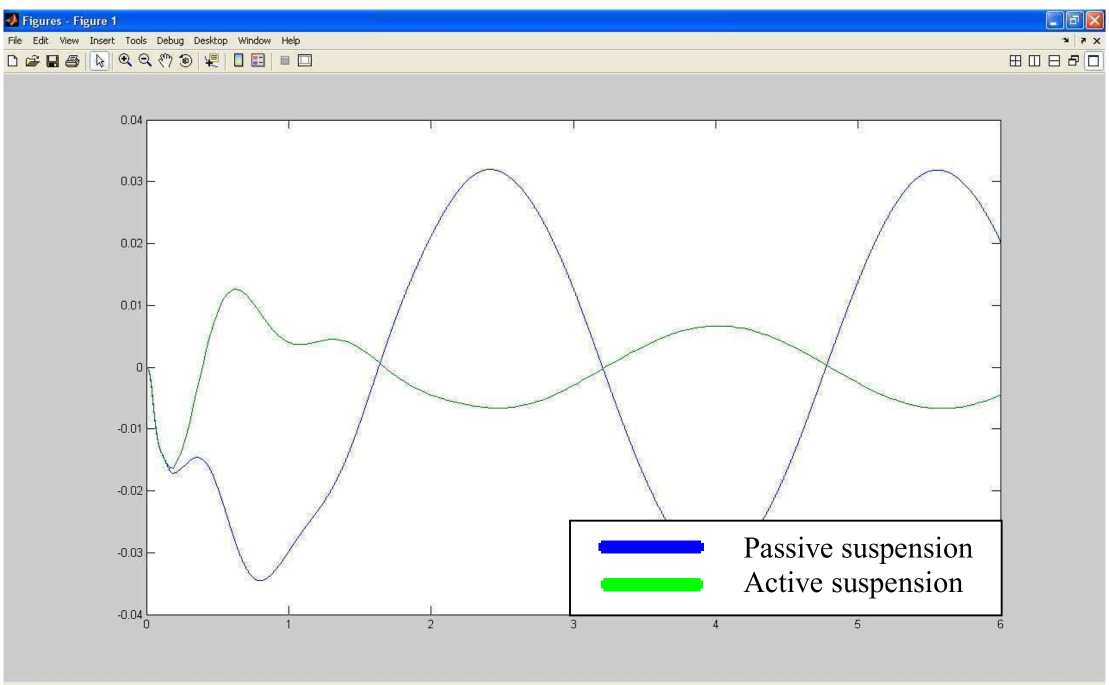


**Figure 4.14**: Spring deflection

### 4.2.7 Analysis of Passive Suspension System Vs Active Suspension System for 4Hz

The comparison between the passive suspension system and active suspension system were determined and the frequency of the damping rate was set to 4Hz. Passive suspension system represented with line of blue and active suspension system represented with line of green. From the simulation, four graphs were produced. The first one is sprung mass (body) acceleration versus time, the second one is sprung mass (body) displacement versus time, the third one is unsprung mass (tire) displacement versus time and the fourth one is spring deflection versus time.

