ANTIROLL SUSPENSION SYSTEM FOR SPORT UTILITY VEHICLES

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A report submitted
in fulfillment of the requirements for the degree of
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DECLARATION

I declare that this project report entitled "Anti Roll Suspension System for Sport Utility Vehicles" is the result of my own work excepts as cited in the references.

Signature : ……………………

Name : MOHD FAIZZ BIN NORDIN

Date : 15.6.2017

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Automotive).

Signature : ....

Name : ....

Date : ....

DEDICATION

To my beloved mother and father

ABSTRACT

Suspension system is the connector between the tire and the body of a vehicle. The main aim of suspension system is to isolate a vehicle body from the road irregularities There are 3 suspension systems have been met in this research which is passive, semi active, and active suspension system. All of this suspension systems affects the performance and stability of a vehicles, include sport utility truck. Passive and active suspension have been test in this simulation MATLAB software to determine which suspension is better to achieve anti rollover of vehicles. This report is developed an active suspension for the half car model of a sport utility truck to improve the performance by using actuator force and proportional integral derivative (PID) controller. All the parameters of 3 different sport utility truck has been taken to analyzed through simulation in MATLAB Simulink. We will be studied by comparing the passive and active suspension system graph. In order to modelling this simulation, the equation of motion has been draft by half model car so we can analyze the data or rollover and vertical displacement of vehicles by comparing the passive and control suspension system.

ABSTRAK

Sistem suspensi adalah penyambung diantara tayar dan badan sesebuah. Tujuan utama system suspensi ialah untuk mengelakkan kenderaan dari jalan penyelewangan. Terdapat 3 jenis suspensi sistem yang diketemukan dalam penyelidikan ini dimana ia ialah pasif, separuh pasif, dan aktif suspensi. Kesemua sistem suspensi ini akan memberi kesan kepada kecekapan dan kesetabilan sesebuah kenderaan, termasuk sport utility vehicle. Suspensi aktif dan pasif akan dicuba dalam simulasi perisian MATLAB untuk menentukan suspensi mana yang sesuai dan bagus untuk mencapai anti bergolek. Kajian ini akan menghasilkan suspensi aktif untuk model separuh kereta untuk meningkatakn lagi kecekapan dengan menggunakan daya penggerak dan system PID. Kesemua 3 kereta ini mempunyai parameter yang berbeza dan akan diambil untuk di analisis melalui simulasi perisian MATLAB Simulink. Kami akan mengkaji dengan membandingkan graph yang dihasilkan oleh pasif dan aktif suspensi. Untuk menghasilkan model simulasi ini, persamaan perlu di draf pada separuh model kereta supaya kami boleh analisis data kenderaan bergolek dan anjakan menegak kereta dengan membandingkan suspensi aktif dan pasif.

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DOF	degree of Freedom
t	track
COG	centre of Gravity
m_b	mass of Body
m_W	weight of Vehicle
l_w	distance Between Front Both Tire
iphi	roll of Vehicle
k_{tr}	stiffness of Right Spring
k_{sr}	stiffness of Left Spring
m_w	mass wheel both side
Zr	road displacement
g	gravity
K	spring
C	damper
m_{wr}	mass wheel right
m_{wl}	mass wheel left
kt	tyre sping
wb	wheelbase
C_{sr}	damper Right Spring
C_{sl}	damper Left Spring

k_{sr}	stiffness of Right Spring
k_{sl}	stiffness of left spring

CHAPTER 1

INTRODUCTION

1.1 Background

Vehicles is a most important to the all user and its function as to move from one destination to another destination. All vehicles have their suspension which is one of the tire system that includes springs, shock absorbers and linkage and it connects a vehicle to its wheel. Suspension is a main role to provide the vehicle good ride and better handling. Besides that, it also to ensure that steering control is maintained during maneuvering, and to provide isolation from high frequency vibration from tire excitation. Sport utility vehicles are always have problem on their suspension due their factor of centre of gravity. It mostly will affect to the vehicle stability when driving through irregularities road, turning the wheel, stability of car and rollover of the vehicle during driving.

Rollover is a major problem of vehicle. There are 3 type of suspension system in vehicles which is passive, semi active and active suspension. Active suspension system uses hydraulic actuator to reduce the amount of external power necessary to achieve the desired performance characteristics and able to exert an independent force on the suspension to improve the riding characteristics. Semi active suspension is the damping force of the damper is controlled by changing the combination of throttle holes that pass the working fluid with quick electromagnetic valves. Both suspension have their own pro and cons.

There are 3 basic translational motions of vehicle axis system in **Figure 1.1** which are the roll motion through x-axis where front direction of vehicle is the positive value, the pitch motion through the y-axis where the direction to left side is positive value, and lastly is the motion through z-axis is yaw where the clockwise direction is positive value.

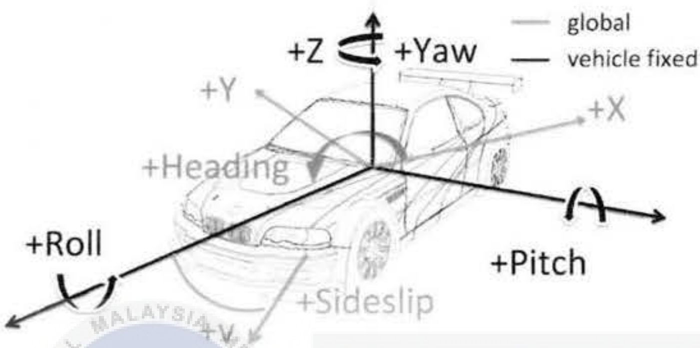

Figure 1.1: Vehicle pitch, yaw and roll

1.2 Problem Statement

From the theory, we all know that all the vehicles have pitch, yaw and roll and all of that have their own movement. Vehicles need a good suspension to avoid from rollover because suspension can improve the vehicle to the better handling and absorb the vibration when through the irregularities road. In order to achieve the good suspension and better comfort during ride, parameter need to change to make sure the isolation of vibration is lower so that the natural frequency become low and the stability of the vehicles is increase. Simulation from Matlab software can control the parameter and design the anti-rollover suspension control system.

1.3 Objective

The research focuses on sport utility truck which to control the suspension of the vehicles and avoid it from rollover. The main objective of this study are:

a) To understand working principles of suspension in vehicle, component and theories through a literature study.
b) To control and improve sport utility truck vehicles to the better handling, safety and comfort.
c) To provide complete analysis and modelling about suspension.
d) To tune suspension parameters and analyse the rollover of sport utility vehicle using Matlab software.

1.4 Scope of Project

The scope of this project is:

a) To analysis the sport utility vehicle rollover by changing the parameter of vehicle such as mass, stiffness, and damping.
b) To study and investigate the parameter of suspension to the comfort handling and avoid rollover.
c) Using Matlab and Simulink to analysis the suspension of vehicles.
d) Degree of freedom will be used for this project.

1.5 General Methadology

The method that need to be carried out to success the objectives in this project are:

a) Literature review

Journals, articles, or any materials that related with the project will be reviewed.

b) Matlab/Simulink

Control and modelling the vehicle dynamic and change the suspension parameter to analyse the factor of vehicle's rollover.

c) Research

Research about the criteria of suspension in vehicle and type of suspension such as semi active/active suspension

d) Simulation

The suspension will be tested by changing the value of mass, spring stiffness and damping coefficient which is influence the rollover of vehicles

e) Report Writing

We need to do a report for this research.

CHAPTER 2

LITERATURE REVIEW

2.1 History

The early years of automative development were an interesting time for the engineers where the period of development without established practice and virtually all ideas were new one and worth trying. As is well known, automobile was initially developed as self-propelled horse carriages. The special of horse at that time is it have its own suspension system with double leaf springs and dead axles but the speed of horse is low. A car is much of complex system and have a high speeds and high possibilities. The innovation of automative suspension at the beginning of the twentieth century. At 1903, Mors from Germany fitted a car with shock absorbers. In 1920, Leyland used torsion bars at suspension system. In 1922, construction and independent front suspension were pioneered on the Lancia Lambda, independent front suspension become more popular which it had wheel drive, unitary Minor with torsion bar independent front suspension. At 1949, Triumph Mayflower created the combined coil spring/damper unit and strut-type telescope damper. From 1950 to 1962, Citroen car used hydropneumatic suspension in its DS 19 model while BMC used independent rubber suspension and improved it in its 110 model using hydrostatic suspension. **Figure 2.1** shows the early model of suspension system which is use leaf spring and have two tyre with one connector made on the year 1900.

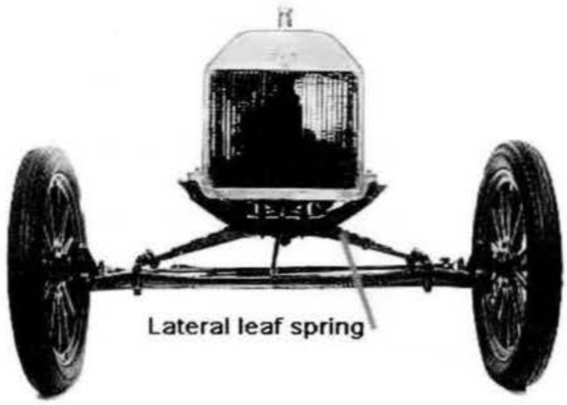

Figure 2.1: Early model of suspension system

Some of European car had tried coil spring leading by Gottlieb Daimler but most of manufactures stood fast with leaf springs. It was less costly, and be simply adding leaves or the shape are changing from full elliptic to three quarter or half elliptic, the function of spring to support weights. Leaf springs have been used since Romans era which suspended a two-wheeled vehicle on elastic wooden poles. At 18th century, the first steel spring put on a vehicle was a single flat plate installed on carriages by the French. Besides that, the venerable leaf spring who was invented by Obadiah Elliot of London in 1804 is manufacture and still use in rear suspension today. He simply piled one steel plate on top of another, pinned them together and shacked each end to a carriage.

At 1908, Henry Ford's Model T Ford featured old fashioned leaf spring and he only used one spring at each axle, mounted transversely, instead of one at each wheel. High strength vanadium steel from a French racing car make the car save weight and cut costs in many areas of the Model T Ford but not focusing their durability. Independent coil spring front suspension maintained for 25 years after the introduction of the Brush Runabout. However in 1934, General Motors, Chrysler, Hudson, and others reintroduced coil spring front suspension which each of the wheel spring independently. During that year, most of the cars started using hydraulic shock absorber and low pressure tires. At the time, not all the cars used coil spring, some of them had independently suspended leaf springs. Then, all manufactured switch to coil spring for the front wheel after World War II.

We can say that the suspension system was revolutionized by the independent suspension system. After the cars started becomes more technology, powerful and lighter, independent front suspension helped the car in handling to keep pace with their escalating power to weight ratios. The shape of independent front suspension changed so the car can improve their ride and road holding. In addition, the disappearance of the front beam axle will make the engine moved further forward and mounted lower. The suspension assemblies were fitted almost at the same height. Today' high speed, sleek automobiles need to a lot of development that tool place like the tiny hammer blows of an artist that chisel out a piece of art.

2.2 Roll-over

2.2.1 Introduction

A rollover is a type of vehicle accident tips over onto its side or roof. Rollover on vehicles is an important to the road safety. To avoid or prevent rollover is a fundamental and significant issue for vehicle dynamics and this topic has been consideration for a long time (Palkovics, et al, 1999). There are two distinct types of vehicle rollover, tripped and un-tripped (Selim, et al, 2006). This two type of rollover is different where a tripped rollover commonly occurs as vehicles skids and digs its tire into soft soil or hits a tripping mechanism such as divider, curb or guardrail with a sufficiently large lateral velocity. Maneuver or unable to move skillful lead to un-tripped rollover which it can occur during typical driving situation and poses a real threat for the vehicles with an elevated centre of gravity. Average percentage of rollover occurrence in fatal crashes significantly higher than in other types of crashes (Chen, 2001). Rollover can occur as a direct result of the lateral wheel forces induced during these maneuvers. Besides that, vehicle rollover also occurs when an external disturbance such side wind then passenger vehicle in position at height centre of gravity such as vans, pickup, and SUVs are more inclined to rollover accident. From **Figure 2.2,** we can see an example of vehicle experienced the rollover situation which the centre of vehicle gravity is no longer in balance condition. Rollover is a critical safety issue, however there is still no safety performance standard available and no well recognized rollover protection standards or design guidelines. During the rollover happen, a driver does not have any hint many case of rollover is cannot be prevented by driver action alone, even when they are correctly warned. Active anti-rollover control can additional assist deficiency in human capability. Hence, two stages can be classified into avoiding rollover which is detection of the possibility of a rollover, and development of a mitigation control algorithm. The research show that rollover prevention focused on two areas: rollover detection system and anti-rollover control system.

Figure 2.2: Rollover of vehicle

2.3 Factor Influencing a Rollover

There are a few factors that can increase the probability of the occurrence of a rollover. There is the position of a vehicles CG, vehicle speed, the angle of impact upon collision with barrier as a tripping factor.

2.3.1 Centre of Gravity

Rollover of a vehicle is directly related to its CG in the sense that a vehicle is unlikely to rollover if it CG in the region of its gravitational patch, viewed from the top. The CG is always balanced within the gravitational geometry of some support structure. **Figure 2.3** shows that a vehicle rollover because the CG is no longer balanced within the gravitational geometry formed by the tyres. From right view, the CG on the right picture is cambering to its side. The CG position is move outside of the gravitational support structure which rollover will occur.

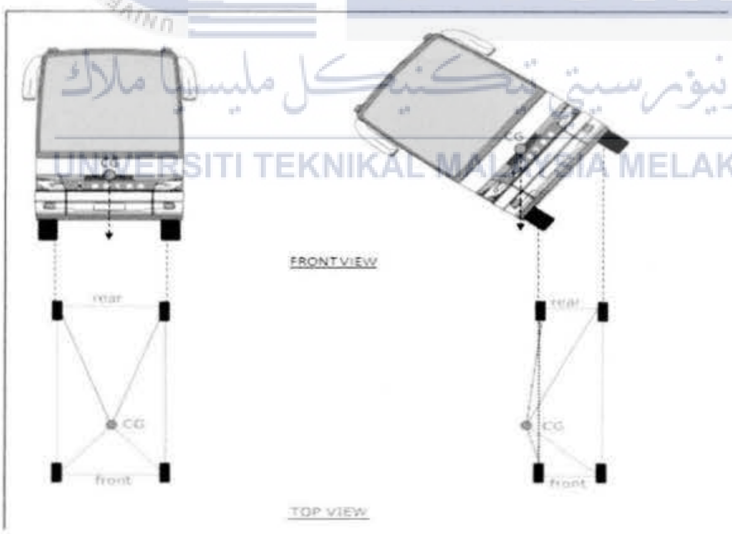

Figure 2.3: Relationship between CG and rollover (Source: Wong, 2012)

2.3.2 Speed

In this case, rollover will occur when a vehicle is moving or sliding sideways hit a solid object such as a curb. The curb provides a pivot point over which the vehicle will rotates. **Figure 2.4** and **Figure 2.5** shows that the condition of vehicle before and after pivoting where the critical point is achieved as the centre of gravity is at the maximum height and may can cause the rollover condition.

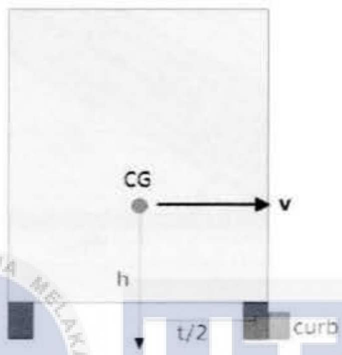

Figure 2.4: Vehicle before pivoting

Figure 2.5: Critical point of rollover (Source: Wong, 2012)

2.3.3 Angle of Impact

Figure 2.6 shows the rollover crashes occur when a vehicle impacts a pivot point such as curb, barrier or solid object at certain angle. The magnitude of the angle will influence either the vehicle will experienced the rollover.

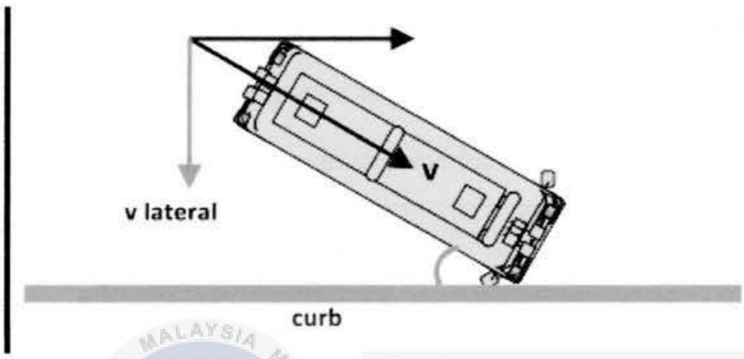

Figure 2.6: Lateral component of vehicle moving with velocity *(v)* and angle *(∅)* (Source: Wong, 2012)

2.4 Suspension System

Suspension is a complicated system which related to a large number of partly in vehicle. The aim of the suspension system in vehicle is to isolate the pasengers from the road disturbance and also to force contact between the wheel and the road (Abdullah et al., 2015). People always assume about horsepower, torque and zero-to-60 acceleration when talk about automobile performance. However, the power generated by a piston engine and it very meaningless if the driver cannot control the car. After the consideration, engineer of automobile turned their focus to the suspension system. The task of a car suspension is to maximize the friction between the tires and the road surface which it will make sure the ability of steering with good handling and for sure the comfort of the passenger. **Figure 2.7** shows how the suspension will work on a flat surface and during irregularities road, let assume the road were perfectly flat means no irregularities, so suspension system can provide a smooth ride in the car and to help maintain control of the vehicle (Aly, 2012). But it is too difficult to hear the road are no irregularities, even if the freshly paved highway have an imperfection that can relate with the wheel of car. The overall objective is to improve ride comfort and maintain crisp handling (Donahue). During the irregularities road, the wheel will move up and down perpendicular to the road surface. The magnitude of the axis depends on wheel when it hit the giant bump or a tiny speck. Then, the car wheel experiences a vertical acceleration after it passes through an imperfection (Yogesh, 2015).

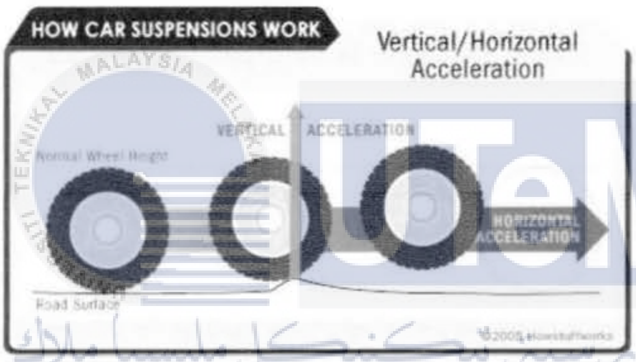

Figure 2.7: Suspension work

2.4.1 Suspension Component

The main of suspension system component is include tires, rims, shock absorber, springs, anti-roll bars, and lower and upper arm. **Figure 2.8** shows the component of suspension system in vehicle which attach to the tire. This component system is very connecting to the work of suspension in vehicle and have their own function. As we know tires and rim components make the vehicle motion possible by way of grip or make a friction to the road. Shock absorber is they can reduce the tendency of the weight unit even the car hit then bounce up and down on its spring. Spring is outside and surround the damper so they can absorb road shocks or impacts when they bounce in road by oscillating. Tires also effect to the spring but only a smaller level. Anti-roll bars to control body roll motion when car make a turning. Lastly, lower and upper arm play an important role which the frame has a pivot at both end.

