COMFORT PARAMETERS TUNING FOR VEHICLE SUSPENSION PITCH MOTION

MUHAMMAD ALIFF ISYRAQ BIN AZMI

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

COMFORT PARAMETERS TUNING FOR VEHICLE SUSPENSION PITCH MOTION

MUHAMMAD ALIFF ISYRAQ BIN AZMI

This report is submitted
in fulfillment of the requirement for the degree of
Bachelor of Mechanical Engineering (Automotive)

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

JUNE 2017

DECLARATION

I declare that this project report entitled “Comfort Parameters tuning for Vehicle Suspension Pitch Motion” is the result of my own work except as cited in the references.

Signature	:	....
Name	:	Muhammad Aliff Isyraq Bin Azmi
Date	:	....

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 of Supervisor : Associate Professor Dr. Mohd Azman bin Abdullah

Date : ....

DEDECATION

To my beloved mother and father

To a respected supervisor

To lecturers

&

To my friends

ABSTRACT

The goal of this project is to analyse the value spring stiffness and damping in order to improve the comfort on the vehicle. Suspension system is the mechanism that apply between the tire and the body of the vehicle. Suspension system also act as mechanism to absorb the undesirable force that exerted on the tire from transmit to the body of the vehicle. Therefore, to reduce the undesirable force from uneven road, the spring stiffness and damping value on the suspension should be tuning in order to improve the comfort for passenger in the vehicle. In tuning process, it should be test on the various spring stiffness and damping value. In order to analyse the performance on each spring stiffness and damping value, it will be run the simulation on three type of vehicle which are Sedan, Hatchback and Sport Utility Vehicle (SUV). In addition, before run the simulation the Four Degree of Freedom (DOF) ride model should create by using Matlab/Simulink based on theoretical equation of motion and need to verify with CarSimEd. The 4 DOF ride model will be simulate on various value of spring stiffness and damping until it produces a result of pitch motion and vertical body acceleration. From the result, it can be analyse the optimal value of spring stiffness and damping that suitable with each of the vehicle in order to improve the comfort on the vehicle.

ABSTRAK

Matlamat projek ini adalah untuk menganalisis nilai kekerasan spring dan damper untuk meningkatkan keselesaan pada kenderaan. Sistem suspensi adalah mekanisme yang dikenakan antara tayar dan badan kenderaan. sistem suspensi juga bertindak sebagai mekanisme untuk menyerap tenaga yang tidak diingini yang dikenakan ke atas tayar dari penghantar kepada badan kenderaan. Oleh itu, untuk mengurangkan daya yang tidak diingini dari jalan yang tidak rata, kekerasan spring dan nilai damper harus di tuning untuk meningkatkan keselesaan untuk penumpang di dalam kenderaan itu. Dalam proses tuning, ia perlu ujian mengenai pelbagai nilai kekerasan spring dan nilai damper. Untuk menganalisis prestasi pada setiap kekerasan spring dan nilai damper, ia akan menjalankan simulasi pada tiga jenis kenderaan yang Sedan, Hatchback dan SUV. Selain itu, sebelum menjalankan simulasi model menaiki 4 DOF perlu mewujudkan dengan menggunakan Matlab / Simulink berdasarkan persamaan teori gerakan dan perlu mengesahkan dengan CarSimEd. Model menaiki 4 DOF akan mensimulasikan tunjukkan nilai kekerasan spring dan damper sehingga ia menghasilkan hasil gerakan pitch dan pecutan badan menegak. Dari keputusan itu, ia boleh menganalisis nilai optimum kekerasan spring dan damper yang sesuai dengan setiap kenderaan untuk meningkatkan keselesaan pada kenderaan.

ACKNOWLEDGEMENT

In the name of Allah, the most Gracious and most Merciful

All praises to God for his blessings and guidance. Thanks for giving me strength to complete this project report. I am grateful as I have completed this *'Projek Sarjana Muda'* with help and support, encouragement and inspirations by various parties. All the knowledge and information that they give are really helpful.

