# FACULTY OF ELECTRICAL ENGINEERING
# UNIVERSITI TEKNIKAL MALAYSIA MELAKA



# INTELLIGENT CONTROLLER DESIGN FOR A NONLINEAR QUARTER-CAR ACTIVE SUSPENSION WITH ELECTRO-HYDRAULIC ACTUATOR SYSTEM

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Bachelor of Electrical Engineering (Control, Instrumentation and Automation)
with Honours

June 2015

“ I hereby declare that I have read through this report entitle “Intelligent Controller Design for A Nonlinear Quarter-Car Active Suspension with Electro-hydraulic Actuator System” and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Control, Instrumentation and Automation) with Honours ”



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Supervisor’s Name : DR. ROZAIMI BIN GHAZALI

Date : ………………………………………………………..

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**MASLINDA BINTI PAHARUDIN**

**A report submitted in partial fulfillment of the requirements for the degree of Bachelor of Electrical Engineering (Control, Instrumentation and Automation) with Honours**

**Faculty of Electrical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2015**

I declare that this report entitle "*Intelligent Controller Design for A Nonlinear Quarter-Car Active Suspension with Electro-hydraulic Actuator System*" is the result of my own research except as cited in the references. The report has not been accepted submitted in candidature of any other degree.

Signature : ……………………………………………………….

Name : MASLINDA BINTI PAHARUDIN

Date : ……………………………………………………….

Specially dedicated:

*To my beloved father Paharudin Bin Ambran,*

*To my beloved mother Hamsiah  Binti ABD Karim,*

*My beloved sister and brothers,*

*My supervisor and all my lecturers,*

*All my friends.*

*For their encouragement, support and motivation through my journey of education*

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# ABSTRACT

Nowadays, active suspension system becomes important to the automotive industries and human life due to its advantages in improving road handling and ride comfort. The aims of this project are developing mathematical modelling and design an intelligent control strategy. The project will begin with a mathematical model development based on the physical principle of the passive and active suspension system. Electro-hydraulic actuator was integrated in order to make the suspension system under the active condition. Then, the model will be analyzed through MATLAB and Simulink software. Finally, the proportional-integral-derivative (PID) controller and an intelligent controller which is Fuzzy Logic are designed in the active suspension system. The results can be obtained after completing the simulation of the quarter-car nonlinear passive and active suspension system. From the simulation made through MATLAB and Simulink, the response of the system will be compared between nonlinear passive and nonlinear active suspension system. Besides that, the comparison has been made between Fuzzy Logic and PID controller through the characteristics of a vehicle body and control force from the suspension system. As a conclusion, developing a nonlinear active suspension system with electro-hydraulic actuator for quarter car model has improved the car performance by using a Fuzzy Logic controller. Otherwise, the suspension control system may serve for ride comfort and to support the body of the vehicle. The improvements in performance will improve road handling and ride comfort performance of both systems.

# ABSTRAK

Pada masa kini, sistem suspensi aktif menjadi penting kepada industri automotif dan kehidupan manusia kerana kelebihannya dalam meningkatkan pengendalian jalan dan keselesaan perjalanan. Tujuan projek ini adalah membangun pemodelan matematik dan mereka bentuk strategi kawalan pintar. Projek ini akan bermula dengan pembangunan model matematik berdasarkan prinsip fizikal sistem suspensi pasif dan aktif. Penggerak elektro-hidraulik telah bersepadu untuk menjadikan sistem penggantungan di bawah keadaan aktif. Kemudian, model ini akan dianalisis melalui MATLAB Simulink dan perisian. Akhirnya, berkadar-asasi-derivatif (PID) pengawal dan pengawal pintar yang logik kabur direka dalam sistem suspensi aktif. Keputusan boleh diperolehi selepas menamatkan simulasi tak linear suku kereta pasif dan sistem gantungan aktif. Dari simulasi yang dibuat melalui MATLAB Simulink dan, sambutan daripada sistem akan dibandingkan antara linear sistem suspensi aktif pasif dan tak linear. Selain itu, perbandingan itu dibuat antara Logik Fuzzy dan pengawal PID melalui ciri-ciri tenaga badan kenderaan dan kawalan dari sistem penggantungan. Sebagai kesimpulan, membangunkan sistem gantungan aktif tak linear dengan elektro-hidraulik penggerak untuk model kereta suku telah bertambah baik prestasi kereta dengan menggunakan pengawal Logik Fuzzy. Jika tidak, sistem kawalan penggantungan boleh menyampaikan untuk keselesaan pemanduan dan untuk menyokong badan kenderaan. Peningkatan dalam prestasi akan meningkatkan pengendalian jalan dan menunggang prestasi keselesaan kedua-dua sistem.

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| | | |
|---|---|---|
| $U$ | - | Hydraulic actuator |
| $X_1$ | - | Displacement of body |
| $X_3$ | - | Displacement of angular version |
| $K_{cr}$ | - | Critical gain |
| $P_{cr}$ | - | Critical period |
| $M_1$ | - | Mass of body |
| $M_2$ | - | Mass of wheel |
| $K_s$ | - | Spring of suspension |
| $K_t$ | - | Spring of tyre |
| $B_s$ | - | Damping coefficient of suspension |
| $B_t$ | - | Damping coefficient of tyre |
| $F$ | - | Force |
| $K_p$ | - | Proportional gain |
| $K_i$ | - | Integral gain |
| $K_d$ | - | Derivative gain |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Project Background

The automobile industry has contributed to the growth of the Malaysian automotive industry. Over the years, the industry has successfully developed and improved its technical capabilities, expertise and resources to manufacture a wide range of cars. Today, Malaysian-made cars are exported to a number of countries such as Singapore, United Arab Emirates, Thailand and Indonesia. In 2004, Malaysia's major import sources were Korea, Japan and Thailand, which accounted for 75.4 % of total import for the cars industry [1].



Nowadays, people do not have to be told how important the automobile industry to their lives. The automobile such as car is used to get people to work, deliver food, and other commodities. Without them realizing it, the condition of the car is a major contributor in road accidents. Acting Transport Minister Datuk Seri Hishammuddin Hussein mentioned that the government was taking the matter seriously over the road accidents which were recorded [2]. According the previous research, condition of the car is a big factor that contributes to the accidents. For instance, the accident statistics in Malaysian shows that our roads are dangerous, which is the condition of the road will be affecting the comfort while driving [3].

In line with the government's aim of making Malaysian as a country with a list of accidents by the year 2020, greater emphasis has been placed by the car industry, major players in engineering design as well as establishing strategic to reduce the accident in this country. The intelligent controller design for the car with the active suspension system might be capable to reduce the accident cases due to road handling.

Technically, a car suspension system functions as the mechanism that a part of the car body and the wheels of the car where it will bear the car's weight which to keep the contact between the tires and the road surface. Due to the high performance, increased of the vehicle capabilities has also changed the performance of the suspension system to imitate the same effect [4].

As known, the vehicle is a piece of mechanism equipment used as the medium of transportation. This agent of transmission has a strong nonlinear characteristic which can be uncertain with the dynamic parameters like masses, inertias, suspension springs and tires sides slip coefficients [5]. Under the vehicle, the suspension is more likely as the linkage between unsprung mass and the sprung mass [6].

## 1.2 Problem Statement

Generally, the main criteria that have deeply taken in vehicle designing are safety and comfort. Suspension system is an important role in completing both requirements in designing, as well continuing the lifetime of other component and give comfort ability during driving. Although, both of events in the system are subjective, the suspension system always gives more safety and comfort factor to the vehicle. As known, passive and active suspension system gives a high performance in the system which is the vibration of the amplitude is high and the time requirement in the system for the vibration in both of suspension is longer.

In order to overcome this condition, the capability of a controller to deal with an uncertainties and highly nonlinear system is analyzed based on quarter-car model. The active electro-hydraulic suspension is introduced in this system. The hydraulically actuated suspension is controlled with the use of hydraulic servomechanism. Other than that, the conventional controller of backstepping, sliding mode, fuzzy logic and PID controller design are always been used to solved a linear system [ 7-16 ].

## 1.3 Objectives of the Project

The objectives of this project are:

a) To develop a nonlinear mathematical modelling for quarter car active suspension with the electro-hydraulic actuator system.
b) To analyze the performance of a passive suspension system for a nonlinear quarter car model.
c) To design and evaluate an intelligent control strategy for an active suspension system based on Fuzzy Logic Controller.

## 1.4 Scope of Project

The scopes works of this project are as follows:

i. Development of mathematical modeling of a nonlinear quarter car active and passive suspension system.
ii. Design a controller PID and Fuzzy Logic for nonlinear active suspension system.
iii. Perform a simulation result of nonlinear passive and active suspension system in MATLAB/Simulink.
iv. Comparison study for nonlinear active suspension system based on PID and fuzzy logic controller in term of deflection velocity, body velocity and body acceleration.



This project will introduced in four stages of work

i. First Stage : Literature Review
    - All the information about the project can get through internet, journals, magazines, published paper and reference books.
    - Learn about the related software (Simulink, MATLAB)
    - Explaining more about the suspension system.

ii. Second Stage : Design and Simulation

- Mathematical modeling of nonlinear passive and active suspension system will be designed.
- The electro-hydraulic actuator system will be introduced in nonlinear active suspension system.
- Comparison between PID and fuzzy logic controller nonlinear active suspension system.
- MATLAB/Simulink software is used to simulate the performance of nonlinear passive and active suspension system.

iii. Third Stage: Implementation

- The simulation result of nonlinear passive and active suspension system will be analyzed.
- The simulation result with different controller will be analyzed

iv. Fourth Stage: Report Writing

- Write all the information which is related to the project.
- Show all the idea using flowchart to present the implementation of project.
- State the starting condition until the project is done.

## 1.5 Thesis Outline

In general this thesis is divided into five chapters, where it consists of:

Chapter 1: Introduction

Chapter 2: Literature Review

Chapter 3: Research Methodology

Chapter 4: Results and Discussions

Chapter 5: Conclusion and Recommendation

Chapter 1 is an overview of the research project in whole. For the first chapter is about introduction. In this chapter describe about the background, problem statement, objective and scope of the project.

Chapter 2 presents the literature review and theory background. In this chapter explain about the background of study which is related to the project. This chapter introduced the evidence that use in this project (e.g. books, internet, lecture notes etc) and focusing on the project report, thesis, journal paper etc).

Chapter 3 discusses about the methodology adopted for this research work. It involves the materials, subjects and equipment that are used in this project.

Chapter 4 shows the result obtained from the data presented. Then the related parameters are arranged tidily using the aid of figures and tables. Hence, all the result is explained and compared with another method. Then from the comparison with another method, it will be discussed.

Chapter 5 explains the conclusion achieved in this project and also the some suggestion to future work.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

In general, an active suspension is widely used in automation system as it is an important part for safety purpose. Balancing the tradeoff between ride quality and road handling performance is a purposed of the suspension system [17]. This performance can be achieved by maintaining the relative position and movement between the vehicle body and wheels. Hence, the effects of vibrations will be reduced for particular road profile. The performance of the handling requires a stiff suspension because the system becomes stable when the tire contact keeping with the road. Suspension can be categorized as a dangerous and safe condition. The dangerous suspension is referring the road irregularities which can allow the body, resulting in poor ride comfort performance.

The ride comfort is referring to the vertical acceleration of sprung mass and ability of the tire deflection will be held by the system. The passenger will feel comfort when maintaining the vertical acceleration. Reducing sprung mass acceleration is one of the factors that can give the passenger comfort while adequate suspension deflection will be provided by the system which to maintain the condition tire to the ground contact [18].

Nowadays, the automotive suspension makes a design method based on the optimal control strategies. Sprung mass acceleration, suspension deflection and tire deflection are optimized by the suspension system. the main components use to designing in suspension system is a spring and parallel damper. All the components are placed together between the vehicle body and the wheels. Ride comfort as well as good handling is an important factor in designing the suspension system.

## 2.2 Basic Principles of Suspension System

Whenever the vehicle passes through bumps or holes in the road, the suspension system will allow moving up and down. As the result, the riding of vehicle becomes smoothly over the various roads. The types of vehicle suspension are available may be categorized as passive vehicle suspension system, semi-active vehicle suspension system and active vehicle suspension system [19].

### 2.2.1 Passive Vehicle Suspension System

A passive suspension system has the shock absorbers and the conventional springs as shown in Figure 2.1. In a passive system, there are two characteristics, linear and nonlinear characteristics. The linear characteristic of the system is a normal spring and relationship in shock absorbers between force and velocity is a nonlinear characteristics. However, the dynamics in the passive suspension system can fully control in term of vertical motion. The passive suspension system element cannot give the energy to the system. Even though no energy supplied, the relative motion can be controlled by different types of damping to the wheel.

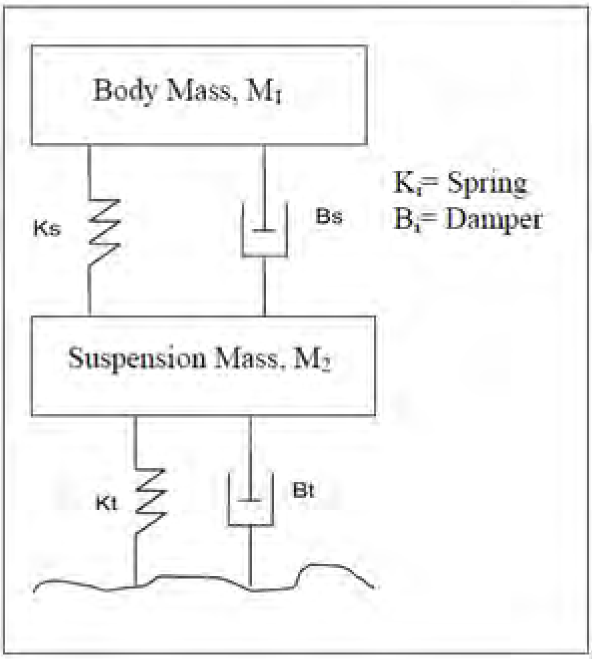



Figure 2.1 : Passive suspension system

### 2.2.2 Semi-active Vehicle System

The semi-active suspension system provides a controller that can control the real-time dissipation of energy. The semi-active system is operated by changing the damping coefficient using the electromagnetic valve which controlled inside the absorbers. The active damper is put in parallel with a normal spring as shown in Figure 2.2. The controllable damper is used to replace the damper. The proportional of body velocity in semi-active suspension needs a force which can apply in the body motion. Next, damper of velocity will cause the body velocity in the same direction and the high state will change using the damper. In the opposite direction of the body velocity, the low state will switch and the input force transmitted rather than dissipating energy.

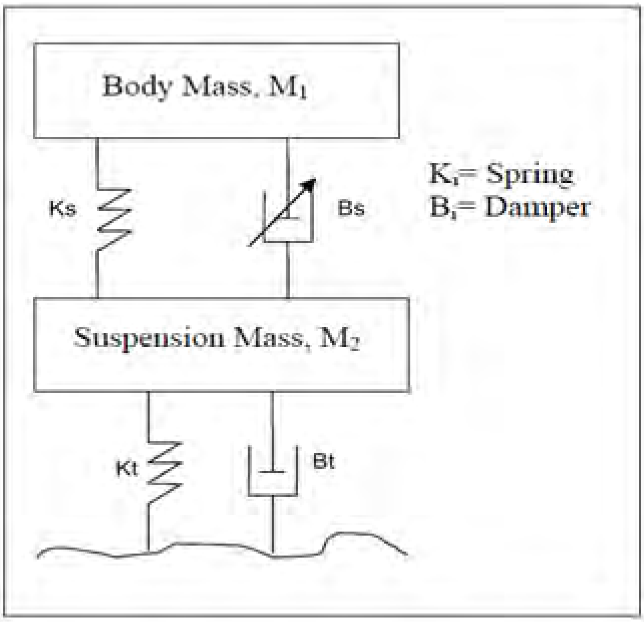



Figure 2.2: Semi-active suspension system

### 2.2.3 Active Vehicle System

An active suspension system uses computer controlled hydraulic rams instead of conventional springs and shock absorber actuators to control ride characteristics. The conventional spring and absorber is connected in parallel with hydraulic actuator as shown in Figure 2.3. The hydraulic rams support the weight of the car and react to the road surface and driving conditions. Basically, pressure sensors on each hydraulic ram provide the main control for the system. They react to suspension system movement and send signals to the computer. The computer can then extend or retract each ram to match the road surface.

Figure 2.4 shows the fully active suspension system while the system can make a car feel as it is floating on a cushion of air. It can theoretically eliminate more body movement as the car travels over small dips and bumps in the road. It can also help keep the body level under various driving conditions. During hard braking, it can keep the front of the body from diving and the rear from rising, thus improving action. In turn, the active suspension system's ability to prevent body roll can make the car stay level to increase cornering ability. It can tilt the vehicle's body against a turn to improve handling.