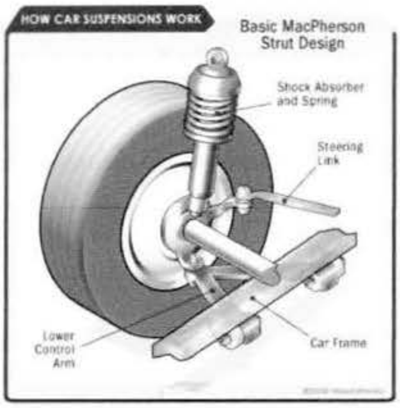

Figure 2.8: Component of suspension system

2.4.2 Type of Spring

Spring is the most important part to suspension of vehicle it acts as reservoirs of energy. **Figure 2.9** is an example of spring which one of the major components that have in suspension system. Function of springs is it can store the energy that produce from the vehicle when they are suddenly hit a bump or a ditch. This spring released their energy and converted the energy into heat then avoided the bounce. Spring need to absorb road shocks very quick then should return or back to the original position slowly

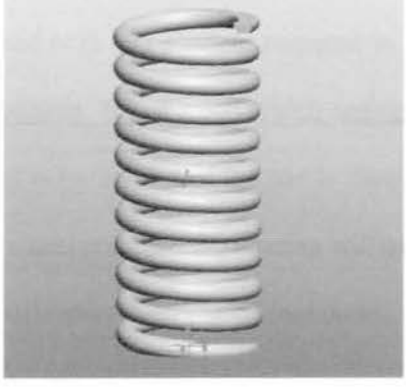

Figure 2.9: Spring in suspension (Source: Lavanya, 2014)

2.4.3 Leaf Spring

Leaf spring have been told as a laminated spring since they use steel strips or lamination one over the other with reducing length. Other name for this spring is Semi elliptical spring and each of their strip called as leaf. They are joined together with a clamp and a central bolt. The arrangement or the assembly of this spring is by decrease the length of each leaf so acts as a flexible. Master leaf in this spring are formed into loops at the end and called it as spring eyes. To assemble this spring is one end of the spring need to attached with frame through a spring bolt passing through the eye while the other end is secured through a shackle.

2.4.4 Coil Spring

This is the most common spring that used in independent suspension system. It widely used in both front and rear suspension system. Coil spring is large metal bed springs, cuishion and absorb it when the vehicle shocks and bumps during on the road. The position of this coil spring usually located at front wheel but some pickup vehicle put them in the rear as well. Coil spring will compress and expand when the vehicles ups and down during on the road.

2.4.5 Torsion Bar

Torsion bar always used with independent suspension. **Figure 2.10** is an example of the torsion bar that have in vehicle. It just a rod which acting under the torsion and taking shear stresses. The way to fix is by on end of the bar is fixed to the frame while the other side is fixed to the end of the wheel arm then the bearing will support for it. When the vehicle drive and hit a bump, the vehicle start vibrating up and down, then the torque on the torsion bar will work as a springs.

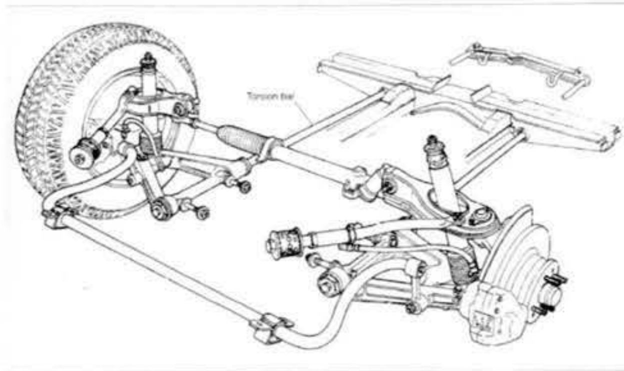

Figure 2.10: Torsion Bar

2.4.6 Rubber Spring

Rubber spring is one of the spring that used in suspension and the ability of this spring is it can store greater energy per unit weight more than the steel. The vibration damping is very excellent when it vibration. Another special for this spring is it not suddenly fail like steel so here is less risk.

2.5 Type of Shock Absorber

Pneumatic and hydraulic shock absorber are commonly used in conjunction with cushion and springs. Every vehicle that have shock absorber contains spring-loaded check valves and orifices to control the flow of oil through an internal piston. The energy of the damper depends on designing or choosing a shock absorber. Most of the shock absorber will convert energy to heat inside the viscous fluid. The different of hydraulic and air cylinder is hydraulic fluid will heat up while air cylinder will exhausted to the atmosphere. Shock absorber reduce the effect of driver over the rough road, which to make ride and vehicle handling better. Shock absorber serve the purpose of limiting excessive suspension movement, their intended solo purpose is to damp spring oscillation (Meghraj, 2015).

2.5.1 Twin Tube

Basic twin-tube

-Known as two tube shock absorber. This device consists of two nested cylindrical tubes, working tube (inner) and outer tube (reserve tube). At the bottom of the device on the inside is a compression valve or base valve. The working of this absorber is the piston is forced up and down when bump on the road, hydraulic fluid moves between different chamber through small holes through the piston.

Twin-Tube Gas Charged

-Known as gas cell two tube. Overall structure is same like twin-tube, but a low pressure charge of nitrogen gas is added to the reserve tube. Twi-tube gas charged shock absorber always used on original modern vehicle suspension installation

Position sensitive damping

-Evolution from twin-tube shock. A set of grooves has been added to the pressure tube which allow the piston move freely during a long distance. It allowed an engineer designer to create shock absorber to more detail and take part more about size vehicle and weight.

Coilover

-Charged shock absorber around by mounted a large metal coil. Common on motorcycle and scooter which locate at rear suspension and not widely design for vehicles. However, coilover shocks for cars is like a special item for high performance and racing.

Mono-tube design

-High-pressure gas shock with only one tube, the pressure tube. They are two pistons in pressure tube which is dividing piston and a working piston. Design of twin tube shock is similar like working piston and rod in Mono-tube design. It can be mounted down upside or right side up then will work. Mono-tube shock absorber does not have valve. Piston will control during compression and expression

2.6 Type of Suspension System

Suspension system absorb major part of the vibration produced from road surface and transfer little to passenger seat. As human has a tolerance to sustain acceleration at various excitation frequencies that vary as the road profile varies (Phalke, 2016). Every consumer has a right to feel comfortable on their vehicle. Suspension is the most important to the vehicle hence engineer design very challenging to design a suspension which can meet consumer need. There are basically three types of suspension system which is passive, semi-active and active suspension system.

2.6.1 Passive suspension

Passive suspension system can be found in controllong the dynamics of vertical motion of a vehicle (Darus, 2008). It can only achieve good ride comfort or good road holding since these two criteria conflict each other and necessitate different spring and damper (Alu, 2012). Passive suspension system have an energy that dissipating element namely dampers and spring which to store energy (Sandage, 2013). Damper in passive suspension is to dissipate the energy and the spring is to store the energy. The load will exerted to the spring, it will compress the force produced by the compression as equal to the load force. Even the load is produced by an external force, it will oscillate around its original position for a period of time. However, passive damper is unable to generate force but able to dissipiate (Abdullah et al., 2015). When two elements that we cannot add any energy to the system so damping coefficient and spring stiffness are totally fixed. The weakness will occur when parameter for ride comfort and good handling with different speed, road surface and disturbances. **Figure 2.11** shows that quarter car diagram of passive suspension system where there are only have a basic components such as spring and damper only.

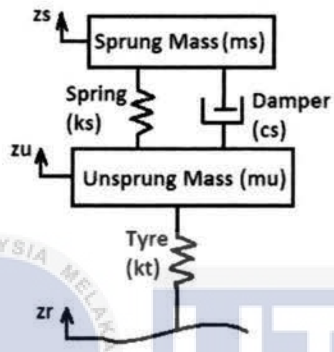

Figure 2.11: Quarter car diagram of passive suspension (Source: Phalke, 2016)

2.6.2 Semi Active Suspension

There is no big different element that have between passive suspension and semi active suspension where it uses external energy on their system. We can see the quarter car diagram of semi active suspension system at **Figure 2.12**. The difference is the damper is replaced with controllable damper which require small amount of external energy (Sandage, 2013). Force actuator in semi active suspension is used in controller where it works to control irregularities and increase level of comfort. Semi-active systems are classified as system where the characteristics can be changed rapidly, typically less than 100milliseconds. The technology of electroheological (ER) and magnetorheological (MR) fluids has boosted research in the field of semi active suspension (Guglielmino, 2010) and their potential implementation in various system, such as vibration control devices and suspension system.

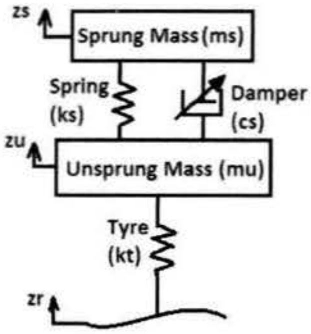

Figure 2.12: Quarter car diagram of semi active suspension (Source: Phalke, 2016)

2.6.3 Active suspension

An active suspension system possesses the ability to reduce acceleration of sprung mass continuously as well as to minimize suspension deflection (Aly, 2013). The difference compared to conventional suspension. Active suspension system is it able to inject energy into vehicle dynamic system via actuators rather than dissipate energy. Active suspension using of more degree of freedom in assigning transfer function then the performance can be improving. Besides that, it consists an extra element which is actuator as to controlled high frequency response servo valve which involves a force feedback loop. The demand force signal, typically generated in a microprocessor, is governed by a control law which is normally obtained by application of various forms of optimal control theory (Ahmad, 2007). Theoretically, optimum ride and handling characteristic can be achieved at this suspension. It because maintaining an approximately constant tire contact force, level vehicle geometry and decrease vertical acceleration to the vehicle but it is quite complicated compare than other suspension system. An important issue in active suspension is energy consumption. It is recognized that full active suspension which must carry the full weight of vehicle, would consume a considerable amount of energy and need high bandwidth actuators (30 Hz) and control valves (100 Hz). It only installed in some expensive and exclusive car or the one that we always known, Fomula One cars. **Figure 2.13** shows the quarter car diagram of active suspension system which have an actuator force as an extra element.

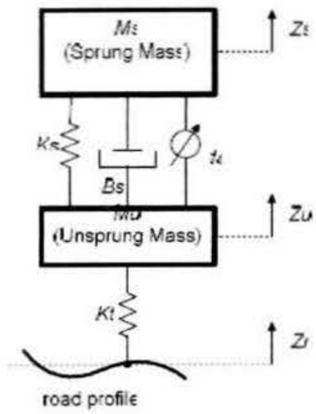

Figure 2.13: Quarter car diagram of active suspension (Source: Phalke, 2016)

2.7 PID Controller

The disturbance reduction will used a Proportional Integral Derivative (PID) as to stabilizes and performing the handling on the ride of vehicle. It consists of three different parameters which used to lower the rise time, eliminate the steady state error, decrease the settling time and overshoot the system. PID controller is used for active suspension system to improves the ride comfort and provides better road-holding characteristics. The Ziegler-Nichols and refined Ziegler- Nichols (RZN) tuning methods are considered while designing the PID controller. PID controller is developed which gives optimal and robust system accounting different road conditions and vehicle sepeed to increase ride comfort (Phalke). The half or quater car model is modelling and it test to the road profile. The simulation a Matlab software founds that all parameters influence the ride quality and it improved compared to the passive suspension system.

2.7.1 Electromagnetic Active suspension

The possibility of utilizing an electromagnetic (EM) actuator on a high-wheel travel active suspension system has recently gain considerable interest in both the commercial and the military sector (Hoogterp, 1995). The heavy vehicle developers are interested in ability of active suspension which give benefits for ride comfort and can control vehicle as well for the accompanying height and altitude control. The active suspension normally provided by the spring and dampers and some form of actuator (e.g. hydraulic, pneumatic, or EM) based on the output of vehicle motion based control algorithms. Electromagnetic active suspension does not just mechanically respond when the vehicles bumps in the road, but it is controlled by an onboard computer. The computer will receive input from accelerometer and other sensor on the vehicle, and adjust the suspension accordingly within a fraction of a second. Active suspension previously mainly been integrated by hydraulic system. According to the Eindhoven researchers, hydraulic cannot react quickly as well as electromagnetic system which can achieve smooth on the ride. The size is same like conventional shock absorber, which consists of a passive spring, an electromagnetic actuator, a control unit and batteries. Spring will provide springing action while magnets provide passive shock absorption. The success of active suspension has been quite impressive in the areas of on road where its stability and handling and has been tested repeatedly.

2.7.2 How Active Suspension Work

Active suspension system is system that uses sensor and microcontrol and feedback loop to improve an optimal suspension according to the require needed. Active suspension use same principle and element like other suspension, but there are only component will added to control the electronic components such as Sensor, Electric Control Unit (ECU), and actuator. Sensor will detect the movement of vehicle body in transverse, and will deliver the information back to ECU. Sensor also can read an extra vertical movement and proceed to ECU. Besides that, ECU will work by all signal from sensor will read by ECU and with the aid of pre-programmed memory, the incoming signal is processed to determine the level of the suspension as needed. Actuator, the order of ECU will be converted into electrical signals and transmitted directly to the actuator to control the suspension system. At the same time, set the actuator to temporarily increase the stiffness of the suspension damper or soften appropriate command from the ECU. **Figure 2.14** shows how the basic of active suspension work where the ECU as the main to control the suspension system.

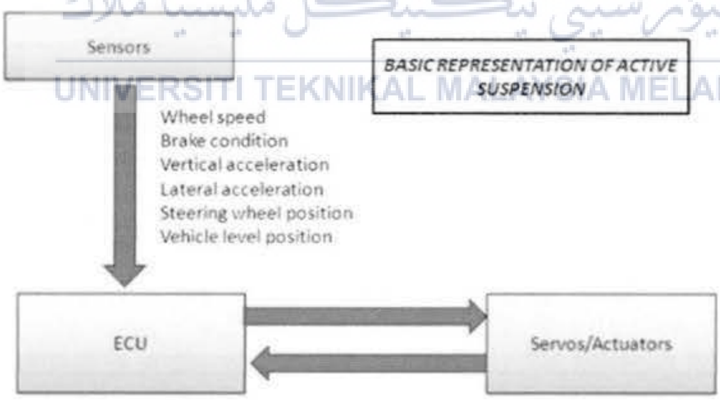

Figure 2.14: Basic of active suspension

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, we are discussed about the whole chapter implementation involving the steps from modelling process until analysis the result. The modelling of half car was design and use an active suspension to antiroll the vehicle. To create this project, the MATLAB 2016 software will be used and analysis simulation will be carried out. Carsim software also used in this project which it as mathematical model and represent the real vehicle model.

MATLAB is a multi-worldview numerical registering envirorenment and fourth-era programming. MATLAB is the abnormal state which high-level language and interactive environment that used by many people such as engineers and scientists from worldwide. A restrictive programming dialect created by MathWork. MATLAB let you investigate and visuallize the animation through disciplines including signal and image processing, communications, control systems, and computational finance.

Carsim is one of the software which specialize to deliver the most accurate, detailed, and efficient for simulating performance of passenger vehicle and variable type of vehicle such include sedan and sport utility vehicles. With more than twenty years of real-world validation by automotive engineers, Carsim is generally the software tool for check the vehicle dynamics, doing the vehicle simulation, developing active controllers, plot the graph, calculating a car's performance characteristics, and step for engineering to make sure the system of vehicle more safety. With many product and design that facing from engineer, Carsim provide an initiative set of tools for engineers to quickly evaluate, complete vehicles, automobile sub- components, and active controllers in complex, simulated driving environments. Carsim also provides us to check the vehicle condition such as pitch, yaw and roll.

3.1.1 Project Flow Chart

The methodology of this project can be described by the flowchart in the figure below. **Figure 3.1** shows the flow chat overall of process to completing my project

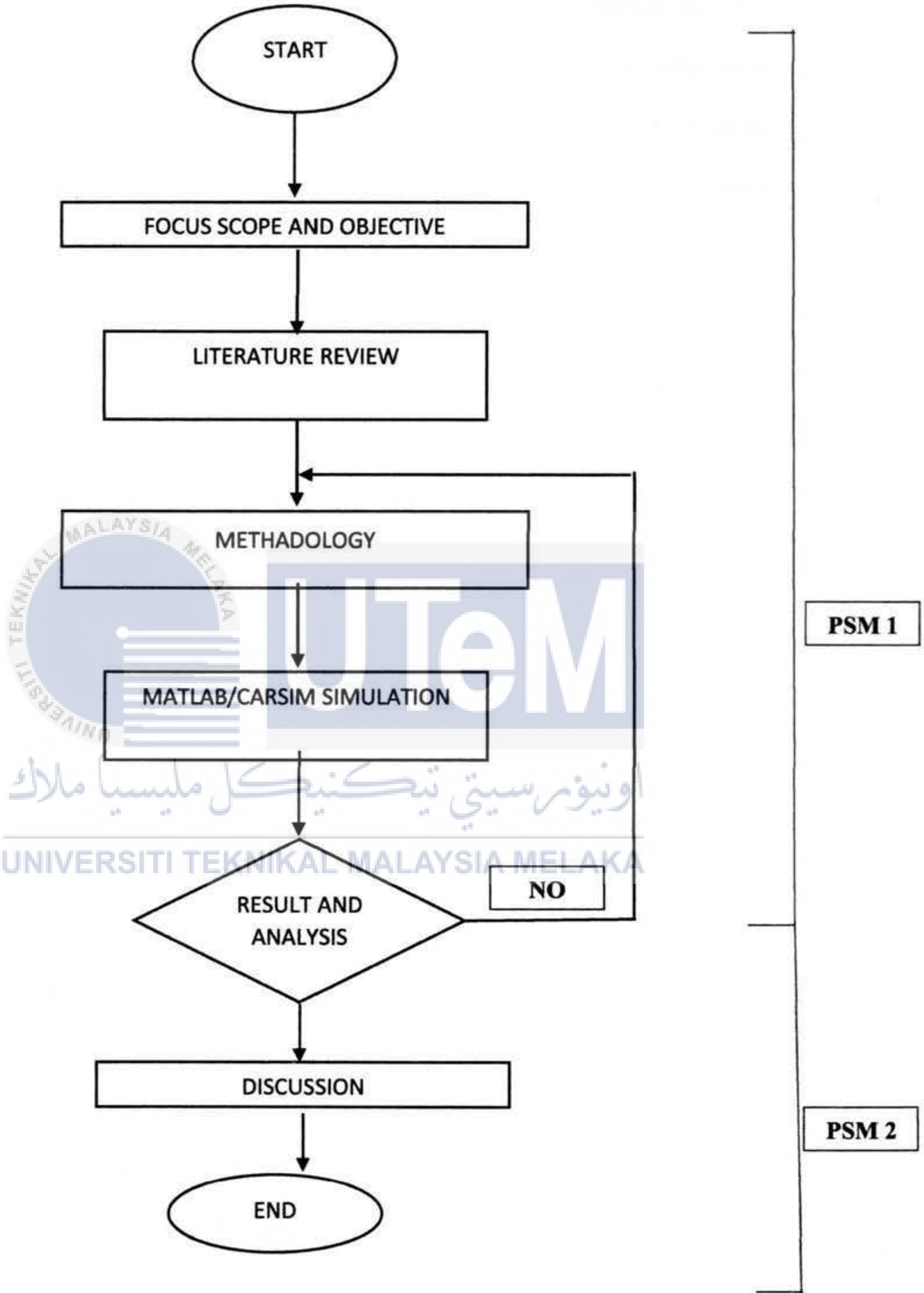

Figure 3.1: Flow for PSM 1 and PSM 2

3.2 Quarter, Half and Full Car Model

A two degree of freedom and quarter car model of suspension system is shown in **Figure 3.2**. It represents the suspension system at any of the four wheels of the vehicle and the degrees-of-freedom are displacement of axle and displace of the vehicle body at the particular wheel (Prasanna, 2009). The body consist of a damper c_s, and spring k_s, and active force actuator F_a, There is no force actuator in passive suspension. The sprung mass M_b and the unsprung mass M_a will consider as mass of the vehicle body which is equal to quarter-car and equivalent mass of the tire and axle. The vertical stiffness of the tire represent as K_t, The vertical displacement of sprung mass, unsprung mass and road profile are represent Z_b, Z_{ax} and Z_{ar} respectively in static equilibrium.