I am sincerely appreciative to my lecturer, Associate Professor Dr. Mohd Azman bin Abdullah for serving as my supervisor and for providing guidance while conducting the research and the writing of this *'Projek Sarjana Muda'*. Other than that, I would like to thanks and convey special appreciation to my beloved family for their continuous support and encouragement in everything I do. All these years of education have been made possible by their support and love.

Last but not least, I would like thank to everyone who involved directly and indirectly in this project. The sacrifice and commitment given towards me earning my bachelor's degree are desirable and without them, this *'Projek Sarjana Muda'* thesis might be not complete. Thanks for all who that support me to complete this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF ABBEREVATIONS AND SYMBOLS

DOF	=	Degree of freedom
SUV	=	Sport Utility Vehicle
Ms	=	mass of body
Mu	=	mass of unsprung
K	=	spring
C	=	damper
kt	=	tyre spring
Zs	=	sprung mass displacement at body center of gravity
Zu	=	unsprung mass displacement at body center of gravity
Zr	=	road displacement
m_b	=	mass of vehicle body
Z_{br}	=	sprung mass displacement of vehicle at rear body
Z_{bf}	=	sprung mass displacement of vehicle at front body
Z_b	=	sprung mass displacement at body center of gravity
l_r	=	distance between rear tire to center of gravity
l_f	=	distance between front tire to center of gravity
c_{sr}	=	rear suspension damping
c_{sf}	=	front suspension damping
k_{sr}	=	rear suspension spring stiffness
k_{sf}	=	front suspension spring stiffness
k_{tr}	=	rear tire spring stiffness
k_{tf}	=	front tire spring stiffness
z_{wr}	=	rear displacement of unsprung mass
z_{wf}	=	front displacement of unsprung mass
z_{rr}	=	rear road input
z_{rf}	=	front road input
I_θ	=	pitch motion of the vehicle
θ	=	pitch inertia

CHAPTER 1

INTRODUCTION

1.1 Background

Suspension system is one of the most important and basic system in a vehicle. The purpose of suspension system is to isolate the vehicle from disturbances that can help driver can keep control of the vehicle and to protect the passenger from feel the shaking when they drive across the road with bump or hole or even on the smooth road. The suspension also helps to support the vehicle weight, improve the stability of vehicles and maintain the correct vehicle ride motion (Oborne, 1978). There are main criteria to improve the comfort parameter the vehicle suspension system which are vibration isolation on the vehicle body, suspension travel between vehicle body with the wheel and road holding between the tire with road surface. Numerous studies have been conducted on the suspension system in order to minimize the vertical motion, as well as pitch and roll movements, as the vehicle passes over an irregular road, performs turning maneuvers, and is accelerated or brakes heavily and to achieve the stability and ride comfort in the vehicle (Cao et al., 2008).

There are three elements that consist in vehicle suspension system which are wishbone, spring and shock absorber. These three elements are to absorb the vibration and transmit the force and torque exerted between the vehicle body and the wheel. There are several forces will affect on the vehicles body which are the vehicle forces or vehicle load, the longitudinal forces for traction and braking force, lateral force and moments of longitudinal forces as shown in **Figure 1.1**. The spring element is important as it carries the body mass and isolates the vehicle from uneven road surface and it also contributes to drive comfort. Moreover, the damper system in the vehicle also contributes to safety as it absorbs the damping of the body wheel oscillations. The damper system also acts as vibration control for reducing the transfer oscillating movements of the wheel and vehicle body to protect and improve the passenger comfort (Gogaa, 2012).

Pitch and bounce vibration modes are as far as the ride is concerned. Basically, a pitch motion is an upward and downward movement of the front and rear of vehicle body. A pitch motion of vehicle is rotating on y-axis or lateral of the vehicle body through its center of gravity and parallel to the air flow. In order to improve the ride comfort, the damping coefficient and the spring stiffness should be an optimal value. The optimal value of damping coefficient and spring stiffness will minimize the transmissibility of vibration from the rough surface that acting on the vehicles body. Furthermore, the ride natural frequency also will affect the pitch motion of the vehicles in order to reduce the resonant peak of the suspension. The higher the ride natural frequency will minimize the transmissibility of vibration. Ride frequency for front body and rear body are generally not same. The rear body needs higher natural frequency to catch up the front body to reduce the pitch motion (Abdullah et al., 2016).