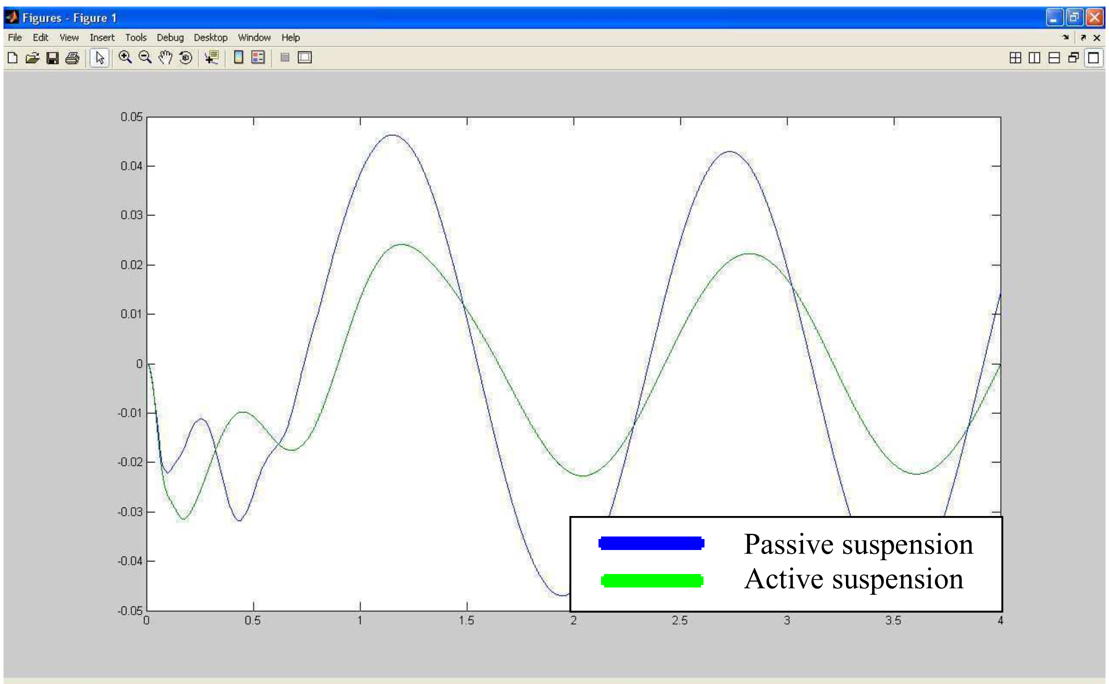


**Figure 4.15**: Sprung mass (body) acceleration

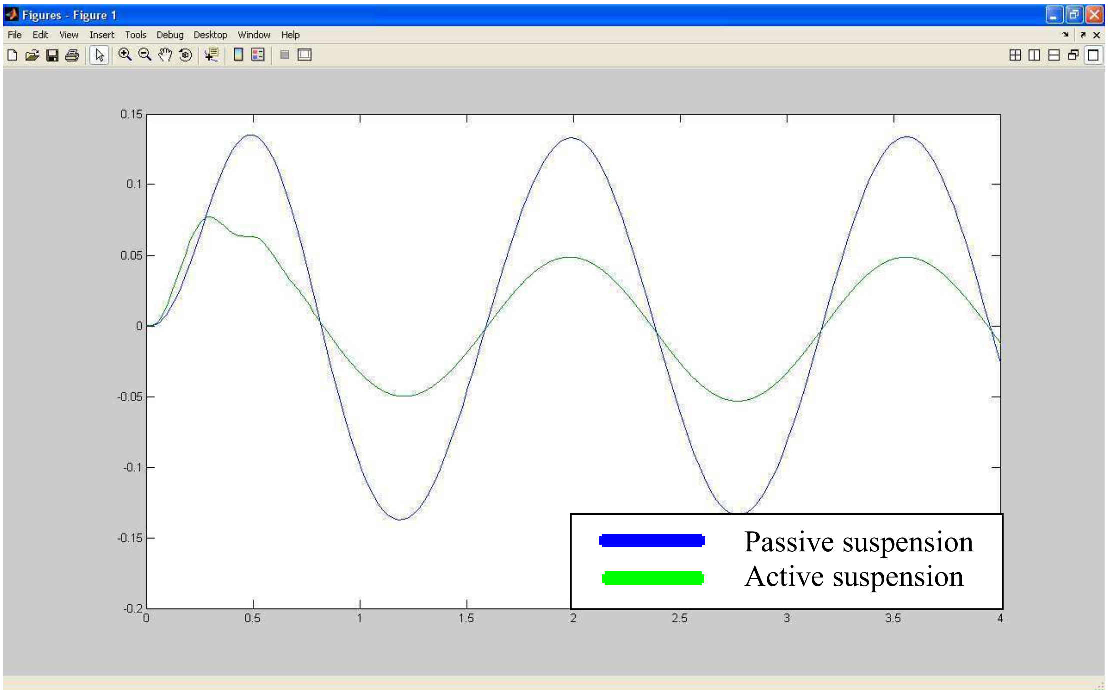


**Figure 4.16**: Sprung mass (body) displacement

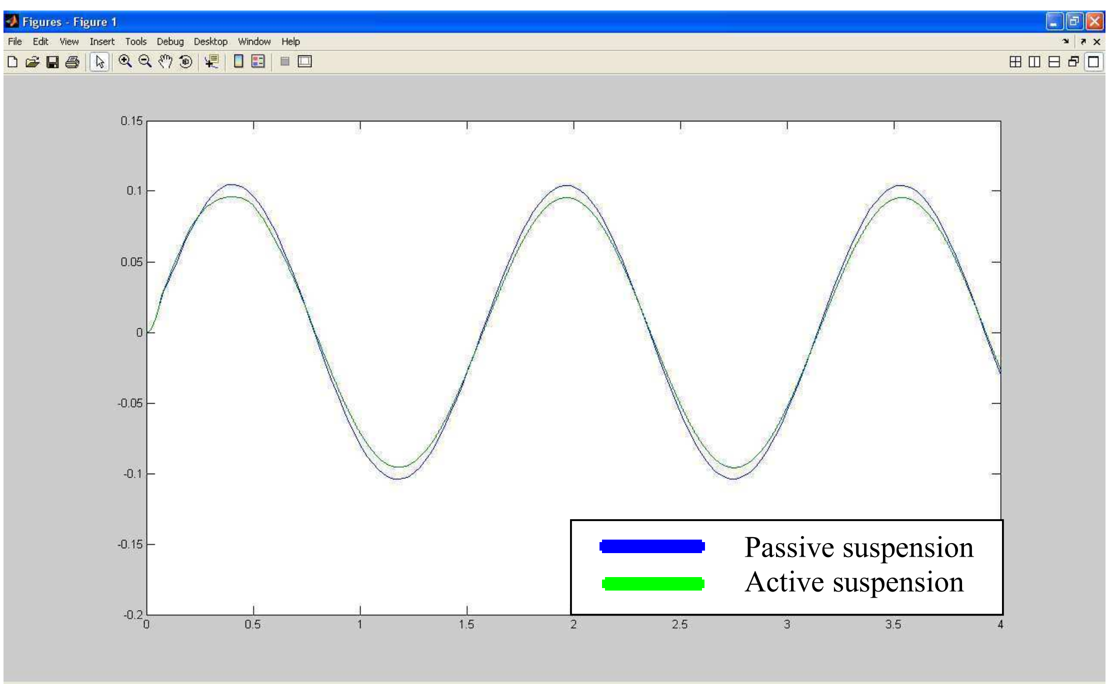


**Figure 4.17**: Unsprung mass (tire) displacement

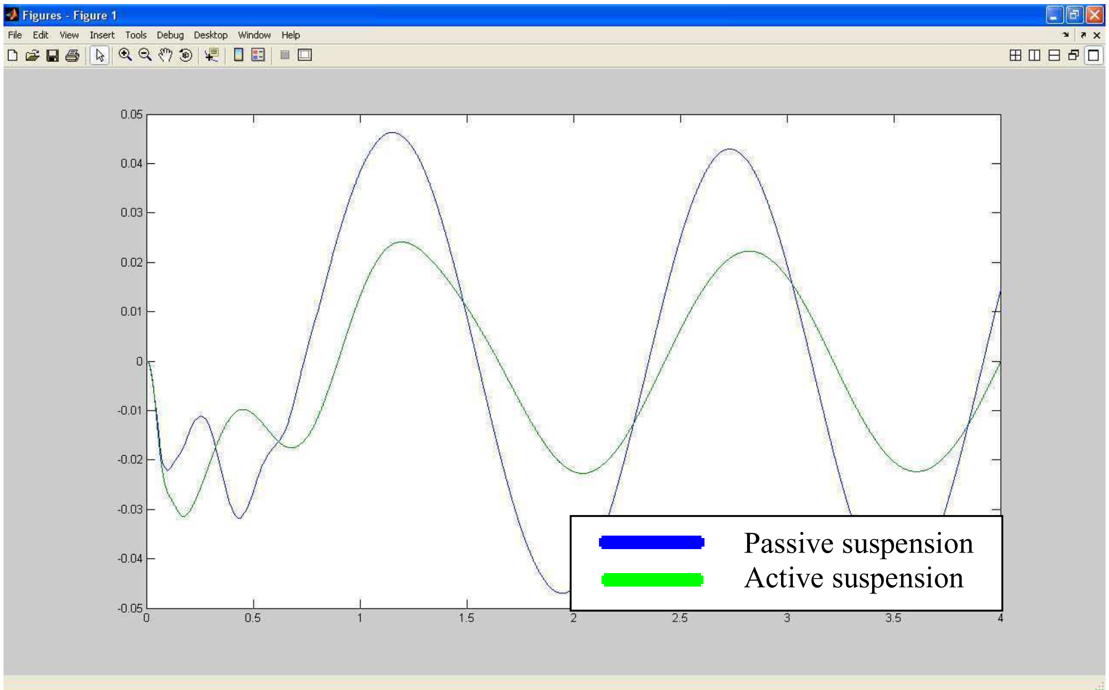


**Figure 4.18**: Spring deflection

### 4.3 Results for Optimal Performance

Quarter car of passive system do not produce the best performance compared to the active suspension system. This performance was evaluated by sprung mass (body) acceleration, sprung mass (body) displacement, unsprung mass (tire) displacement and spring deflection. It was reflected by the results from the graph that had been analyzed earlier in this chapter. All the values that obtained from the graph are larger from data that obtained from active suspension system.

The value of sprung mass (body) displacement is smaller for the lowest value of frequency that is 1Hz compared to 2Hz and 4Hz. It also same for spring deflection, the value is smaller for 1Hz than 2Hz and 4Hz. However, this will cause the situation to passengers who are not comfortable because of suspension seems a bit hard. The value of sprung mass (body) acceleration also small for lower frequency compared to the higher frequency.

The lower frequency gives a better performance results compared to the higher frequency. This cause by the oscillations rate of the suspension is lower and time period for one complete oscillation become longer.

Active suspension system is the best system than passive suspension system because of the incorporate actuators (hydraulic actuator) that generate the desired forces in the suspension. This system can be improved by adding controller such as skyhook controller. In addition, modified skyhook controller give an increment in performance than normal skyhook controller.