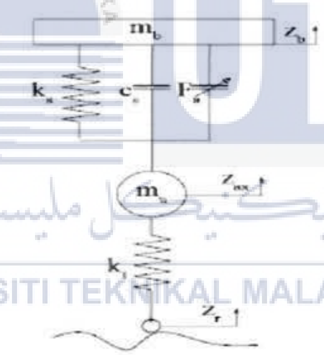

Figure 3.2: 2 DOF model (Source: Prassana, 2009)

A half car of model suspension system or a four degrees-of-freedom system is shown in **Figure 3.3**. The model represent roll motion of the vehicle body and the vertical of the front left and front right (Z_{u1} and Z_{u2}). The unsprung masses at front left axle and front right axle represent as M_{u1} and M_{u2}.

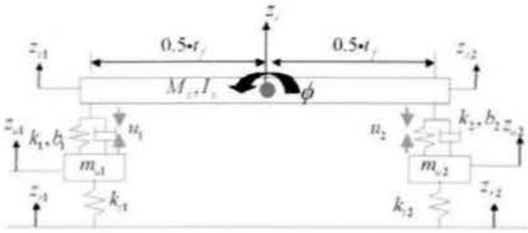

Figure 3.3: 4 DOF model (Source: Prassana, 2009)

If the car is in full model, we call it as seven degrees of freedom. In this condition, there will be pitch θ and roll $\emptyset$ of the vehicle body and the vertical motions (Z_{axfR}, Z_{axrR}, Z_{axfL}, Z_{axfR}) of each of the four unsprung mass (m_{axfR}, m_{axrR}, m_{axfL}, m_{axrL}). Besides that, vehicle body mass, stiffness of suspension are represent using m_b, k_{sfR}, k_{sfL}, and k_{srL}, where stiffness of tires are represent by K_{tfR}, K_{trR}, K_{tfL} and $K_{trL.}$ The model is shown in **Figure 3.4.**

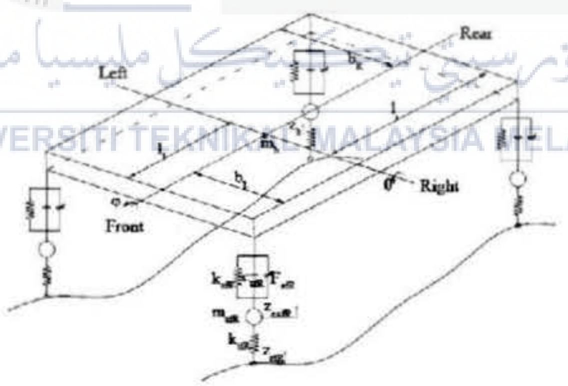

Figure 3.4: 7 DOF model (Source: Manoj et al., 2009)

3.3 Modeling of 4 DOF

To know the roll of the vehicle during on the road, the vehicle need to be 4 DOF which that is only front view of car we can see. A 4 DOF quarter car model has been developed to study important effect on vehicles (Mitra, 2013). There are 4 equations of motion to plot the vehicle graph and to run Matlab/Simulink and Carsim software. We can see the graph from this software which is we need roll of the body and vertical acceleration of the vehicle. The derivation of the equation for 4DOF model are shown at **Figure 3.5**.

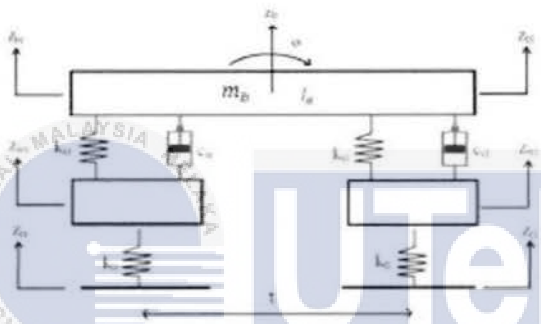

Figure 3.5: 4 DOF roll model (Source: Abdullah et al., 2016)

$\dot{Z}_b$

$Z_{bl} = Z_b + 0.5t \sin \emptyset$

(3.1)

$Z_{bR} = Z_b - 0.5t \sin \emptyset$

(3.2)

$\dot{Z}_{bl} = \dot{Z}_b + 0.5t \sin \dot{\emptyset}$

(3.3)

$\dot{Z}_{br} = \dot{Z}_b - 0.5t \sin \dot{\emptyset}$

(3.4)

Assuming ø is very small

Sin ø = ø

$Z_{bl} = Z_b + 0.5t\o$

(3.5)

$Z_{br} = Z_b - 0.5t\o$

(3.6)

$\dot{Z}_{bl} = \dot{Z}_b + 0.5t\dot{\emptyset}$

(3.7)

$\dot{Z}_{br} = \dot{Z}_b - 0.5t\dot{\emptyset}$

(3.8)

Equation 1- The vertical motion of vehicle body

$$\ddot{Z}_b = \frac{1}{m_b} [\, k_{sr}(Z_{wr} - Z_b + 0{,}5t\emptyset) + C_{sr}(\dot{Z}_{wr} - \dot{Z}_b + 0{,}5t\dot{\emptyset}) + k_{sl}\,(Z_{wl} - Z_b - 0{,}5t\emptyset))$$
$$+ C_{sl}(\dot{Z}_{wl} - \dot{Z}_b + 0{,}5t\dot{\emptyset})]$$

(3.9)

Equation 2- The rotational motion of vehicle body (roll)

$$\ddot{Z}_b = \frac{1}{I_\emptyset} 0.5_t\, [\, k_{sl}(Z_{wl} - Z_b - 0{,}5t\emptyset) + C_{sl}(\dot{Z}_{wl} - \dot{Z}_b - 0{,}5t\dot{\emptyset})\,] - 0.5_t\, [\, k_{sr}(Z_{wr} - Z_b +$$
$$0{,}5t\emptyset + C_{sr}(\dot{Z}_{wr} - \dot{Z}_b + 0{,}5t\dot{\emptyset})\,]$$

(3.10)

Equation 3- The vertical motion of left wheel (Tyre)

$$\ddot{Z}_{wl} = \frac{1}{M_{wl}} K_{tl}\,(\,Z_{rl} - Z_{wl}) - K_{sl}\,(\,Z_{wl} - Z_b - 0{,}5t\emptyset) - C_{sl}(\dot{Z}_{wl} - \dot{Z}_b - 0{,}5t\dot{\emptyset})$$

(3.11)

Equation 4- The vertical motion of right wheel (Tyre)

$$\ddot{Z}_{wr} = \frac{1}{M_{wr}} K_{tr}\,(\,Z_{rr} - Z_{wr}) - K_{sr}\,(\,Z_{wr} - Z_b - 0{,}5t\emptyset) - C_{sr}(\dot{Z}_{wr} - \dot{Z}_b - 0{,}5t\dot{\emptyset})$$

(3.12)

3.3.1 Modeling of 4 DOF

After the derivation, we need to use Matlab software and do the Simulink for this all equation to get the roll and vertical acceleration graph.

Then, summarize the Simulink equation into the subsystem and put the scope from the library as the output of our graph such as roll of the vehicle (phi) and vertical accelearation (zbdotdot). **Figure 3.6** shows the subsystem of Roll 4 degree of freedom.

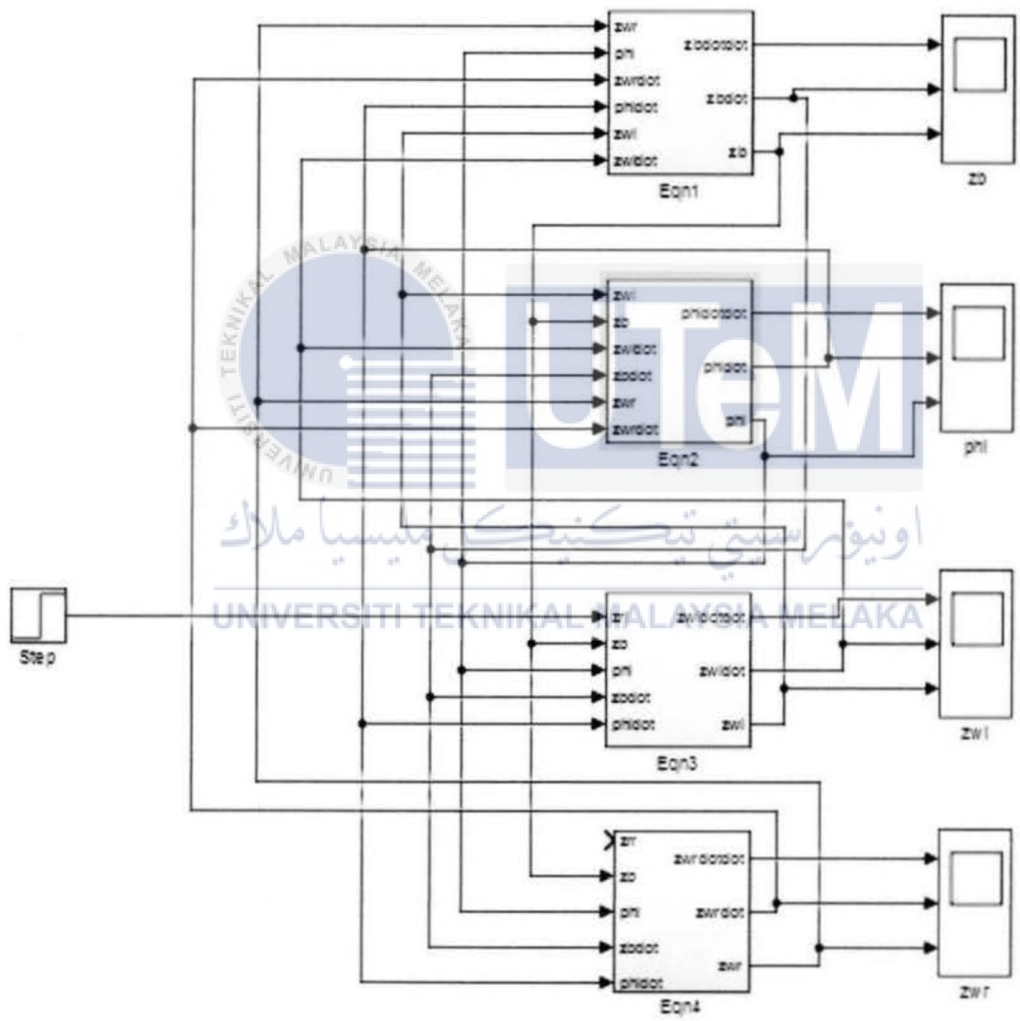

Figure 3.6: Subsystem of Roll 4 DOF

The parameter at **Table 1** is the information of the utility truck that we need to run into Matlab coding. Then, we can plot graph from Matlab software.

Table 1: Parameter of 4DOF

Parameter	Value
Weight of vehicle, m_W	600 kg
T	1.26 m
Iphi	846.6 kg/m^2
k_{sr}	35000 N/m
k_{sl}	35000 N/m
C_{sr}	30000 Ns/m
C_{sl}	30000 Ns/m
k_{tr}	220000 N/m
k_{tl}	220000 N/m

Figure 3.7 shows that the selected utility truck vehicle from CarsimEd as our data analysis and parameter. All the parameter will be take out from CarSimEd and put it into the simulation Matlab software.

Figure 3.7: Utility truck in Carsim

Figure 3.8 and **Figure 3.9** is a graph which came out from the Matlab Simulink software. The graph show about the vertical acceleration motion and roll dynamic of utility truck. The input for this graph is step.

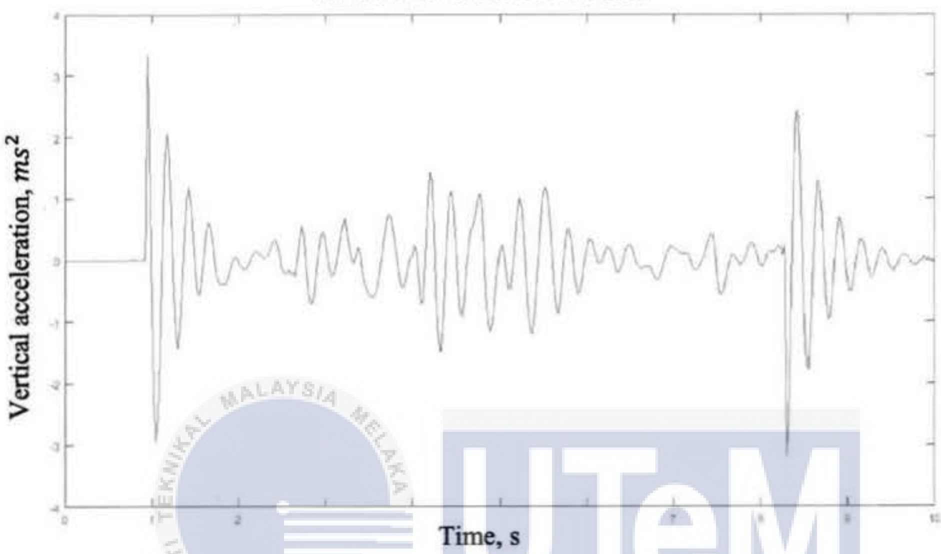

Figure 3.8: Graph of Vertical acceleration versus time

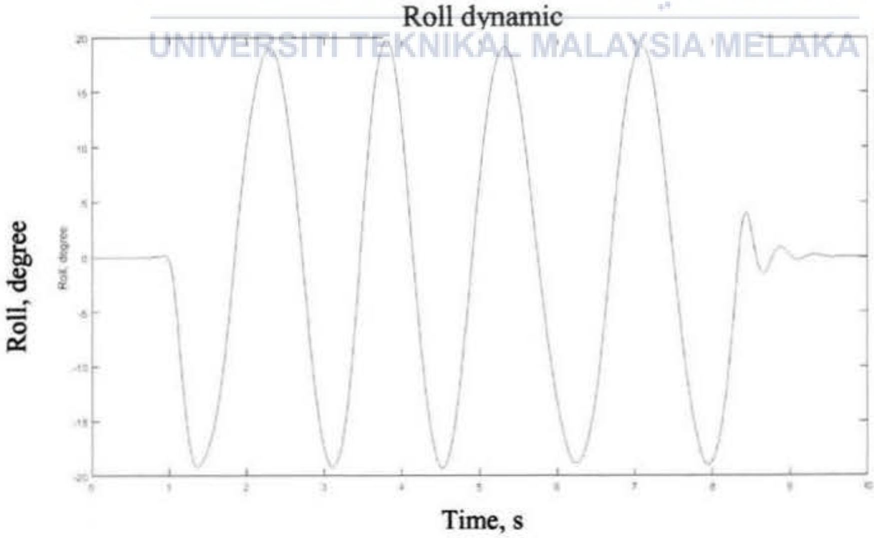

Figure 3.9: Graph of Roll versus time

3.3.2 Validation of 4 DOF Using Carsim

The 4 DOF of the vehicle on the road will be validated with the carsim for drive and hit a bump at 10 km/h. Input parameter are determined and will put to the 4 DOF ride model. All the vehicle parameter including height of COG, wheelbase, mass of the vehicle, pitch, roll, and yaw inertia.

3.3.3 Verification of vehicle dynamic modelling

Matlab/Simulink and Carsim is the two software which both of them can plot the graph of the vehicle such as vertical acceleration of the vehicle, ground elevation, vehicle roll and so on. Then, we can compare the graph from Simulink and from Carsim. We need to use Matlab coding to make sure MATLAB and Carsim graph combine become one graph.

Based on **Figure 3.10** and **Figure 3.11**, the graph is about the roll dynamic and vertical acceleration in 4 degrees of freedom are similarly the graph in Carsim simulation. The shape is same but the magnitude is difference is may be cause to the compliance effect in the suspension.

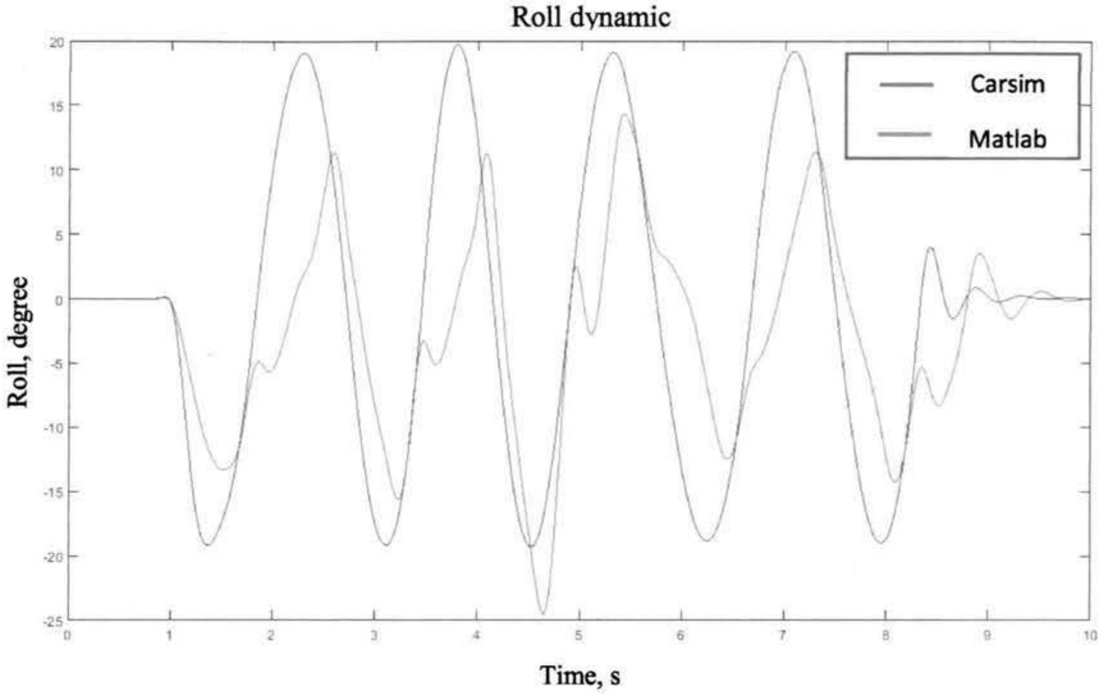

Figure 3.10: Roll dynamic verification with Carsim

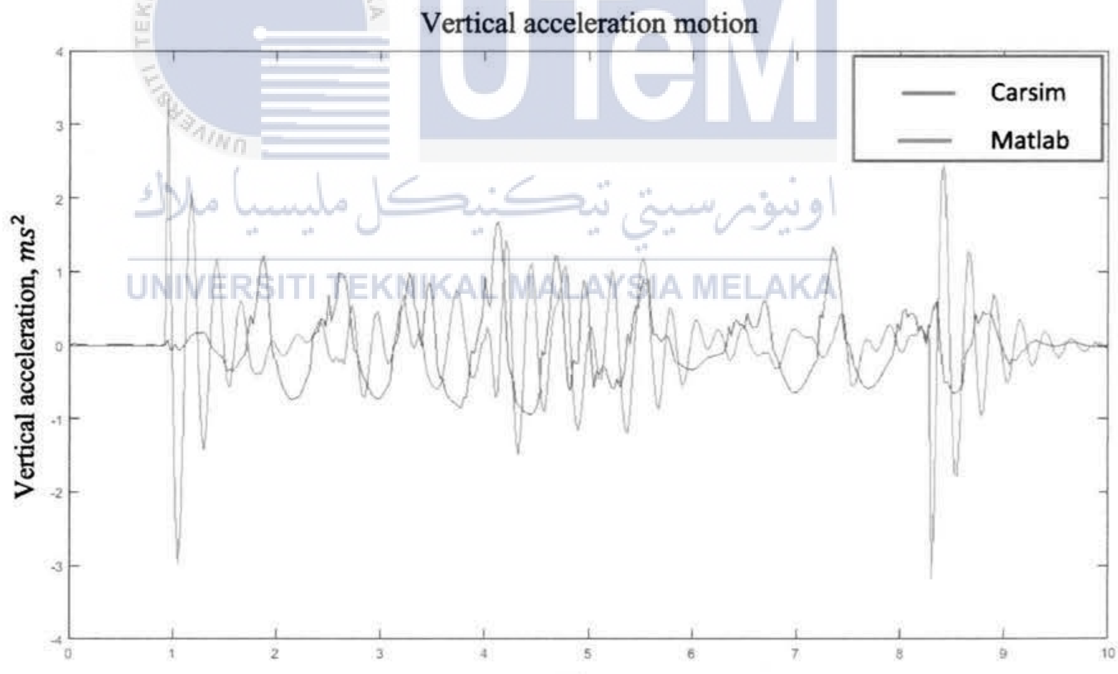

Figure 3.11: Vertical acceleration verification with Carsim

3.4 Modeling of Active suspension system

Half cars roll plane model (4DOF)

Equation 1:

$$\sum F_b = M_b\ddot{Z}_b$$

$$F_{sl} + F_{al} + F_{sr} + F_{ar} = M_b\ddot{Z}_b$$

$$K_{sl}\,(Z_{wl} - Z_b + \tfrac{T_w}{2}\theta\,) + F_{al} + K_{sr}(Z_{wr} - Z_b - \tfrac{T_w}{2}\theta\,) + F_{ar} = M_b\ddot{Z}_b$$

(3.13)

Equation 2:

$$\sum M_r = I_r\ddot{\theta}$$

$$\left[K_{sr}\left(Z_{wr} - Z_b - \tfrac{T_w}{2}\theta\right) + F_{ar}\right]\tfrac{T_w}{2} - \left[(K_{sl}\left(Z_{wl} - Z_b - \tfrac{T_w}{2}\theta\right) + F_{al}\right]\tfrac{T_w}{2} = I_r\ddot{\theta}$$

(3.14)

Equation 3:

$$\sum F_{wl} = M_{wl}\ddot{Z}_{wl}$$

$$K_{tl}(Z_{rl} - Z_{wl}) - (K_{sl}\left(Z_{wl} - Z_b + \tfrac{T_w}{2}\theta\right) - F_{al} = M_{wl}\ddot{Z}_{wl}$$

(3.15)

Equation 4:

$$\sum F_{wr} = M_{wr}\ddot{Z}_{wr}$$

$$K_{tr}(Z_{rr} - Z_{wr}) - K_{sr}\left(Z_{wr} - Z_b - \tfrac{T_w}{2}\theta\right) - F_{ar} = M_{wr}\ddot{Z}_{wr}$$

(3.16)

3.4.1 Selecting the vehicles

For this research, we need to find suspension system which suitable and can decrease the rollover of vehicles to achieve the objective. So, we decide to choose the sport utility truck as our vehicle to test in this simulation system. There are 3 vehicles have been choosing in this simulation test which is Large European Van, Pickup, and SUV. All these 3 vehicles categorized as sport utility vehicles. All of this vehicle shown in **Figure 3.12**, **Figure 3.13**, and **Figure 3.14**.