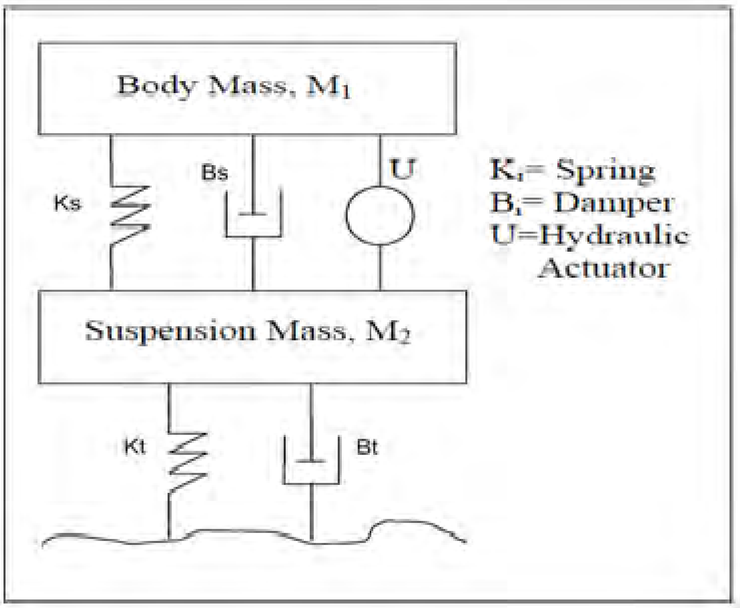



Figure 2.3: Active suspension system

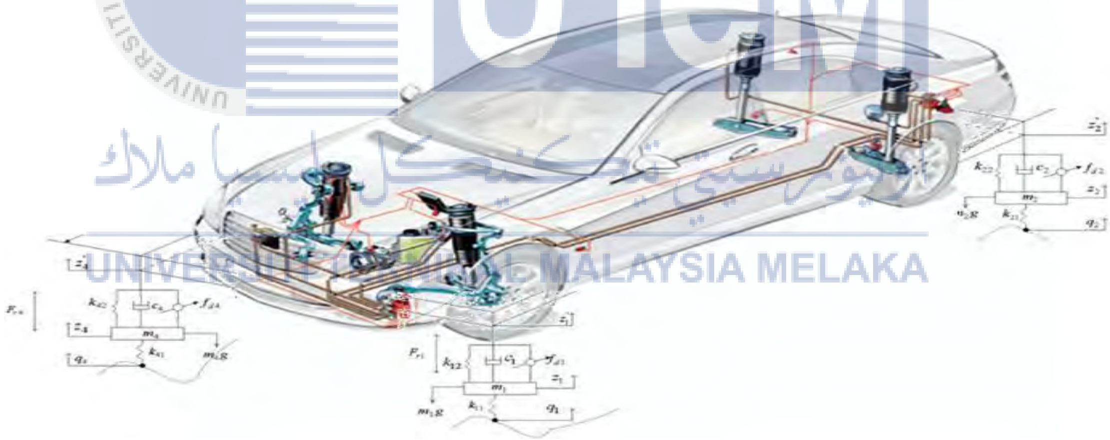


Figure 2.4: Fully active suspension system

## 2.3 Purpose of the Suspension System

As the suspension system components and how they work together are reviewed in this chapter. Firstly, the dynamic state of balance is used in the suspension system to make the tires will move smoothly without disturbance [20]. Next, the suspension system will change the driving condition, whether is good or bad condition. Six basic components will be categorized in the suspension system [21]. There are maintaining the vehicle ride height, minimizing the factor of shock forces, making the wheel alignment in a good condition, keeping the weight of the vehicle, maintaining the tires in contact with the road and controlling the direction of vehicle travel.

### 2.3.1 Main Components of a Modern Suspension System

Shock absorbers, springs and tires are the main components of a moving vehicle suspension system are shown in Figure 2.5. All the functionality of the main component in the suspension system will be reviewed thoroughly in the following section.

Spring is used in the system to support the weight of the vehicle, maintaining the ride height in stable condition and absorbing the road shock from the vehicle. Spring function as a flexible links which to give the frame and the body of the vehicle to ride comfortably without disturbance while the tires and suspension hit the bumps on the road. When the load is put in the springs or the wheel hit the bump in the road, the load will be absorbed by the spring using compressed technique. Ride comfort will occur when the main components which is spring is placed in the system [22].



The Shock absorber is used to control movement of the suspension, which is to make the tires keeping maintain with the road. From the previous study about the springs, in term of bounce is referring to the vertical movement of the suspension system [23]. The compressing is occurring in the upward suspension travel which the spring and shock absorber will be compressed together. The extension is occurring when the downward travel of the tire and wheel extends the condition of spring and shock absorber. When the spring is not in the original condition, it will store energy. The spring become unstable without shock absorber and makes the spring extend and release the energy. Spring will become bounce and overextend cause of spring's inertia.

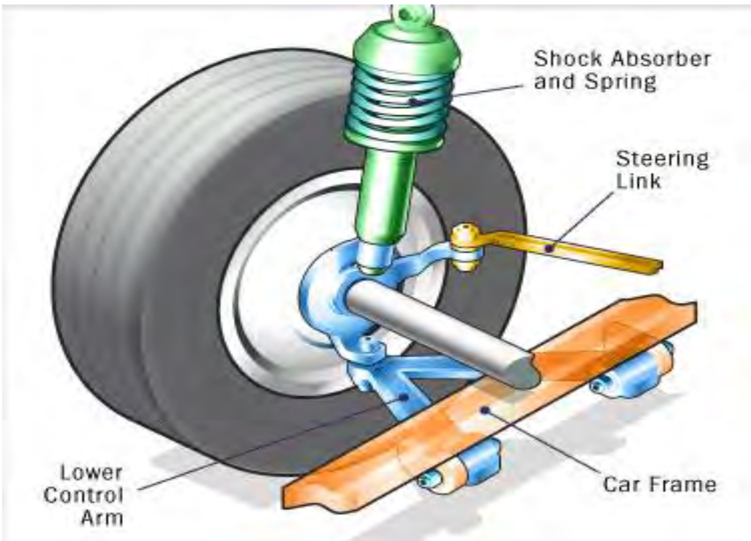



Figure 2.5: Main component of suspension system



## 2.4 Mathematical Modelling of Suspension System

The first step to develop a control algorithm for suspension system is mathematical modelling. To understand the behavior of the suspension system, the dynamic model will be introduced. Input and output of the suspension system have the relationship to describe the dynamic model. The objective of the model is to lessen the x-axis of the acceleration car body and maintain contact between tires and road. The mathematical equation modelling can be designed using dynamic model.

After that, model in state space form of the suspension system can be represented using the mathematical modelling. The equation from the mathematical modelling will be derived in the state space representation. Besides that, suspension system can be categorized in linear and nonlinear suspension system [24]. For a linear suspension system, vertical movement of the wheel and the movement of the car body can be represented in the state variables. For a nonlinear active suspension system design, two parts of movement take place which is a rotational movement of body suspension and rotational movement of the control arm. In this situation, the system will become four degree of freedom system. Designing of the nonlinear suspension system is quite similar with a designing of active suspension system which the system has a control force. Control force from the system will be generated by electro-hydraulic or pneumatic actuator.

## 2.5 Literature Review

This part reviews of previous related works in term of control strategy design. Several types of control strategy, design can be categorized which are backstepping controller design, sliding mode controller design, fuzzy logic controller design, proportional integral derivative control design.

### 2.5.1 Backstepping Controller Design Literature Review

Backstepping is systematically constructed the feedback control law. Backstepping controller has a procedure to design the system which can break the problem for the full system into the problem for lower order system. Several types of backstepping control can be categorized which are integrator backstepping and backstepping for strict feedback.

Backstepping nonlinear controller design for quarter car suspension system is presented in [7]. The first step to the design of backstepping controller is to choose the regulated variable. The closed loop system in the nonlinear backstepping shows that a good performance depends on the regulated variable. The regulated variables can be formed in term of $Z_1 = X_1 - X_3$, where $X_1$ is displacement of the body car and $X_3$ is a displacement of the angular version. This step can avoid the swing of zero dynamics in the system. This project introduced wheel displacement which the wheel is a nonlinear filter and the bandwidth in the suspension travel is a nonlinear function. For the passenger's comfort, the resulting response must be soft. With the choice of regulated variable, the backstepping design procedure will take a few step

### 2.5.2 Sliding Mode Controller Design

This project presents a proportional-Integral Sliding Mode Controller design for quarter car active suspension system [8]. Sliding mode controller introduced in this project to control an active suspension system. This project presents the stability of the asymptotic when the existence of the sliding mode system. Thus, linear suspension system in this project uses the quarter car as a model.

Sliding mode control is designed to drive the system. There are two main advantages when use the sliding mode controller. Firstly, the switching function must be chosen that easy to be tailored to the dynamic system. Secondly, the particular classes of uncertainty to be totally insensitive because of the closed loop response. Sliding mode controller is characterized by a suite of feedback control laws and a decision rule [9]. However, to make the sliding mode more attractive for the design, the specify performance must be developed from the system. The first step to begin the controller design is to be determined the sliding mode surface.

### 2.5.3 Fuzzy Logic Controller Design



This project presents a fuzzy logic control design for half-car active suspension system [10]. This project describes a fuzzy based intelligent, active suspension system. This system provides improvement of the riding quality and at the same time can minimize both of displacement and accelerations between the centre of the vehicle and max angle. The first rule to design the logic control is determining the type of design. For this situation, the mean square must minimize which can easy to get the good time performance. As known, the relative displacement between suspension part and vehicle body are acceptable in the constraints.

A fuzzy logic control design for quarter car models with a satisfactory performance is proposed in [11, 12]. This project introduces the genetic algorithm to apply on the vehicle suspension. In this project the deterministic of the sinusoidal function is used as a road surface. Otherwise, the paper presents a main objective where passengers' cars feel comfortable with active suspension system. The active suspension system is categorized followed by principle criterion of vehicle body like suspension deflection and complementary control of the fuzzy-logic. To minimizing the maximum deflection between characteristics vehicle body and suspension parts, the genetic algorithm method is used on the system.

The fuzzy logic control provides stability of the system under control is quite an issue that always be discussed. As well as its ability to ensure robustness with respect system of parameter changes [13]. The result of the fuzzy logic controller design can easily to be appointed using the principle of model equivalent. The model can be categorized in term of output controllers which are linear and nonlinear system. For the input model consists a Fuzzy Logic controller.

### 2.5.4 Proportional-Integral-Derivative (PID) Controller Design

Optimal design of PID control into the nonlinear quarter-car vehicle suspension system is presented in [14]. This method is an effectively in designing of specifications on the ride comfort. Main objective of this paper is to improve the suspension system in term of steady-state characteristics and transient response as well as road handling. The large of derivative gains is produced to increase the rise time where to make the suspension system more sensitive to output.



PID controller design for the fully active suspension system is presented in [15]. The development of this system is used for tuning road input using PID controller. Zieglar-Nichols tuning rules are used in this system which to find the proportional gain, reset rate and determine the derivative time of PID controller. The system is designed for a bumpy road, pothole and random road inputs.

Firstly, $T_i$ = infinity and $T_d$=0 are set and using the proportional control method, the value of $K_p$ is increased from 0 to a max value $K_{cr}$. This situation occurs when the output of the system achieves sustained oscillation [16]. Next, the max gain $K_{cr}$ and the period $P_{cr}$ are solved using the formula which given in Table 1.0 :

Table 1.0: Zeigler-Nicholas tuning rule

| Type Controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|
| P | $0.5K_{cr}$ | infinity | 0 |
| PI | $0.45K_{cr}$ | $0.83P_{cr}$ | 0 |
| PID | $0.6K_{cr}$ | $0.5P_{cr}$ | $0.125P_{cr}$ |

## 2.6 Conclusion

This chapter discusses about the system that have been made by researchers in active suspension system. Based on the knowledge gained from the literature review, many controllers can be designed into the suspension system. The controllers are used to increase the performance of the riding comfort and give a good road handling. The suspension can be done by two concept which are nonlinear and linear suspension system. Both of concepts are categorized into three types of vehicle suspension. There is passive, semi active and active suspension system. This project uses principle that need to satisfy for a purpose of the passenger's comfort.



Often, the controller can be designed to increase the performance of the riding comfort and give a good road handling. Therefore, disturbance effects in the controllers are proposed for nonlinear model for the suspension system.

# CHAPTER 3

# METHODOLOGY

## 3.1 Project Methodology

In the methodology, several procedure will be conducted. The details consists of the information about the quarter-car suspension system, mathematical modelling, and designing of controller to improve the performance. This project will use Simulink-MATLAB software in order to verify the quarter-car suspension system. Figure 3.1 shows the procedure of this project.

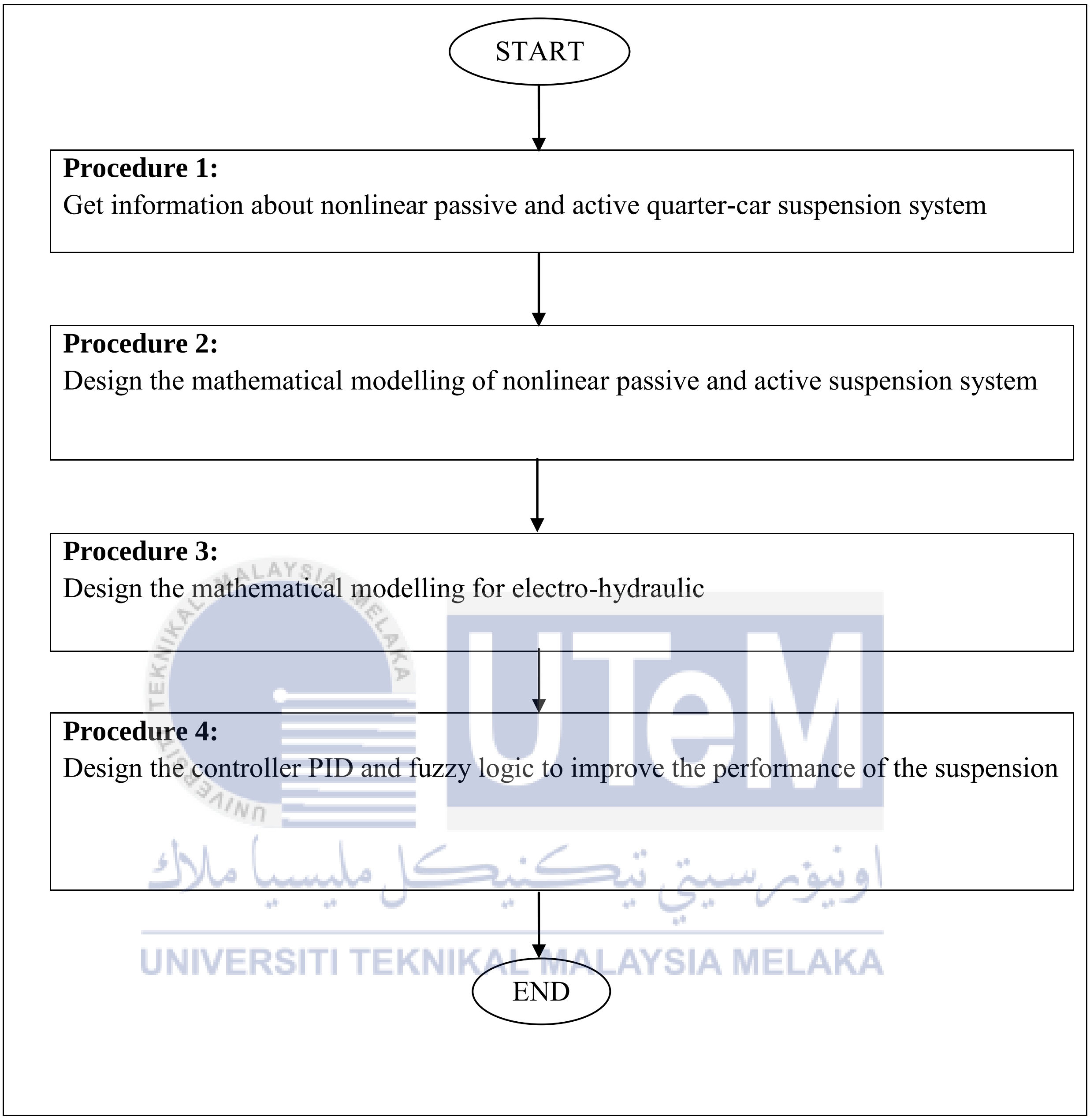



Figure 3.1: Flowchart of project procedure

## 3.2 Procedure 1: Get information about nonlinear passive and active quarter-car suspension system.

### 3.2.1 Nonlinear passive suspension system

Passive suspensions are designed with linear spring and dampers. According to [25] the passengers will be show the ride comfort through the r.m.s acceleration and on the derivative of the acceleration. The suspension system will give good performance when the larger rates must be stiffen up and the smaller rates of acceleration input will be soft from the road when the car hit the bumps. The nonlinearity both in spring and damper is related to this situation [26]. Passive system will be tuned the nonlinearity by itself, although the algorithm continuously on the road input is not possible to change the system.

### 3.2.2 Nonlinear active suspension system

In order to maintain passenger comfort and road handling, active suspension is introduced by additional consideration of suspension travel. When riding comfort and road handling tradeoff is usually in most approaches. To reduce the vertical acceleration of the car body needs more suspension travel. When the driver over a speed bump, the suspension travel limit is increased which causes the passenger discomfort and passengers need wear the vehicle component for safety. The nonlinear active suspension is designed to improve the tradeoff between ride quality and suspension travel.

## 3.3 Procedure 2 : Design the mathematical modelling of nonlinear passive and an active suspension system.

The first step to develop a control algorithm for suspension system is mathematical modelling. To understand the behavior of the suspension system, the dynamic model will be introduced. Input and output of the suspension system have the relationship to describe the dynamic model. The objective of the model is to lessen the x-axis of the acceleration car body and maintain contact between tires and road. The mathematical equation modelling can be designed using dynamic model.

### 3.3.1 Suspension System

In this section, the modeling of the nonlinear passive and active suspension system will be discussed. In order to completing the objectives of project, the quarter car passive and active suspension will also be introduced.

#### 3.3.1.1 Nonlinear Passive Suspension System

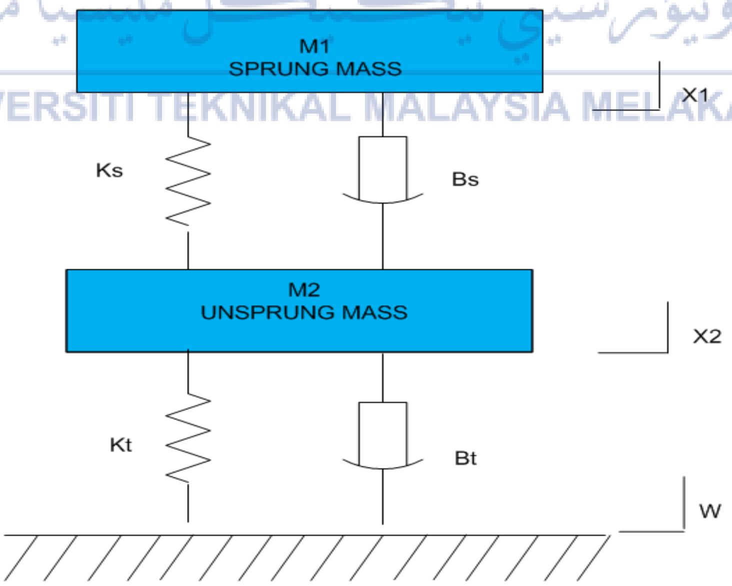



Figure 3.2: Nonlinear passive suspension for quarter car model

The quarter car model of nonlinear passive suspension system is shown in figure 3.2. The combination of the spring and damper are connected in single wheel and axle of the quarter portion of the body. Futhermore, the modeled of tyre is using the simple spring with the damper.