The performance of the modified skyhook controller for active suspension system is better from normal skyhook controller for active suspension system based on the sprung mass (body) acceleration, sprung mass (body) displacement, unsprung mass (tire) displacement and spring deflection.

The value of sprung mass (body) displacement is smaller for the lowest value of frequency that is 1Hz compared to 2Hz and 4Hz. It also same for spring deflection, the value is smaller for 1Hz than 2Hz and 4Hz. Eventually, this provides a comfortable for passengers because the spring will absorb impacts more effectively than passive system (suspension seems soft). The value of sprung mass (body) acceleration also small for lower frequency compared to the higher frequency. The tire displacement is same for all type of system because of the same input that is 0.1m.

The lower frequency gives a better performance results compared to the higher frequency. This cause by the oscillations rate of the suspension is lower and time period for one complete oscillation become longer.

**Table 4.1**: Data comparison for active suspension system

| Parameter / Frequency | Sprung Mass (Body) Acceleration | Sprung Mass (Body) Displacement | Spring Deflection | Unsprung Mass (Tire) Displacement |
|---|---|---|---|---|
| 1 Hz | 0.021 | 0.050 | 0.005 | 0.100 |
| 2 Hz | 0.022 | 0.055 | 0.012 | 0.100 |
| 4 Hz | 0.022 | 0.075 | 0.020 | 0.100 |

# CHAPTER 5

# CONCLUSION

## 5.1 Introduction

Starting from the process of literature review the process of design and simulation of modified skyhook controller for active suspension system in Matlab/Simulink software and finally analyzing the system in order to complete the project objectives. The analysis is done to determine the effectiveness of semi-active suspension system for improvement in vehicle suspension characteristics by comparing the active suspension system with the passive suspension system.

## 5.2 Conclusion

This report outlines the design and simulation of modified skyhook controller for active suspension system. The goal of the use of modified skyhook controller to the active suspension system was to allow both comfort and performance compared to the passive suspension system.

In conclusion, all objective for this report were achieved. For the first phase (FYP 1) of this study, design and simulation of hydraulic actuator and force tracking controller were been done. The second phase (FYP 2), design and simulation of quarter car for passive suspension system and modified skyhook controller for active suspension system also done successfully. These designs were combined together and simulated to get the final results. All the objectives were done by referring to the article and the journal that had been published.

Simulation results showed that the active suspension system could provide significant improvements in the sprung mass (body) displacement, sprung mass (body) acceleration and spring deflection. This system can be improved by adding controller such as skyhook controller. In addition, modified skyhook controller give an improvement in performance than normal skyhook controller.

## 5.3 Recommendation for the Future Research

The active suspension system can be improved by utilizing the hydraulic actuator as the control input. To study the influence of cornering on vehicle roll and the influence of braking and longitudinal acceleration on vehicle pitch, half car and/or full car models are recommended. A high order multi-degree-of-freedom model involving many suspension parameters is typically required in order to analyze the influence of suspension design on all the performance functions.