Figure 3.12: Large European in Carsim

Figure 3.13: Pickup in Carsim

Figure 3.14: SUV vehicle

3.4.2 Modelling Passive suspension and Active suspension

Figure 3.15 shows the modelling of passive and control suspension system in Matlab software. This modelling of two different suspension systems will produce roll motion, vertical acceleration, and vertical displacement graph output.

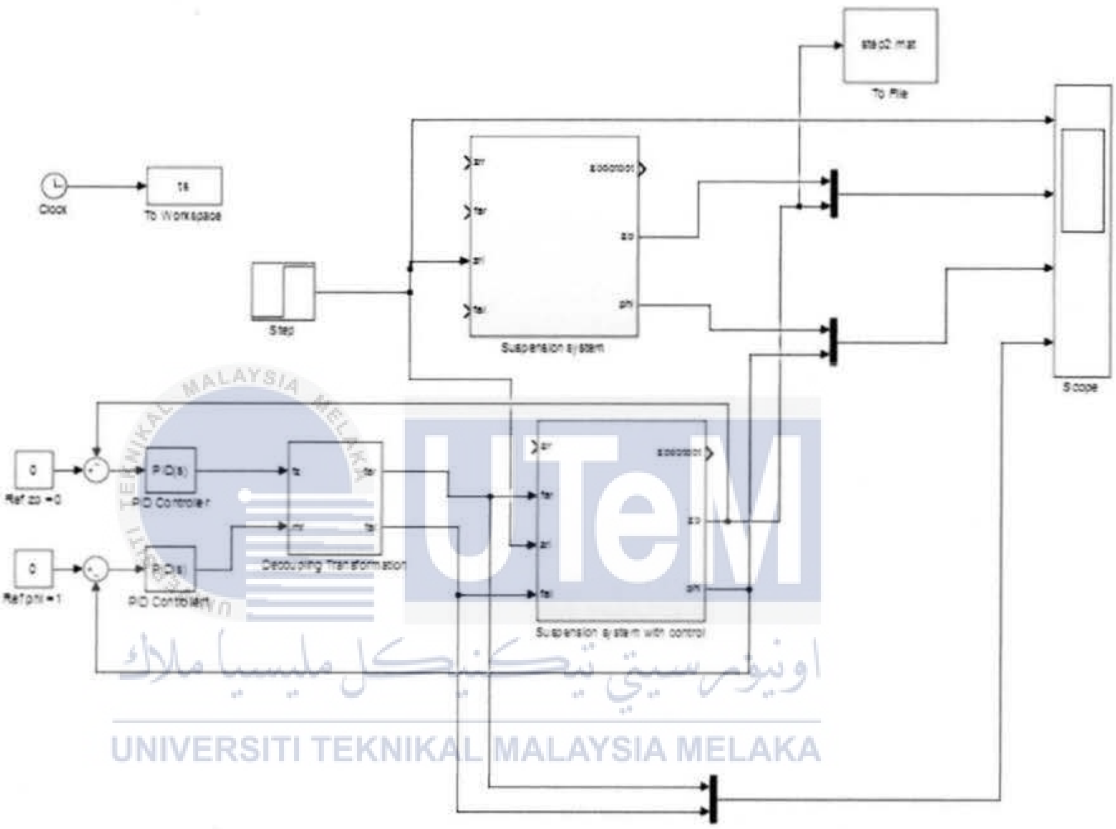

Figure 3.15: Modelling of passive and control suspension system

3.4.3 Road Surface Input and System Response

There are two suspension system that we used in this Matlab software which is passive and active suspension. Passive suspension system includes 3 basic elements which is element (masses), dampers and spring. Passive suspension system is passive during hit the disturbance on the road which is no external to control the system. Active suspension system also have basic elements of passive suspension system but there is elements added naming as actuator which to control the suspension system during the response of road surface. PID controller also used as stabilizes and performing the handling on the ride of vehicles.

3.4.4 Road profile description

There are many input can we put in our modelling system to test the rollover of vehicles such as sinusoidal input or ramp input. This road profile depends on our way to test the vehicle along the ride. For this research, we put step and pulse generator as our responsive system, it is because we easily to test and differentiate the vehicles roll motion and vertical displacement after response the input. For step input, the step time we use for the vehicle hits the disturbance is 0.5m while the amplitude for pulse generator is 0.1m with the 5 periods. **Figure 3.16** and **Figure 3.17** shows the road profile 1 and road profile 2 that we used as simulation in Matlab Software.

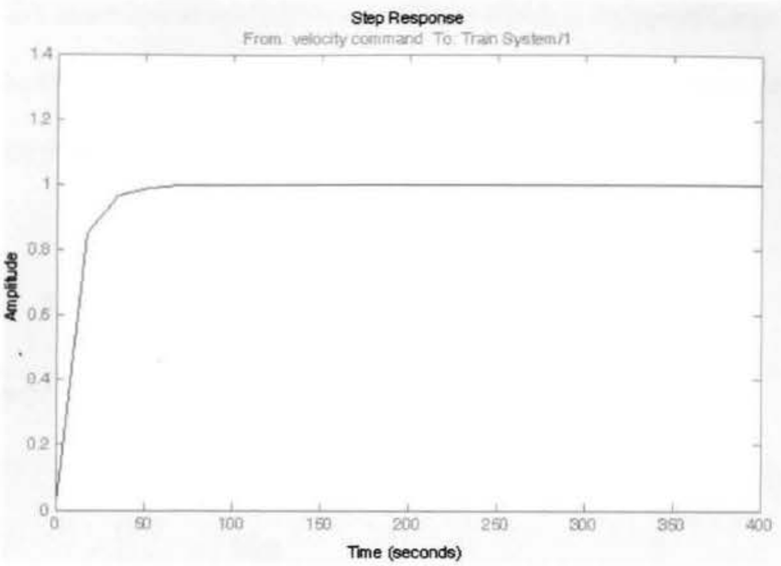

Figure 3.16: Road Profile 1

Figure 3.17: Road Profile2

This **Table 2** is a parameter about 3 different vehicles which is European Large Van, Pickup, and SUV. All of this vehicle will be running into Matlab software to compare the result of passive and active suspension system.

Table 2: Parameter of 3 different sport of sport utility truck

Parameter	**Value**		
	European Large Van	**Pickup Truck**	**SUV**
C_{sl}	50000	5000	50000
C_{sr}	50000	5000	50000
iphi	486.2	846.6	846.6
k_{sl}	198000	198000	189000
k_{sr}	198000	198000	189000
m_b	2100	1998	2257
m_{wl}	150	120	125
m_{wr}	150	120	125
k_{tl}	250000	250000	250000
k_{tr}	250000	250000	250000
t	1.2	1.2	1.2

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will present the result of simulation that was carried out from Matlab Software. The previous chapter are discussed and modelling system about rollover of sport utility truck. From the modelling. Matlab software can produce vertical acceleration vs time and Roll vs time graph. We also make a verification of vehicle using Matlab and Carsim to make sure our graph is valid because to make sure our modelling is good to use. So from the previous graph, we can see the graph of roll motion and vertical acceleration are increase and we modelling active suspension system to decrease the rollover of the vehicle and to achieve the better handling, safety, and comfort of driver.

4.2 Results

4.2.1 Analysis of Passive Suspension System

These Graph in **Figure 4.1, 4.2, 4.3**, and **4.4** are shows the graph about 3 different sport utility truck which is test in modelling of passive suspension. There are two different road profile test for these 3 vehicles which is step and pulse generator input. This passive suspension simulation will test to carried out graph vertical displacement and roll motion of vehicles. For the graph in **Figure 4.1**, its shows that the vertical displacement for pickup vehicle have the highest amplitude compare than European large van then followed by SUV. Graph roll **Figure 4.2** also shows that pickup vehicles have the highest and longest roll motion compare than European large van and SUV.

Figure 4.3 and **4.4** are used pulse generator as their road profile. The result for the vertical displacement for these 3 sport utility truck shows that Pickup vehicle get the highest amplitude compared than European large van then followed by SUV. For the graph roll at **Figure 4.4**, the result also shows that Pickup vehicles have the highest roll motion and take much time to decrease the roll motion. At the same time, the roll motion graph for European large van is quite similar to SUV vehicles.

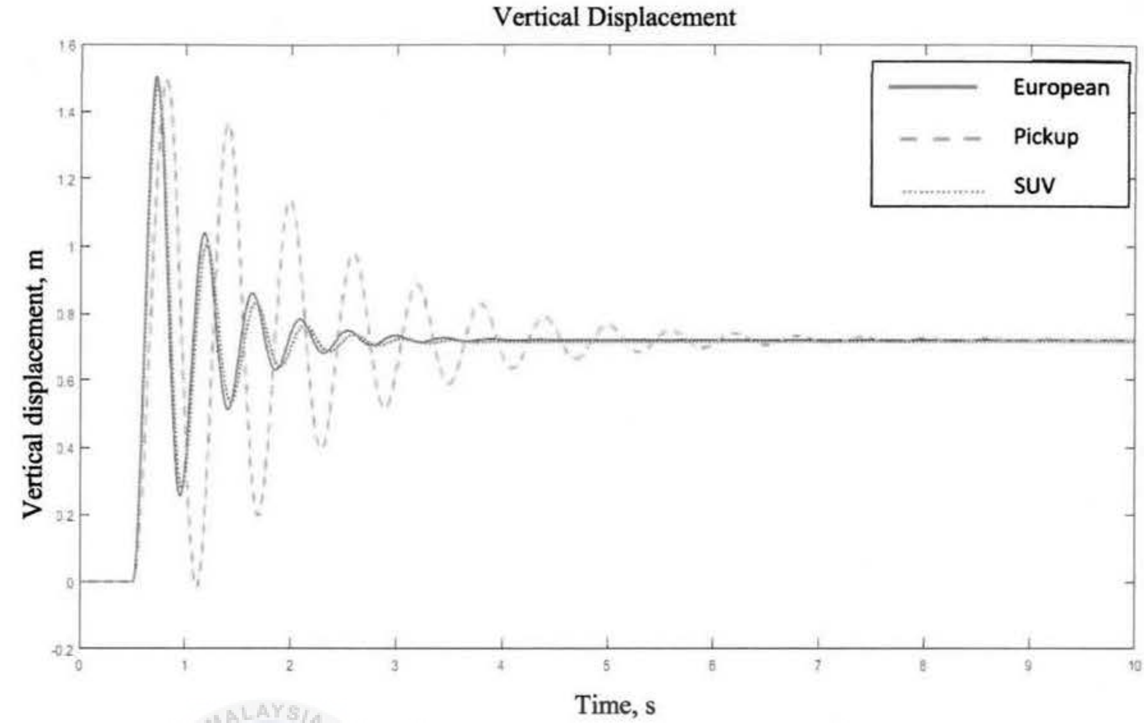

Figure 4.1: Vertical displacement versus time with Road Profile 1

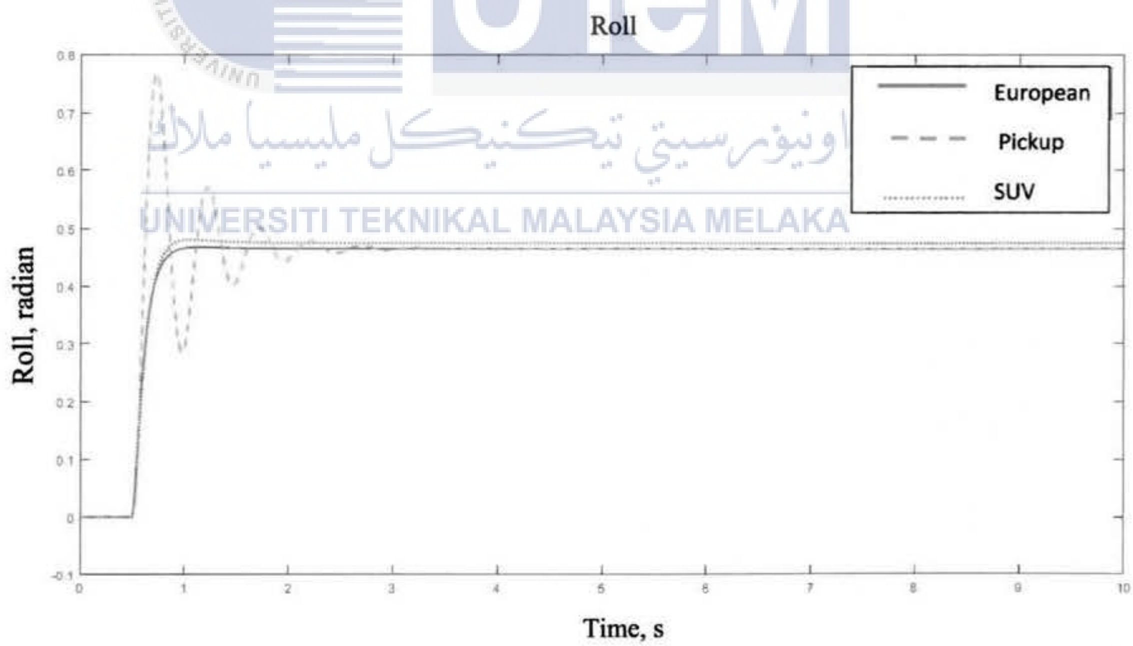

Figure 4.2: Roll versus time with Road Profile 1

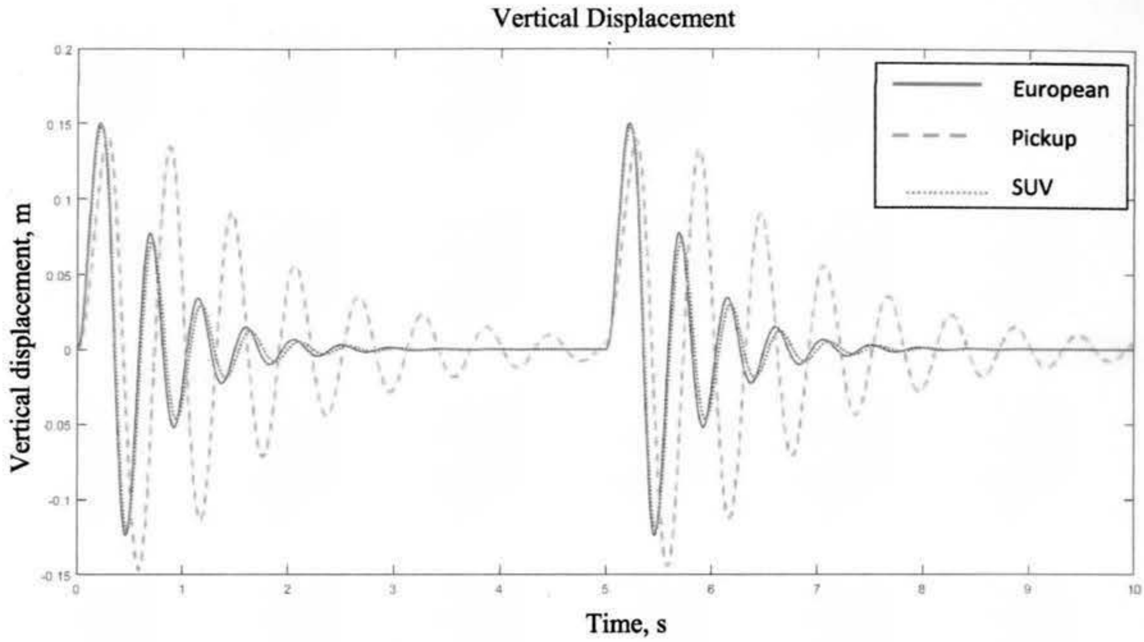

Figure 4.3: Vertical displacement versus time with Profile Road 2

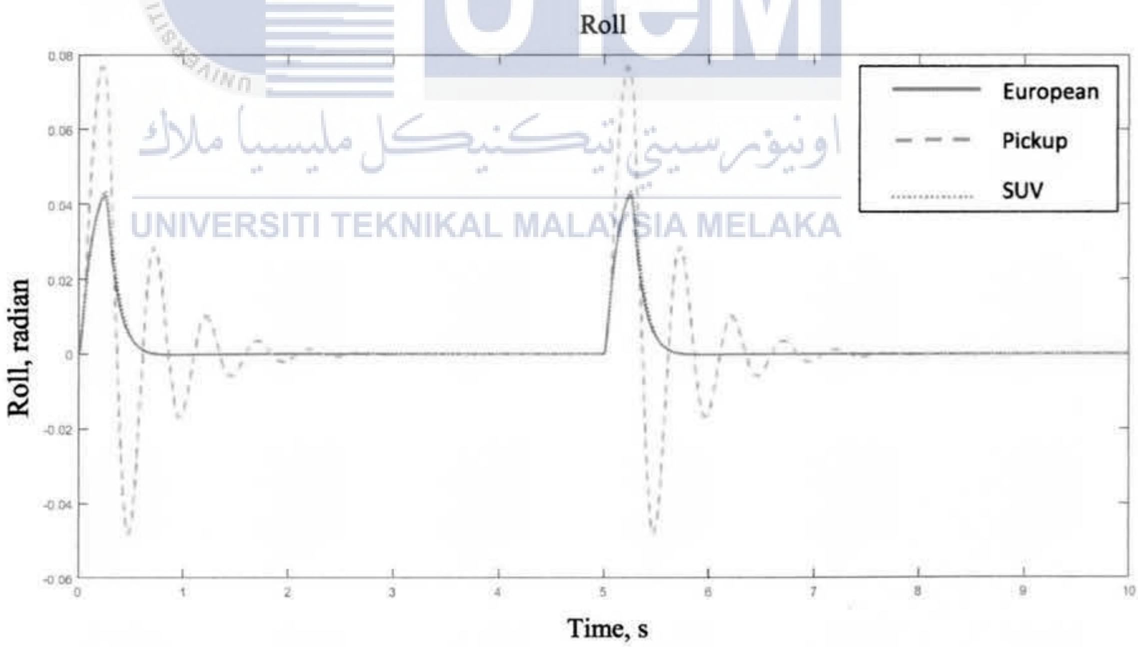

Figure 4.4: Roll versus time with Profile Road 2

4.2.2 Analysis of Control Suspension System

Figure 4.5, 4.6, 4.7, and **4.8** are graph about vertical displacement and roll motion of sport utility vehicles which is test with control suspension system. We are test the same vehicles at control suspension system simulation and the results is good compare than test with passive suspension. We can see at **Figure 4.5**, vertical displacement of these 3 vehicles is slightly lower than graph vertical displacement in **Figure 4.3**. Pickup vehicles have a highest amplitude in **Figure 4.5** more than European large van and lastly followed by SUV. For the graph roll in **Figure 4.6**, pickup vehicles also have the highest amplitude and the roll motion is not smooth like European large van and SUV. There are not much different between SUV and European in graph roll motion.