From the Figure 3.2 derivations of mathematical equation of nonlinear passive suspension system of quarter car system are given by:

$$F_{m1} = m_1\ddot{x}_1 \tag{3.0}$$

$$F_{m2} = m_2\ddot{x}_1 \tag{3.1}$$

$$F_{ks} = {k_s}^{l}(x_2 - x_1) - {k_s}^{nl}(x_2 - x_1)^3 \tag{3.2}$$

$$F_{kt} = k_t\,(x_2 - w) \tag{3.3}$$

$$F_{bt} = b_t(\dot{x}_2 - \dot{w}) \tag{3.4}$$

$$F_{bs} = {b_s}^{l}(\dot{x}_2 - \dot{x}_1) - {b_s}^{sym}|\dot{x}_2 - \dot{x}_1| + {b_s}^{nl}\sqrt{|\dot{x}_2 - \dot{x}_1|sgn(\dot{x}_2 - \dot{x}_1)} \tag{3.5}$$

**From M1 (Sprung Mass)**

$$F_{m1} = F_{ks} + F_{bs} \tag{3.6}$$

$$m_1\ddot{x}_1 = {k_s}^{l}(x_2 - x_1) + {k_s}^{nl}(x_2 - x_1)^3 + {b_s}^{l}(\dot{x}_2 - \dot{x}_1) - {b_s}^{sym}|\dot{x}_2 - \dot{x}_1| + {b_s}^{nl}\sqrt{|\dot{x}_2 - \dot{x}_1|sgn(\dot{x}_2 - \dot{x}_1)} \tag{3.7}$$

**From M2 ( Unsprung Mass)**

$$F_{m2} = -F_{ks} - F_{bs} + F_{kt} + F_{bt} \tag{3.8}$$

$$m_2\ddot{x}_1 = -{k_s}^{l}(x_2 - x_1) - {k_s}^{nl}(x_2 - x_1)^3 - {b_s}^{l}(\dot{x}_2 - \dot{x}_1) + {b_s}^{sym}|\dot{x}_2 - \dot{x}_1| - {b_s}^{nl}\sqrt{|\dot{x}_2 - \dot{x}_1|sgn(\dot{x}_2 - \dot{x}_1)} + k_t\,(x_2 - w) + bt(\dot{x}_2 - \dot{w}) \tag{3.9}$$

where;

$m_1$= mass of the car body / sprung mass (kg)

$m_2$ = mass of the wheel / unsprung mass (kg)

$k_t$ = suspension and wheel sttiffnesses (N/m)

$b_s$ = damping coefficient of the suspension ($N_s$/m)

$b_t$ = damping coefficient of the tyre ($N_s$/m)

$x_2$ *and* $x_1$ = vertical displacement of the body and wheel

$w$ = road disturbance

$x_2 - x_1$= suspension travel

$x_2 - w$ = wheel deflection

${k_s}^l$ = spring constant

${b_s}^l$= damping coefficient

${b_s}^{sym}$= asymmetric characteristics

${k_s}^{nl}$ = nonlinear component of the spring forces

${b_s}^{nl}$ = nonlinear component of the damper forces

3.3.1.2 Nonlinear Active Suspension System

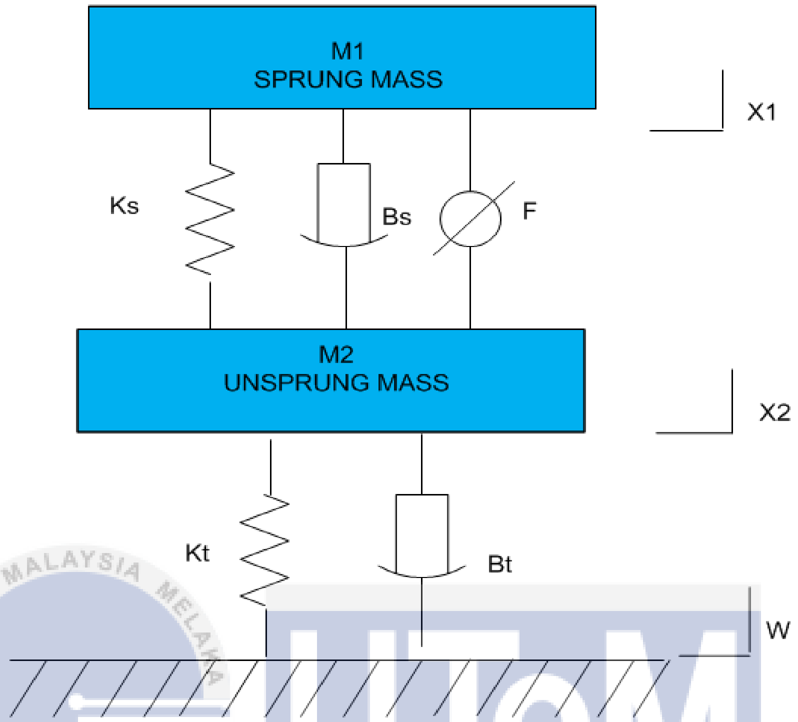



Figure 3.3: Active nonlinear suspension for quarter car model

The quarter car model of nonlinear active suspension system is shown in Figure 3.3. The nonlinear active suspension system has the additional advantages which a negative damping can be produced and generating the large range of force into the system at low velocities. Besides, this conditon potentially will increase the performance of the suspension system.

From Figure 3.3, derivations of mathematical equation of nonlinear passive suspension system of quarter car system are given by:

$$F_{m1} = m_1\ddot{x}_1 \tag{4.0}$$

$$F_{m2} = m_2\ddot{x}_1 \tag{4.1}$$

$$F_{ks} = {k_s}^l(x_2 - x_1) - {k_s}^{nl}(x_2 - x_1)^3 \tag{4.2}$$

$$F_{kt} = k_t\,(x_2 - w) \tag{4.3}$$

$$F_{bt} = b_t(\dot{x}_2 - \dot{w}) \tag{4.4}$$

$$F_{bs} = {b_s}^l(\dot{x}_2 - \dot{x}_1) - {b_s}^{sym}|\dot{x}_2 - \dot{x}_1| + {b_s}^{nl}\sqrt{|\dot{x}_2 - \dot{x}_1|}\,sgn(\dot{x}_2 - \dot{x}_1) \tag{4.5}$$

$$F = A_{xp} \tag{4.6}$$

**From M1 (Sprung Mass)**

$$F_{m1} = F_{ks} + F_{bs} - F \tag{4.7}$$

$$m_1\ddot{x}_1 = {k_s}^l(x_2 - x_1) - {k_s}^{nl}(x_2 - x_1)^3 + {b_s}^l(\dot{x}_2 - \dot{x}_1) - {b_s}^{sym}|\dot{x}_2 - \dot{x}_1| + {b_s}^{nl}\sqrt{|\dot{x}_2 - \dot{x}_1|}\,sgn(\dot{x}_2 - \dot{x}_1) - A_{xp} \tag{4.8}$$

**From M2 ( Unsprung Mass)**

$$F_{m2} = -F_{ks} - F_{bs} + F_{kt} + F_{bt} + F \tag{4.9}$$

$$m_2\ddot{x}_1 = -{k_s}^l(x_2 - x_1) - {k_s}^{nl}(x_2 - x_1)^3 - {b_s}^l(\dot{x}_2 - \dot{x}_1) + {b_s}^{sym}|\dot{x}_2 - \dot{x}_1| - {b_s}^{nl}\sqrt{|\dot{x}_2 - \dot{x}_1|}\,sgn(\dot{x}_2 - \dot{x}_1) + k_t\,(x_2 - w) + bt(\dot{x}_2 - \dot{w}) + A_{xp} \tag{5.0}$$

where;

$m_1$= mass of the car body / sprung mass (kg)

$m_2$ = mass of the wheel / unsprung mass (kg)

$k_t$ = suspension and wheel sttiffnesses (N/m)

$b_s$ = damping coefficient of the suspension ($N_s$/m)

$b_t$ = damping coefficient of the tyre ($N_s$/m)

$x_2$ *and* $x_1$ = vertical displacement of the body and wheel

$w$ = road disturbance

$x_2 - x_1$= suspension travel

$x_2 - w$ = wheel deflection

$k_s{}^{l}$ = spring constant

$b_s{}^{l}$= damping coefficient

$b_s{}^{sym}$= asymmetric characteristics

$k_s{}^{nl}$ = nonlinear component of the spring forces

$b_s{}^{nl}$ = nonlinear component of the damper forces

$F$ = actuator force

### 3.4 Procedure 3 : Design the mathematical modelling for electro-hydraulic actuator system

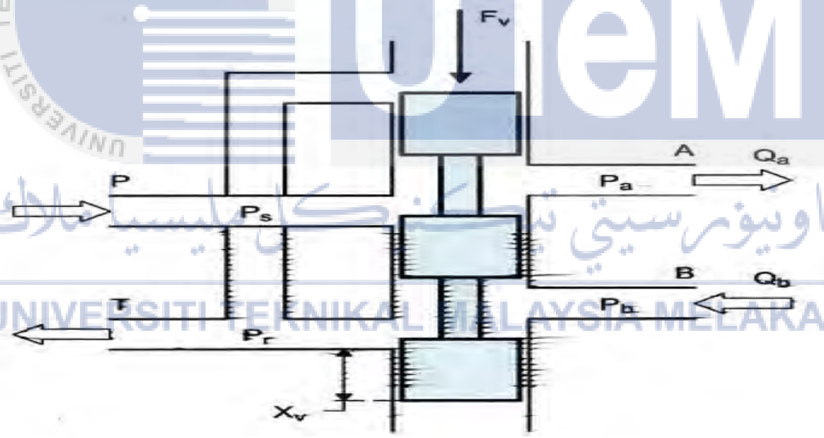



Figure 3.4: Three-land four-way valve-piston system



Figure 3.4 shows the three-land four-way valve-piston system where is used in designing of the hydraulic controller. The derivative of the system is shown based on the equation of $\dot{x_p}$.

$$\frac{V_t}{4\beta_e}\dot{x_p} = Q - C_{tp}\,xp - A(\dot{x_1} - \dot{x_2}) \qquad (5.0)$$

$$\dot{x_p} = \alpha Q - \beta xp - \alpha A(\dot{x_1} - \dot{x_2}) \qquad (5.1)$$

$$\alpha = \frac{V_t}{4\beta_e}, \quad \beta = \alpha C_{tp} \qquad (5.2)$$

Where $V_t$ the volume of actuator system, $\beta_e$ is the effective bulk modulus of the system, $Q$ is the hydraulic load and $C_{tp}$ is the total leakage coefficient of the piston. Next, the equation of the valve is shown in equation

$$C_d S x_v \sqrt{\frac{1}{p}\left|P_s - sgn(x_v)x_p\right|} \tag{5.3}$$

Where $C_d$ is the discharge coefficient, $S$ is the spool-valve area, $p$ is the hydraulic fluid density and $P_s$ is the supply pressure. The equation of the corrected flow is shown in equation 8

$$Q = sgn\left[P_s - sgn(x_v)x_p\right] C_d S x_v \sqrt{\frac{1}{p}\left|P_s - sgn(x_v)x_p\right|} \tag{5.4}$$

## 3.5 Procedure 4: Design the controller PID and Fuzzy logic to improve the performance of the suspension

### 3.5.1 Proportional-Integral-Derivative (PID) controller

The controller parameters are selected based on performance specification is known as controller tuning. Trial and error tuning method is used in this system for tuning PID controllers (meaning to set values $K_p$, $K_i$, $K_d$). PID controller as shown in Figure 3.5 is mean for proportional, integral and derivative. These controllers are used to abolish the requirement of the system. Hence, the PID controller is designed to prevent the smallest variation of the output at the steady state. Designing of the PID also can minimize the error by the controller in term of the derivative. Error in the controller will be defined as the difference measurement of the variable and the set point.

For the proportional controller, offset of the controller, which deviation from set point will be introduced. The system goes to unstable when the gain of the controller is increased. Integral action will be abolishing the offset when the output of the controller is proportional to the total time error is present. Derivative action is introduced when the output of the controller is proportional to the derivative of the measurement of error. The derivation of measurement with time is used to calculate the controller output. In order to compensate for a change in measurement, the derivative action will be introduced in the system. Hence, derivatives will use to inhibit faster changes of the measurement than proportional action. In this system, derivative is usually used to avoid the percent of overshoot.

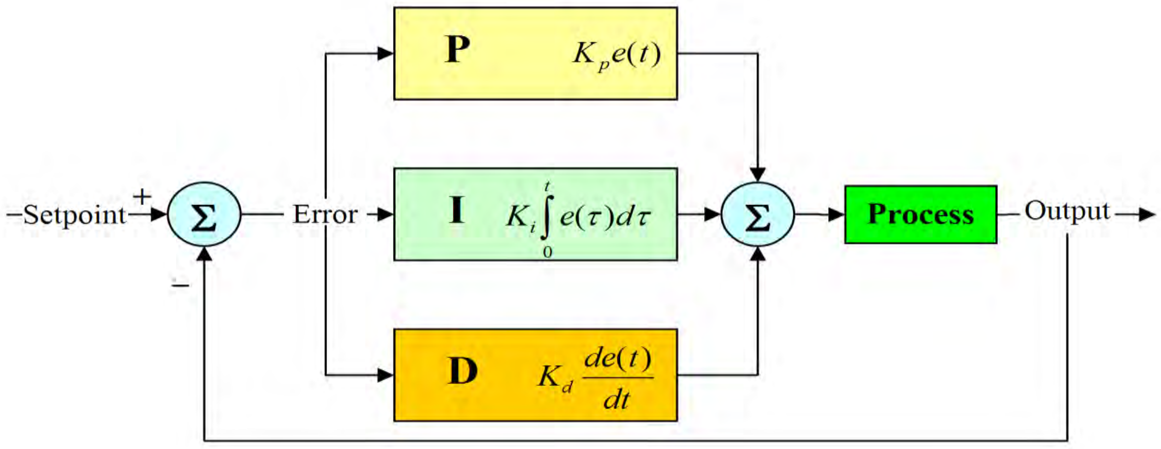



Figure 3.5: Structure of PID controller

3.5.2 Car suspension systems designed with Fuzzy Logic controller (FLC)

3.5.2.1 Fuzzy Logic Controller

The FLC is categorized into three inputs which are body acceleration $\ddot{x}_1$, body displacement $x_1$, body deflection displacement $x_2 - x_1$, and one output which is desired actuator force u. The entire elements are used in an active suspension system. In FLC consist of three stages are fuzzification, fuzzy inference machine and defuzzification are shown in Figure 3.6.

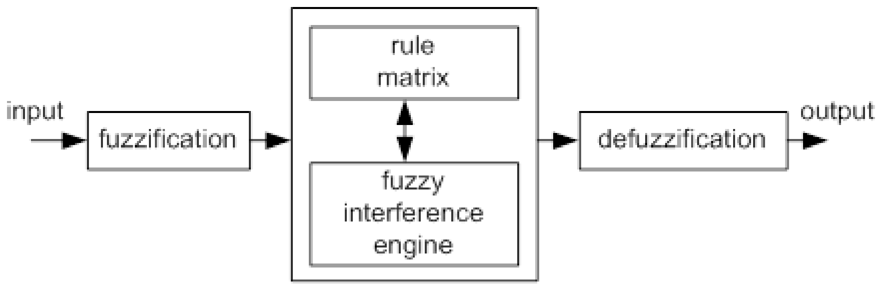



Figure 3.6: Structure of Fuzzy Logic control

The fuzzification stages usually modify the inputs and it will be compared to the rules in the rule base. In short, it converts the crip quantities (real-number) into fuzzy quantities. For the defuzzification stages converts the conclusions reached by the inference mechanism into inputs to the plants. An inference mechanism stages is about control rules are relevant at the current time and then decides what the input to the plant should be. Next, the rule matrix holds the knowledge, and a set of IF-THEN rules will be formed.

The main objective of fuzzy logic designing with the controller is to reduce the problem and to improve the performance of the nonlinear quarter car active suspension system in term of performance ride comfort and road handling. The fuzzy logic controller will be introduced in the in this system.

There are following steps to design the Fuzzy Logic Controller:

i. Selecting the inputs of the Fuzzy Logic. There are three inputs which are deflection velocity, body velocity and body acceleration.
ii. Output (force) will be selected.
iii. The range of each input and output will be set into the Fuzzy Logic controller.
iv. Use the formulating of the Fuzzy rules (IF-THEN)

In the universe discourse of Fuzzy Logic controller have three input variables (deflection velocity, body velocity and body acceleration). Two of the inputs were divided into five categories and another one input divided into three categories as follows by linguistic variables. There are negative medium (NM), negative small (NS), zero (Z), positive small (PS) and positive medium (NM). For the output variable (force) is divided into nine categories followed by linguistic variables, are negative very big (NV), negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), positive big (PB) and positive very big (PV). In the designing of Fuzzy Logic, trapezoidal membership function will be used in the linguistic variables. This is because the system can present a smoother of control action according flatness at the top of the trapezoidal shape. The fuzzy conditional statement is used to form fuzzy rule base to achieve the control action. The statement of IF and THEN are used in the control rule. For example the control rules will be stated as “IF deflection velocity is positive medium AND the body of velocity is positive medium AND the body of acceleration is zero THEN force that applied in the system is zero". In this system, 75 rules of fuzzy are used to completing the design of fuzzy logic. The max- min is used in the procedure of fuzzy reasoning inference. The centroid of procedure is used in the defuzzification stage.

3.5.2.2 Set of fuzzy controller

The set of fuzzy controller will be introduced in plots of membership functions. The membership function with input variable of deflection velocity is shown in Figure 3.7. Range input that has been used in membership function is [-0.2, 0.2] and the range of outputs value between [0, 1].