Another recommendation is to compare the simulation results with experimental results to validate its results. By comparing the simulation results with experimental, the difference will illustrate the percentage of error between simulation and experimental results.

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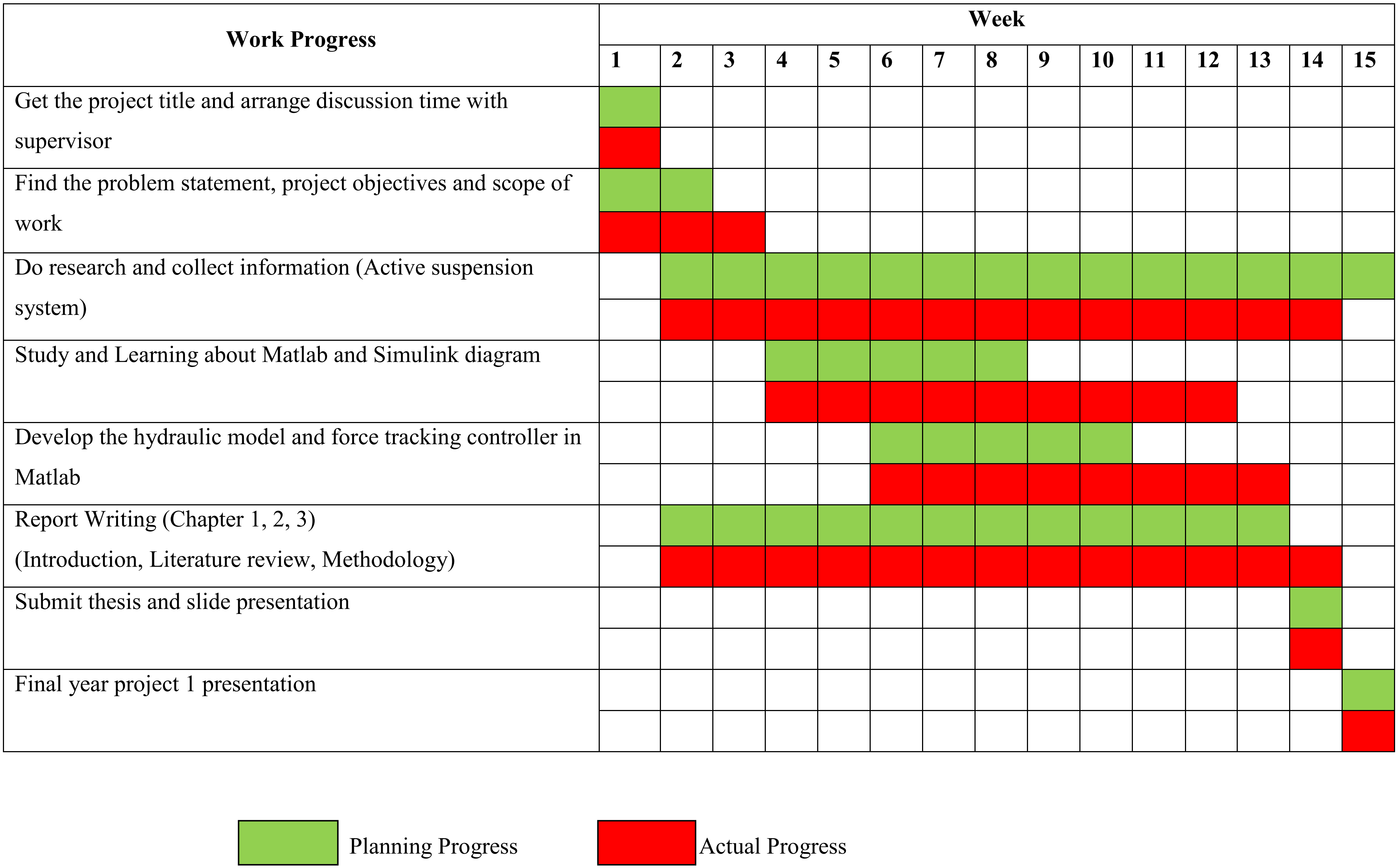
**Project Planning (Gantt chart): Final Year Project 1**



**Project Planning (Gantt chart): Final Year Project 2**