For graph in **Figure 4.7** and **4.8**, the road profile is pulse generator and its test for vertical displacement and roll of vehicles. As result before, pickup vehicles lead as the highest amplitude of the vertical displacement more than European large van and SUV. For the graph roll motion in **Figure 4.8**, the highest amplitude and have longest roll motion is also a pickup. Roll motion of European large van and SUV roll is quite similar between each other.

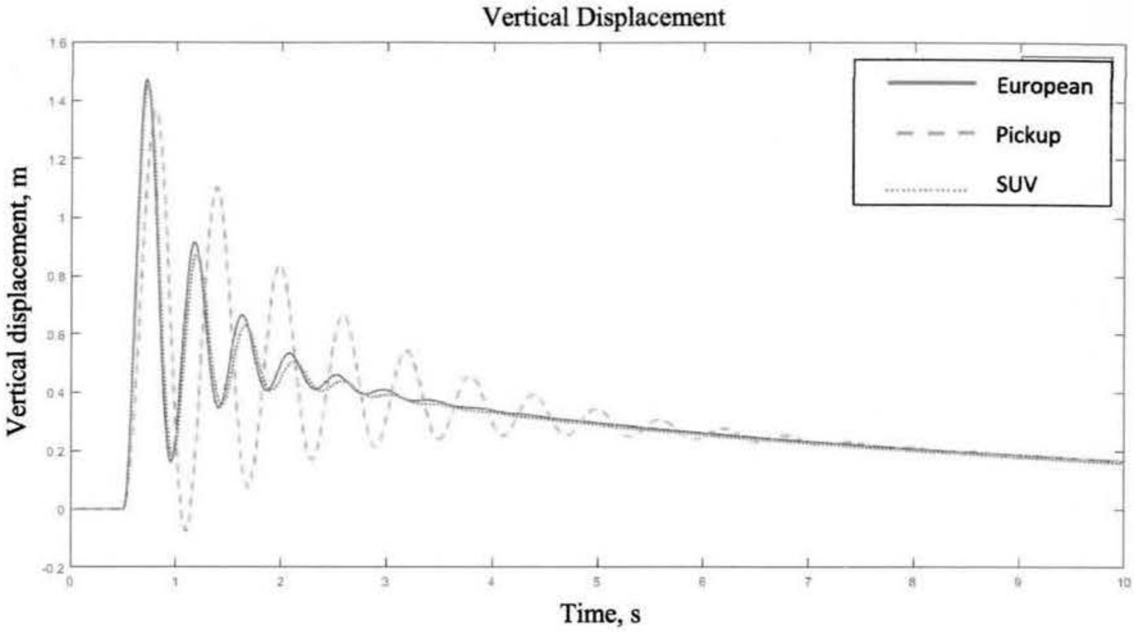

Figure 4.5: Vertical displacement versus time with Profile Road 1

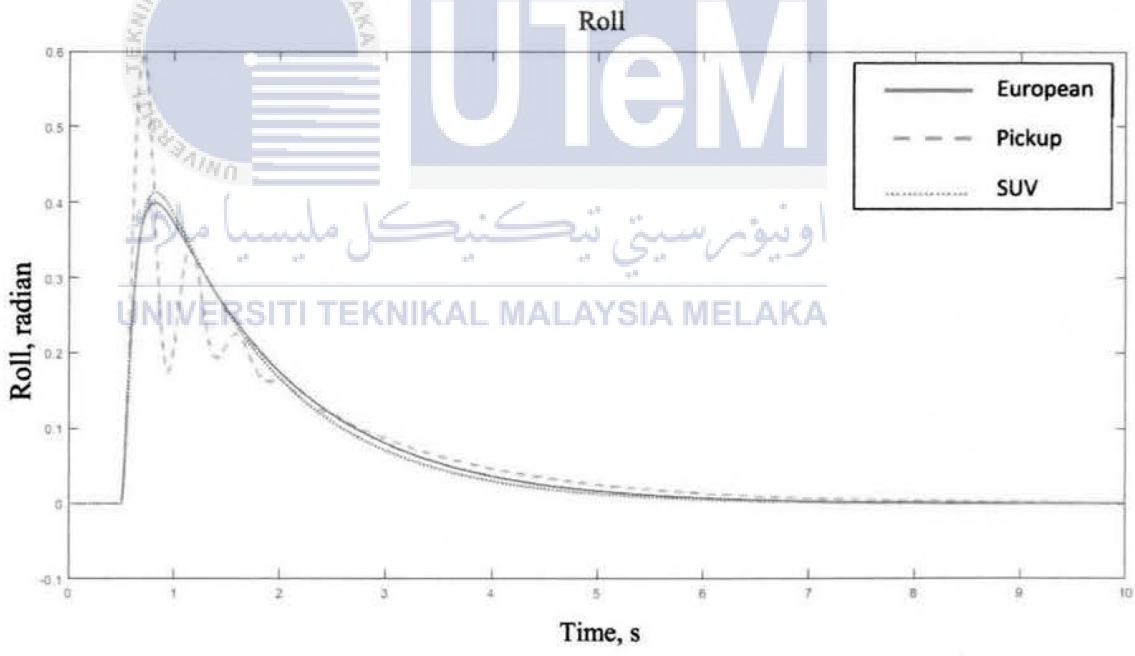

Figure 4.6: Roll versus time with Profile Road 1

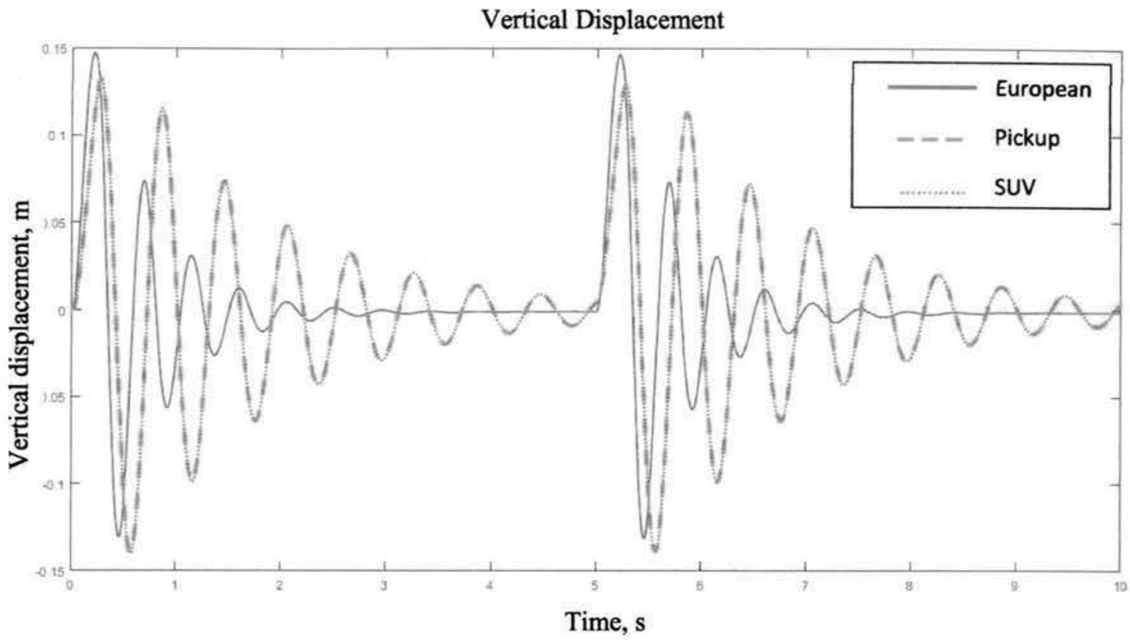

Figure 4.7: Vertical displacement versus time with Road Profile 2

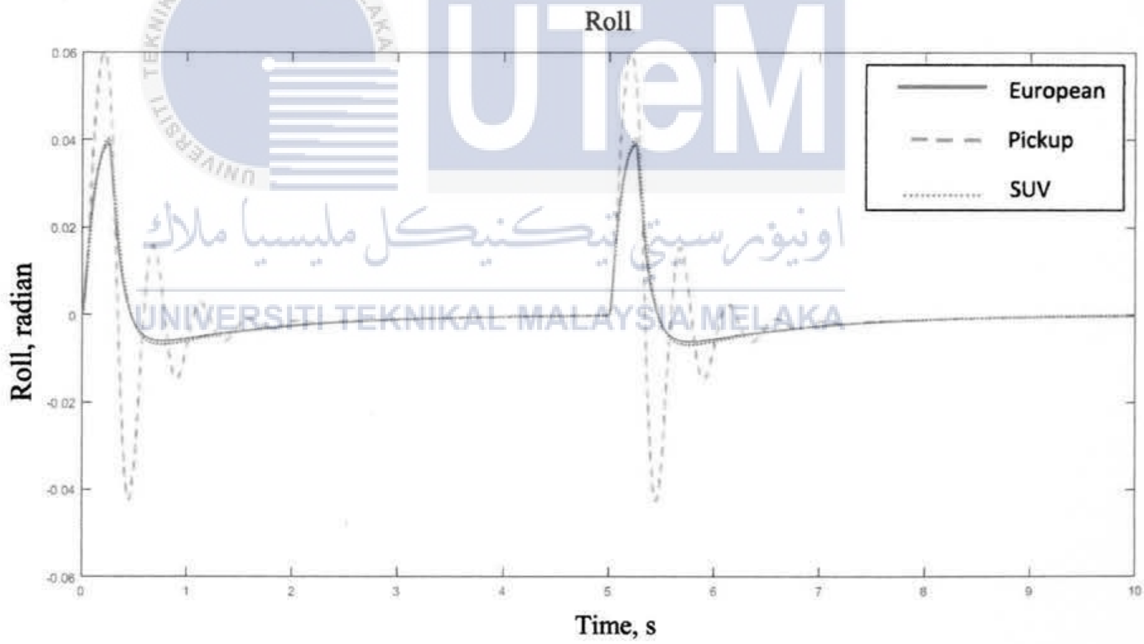

Figure 4.8: Roll versus time with Road Profile 2

4.2.3 Analysis of Passive vs Control Suspension System (European Large Van)

Figure 4.9, 4.10, 4.11, and **4.12** are graph which we test European large van vehicles only into the simulation of passive and control suspension system. The road profile still same as before which is step and pulse generator. **Figure 4.9** shows that the European large van have the highest amplitude with passive suspension while control suspension make the vertical displacement become decrease till the end of graph. For the graph roll **in Figure 4.10**, the graph shows that passive suspension also get the highest amplitude and not wave compare than active suspension system which the amplitude is little lower.

For the **Figure 4.11** and **4.12**, the graph shows that the road profile test in this simulation is pulse generator and the vehicles test for graph vertical displacement and roll motion. Graph in **Figure 4.11** shows that the vertical displacement for passive and control suspension is not much different which is the amplitude is close each other until the end of the time. However, vertical displacement for passive suspension is higher more than active suspension. For the graph in **Figure 4.12**, the amplitude of passive and control suspension also close each other but passive is higher more than control suspension. The roll motion for control suspension is a little bit wave compare than passive suspension.

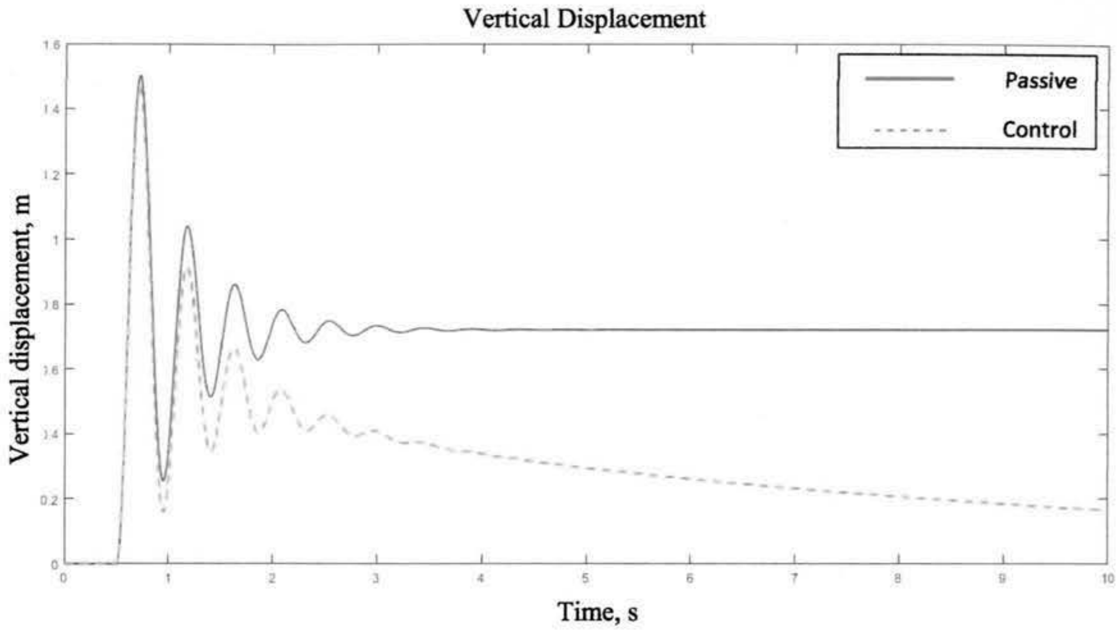

Figure 4.9: Vertical displacement versus time with Road Profile 1

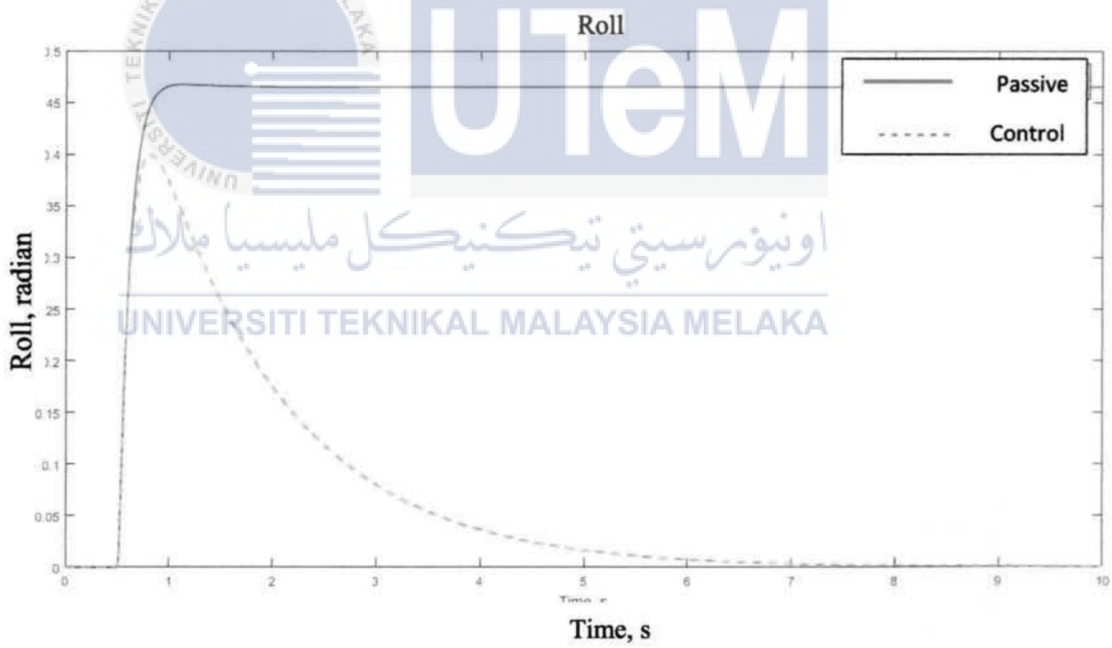

Figure 4.10: Roll versus time with Road Profile 1

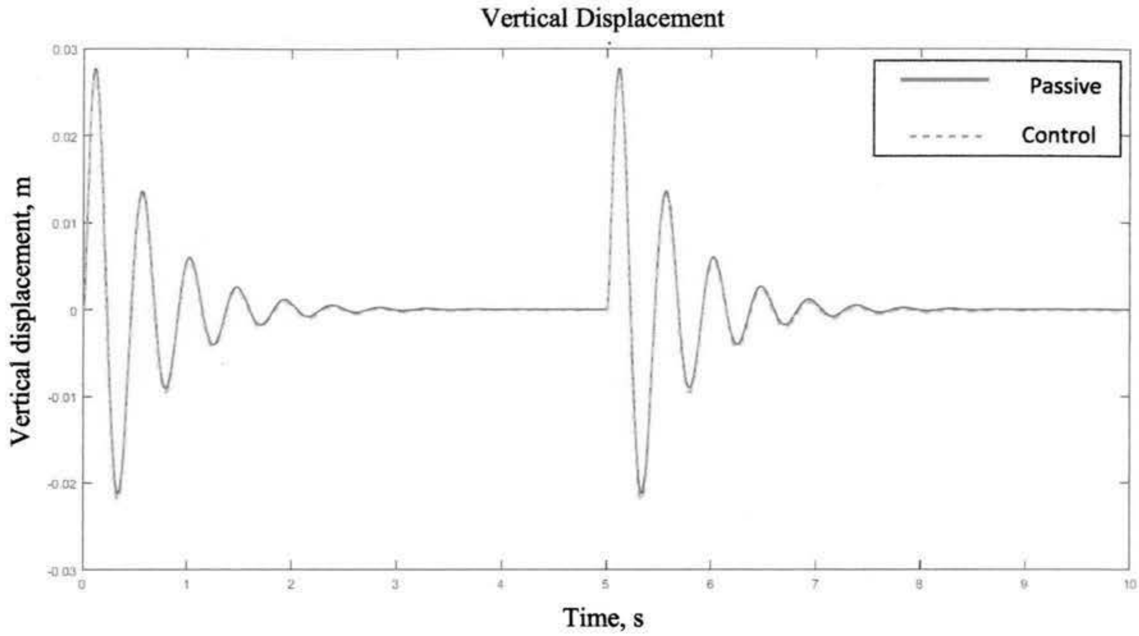

Figure 4.11: Vertical displacement versus time with Road Profile 2

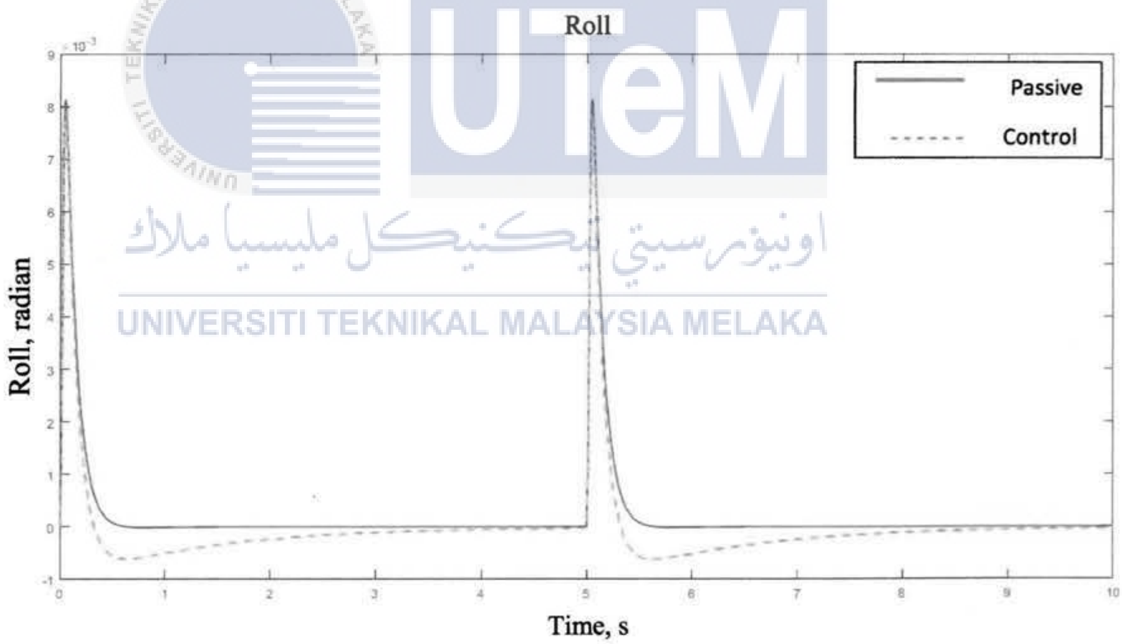

Figure 4.12: Roll versus time with Road Profile 2

4.2.4 Analysis of Passive vs Control Suspension System (Pickup)

Figure 4.13, 4.14, 4.15, and **4.16** are graph which we test for Pickup full size vehicles only into the simulation of passive and control suspension system. The road profile use for this simulation still same which is step and pulse generator. **Figure 4.13** shows that Pickup truck have the highest amplitude when it simulation on passive suspension while the vertical displacement is lower when it simulation on control suspension. For the graph roll in **Figure 4.14,** the graph shows that a lot of different between control and passive suspension which is the amplitude of passive is much highest more than control suspension. The movement of roll motion for control suspension also only a little wave and fast stop compare than passive suspension.