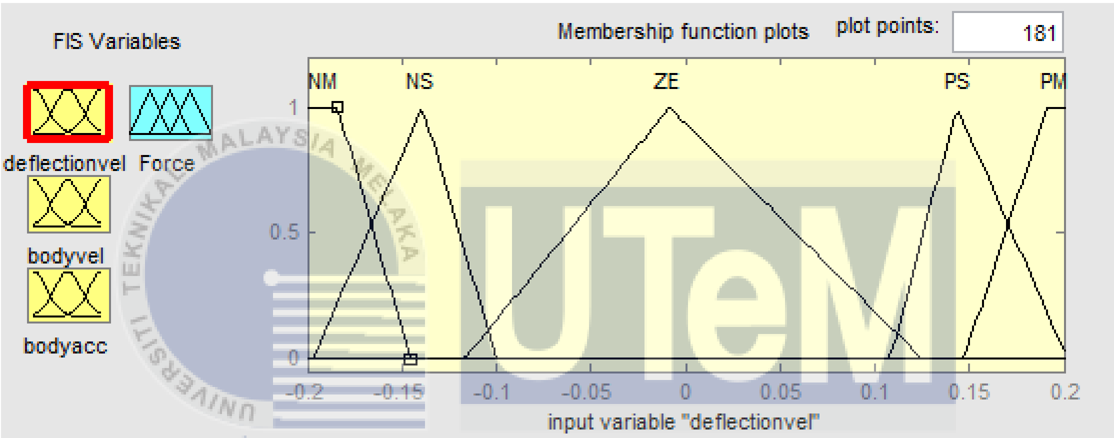



Figure 3.7: Membership function of deflection velocity



The membership function of body velocity is shown in Figure 3.8. The range of input of membership function is [-1.5, 1.5] and the range of output between [0, 1].

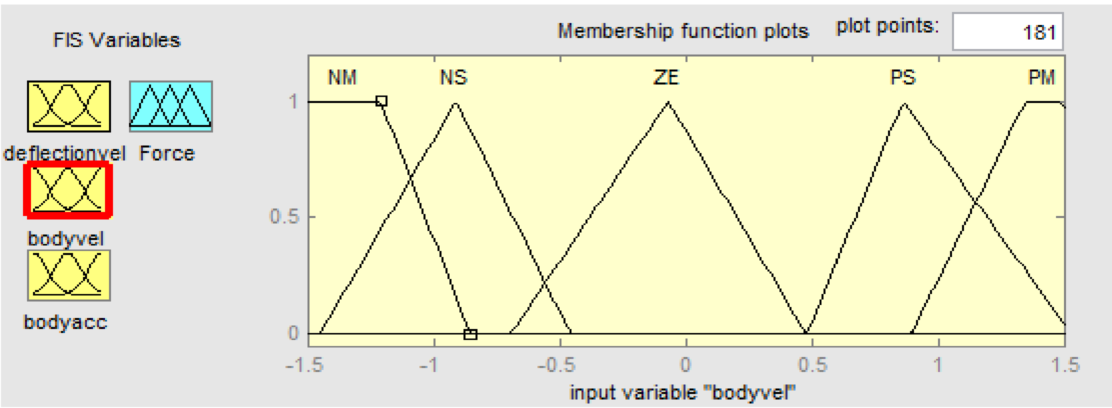



Figure 3.8: Membership function of body velocity

The membership function of body acceleration is shown in Figure 3.9. The range of input of membership function is [-10, 10] and the range of output between [0, 1].

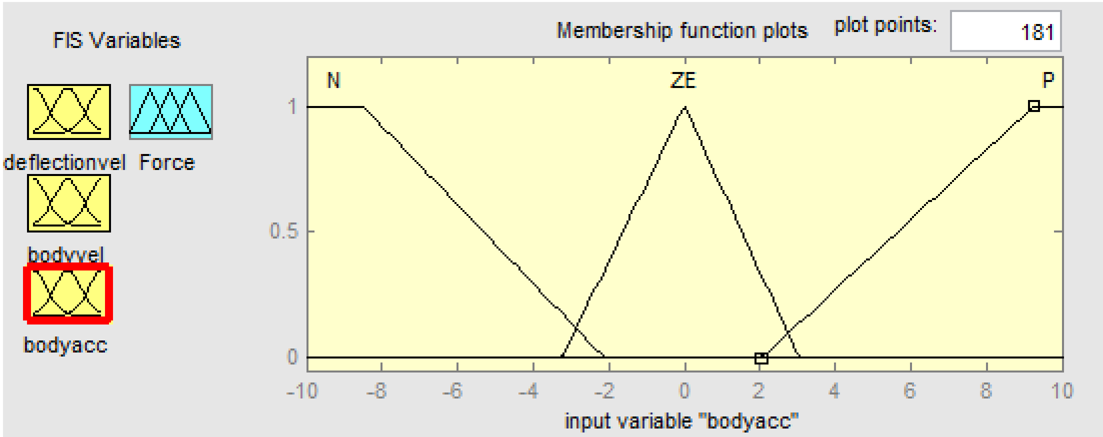



Figure 3.9: Membership function of body acceleration

The output membership function of force is shown in Figure 3.10. The range of output of membership function is [-1.5, 1.5] and the range of output between [0, 1].

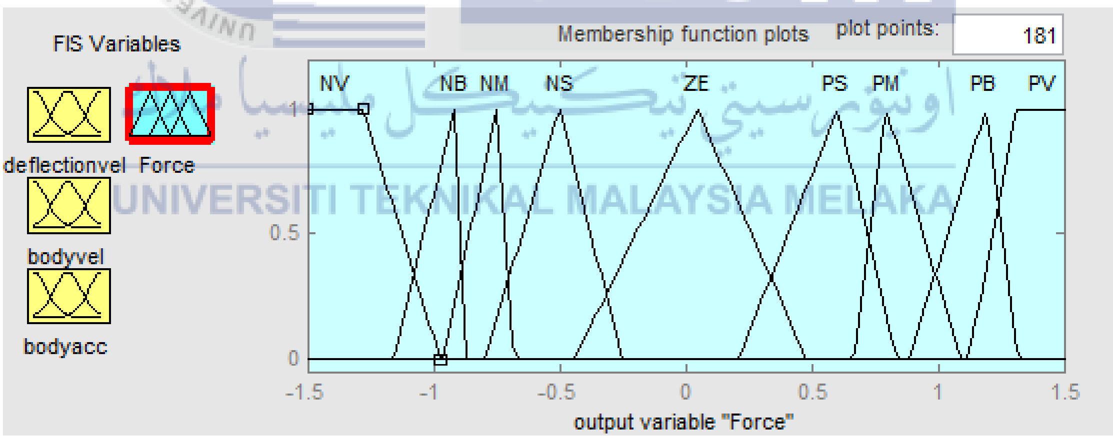





Figure 3.10: Membership function of force

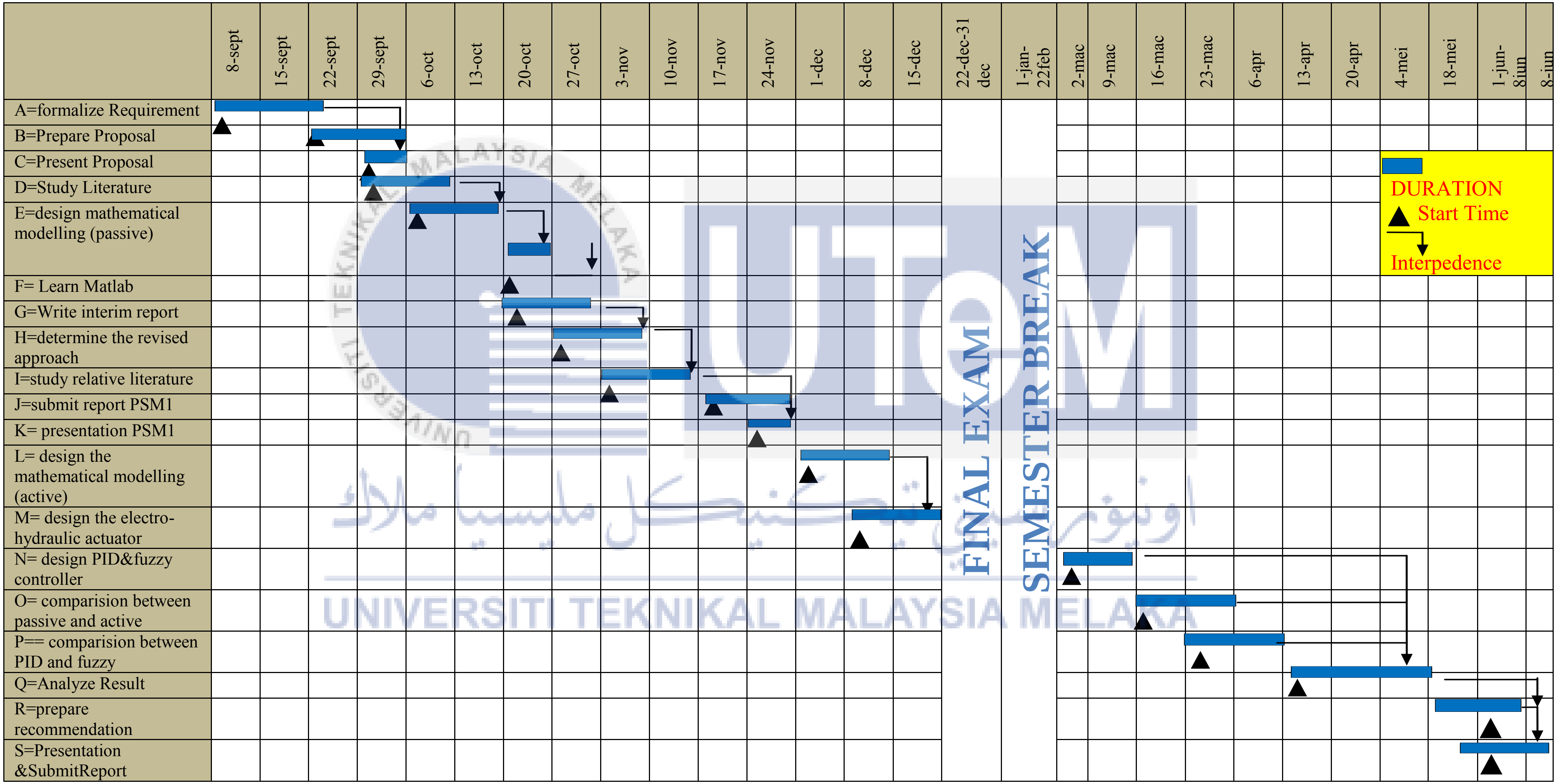
There are consists 75 of rule bases in the Fuzzy Logic. Table 3.1 shows the rule of base of Fuzzy Logic and all the result of simulation based on Fuzzy Logic will be analyzed. Fuzzy logic controller obtains the linguistic control of rules from the Table 3.1 are referred to appendix. Toolbox window of fuzzy logic in FUZZY/MATLAB show more details and refer to appendix.

Table 3.1: Rules base of Fuzzy Logic model

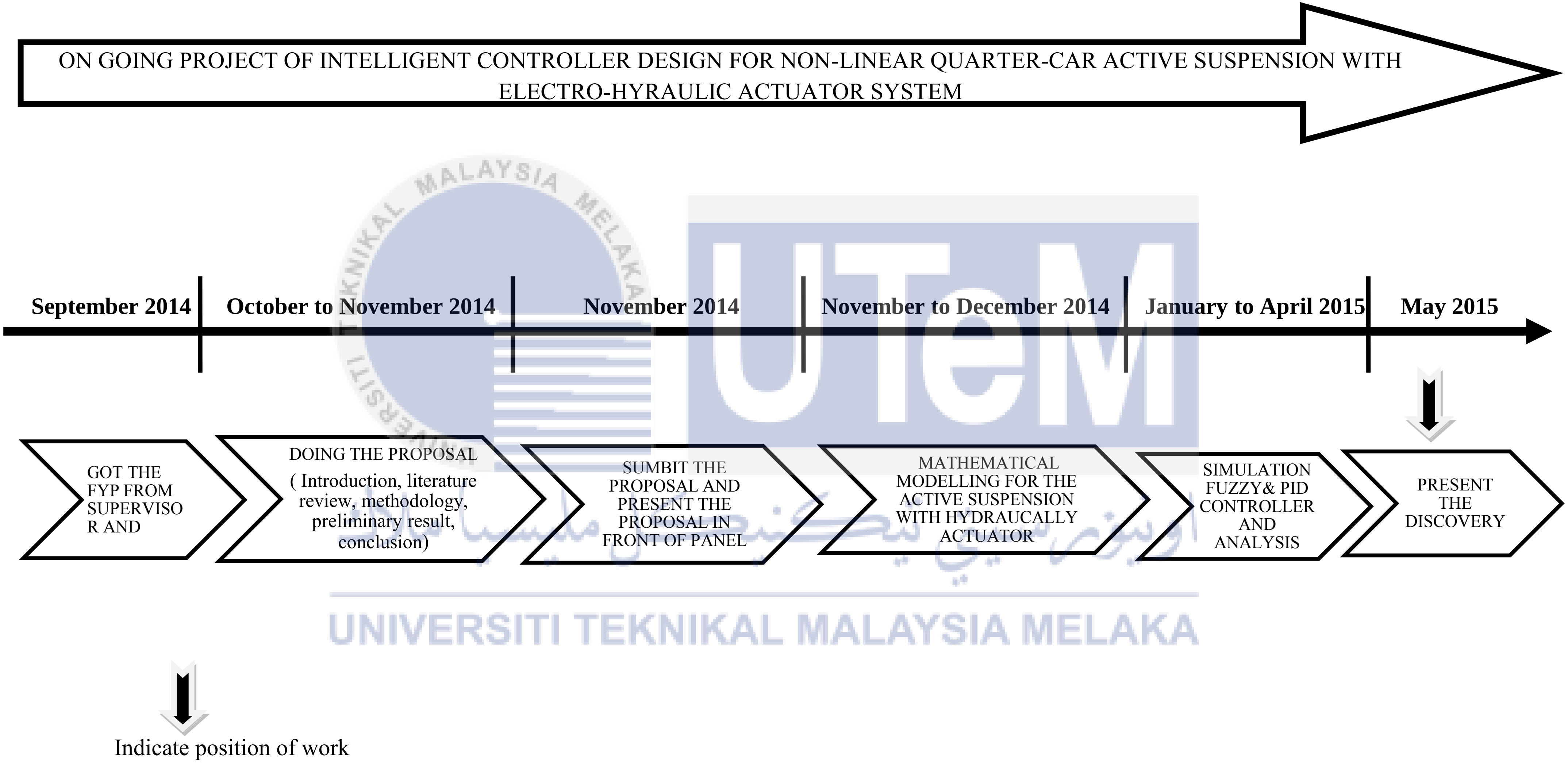
| $\dot{x_1} - \dot{x_2}$ | $\dot{x_1}$ | $\ddot{x}_1$ | $u$ | | $\dot{x_1} - \dot{x_2}$ | $\dot{x_1}$ | $\ddot{x}_1$ | $u$ |
|---|---|---|---|---|---|---|---|---|
| PM | PM | ZE | ZE | | PM | PM | P or N | NS |
| PS | PM | ZE | NS | | PS | PM | P or N | NM |
| ZE | PM | ZE | NM | | ZE | PM | P or N | NB |
| NS | PM | ZE | NM | | NS | PM | P or N | NB |
| NM | PM | ZE | NB | | NM | PM | P or N | NV |
| PM | PS | ZE | ZE | | PM | PS | P or N | NS |
| PS | PS | ZE | NS | | PS | PS | P or N | NM |
| ZE | PS | ZE | NS | | ZE | PS | P or N | NM |
| NS | PS | ZE | NM | | NS | PS | P or N | NB |
| NM | PS | ZE | NM | | NM | PS | P or N | NB |
| PM | ZE | ZE | PS | | PM | ZE | P or N | PM |
| PS | ZE | ZE | ZE | | PS | ZE | P or N | PS |
| ZE | ZE | ZE | ZE | | ZE | ZE | P or N | ZE |
| NS | ZE | ZE | ZE | | NS | ZE | P or N | NS |
| NM | ZE | ZE | NS | | NM | ZE | P or N | NM |
| PM | NS | ZE | PM | | PM | NS | P or N | PB |
| PS | NS | ZE | PM | | PS | NS | P or N | PB |
| ZE | NS | ZE | PS | | ZE | NS | P or N | PM |
| NS | NS | ZE | PS | | NS | NS | P or N | PM |
| NM | NS | ZE | ZE | | NM | NS | P or N | PS |
| PM | NM | ZE | PB | | PM | NM | P or N | PV |
| PS | NM | ZE | PM | | PS | NM | P or N | PB |
| ZE | NM | ZE | PM | | ZE | NM | P or N | PB |
| NS | NM | ZE | PS | | NS | NM | P or N | PB |
| NM | NM | ZE | ZE | | NM | NM | P or N | PS |

## 3.6 Project Gantt Chart and Key Milestone

3.6.1 Project Gantt Chart PSM 1 & PSM 2



3.6.2 Key Milestone



# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 Introduction

Simulation results using the MATLAB/Simulink platform will be observed in this chapter. The performance criteria that have been analyzed are the ride comfort and the road handling. The force used in this system is directly transmitted to the passenger and this situation will be affected to the ride comfort of a vehicle while the displacement of wheel characteristics will show the road handling achievement of active suspension system.

## 4.2 Software Development

Table 4.1 shows the parameters of the quarter-car model and Table 4.2 shows the parameters of Electro-hydraulic actuator system.