For the **Figure 4.15** and **4.16**, the graph shows that the road profile test in this simulation is pulse generator and this pickup test for vertical displacement and roll motion graph. Graph in **Figure 4.15** shows that the amplitude for vertical displacement on passive suspension is higher more than control suspension. For the graph roll in **Figure 4.16**, the result shows the higher amplitude and the higher roll motion is on the passive suspension. Control suspension simulation shows the pickup has the lower amplitude and the roll motion wave is fast back to original position compare than passive suspension.

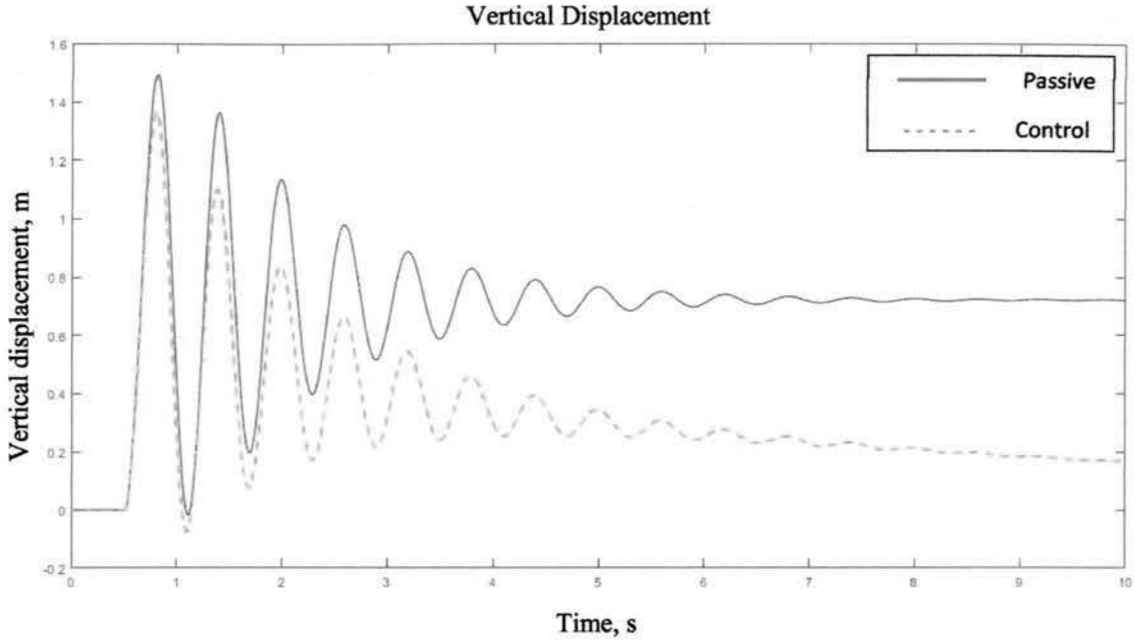

Figure 4.13: Vertical displacement versus time with Road Profile

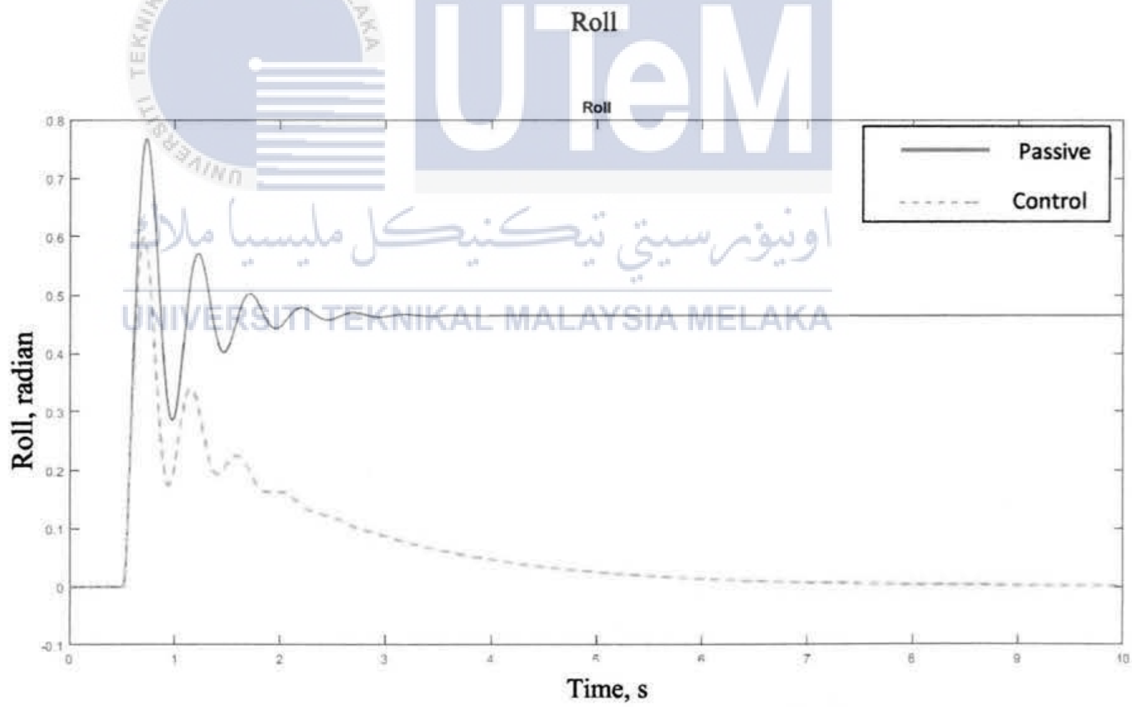

Figure 4.14: Roll versus time with Road Profile 1

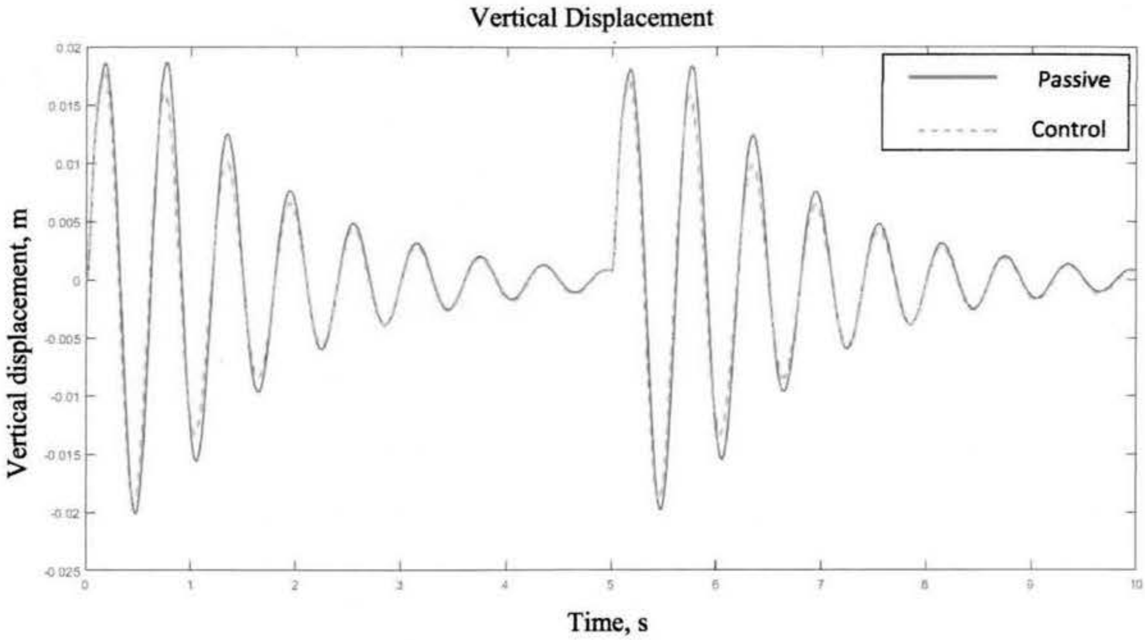

Figure 4.15: Vertical displacement versus time with Profile 2

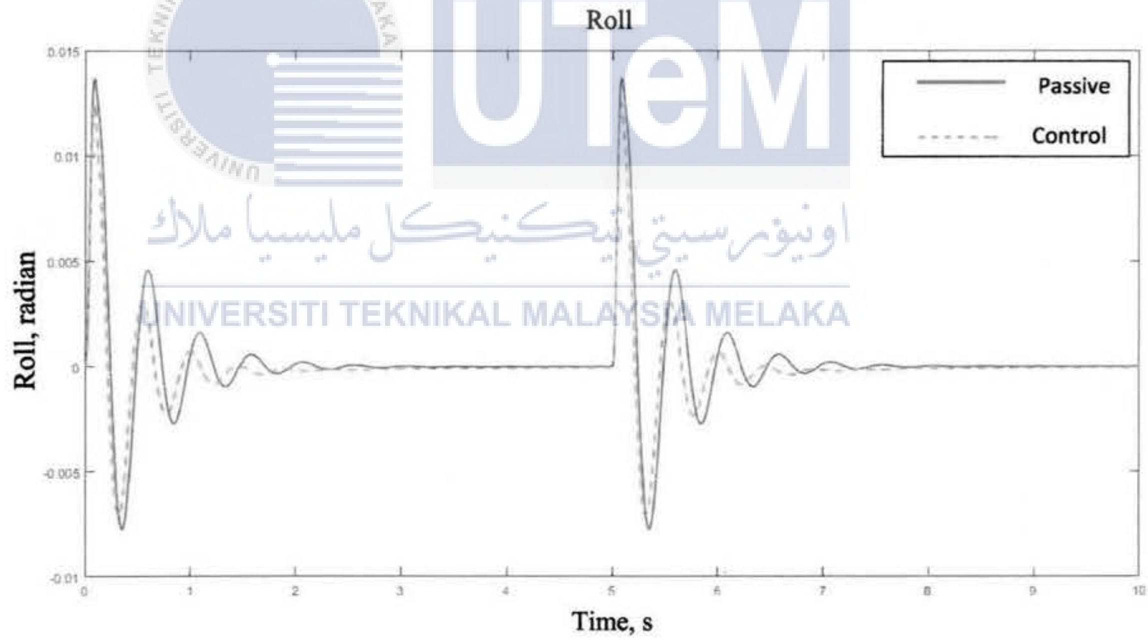

Figure 4.16: Roll versus time with Profile 2

4.2.4 Analysis of Passive vs Control Suspension System (SUV)

Figure 4.17, 4.18, 4.19, and **4.20** are graph which we test SUV vehicles into the simulation of passive and control suspension system. The road profile still same as before which is step and pulse generator. **Figure 4.17** shows that the SUV have the highest amplitude on passive suspension while control suspension make the vertical displacement become decrease till the end of graph. For the graph roll in **Figure 4.18**, the graph shows that passive suspension also get the highest amplitude and not wave compare than active suspension system which the amplitude is little lower than passive suspension.

For the **Figure 4.19** and **4.20**, the graph shows that the road profile test in this simulation is pulse generator and the vehicles test for vertical displacement and roll motion graph. The graph in **Figure 4.19** shows that the vertical displacement for passive and control suspension is not much different which is the amplitude is close each other until the end of the time. However, vertical displacement for passive suspension is higher more than active suspension. For the graph in **Figure 4.20**, the amplitude of passive and control suspension also close each other but passive is higher more than control suspension. The roll motion for control suspension is a little bit wave compare than passive suspension.

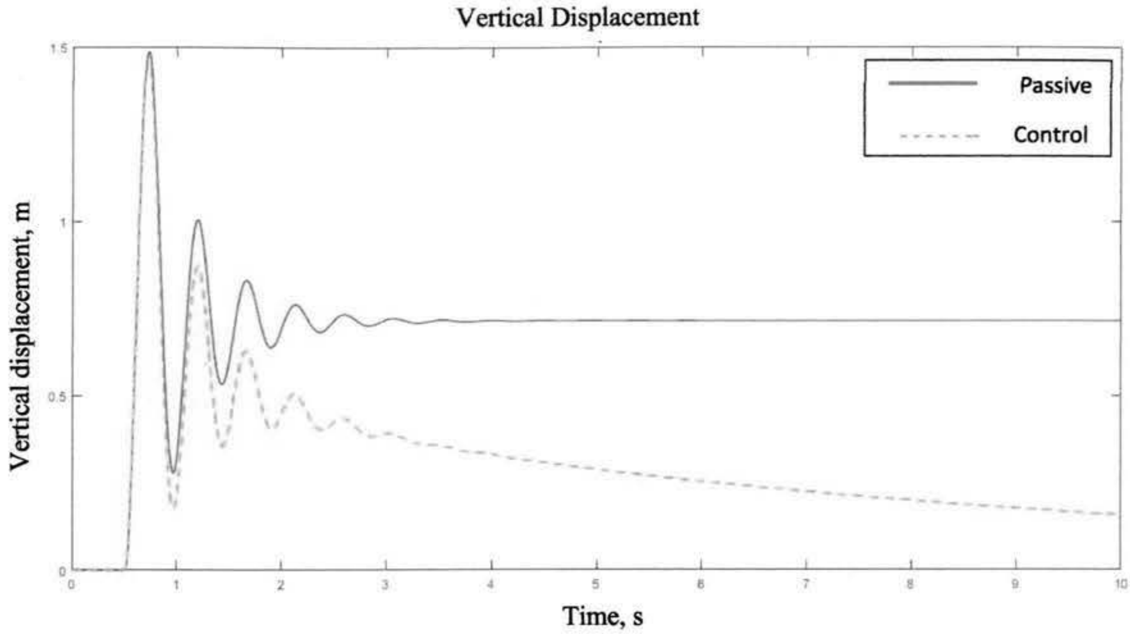

Figure 4.17: Vertical displacement versus time with Profile Road 1

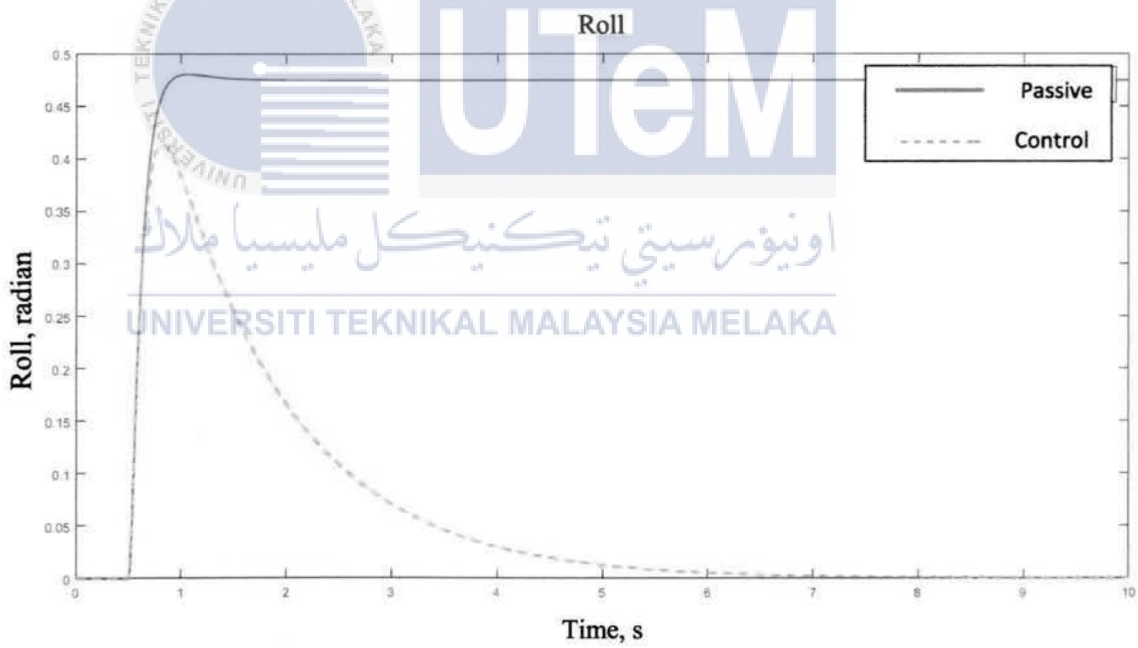

Figure 4.18: Roll versus time with Profile Road 1

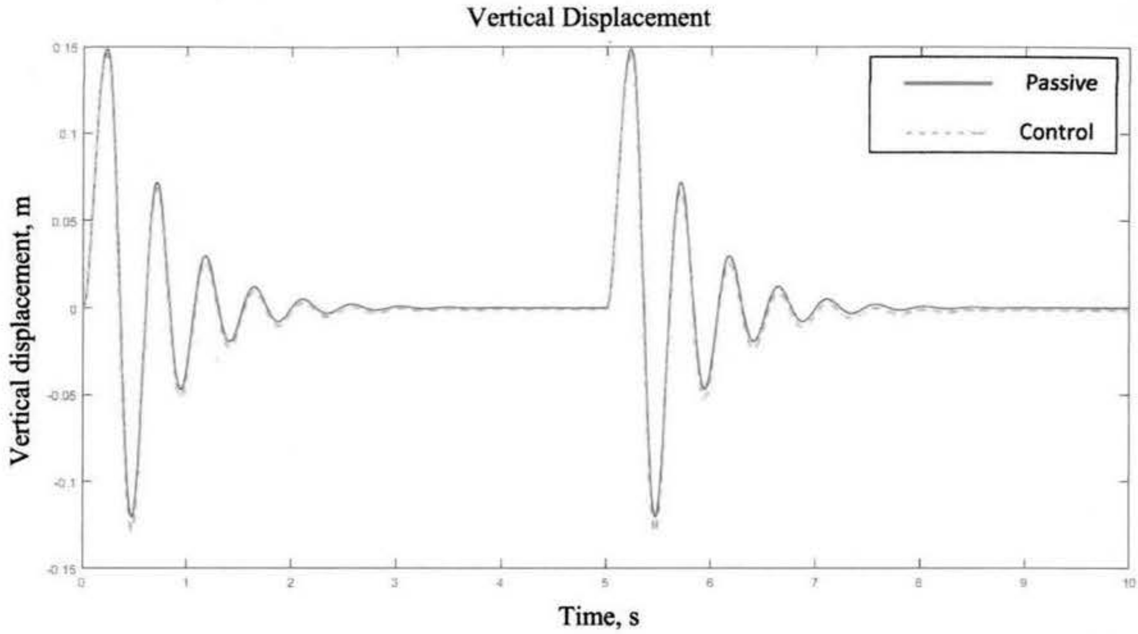

Figure 4.19: Vertical displacement versus time with Profile Road

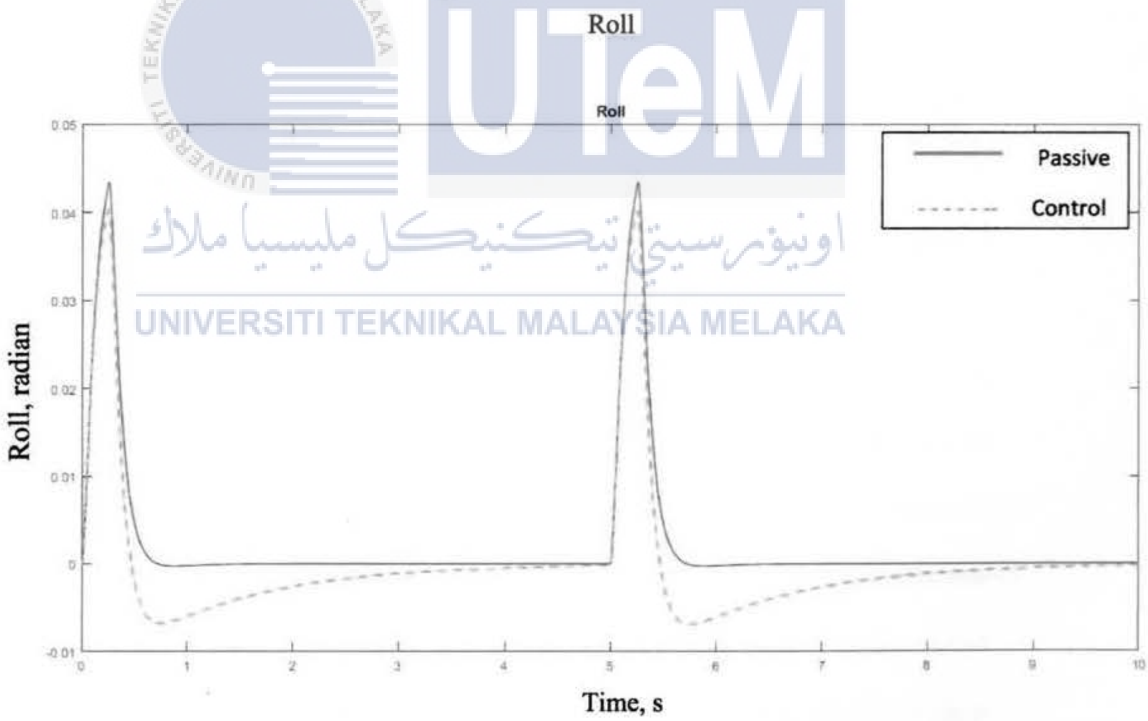

Figure 4.20: Roll versus time with Profile Road 2

4.3 Discussion

This chapter has described on output performance for active and passive suspensions system. There are 3 sport utility vehicles have been test in this research which all of this vehicle have differents parameter such as mass body vehicle, stiffness of spring, damping, and so on. After modelling passive and active suspension system using Matlab software, we also need to decide the road surface input for these 3 vehicles and we choose step and pulse generator. It because we can see more differentiate of vertical displacement and roll motion by using these road profile as our input. From the all graph above, we can see the difference results when we test using passive and control suspension. The objective of control suspension use into this simulation is to decrease the vertical displacement and reduce the roll motion of the vehicle. With that, we can control and improve sport utility truck vehicles to the better handling, safety and comfort during on or off the road. So, among of these 3 sports vehicles, we can see that Pickup have the highest vertical displacement and roll motion on their suspension more than European large van then followed by SUV. These simulation shows that control suspension can reduce the amplitude of vertical displacement and roll motion of these 3 vehicles. The reasons pickup get the highest vertical displacement and not good in roll motion is it because the different parameter between these 3 vehicles such as mass body, stiffness of spring, damper of suspension. However, we can see the damper of spring in this suspension system is main affecting to the result of vertical displacement and roll motion of vehicle. We can see the damping suspension on pickup vehicle is the lowest compare than European large van and SUV. So, the graph show pickup get the highest vertical displacement and roll motion. It because function of damping is to absorb energy of impact and damp shock impulse. The higher energy of damper in suspension system will absorb some or all of the energy imparted to the suspension by a bump and reduced the rollover of vehicles. So, the higher energy of damping will influence to the reduce of roll motion and vertical displacement of vehicles. So, control suspension can reduce the rollover and vertical displacement of vehicle because actuator force and PID controller have added into passive suspension. Function of actuator force is to counterbalance the reaction force from the road and it control by the controller. Controller will calculate by add or dissipate energy from suspension system which the sensor will give the data based on road profile. Then, active suspension will improve the stability of the vehicle and reduce the rollover.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The methodology was developed to modelling suspension system which can control and improve sport utility truck vehicles to the better handling, safety, and comfort. This research also focuses about to avoid the vehicles from rollover during on or off the road. There are 3 suspension system in vehicle which is passive, semi active, and active suspension system. A 4 degree of freedom have been developed to stimulate the dynamic behaviour of the vehicle ride to the profile road. MATLAB and Carsim software have been used in this research to test and do the simulation of the vehicles. At first, to make sure the 4 DOF of Simulink simulation represent the real world of the vehicle, this 4 DOF was modelling and it was validated with the Carsim. The result is satisfaction and similar to Carsim software so we can use these models to study about the rollover of sport utility vehicle as the vehicle experience the vehicle dynamic behaviour. Three sport utility vehicles have been choosing in this research which is Pickup, European Large van, and SUV. These vehicles have their own parameter value such as the damper, stiffness spring, mass body, and so on. The parameter will differentiate the condition of vehicle after hit the disturbance. Two road profiles have been used in this simulation which is step and pulse generator so we can compare the result of these three vehicles. Active suspension is a good suspension system which its adding actuator force and PID controller. The force actuator is mechanical part that added inside the system that control by the controller. Controller will calculate either add or dissipate energy from the system, from the helps of sensor as input (Agharkakli et al., 2012). Active suspension use hydraulic or pneumatic actuator for additional energy. The potential to improved ride comfort and better road handling when using active suspension system is examined. The results of active and passive suspension system of the vehicle have been compared. As expected, the results proved that an active suspension system is the best method to control vehicle stability, rollover, and comfort.

5.2 RECOMMENDATION

Work study that has been done, on control suspension system on half car model. In this research, the actuator force and PID controller have been used to achieve the anti roll of the vehicles. However, we are not tuning the PID controller in this active suspension system. Tuning the PID controller is important so it give the real time performance. The percentage improvement also needed between passive and active suspension system to make the detail result. Modelling 7 DOF of vehicles into this simulation can obtained the real result and improve the mathematical model of suspension system include more details of full car.

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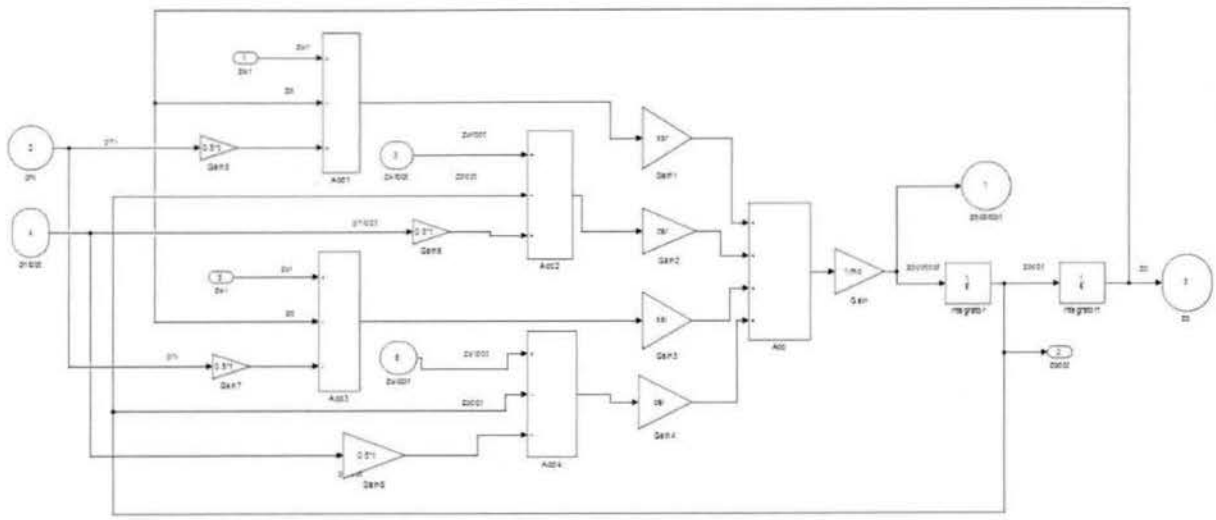
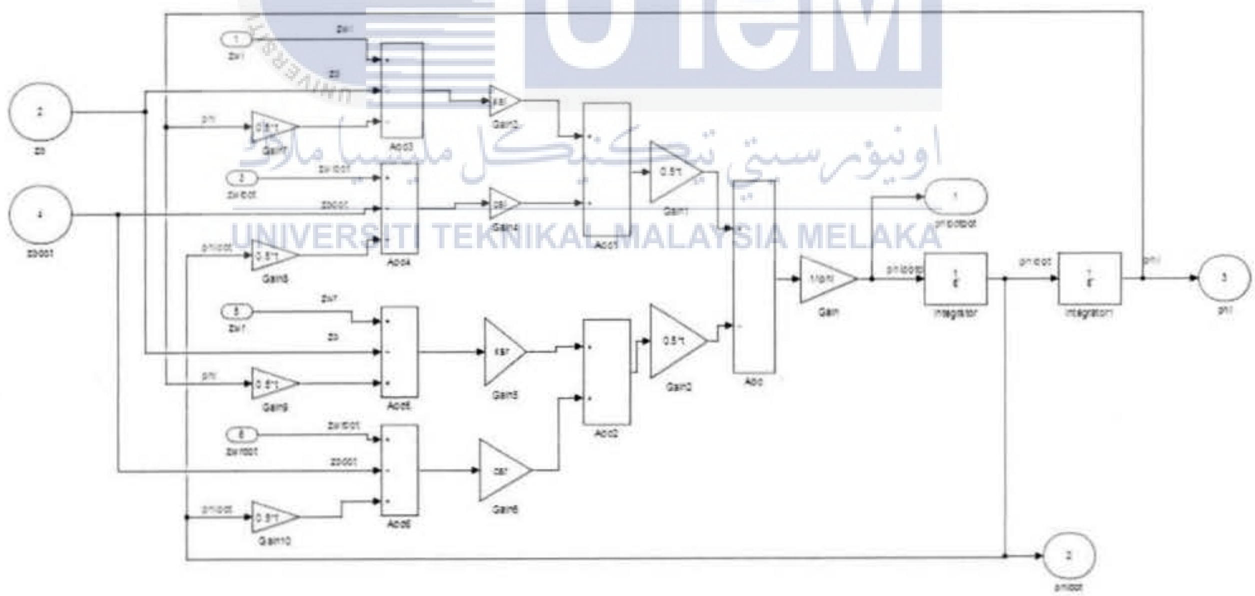
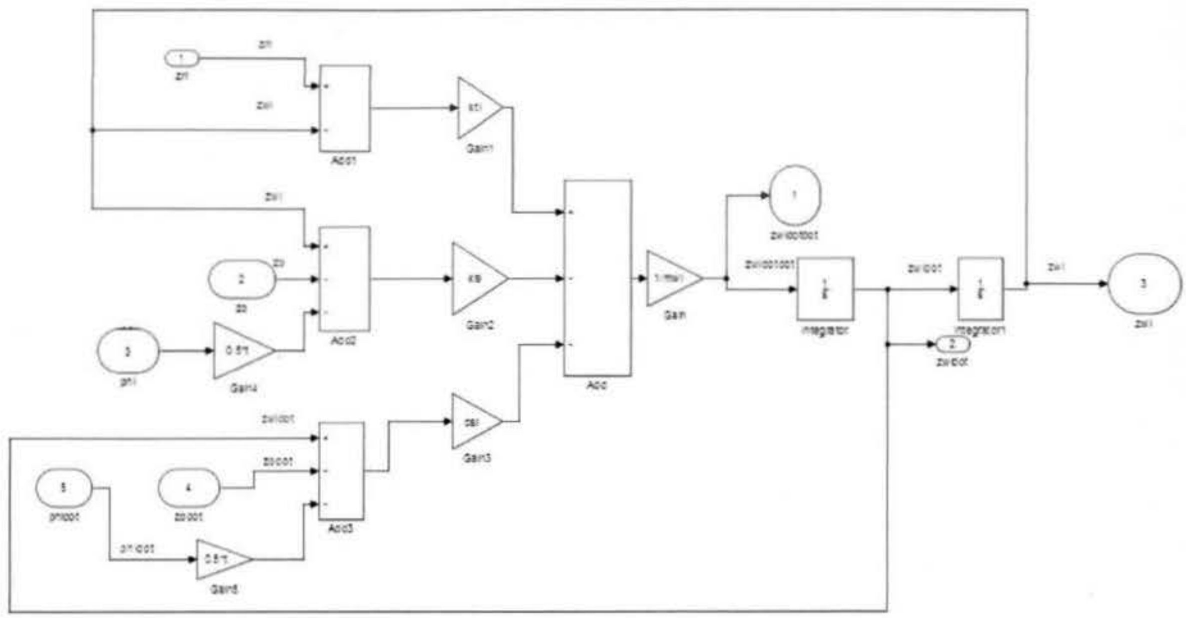
LIST OF APPENDICES