Table 4.1: Parameters of Quarter Car Model [27]

| Types | Value of Parameter | Unit |
|---|---|---|
| The mass of the car body / sprung mass ($M_1$) | 290 | Kg |
| The mass of the wheel / unsprung mass ($M_2$) | 40 | Kg |
| Tyre stiffness ($k_t$) | 1.5 x $10^5$ | N/m |
| Suspension stiffness (linear), $k_s$ | 2.35 x $10^4$ | N/m |
| Suspension stiffness (nonlinear), $k_s{}^{nl}$ | 2.35 x $10^6$ | N/m |

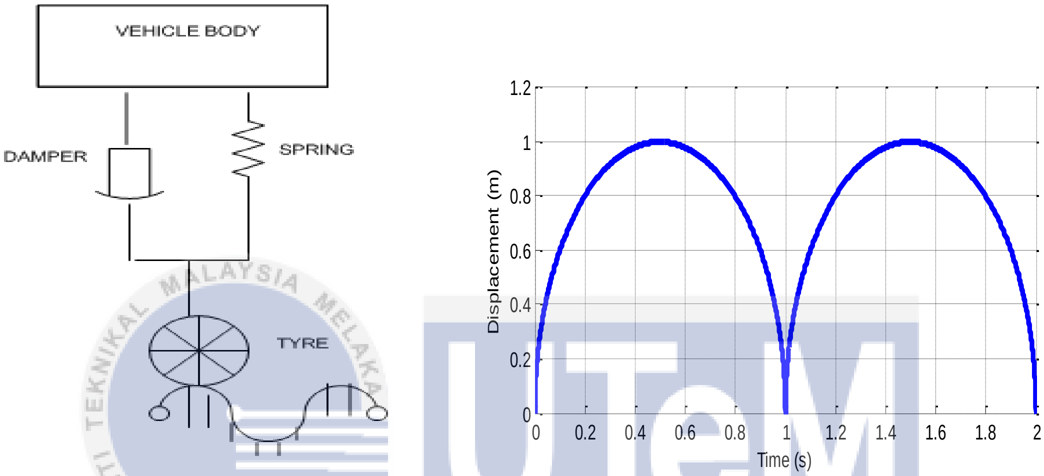
| | | |
|---|---|---|
| Suspension damping (linear) $b_s$ | 700 | $N_s/m$ |
| Suspension damping (nonlinear) $b_s{}^{nl}$ | 400 | $N_s/m$ |
| Suspension damping (asymmetrical) $b_s{}^{sym}$ | 400 | $N_s/m$ |

Table 4.2: Parameters of electro-hydraulic actuator system [27]

| Types | Value of Parameter | Unit |
|---|---|---|
| Piston area, A | $3.35 \times 10^{-4}$ | $m^2$ |
| Actuator time constant, τ | $3.33 \times 10^{-2}$ | S |
| Supply pressure ($P_s$) | 10,342500 | Pa |
| Servo-valve gain ($k_v$) | 0.001 | m/v |
| Actuator Parameter (α) | $4.515 \times 10^{13}$ | - |
| Actuator parameter (β) | 1 | - |
| Actuator parameter (ϒ) | $1.545 \times 10^{9}$ | - |

### 4.2.1 Road Profile

Irregularities of road profile can be categorized into smooth, rough minor and rough in nature. Single bump disturbance is represented as a smooth road. Otherwise, the rough minor and rough in nature are represented in term of uniform or non-uniform. Road disturbance with double bump was used in this project as the input disturbance. Figure 4.1 represents the bumpy road input with 1 meter bump height which will be implemented.




a) Actual bumpy road b) Bumpy road input

Figure 4.0: Bump road disturbance input



## 4.3 Performance of nonlinear passive and nonlinear active suspension system on ride comfort and road handling.

The performance of the ride comfort may be analyzed through the car body acceleration and the performance of road handling may be analyzed through the wheel deflection. Four parameters will be obtained in the simulation. There are body acceleration of sprung mass, suspension travel, acceleration of unsprung mass and wheel deflection. Figure 4.1 shows the block simulink of nonlinear passive and nonlinear active suspension system. The simulation through MATLAB/Simulink is used to make the comparison between nonlinear passive and nonlinear active suspension systems. All the comparison result will be discussed in this chapter.

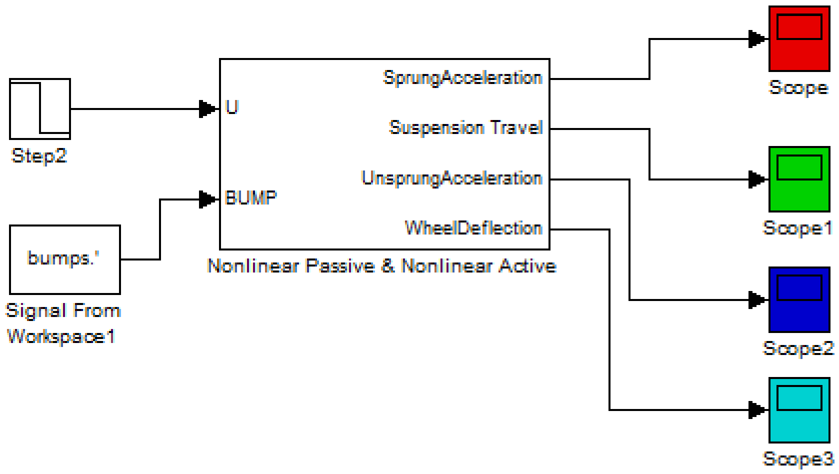



Figure 4.1: Block simulink of nonlinear passive and nonlinear active suspension system

### 4.3.1 Sprung and unsprung mass acceleration of nonlinear passive and active suspension system.

The performance of the car in term of car body acceleration, are clearly illustrated in this section. Figures 4.2 and 4.3 show the performance of body acceleration of the sprung mass of nonlinear passive and a nonlinear active suspension system that related to the ride comfort. The ride comfort is always having a connection with the height bump. The body acceleration increase according the heights of the bump. So the passengers can feel comfort depend the road disturbance. This is because of the controlling of the spring motion in the suspension system. The oscillations up and down will be occurring in the over damped car. But, the car will be back to normal condition based on proper damping levels in a minimal amount of time. It can be seen that, if the damping is very strong, the ability of ride comfort will go to negative part.

Figures 4.4 and 4.5 show the performance of body acceleration of unsprung mass for both suspension where nonlinear passive and active system. From the graft, the body acceleration of unsprung mass is directly proportional to the road disturbance. Hence to minimize the road disturbance, the body acceleration must be directly reduced.

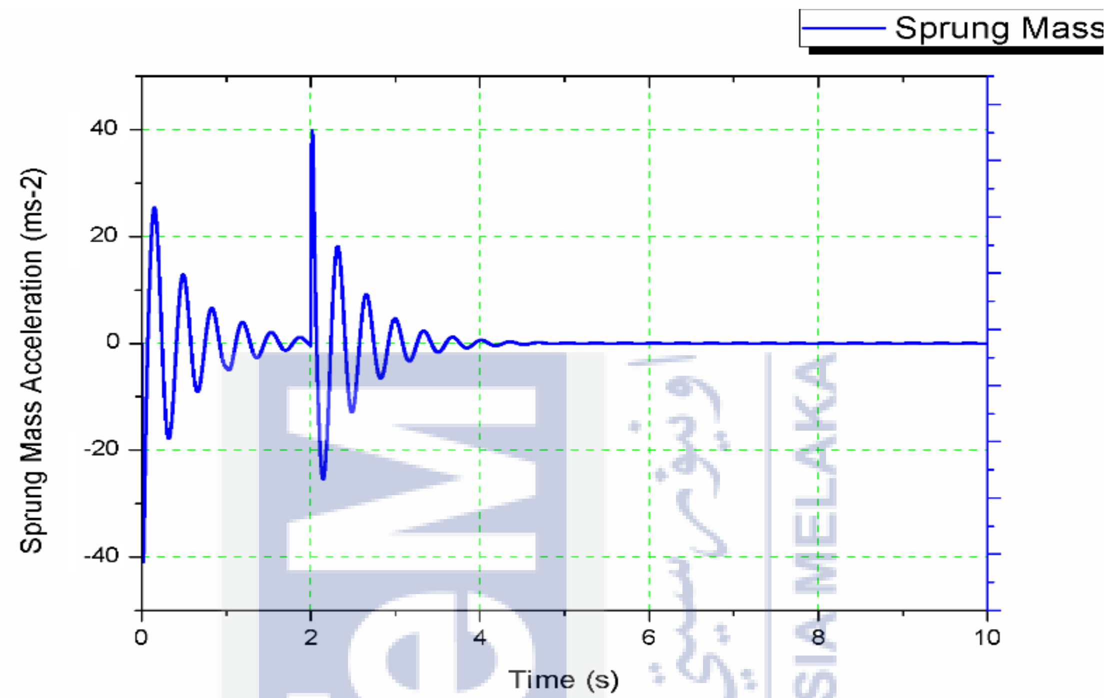



Figure 4.2 : Car body acceleration of nonlinear passive suspension system

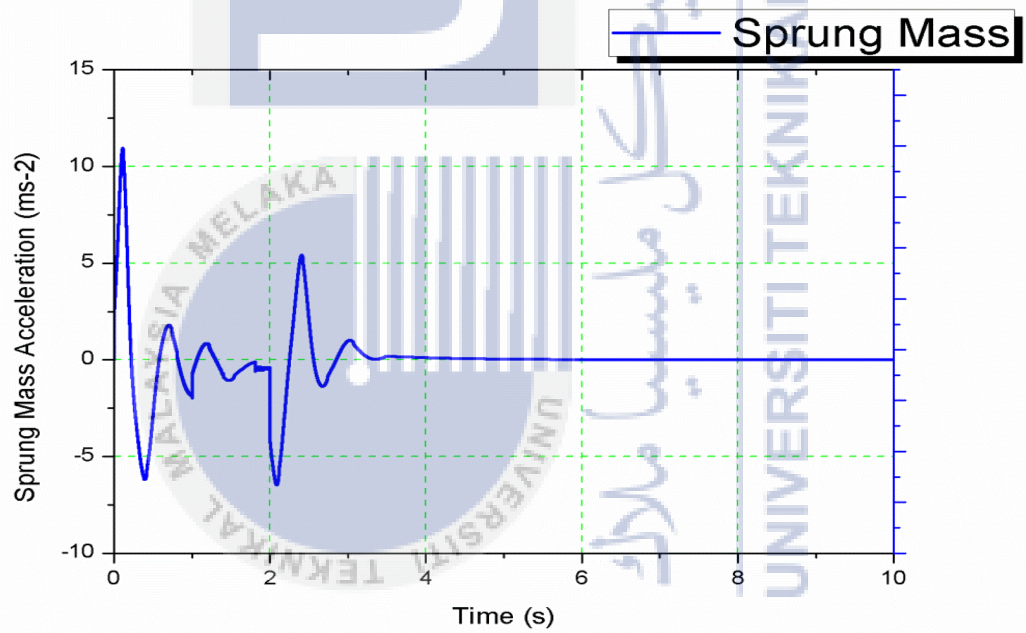



Figure 4.3 : Car body acceleration of nonlinear active suspension system

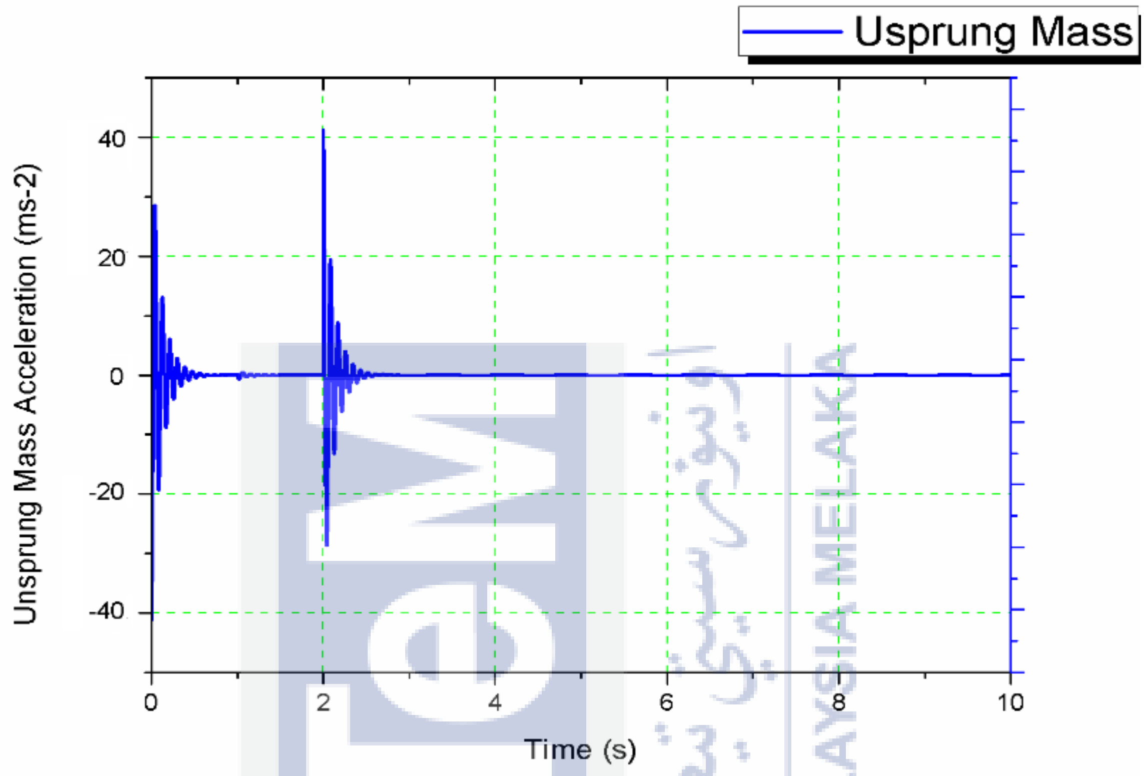



Figure 4.4 : Car body acceleration of nonlinear passive suspension system

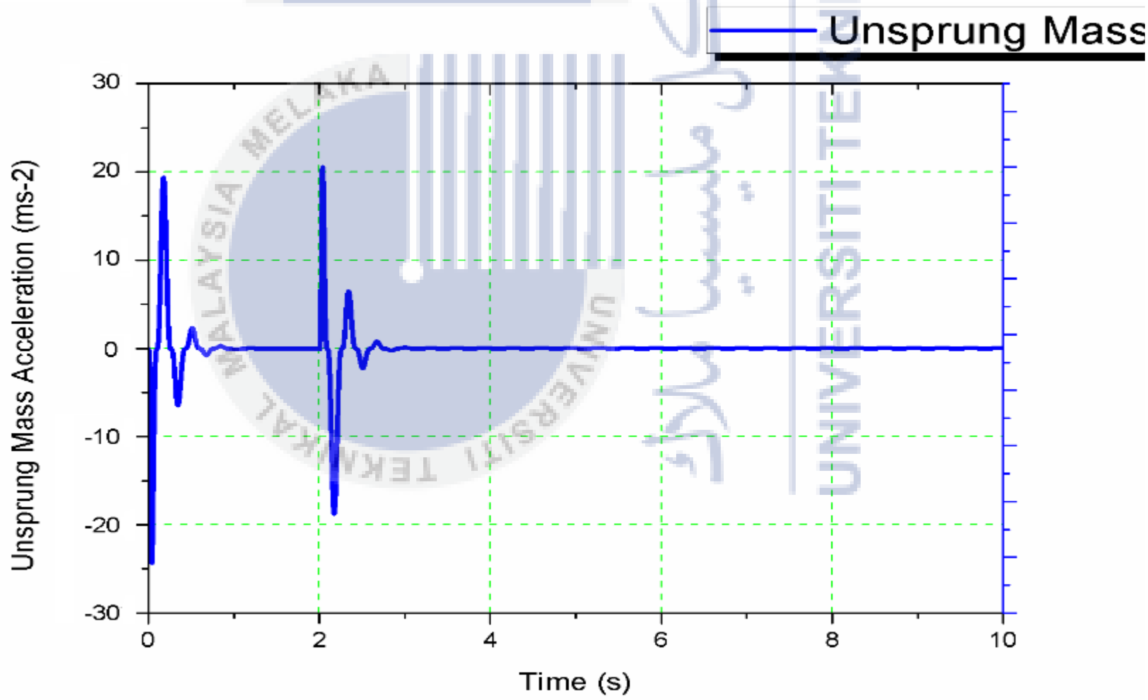



Figure 4.5 : Car body acceleration of nonlinear active suspension system

### 4.3.2 Suspension travel and wheel deflection of nonlinear passive and active suspension system.

Suspension travel of the nonlinear passive and active suspension system is shown in Figure 4.6 and 4.7. In this situation, the connection both of the figure is related to the sprung mass and unsprung masses. The result both of suspension must be lesser than the rattle space in the system.

Figure 4.8 and 4.9 illustrate to the wheel deflection of the nonlinear passive and active suspension system. Both of the figures are related to the road handling of the system. This situation refers to the forces that given to the contact with tyre and the road surface. Otherwise, the spring that used in the system can absorb the impact of the car. It can see that, if the suspension of the car is too strong then the car will go steady without disturbance on the road. Meanwhile, if the suspension of the car too low then the car will be unstable because the car lost the contact between wheels and the road.



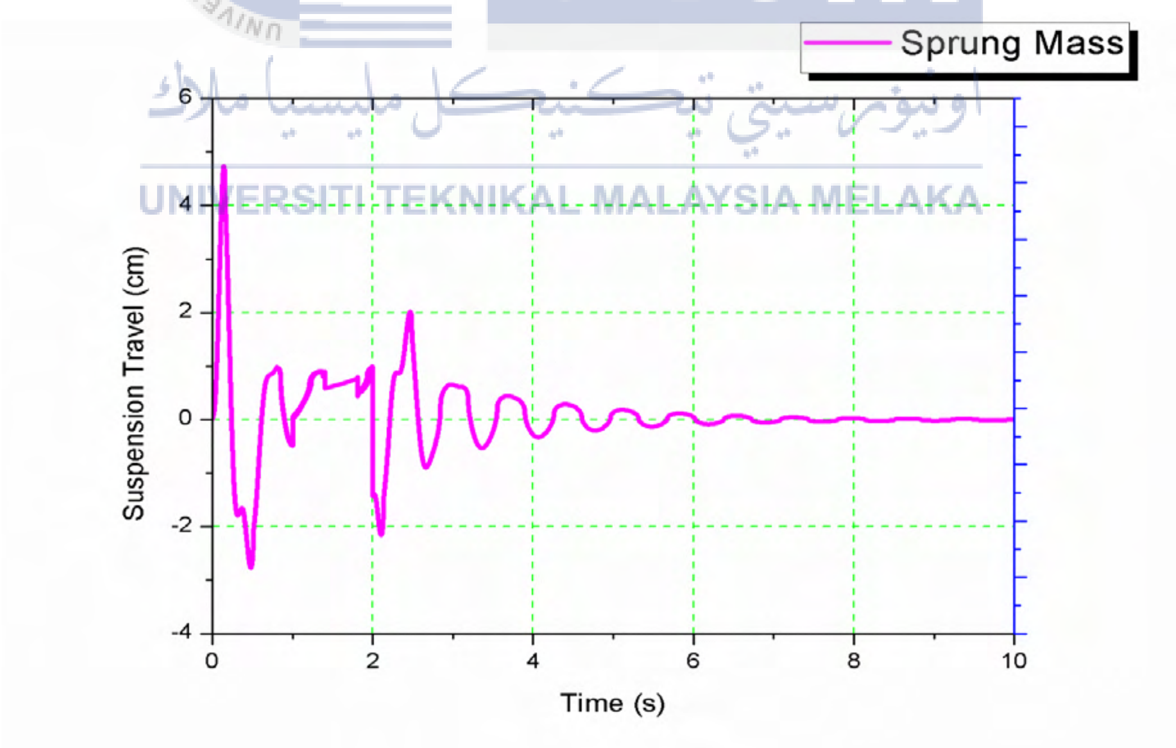



Figure 4.6: Suspension Travel of nonlinear passive suspension system

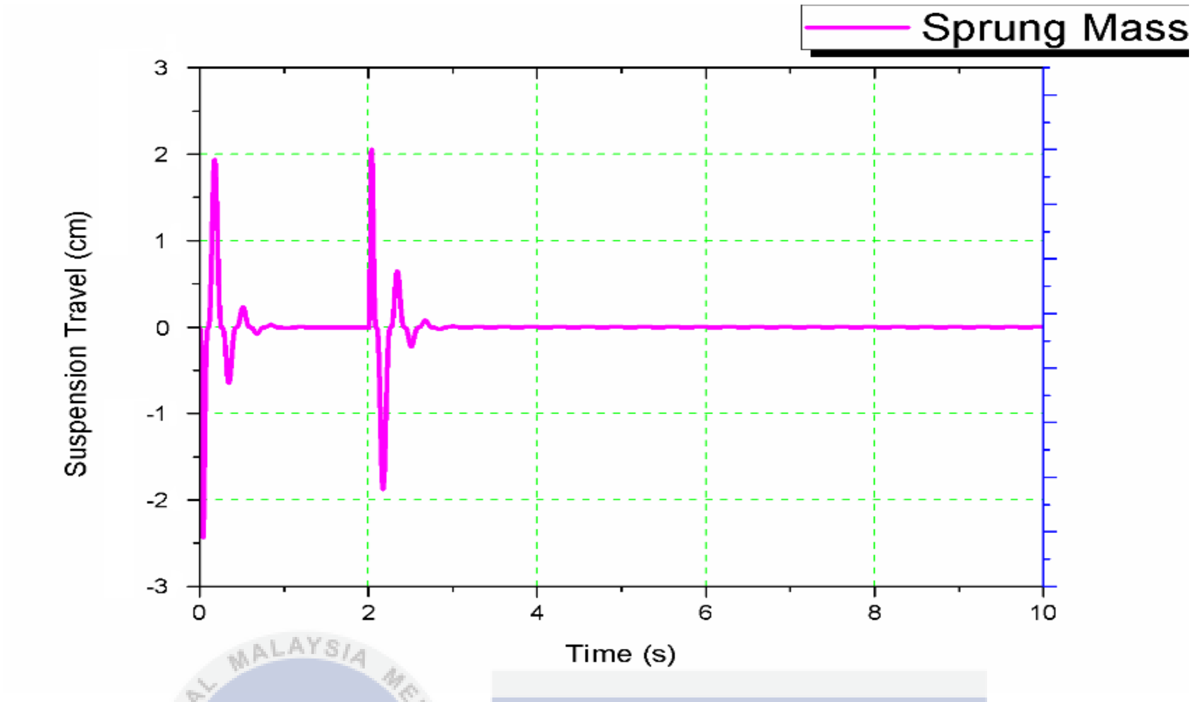



Figure 4.7: Suspension Travel of nonlinear active suspension system



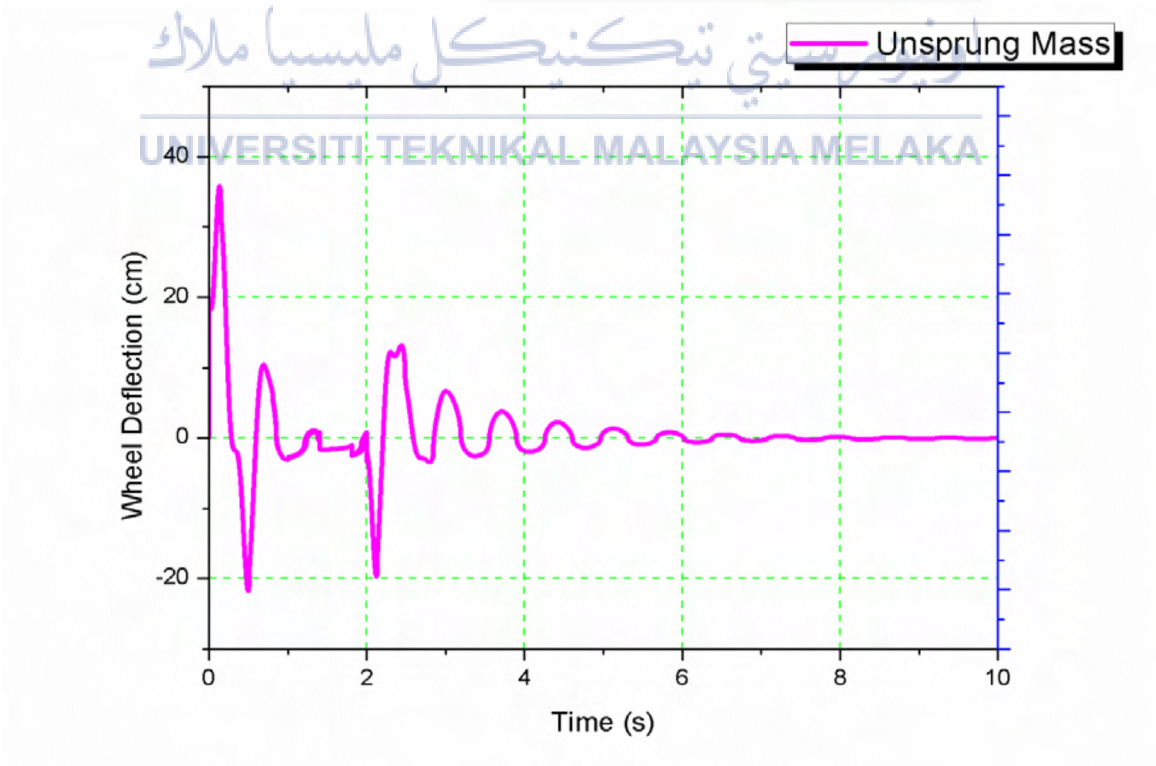



Figure 4.8 : Wheel deflection of nonlinear passive suspension system

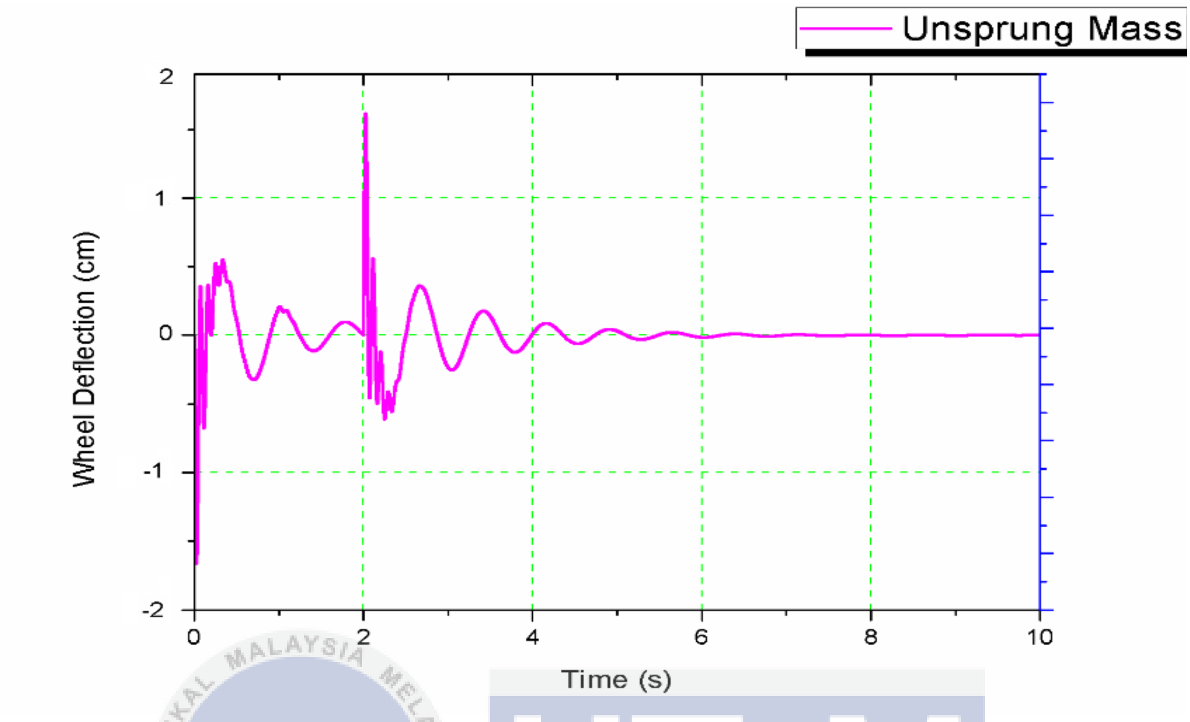



Figure 4.9 : Wheel deflection of nonlinear active suspension system

### 4.3.3 Comparison between nonlinear passive and active suspension system.

Table 4.3 shows the nonlinear passive simulation values and Table 4.4 shows nonlinear active simulation values. Comparison between both systems will be compared with the performance at bump 1 and bump 2. The performances include the maximum and minimum values of simulation result. From the comparison, the performance of the nonlinear passive is bad because the oscillation of the system very long. Otherwise, the nonlinear passive also takes a long time to make the system stable. This factor occurs because of the no force applied in the system. But, the performance of nonlinear active suspension system is very good because of the force that applied in the system. From nonlinear active situation, the oscillation result is good which the results show the oscillation is reduced and the system not takes a long time to make the system stable. In order to make improvement of the nonlinear active suspension system, we apply the PID controller and Fuzzy Logic controller in the nonlinear active suspension system. So, the results of body acceleration for sprung mass and unsprung mass, suspension travel and wheel deflection are reduced as well as the road disturbance.

Table 4.3: Nonlinear passive Simulation values

| Element | Bump 1 | | Bump 2 | |
|---|---|---|---|---|
| | max | min | max | Min |
| Sprung Mass Acceleration ($ms^{-2}$) | 25 | -16 | 40 | -20 |
| Unsprung Mass Acceleration ($ms^{-2}$) | 30 | -15 | 40 | -30 |
| Suspension Travel (cm) | 4.8 | -3 | 2 | -1 |
| Wheel Deflection (cm) | 35 | -20 | 10 | -4 |

Table 4.4: Nonlinear active simulation values

| Element | Bump 1 | | Bump 2 | |
|---|---|---|---|---|
| | max | min | max | Min |
| Sprung Mass Acceleration ($ms^{-2}$) | 11 | -6 | 5 | -1 |
| Unsprung Mass Acceleration ($ms^{-2}$) | 18 | -7 | 20 | -18 |
| Suspension Travel (cm) | 2 | -0.5 | 2 | -1.5 |
| Wheel Deflection (cm) | 0.6 | -0.5 | 1.5 | -0.4 |

## 4.4 Nonlinear active suspension with electro-hydraulic using PID controller and Fuzzy controller

In Table 4.3 and 4.4 show the result simulation that the passenger uncomfortable for best ride. Hence, the nonlinear active suspension system with PID controller and fuzzy logic controller will be designed to minimize the disturbance in the system. First of all, the hydraulic actuator is introduced into the suspension system as a control input as shown in Figure 4.10. Control input from the hydraulic actuator make the nonlinear active suspension system more stable. Next, the Figure 4.11 illustrates the PID controller is applied in the system. In order to achieve better performance than PID controller, the Fuzzy Logic will be design in the system as shown in Figure 4.12. The input that related using the fuzzy set are deflection velocity, body acceleration and body velocity, while the output is a force that applied in the system. All the result using PID controller and fuzzy controller will be discussed based on plots and tables.

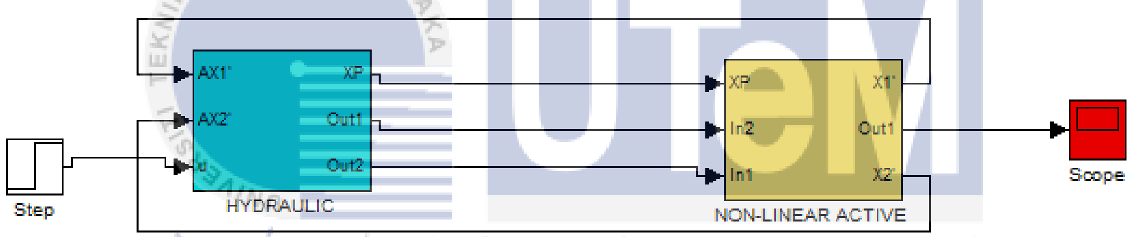



Figure 4.10: Block simulink of nonlinear quarter-car active suspension with electro-hydraulic actuator



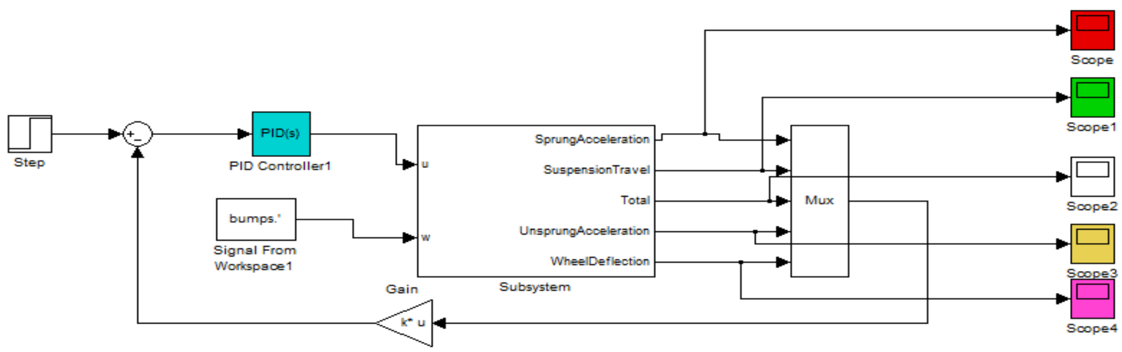



Figure 4.11: Block simulink of nonlinear quarter-car active suspension with PID controller

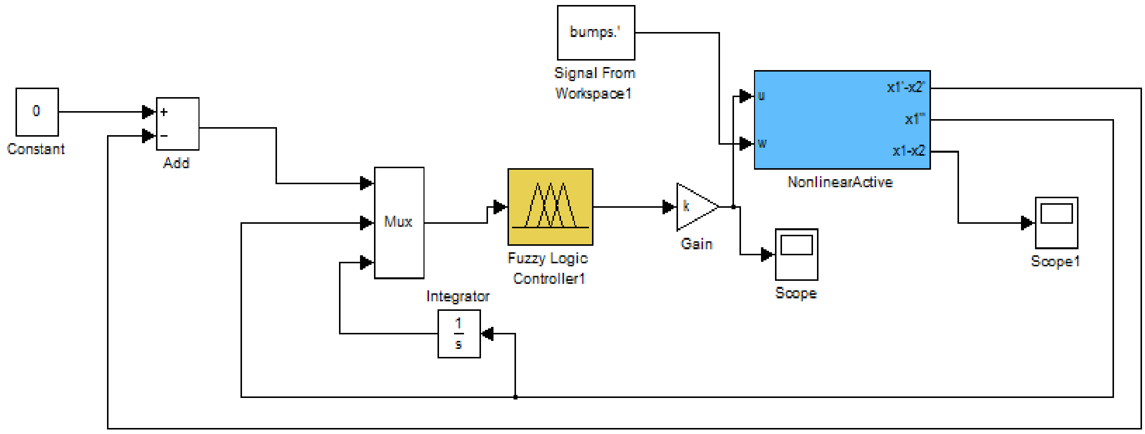



Figure 4.12: Block simulink of nonlinear quarter-car active suspension with Fuzzy Logic controller

4.4.1 Comparison nonlinear active with PID controller and Fuzzy Logic controller

Figure 4.13 and 4.15 show the comparison nonlinear active of body acceleration of sprung mass and unsprung mass. It can see that using the fuzzy logic can give better performance to ride comfort and road handling. From the sprung mass using a PID controller shows that the period of 6 seconds, the process of systematically decreasing oscillation amplitude is become to zero but for the fuzzy logic controller show that the period of 2.5 seconds where oscillation amplitude is become to zero. The reduction percentage also shows the performance of both controllers where for PID controller is about 96.8% reduction meanwhile the fuzzy logic is about 97.6%. Meanwhile, unsprung mass using PID controller shows that the time taken for the system becomes zero is about 3 seconds and the process symmetrically decreasing oscillation amplitude to become zero after using Fuzzy Logic controller is 2.5 seconds. Therefore, the percentage reduction between PID and Fuzzy Logic controller are 98.05% and 99.5% respectively.