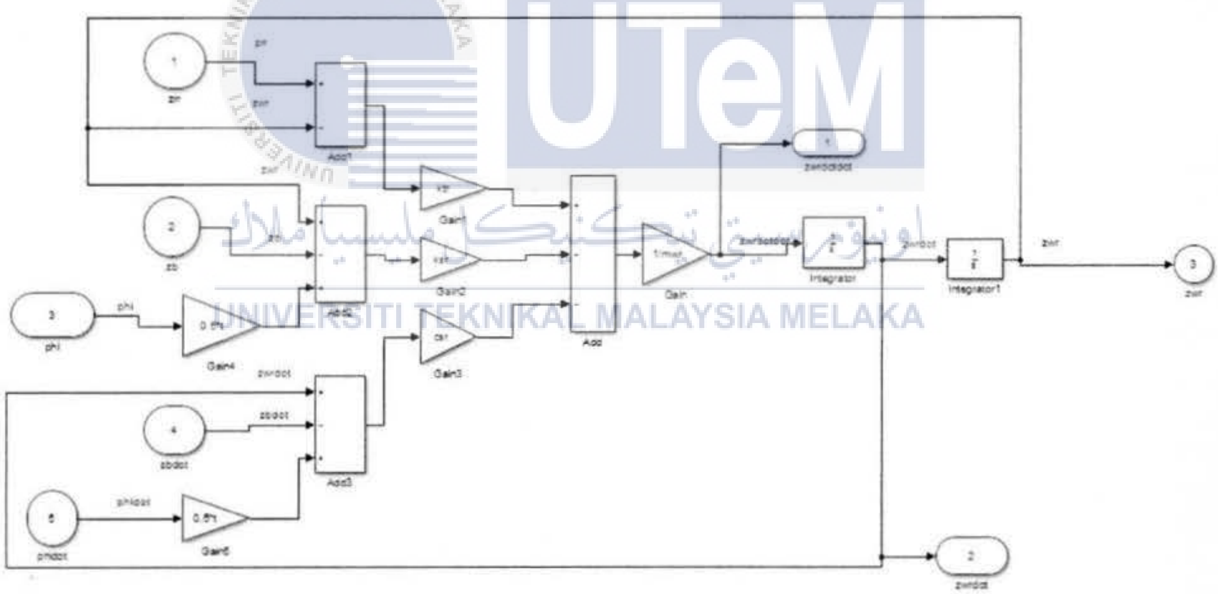
Appendix A: Subsystem 1 4dof



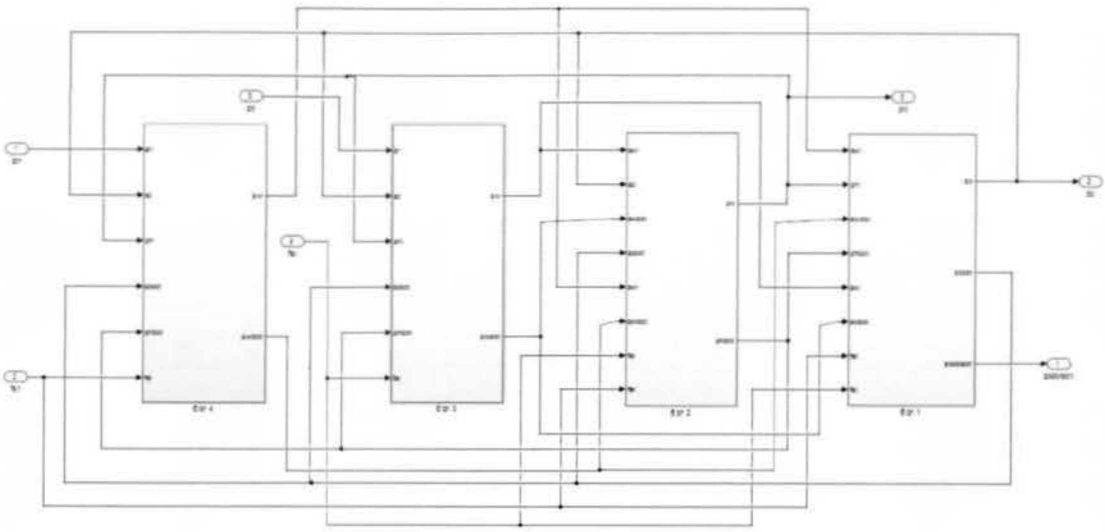
Appendix B: Subsystem 2 4dof



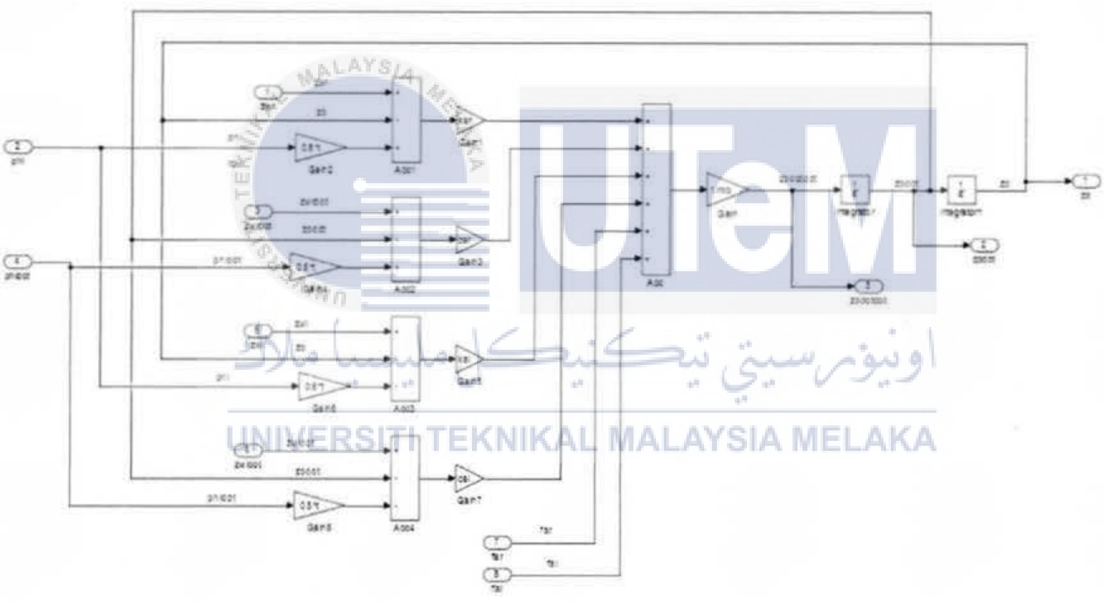
Appendix C: Subsystem 3 4dof



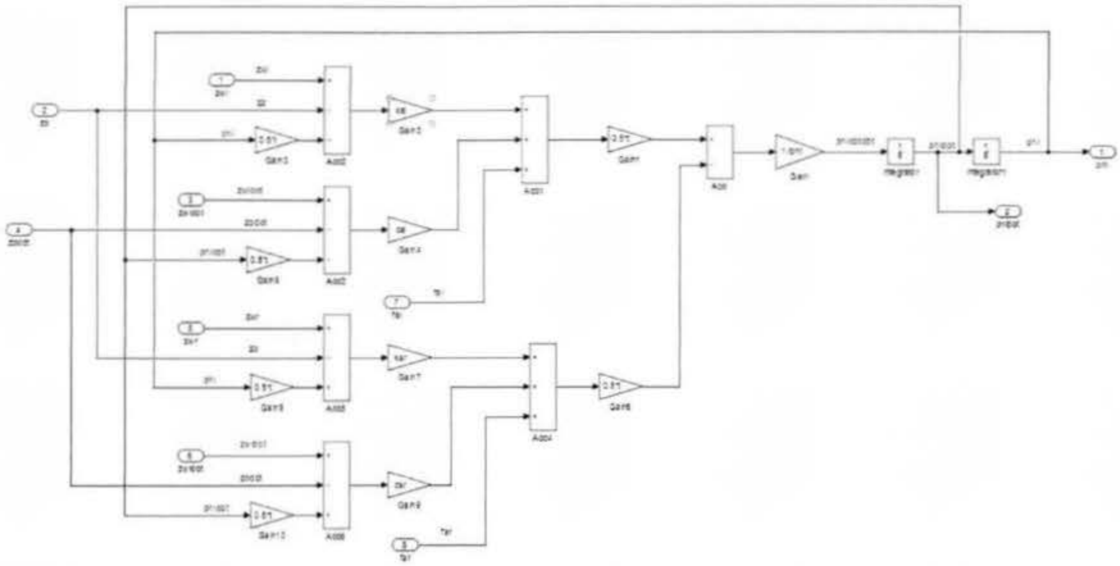
Appendix D: Subsystem 4 4dof



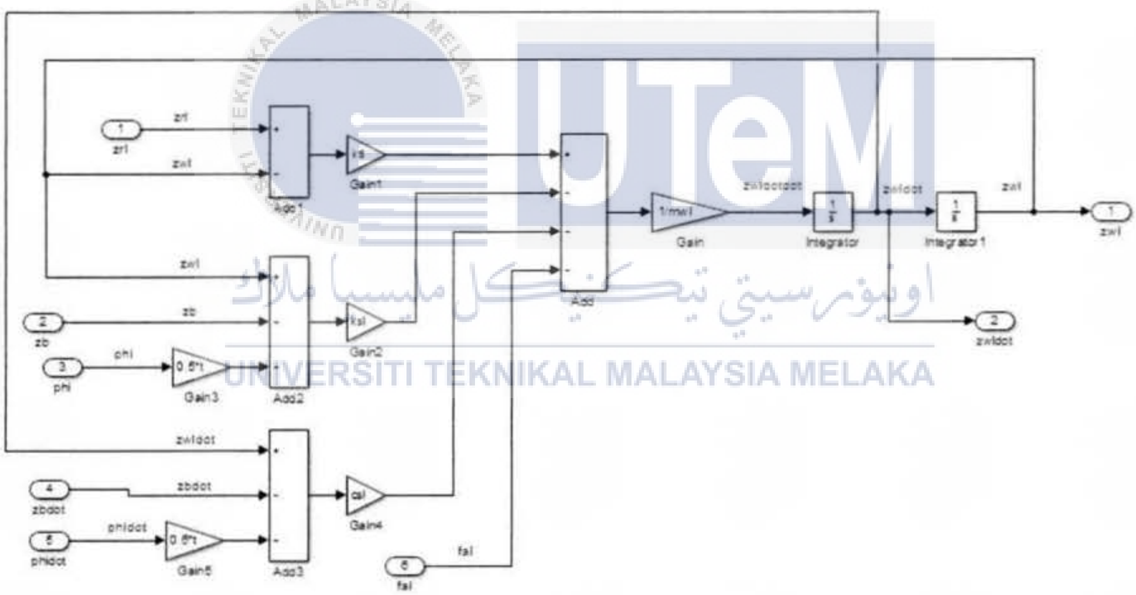
Appendix E: Passive suspension



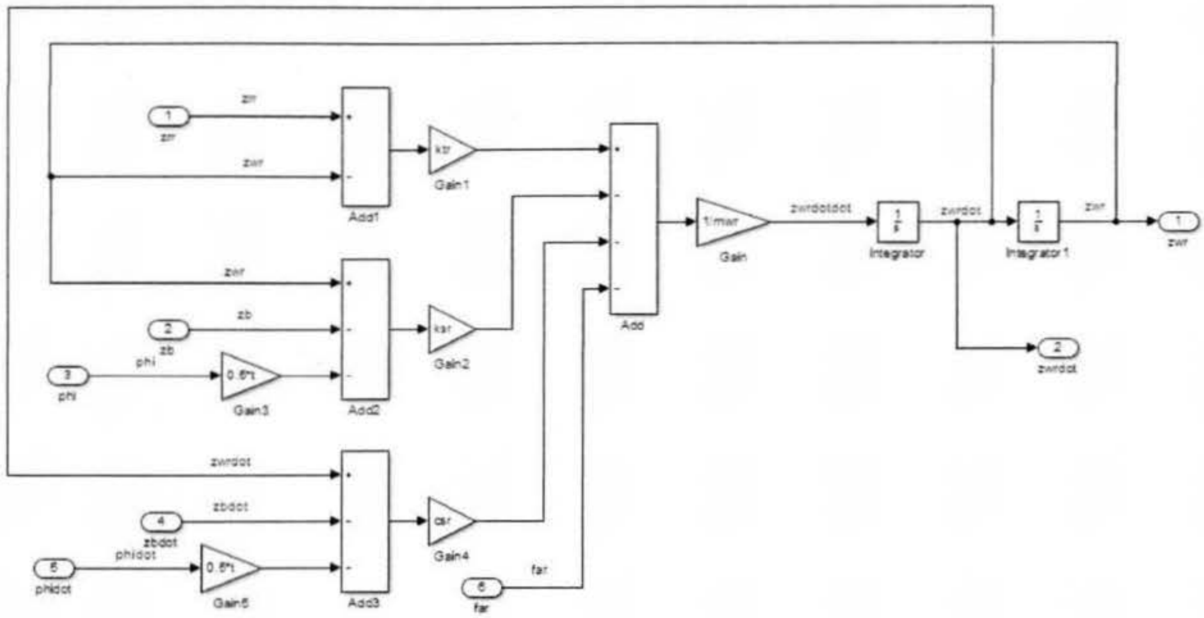
Appendix G: Subsystem1



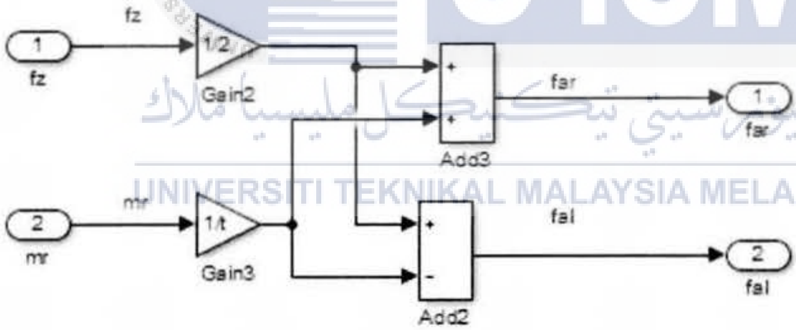
Appendix F: Subsystem 2



Appendix G: Subsystem 3



Appendix H: Subsystem 4



Appendix I: Decoupling transformation

```
mb=600;
lw=1.26;
Iphi=846.6;
ksr=35000;
ksl=35000;
csr=30000;
csl=30000;
ktr=220000;
ktl=220000;
mwr=80;
mwl=80;
t=1.26;
load data_roll.mat;
load phi_model.mat;
figure(1)
plot (roll(1,:),roll(2,:),'b');
hold on;
plot (phi(1,:),phi(2,:)*180/3.142,'r');
title('Roll dynamic');
xlabel('Time, s');
ylabel('Roll, degree');
legend('Roll Carsim','Roll matlab');
load data_vertical.mat;
load zbdotdot_model.mat;
figure(2)
plot(vertical(1,:),vertical(2,:),'b');
hold on;
plot (zbdotdot(1,:),zbdotdot(2,:),'r');
title('Vertical accelartion');
xlabel ('Time, s');
```


Appendix J: Coding of verification Matlab and Carsim

2 Degree of Freedom (Matlab)

```
clc;
close;
clear;

mb=454.5;
mt=45.45;
ks=22000;
cs=2400;
kt=176000;

A= tf([mb cs ks],[1]);
B= tf([cs ks],[1]);
C= tf([mt cs ks+kt],[1]);
D= tf([kt]);

ZbZr= (B*D)/(A*C-B*B);

figure(1)
step(ZbZr);

wnb= sqrt(ks/mb)
wnt= sqrt(kt/mt)

figure(2)
bode(ZbZr);

mt0 = mb*0.05;
mt1 = mb*0.20;
mt2 = mb*0.75;

wnt0 = sqrt(kt/mt0)
wnt1 = sqrt(kt/mt1)
wnt2 = sqrt(kt/mt2)

C0= tf([mt0 cs ks+kt],[1]);
C1= tf([mt1 cs ks+kt],[1]);
```

Figure 1.2: Parameter Matlab 2 DOF

```
C0= tf([mt0 cs ks+kt],[1]);
C1= tf([mt1 cs ks+kt],[1]);
C2= tf([mt2 cs kt],[1]);

ZbZr0 = (B*D)/(A*C0-B*B);
ZbZr1 = (B*D)/(A*C1-B*B);
ZbZr2 = (B*D)/(A*C2-B*B);

figure(2)
bode(ZbZr0,'g--');
hold on;
bode(ZbZr);
bode(ZbZr1,'r--');
bode(ZbZr2,'y');
legend('mt/mb=0.05','mt/mb=0.10','mt/mb=0.20','mt/mb=0.75')
title('ZbZr')

ks0= kt/5;
ks1= kt/8;
ks2= kt/10;

A0= tf([mt cs ks0],[1]);
A1= tf([mt cs ks1],[1]);
A2= tf([mt cs ks2],[1]);

B0= tf([cs ks0],[1]);
B1= tf([cs ks1],[1]);
B2= tf([cs ks2],[1]);
```


Figure 1.3: Parameter Matlab 2DOF

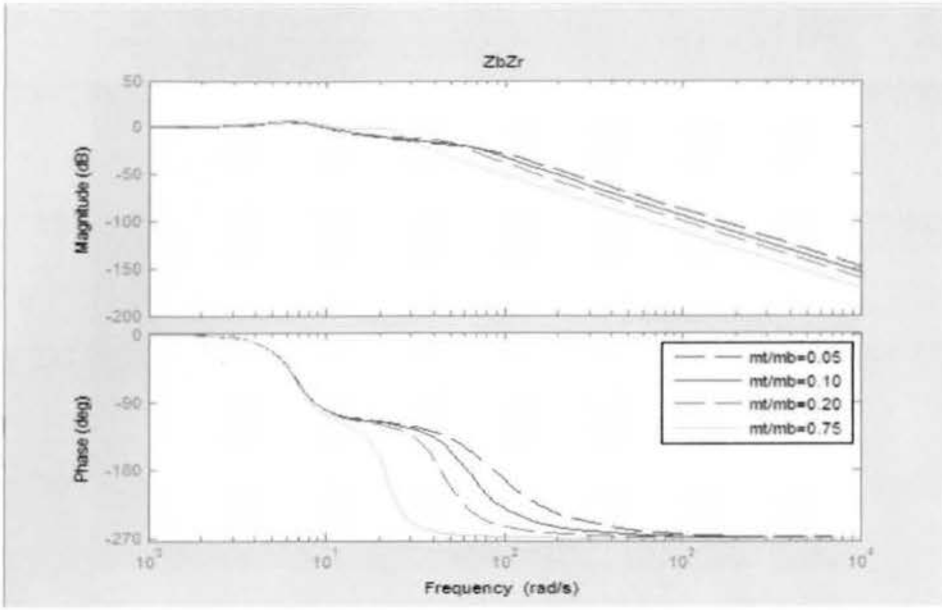


Figure 1.4: Bode diagram 2DOF

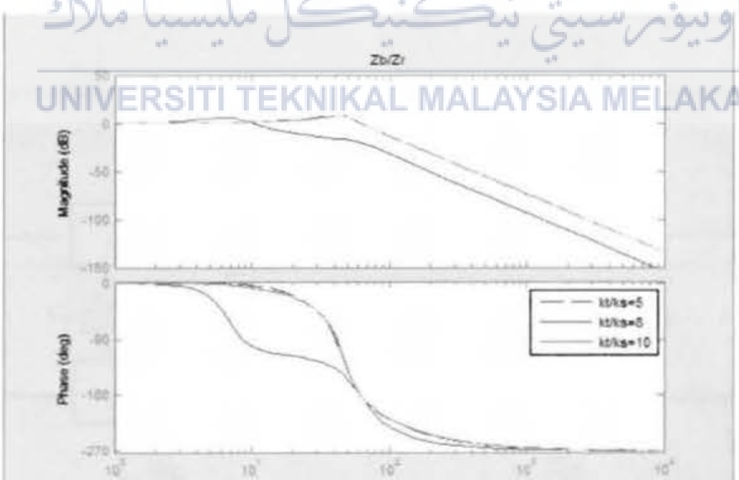


Figure 1.5: Bode diagram 2DOF

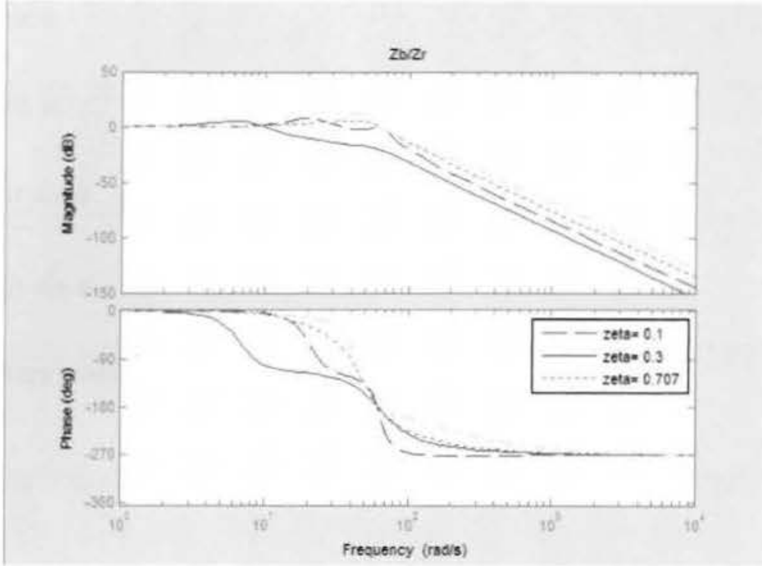


Figure 1.6: Bode diagram 2DOF

4Degree of Freedom(Simulink)

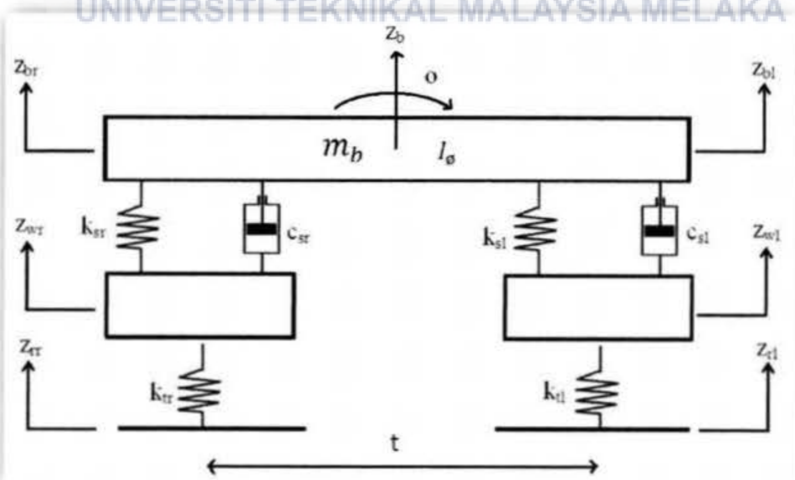


Figure 1.7: Roll Model

$$Z_{bl} = Z_b + 0.5t \sin ø \tag{1.1}$$

$$Z_{br} = Z_b - 0.5t \sin ø \tag{1.2}$$

$$\dot{Z}_{bl} = \dot{Z}_b + 0.5t \sin \dot{ø} \tag{1.3}$$

$$\dot{Z}_{br} = \dot{Z}_b - 0.5t \sin \dot{ø} \tag{1.4}$$

Assuming ø is very small

Sin ø = ø

$$Z_{bl} = Z_b + 0.5tø \tag{1.5}$$

$$Z_{br} = Z_b - 0.5tø \tag{1.6}$$

$$\dot{Z}_{bl} = \dot{Z}_b + 0.5t\dot{ø} \tag{1.7}$$

$$\dot{Z}_{br} = \dot{Z}_b - 0.5t\dot{ø} \tag{1.8}$$

Equation 1 – The vertical motion of vehicle body

$$m_b\ddot{z}_b = k_{sr}(z_{wr} - z_b + 0.5tø) + c_{sr}(\dot{z}_{wr} - \dot{z}_b + 0.5t\dot{ø}) + k_{sl}(z_{wl} - z_b - 0.5tø)$$

$$+ c_{sl}(\dot{z}_{wl} - \dot{z}_b - 0.5t\dot{ø}) \tag{1.9}$$

Equation 2 – The rotational motion of vehicle body (roll)

$$I_ø\ddot{ø} = 0.5t\,[k_{sl}(z_{wl} - z_b - 0.5tø) + c_{sl}(\dot{z}_{wl} - \dot{z}_b - 0.5t\dot{ø})] - 0.5t\,[k_{sr}(z_{wr} - z_b - 0.5tø)$$

$$+ c_{sr}(\dot{z}_{wr} - \dot{z}_b + 0.5t\dot{ø})] \tag{1.10}$$

Equation 3 – The vertical motion of left wheel (tyre)

$$m_{wl}\ddot{z}_{wl} = k_{tl}(z_{rl} - z_{wl}) - k_{sl}(z_{wl} - z_b - 0.5tø) - c_{sl}(\dot{z}_{wl} - \dot{z}_b - 0.5t\dot{ø}) \tag{1.11}$$

Euation 4 – The vertical motion of right wheel (tyre)

$$m_{wr}\ddot{z}_{wr} = k_{tr}(z_{rr} - z_{wr}) - k_{sr}(z_{wr} - z_b + 0.5t\phi) - c_{sr}(\dot{z}_{wr} - \dot{z}_b + 0.5t\dot{\phi}) \quad (1.12)$$