Figure 4.14 shows the comparison of suspension travel in the system. The result of the PID controller shows the oscillation from the system is worse performance than from the fuzzy logic controller with the percentage of reduction of PID is 80.5% and fuzzy logic is 97.5%. The fuzzy logic controller shows the best performance which the suspension travel becomes smoothness on the road. Fuzzy logic only takes 2.5 seconds to become the system stable. Figure 4.16 shows the comparison wheel deflection of the system. This system is related to the road handling which oscillation from the system become well after reach 2.5 seconds using the fuzzy logic. A comparison using the PID controller shows the contact forces of the tires and the road surface with the reduction percentage is 96.0% less than when using the fuzzy logic controller with reduction percentage is 99.85%.

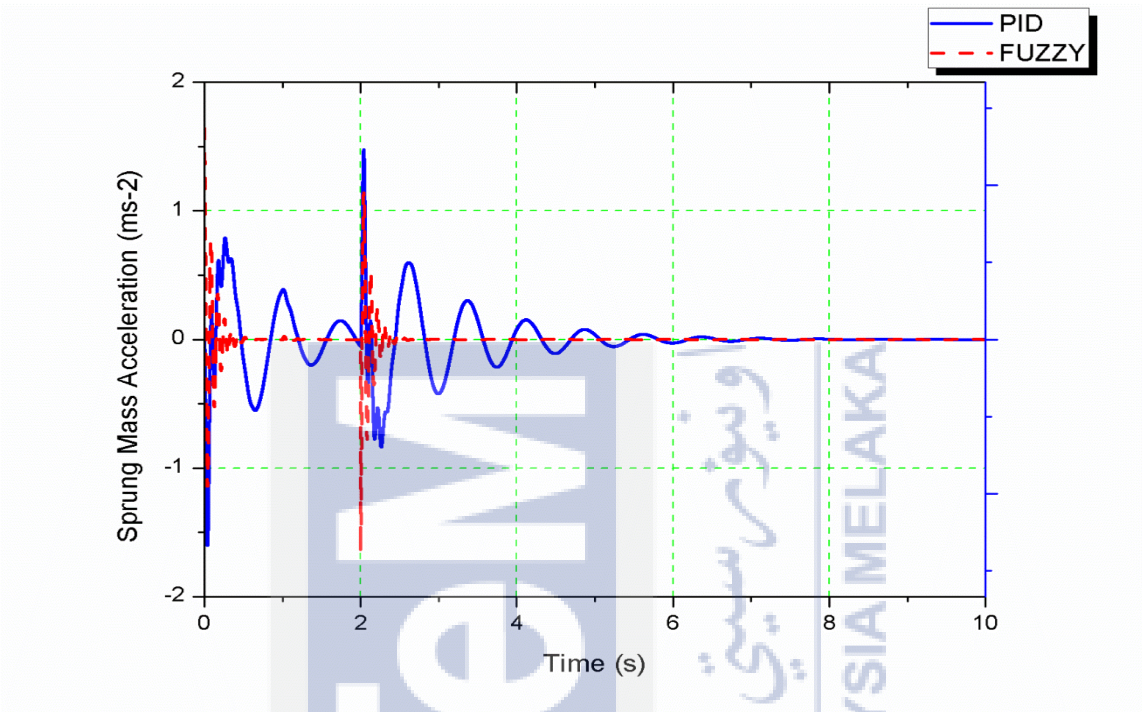



Figure 4.13 : Comparison of body acceleration of sprung mass

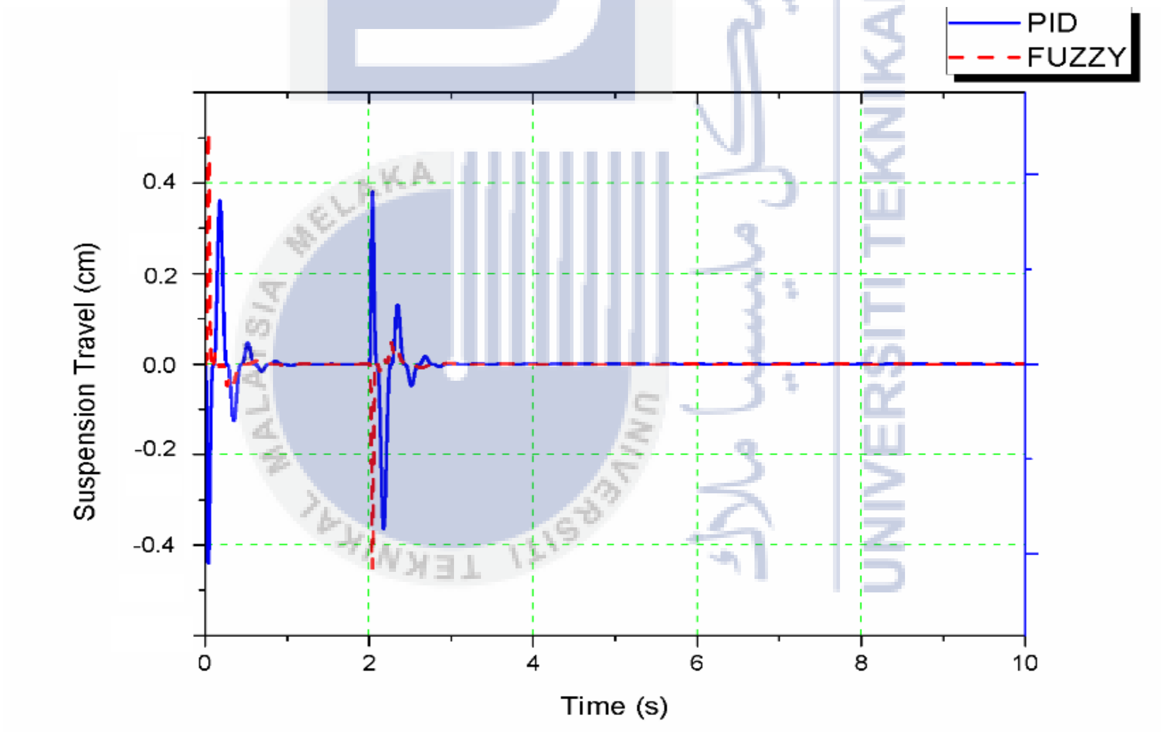



Figure 4.14 : Comparison suspension travel of sprung mass

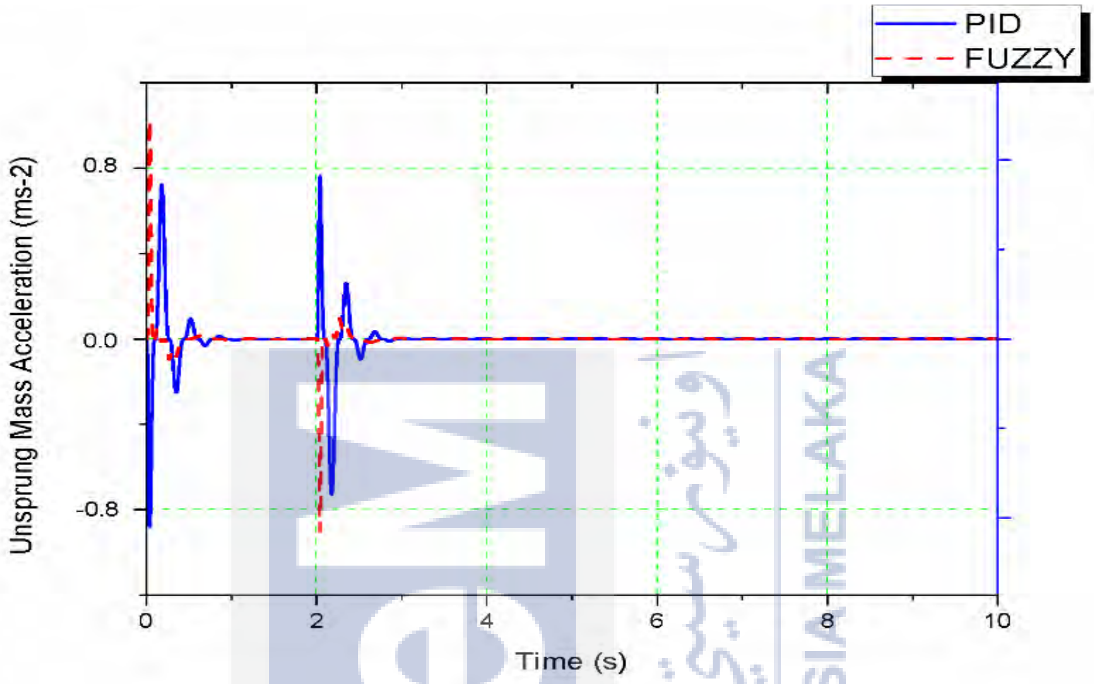



Figure 4.15 : Comparison body acceleration of unsprung mass

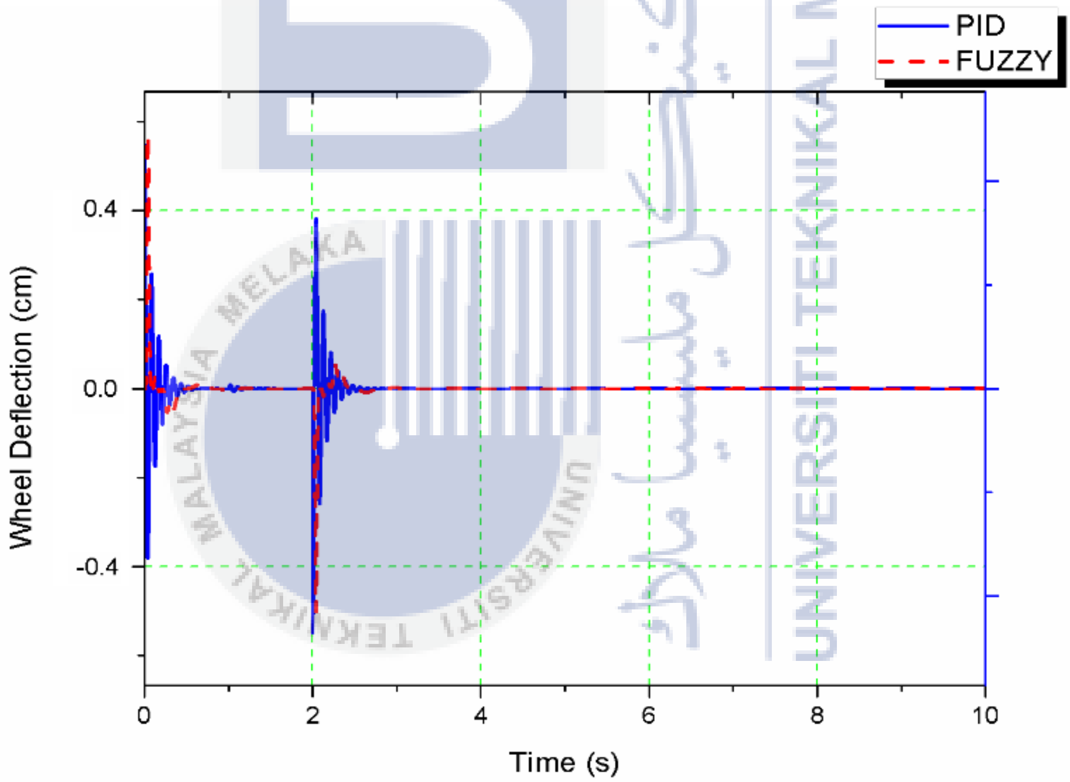



Figure 4.16 : Comparison wheel deflection of unsprung mass

First controller will be designed in this system is PID controller. PID controller is design to improve the steady state error and percent of overshoot (%). PID controller of the suspension system is modelled in the Simulink environment. Controller block of PID uses gains of $K_p$= 1664200, $K_i$= 1248150 and $K_d$= 416050.These model has been operating for 10 seconds. Designing of the PID controller makes the system in a good performance because of the both maximum body acceleration, suspension travel and wheel deflection are decrease than the suspension model without a controller. Another controller that has been designed in the suspension system is Fuzzy logic. The fuzzy logic is designed to improve performance of the suspension system than using the PID controller. Fuzzy logic is an intelligent controller that capable to give a better performance in term of body acceleration, suspension travel and wheel deflection. The input that related using the fuzzy set are deflection velocity, body acceleration and body velocity, while the output is a force that applied in the system. In order to make the suspension system more stable, 75 rules of fuzzy logic are used to get better performance.

From the simulation the road disturbance is applied to the system and it react with the input of the magnitude. When the magnitude is higher, the displacement of car also will be higher. This system using application of Newton’s third law because the equilibrium of the system can be maintain based on force that apply in the suspension system. Table 3.4 shows the comparison results nonlinear passive and active with PID and Fuzzy Logic controller and the reduction percentage using both controllers also shown in table 3.5.

Table 4.5: Comparison results nonlinear passive and active with PID and Fuzzy Logic controller

| Elements | Nonlinear Passive | | | | Nonlinear active with PID controller | | | | Nonlinear active with Fuzzy Logic controller | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Bump 1 | | Bump 2 | | Bump 1 | | Bump 2 | | Bump 1 | | Bump 2 | |
| | max | Min | max | Min | max | min | Max | min | max | Min | Max | min |
| Sprung Mass Acceleration ($ms^{-2}$) | 25.0 | -16.0 | 40.0 | -20.0 | 0.8 | -0.5 | 1.5 | -0.8 | 0.6 | -1.0 | 1.0 | -0.9 |
| Suspension Travel (cm) | 4.8 | -3.0 | 2.0 | -1.0 | 0.38 | -0.15 | 0.39 | -0.38 | 0.44 | -0.05 | 0.05 | -0.41 |
| Unsprung Mass Acceleration ($ms^{-2}$) | 30.0 | -15.0 | 40.0 | -30.0 | 0.76 | -0.38 | 0.78 | -0.78 | 1.10 | -0.10 | 0.20 | -0.90 |
| Wheel Deflection (cm) | 35.0 | -20.0 | 10.0 | -4.0 | 0.25 | -0.40 | 0.40 | -0.30 | 0.56 | -0.10 | 0.14 | -0.48 |

Table 4.6: Comparison of percentage reduction with both controllers

| Elements | Nonlinear Passive | | Nonlinear active with PID controller | | Nonlinear active with Fuzzy Logic controller | | Percentage Reduction | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | PID | | Fuzzy Logic | |
| | Bump 1 | Bump 2 | Bump 1 | Bump 2 | Bump 1 | Bump 2 | Bump 1 | Bump 2 | Bump 2 | Bump 2 |
| Sprung Mass Acceleration ($ms^{-2}$) | 25 | 40 | 0.8 | 1.5 | 0.6 | 1.0 | 96.8% | 96.25% | 97.6% | 97.5% |
| Suspension Travel (cm) | 4.8 | 2 | 0.38 | 0.39 | 0.44 | 0.05 | 92.08% | 80.5% | 90.83% | 97.5% |
| Unsprung Mass Acceleration ($ms^{-2}$) | 30 | 40 | 0.76 | 0.78 | 1.0 | 0.2 | 97.47% | 98.05% | 96.67% | 99.5% |
| Wheel Deflection (cm) | 35 | 10 | 0.25 | 0.4 | 0.56 | 0.14 | 99.29% | 96.0% | 98.4% | 98.6% |

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

The intelligent controller design for nonlinear quarter-car active suspension with electro-hydraulic system has been successfully implemented. The project starts with modelling of the quarter car model before the implementation of the full car model. The results of the system clearly show that the performance of nonlinear passive and nonlinear active. The development suspension system without controller shows the increasing of amplitude at early oscillation is worst before the system become stable on the road. Therefore, the PID and Fuzzy Logic controller are introduced into the system to improve the performance of the suspension system.

In the simulation study, it was illustrated that the Fuzzy Logic controller gives a better achievement than PID controller. The capability to resolve the problem in term of performance, like to keep maintain the road handling in the proper condition and give the passengers' comfort for Fuzzy Logic is much better than PID controller. Otherwise, the Fuzzy Logic controller proves that the reducing enforcement such as reducing the percent of overshoots and transient respond while driving on the irregularities of the road.

The purpose of an intelligent controller, which is a Fuzzy Logic controller with the related rules is performed well in the system. The performance that occurs in the system is body displacement, velocity and acceleration. The characteristic of suspension system improves the ride comfort and the road handling. The purpose of both controllers increased the suspension travel on the irregularities road. Thus, the designing the intelligent controller can give the smoothness of the vehicle performance on the road as well as to keep maintain in proper condition and give the passengers' comfort.

## 5.2 Recommendation

Many control problems will be solved with several unique features from fuzzy logic. In this project, body displacement and body acceleration will be reduced effectively by developing a multi controller into the system. The Fuzzy-PID will be designed using a Fuzzy Logic algorithm that capability to tune the PID parameters. As known, the Fuzzy-PID controller able to improve the better settling time in the system, reduce the percent of overshoot and give more stability in the system.

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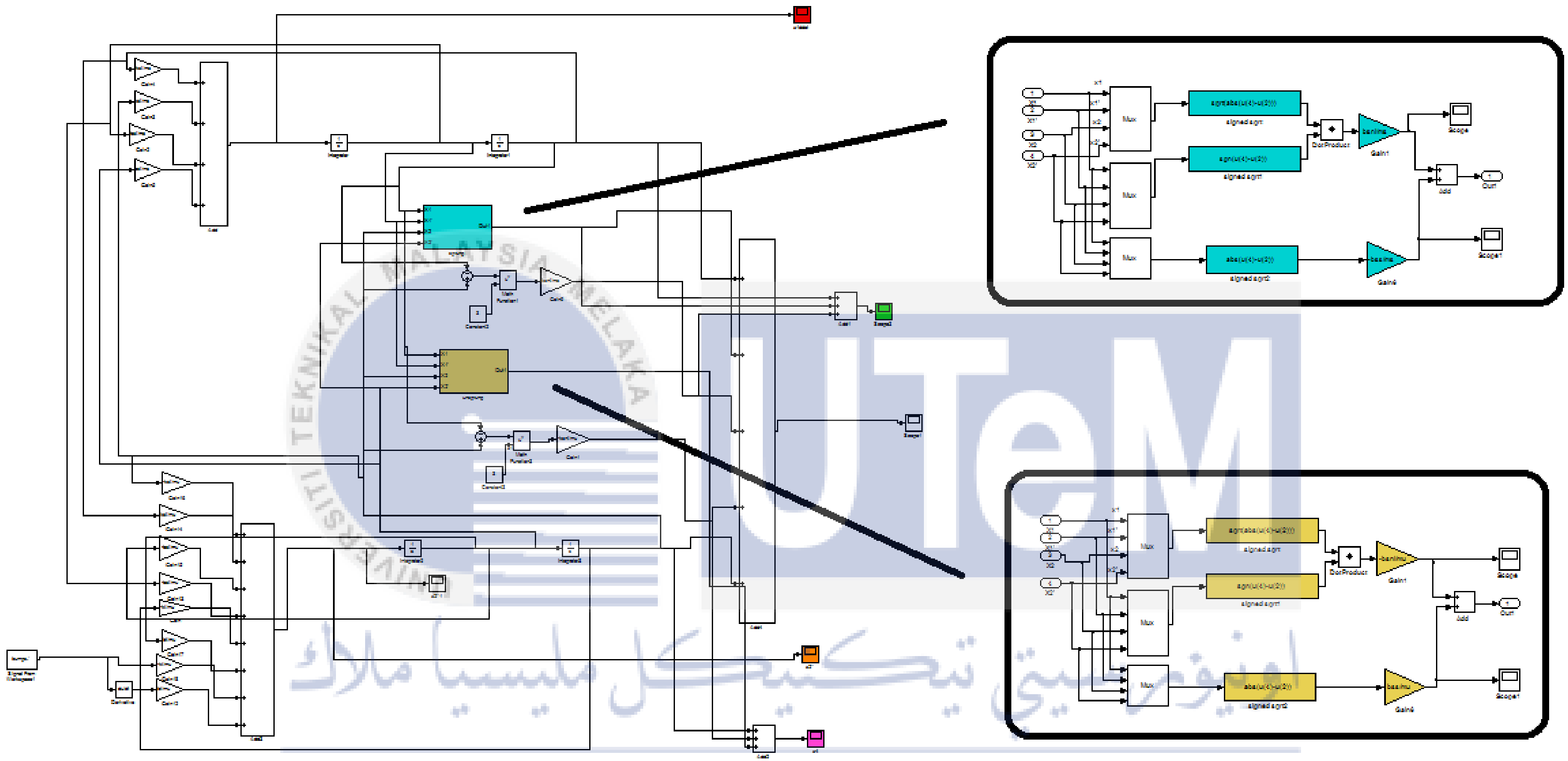
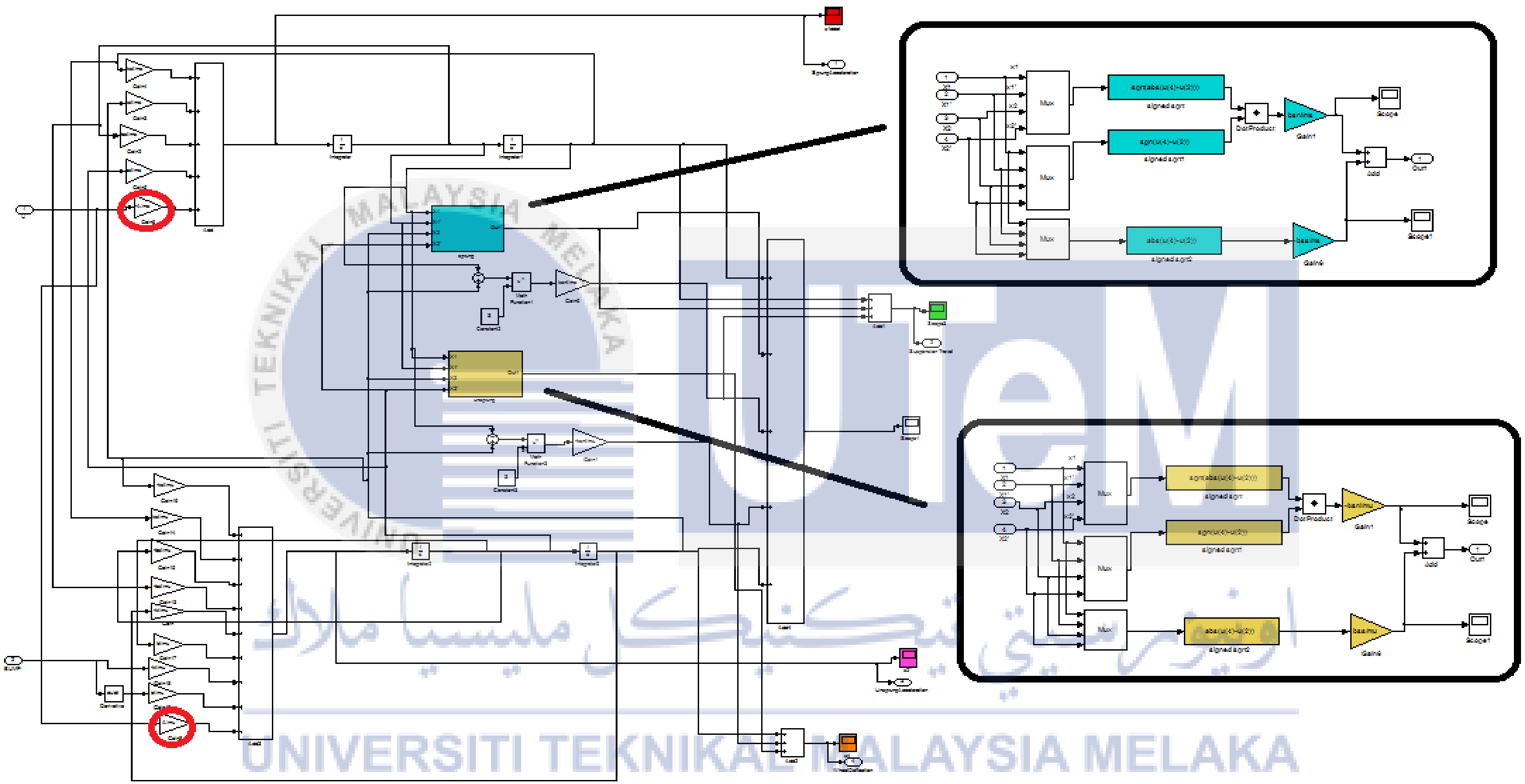
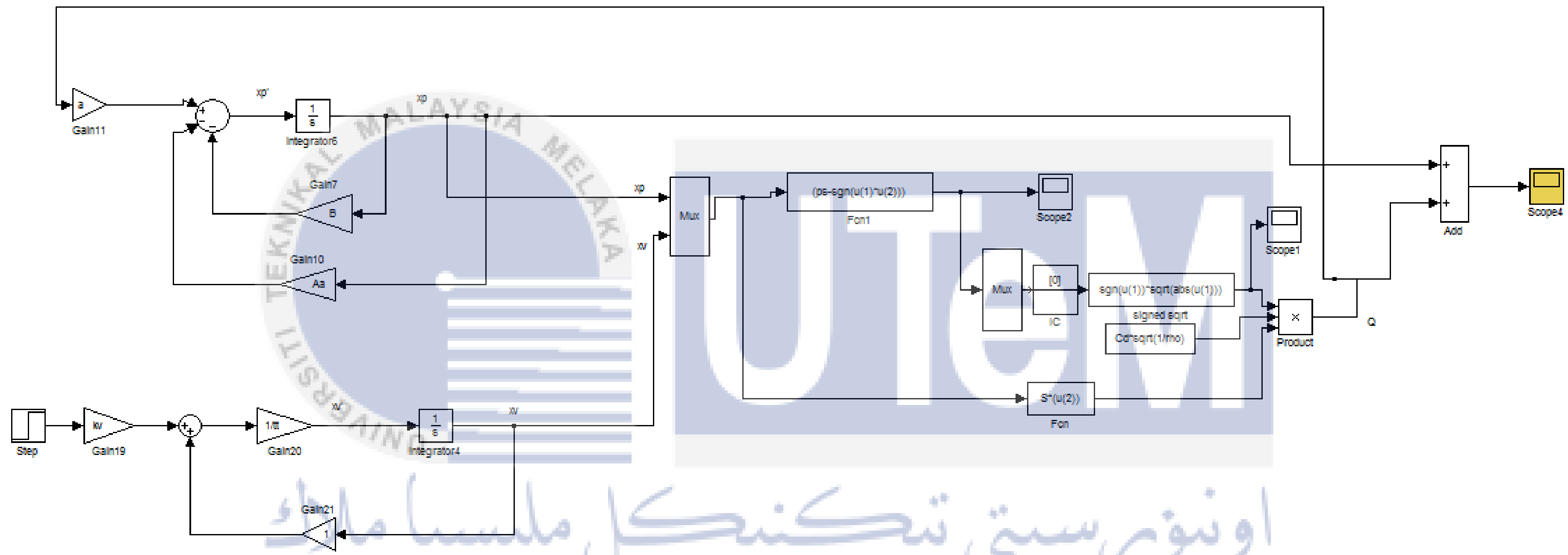




Open loop nonlinear passive suspension system

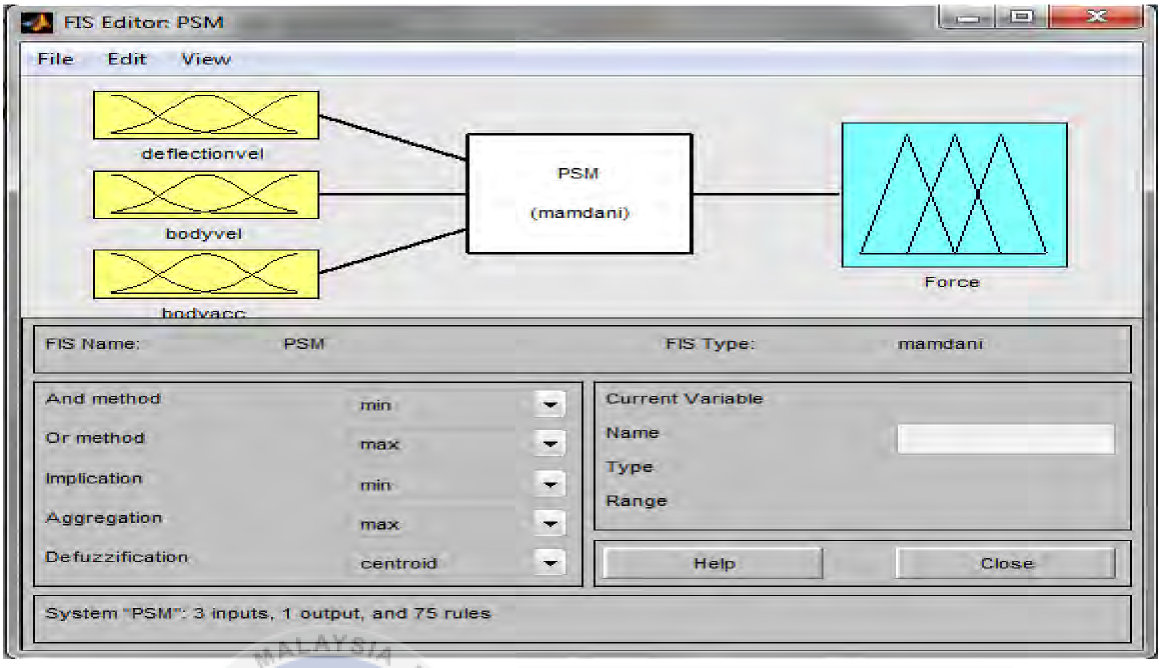



Open loop nonlinear active suspension system



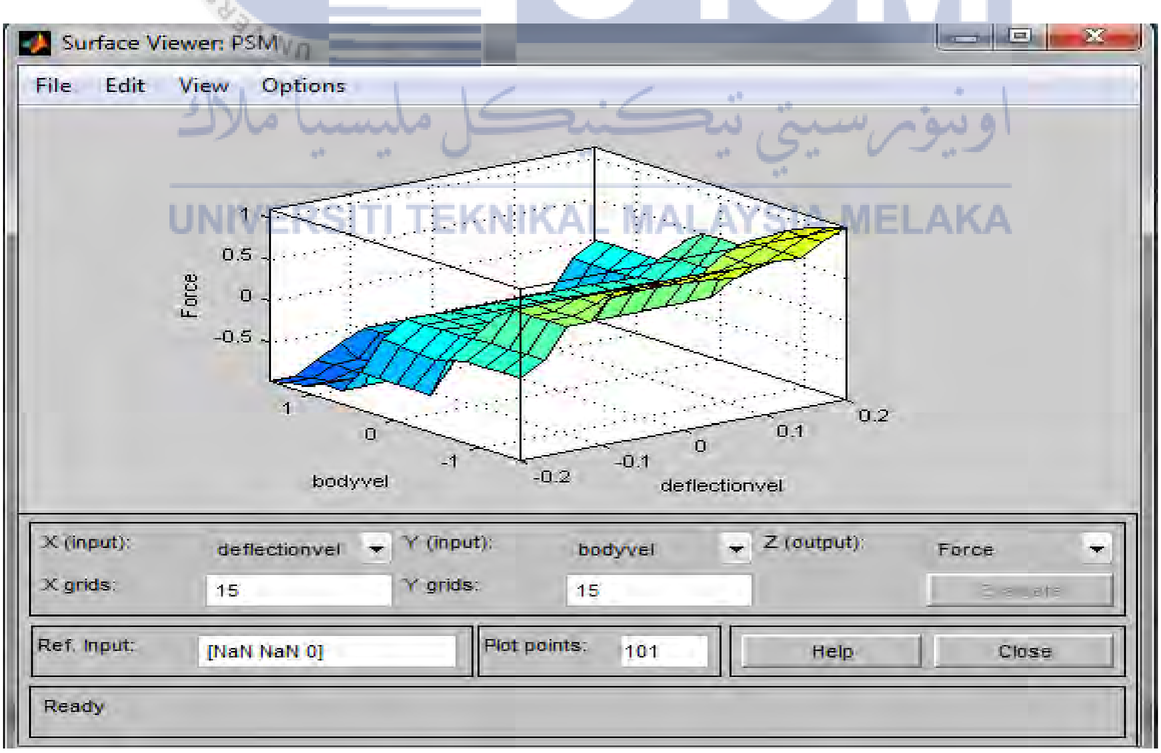



Hydraulic Actuator System

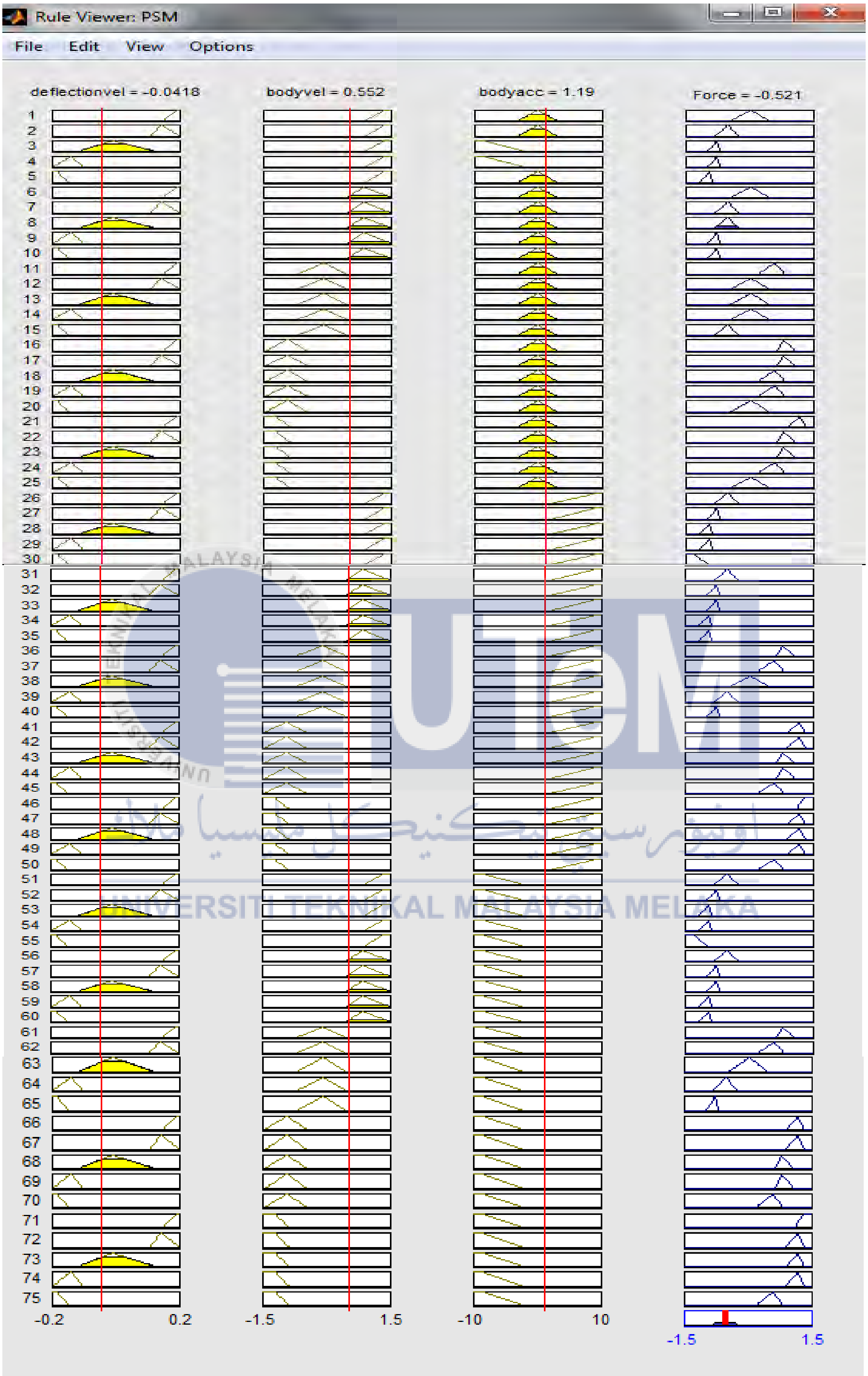



Toolbox of Fuzzy Logic Controller






Surface Viewer of Fuzzy Logic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10
-1.5
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Rule Viewer