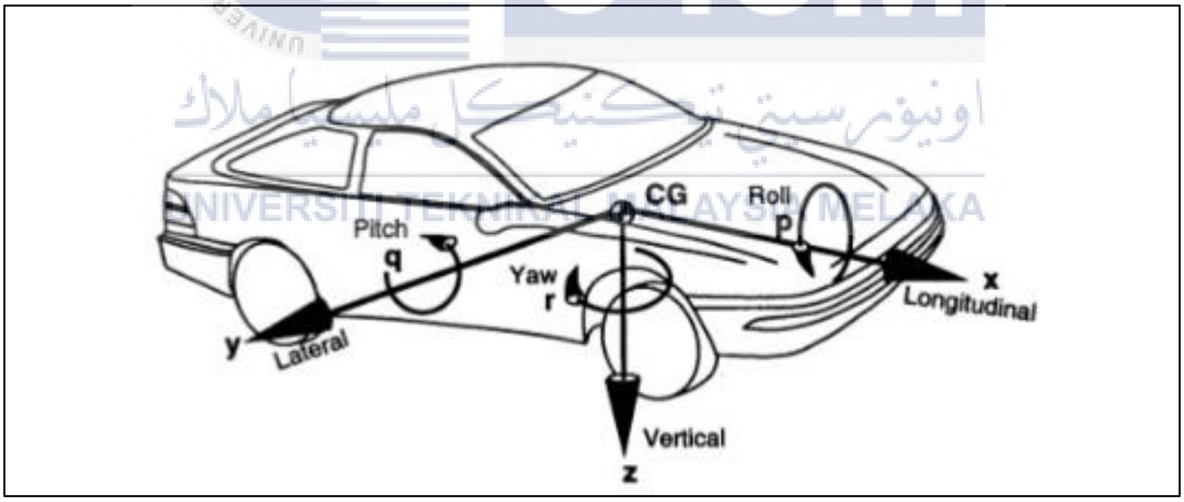


Figure 1.1: Motion of vehicle body

1.2 Problem Statement

In this project, it will be cover on the 4 DOF half car pitch plane ride model that allowed the vehicle body to move in vertical or pitch direction and each wheel is allowed to move in vertical direction. Basically, in the pitch movement of vehicle body, the suspension system will produce a ride comfort rate and natural frequency. In order to improve the ride comfort of the vehicle, it need to reduce the vibration isolation on the suspension. The best vibration isolation will be achieved by keeping the natural frequency as low as possible. The lower the vibration isolation between the vehicle body vertical displacement response and road input, it will form a better performance on the suspension system for the vehicle.

The aim of this project to analyze the comfort parameters for vehicle suspension tuning. This project will be focus on the 4 DOF of half car pitch plane ride model based on the vertical or pitch movement of the vehicles. In order to achieved the ride comfort for the vehicle, it need to find the suitable spring stiffness and the damping coefficient for ride dynamic of the vehicles by using the Matlab Simulink software. From the simulation process, it will produce line graph that need to simulate the different effect of vibration isolation when varied the value of spring stiffness and damping coefficient. The result from Matlab Simulink software need to transfer in Carsim software to analyze the real motion of the passenger vehicle with different effect of real situation. The suspension will be test in the Carsim software with varies input parameter tuning until achieve the ride comfort of the passenger vehicles.

1.3 Objective

There are several objectives included in this research as mentioned below:

a) To identify the most suitable value of spring stiffness and damping coefficient tuning that will ensure optimal ride comfort.
b) To study the effect of spring stiffness and damping coefficient of the vehicle.
c) To simulate a different load condition and road inputs.

1.4 Scope of Project

This research is focused on the analysis of car ride dynamic based on different value of spring stiffness and damping coefficient. This project will be cover a simulation and analysis using Matlab Simulink software. The 4 DOF will be used to study the ride comfort of the vehicle body and will be apply in the Carsim software.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of The Suspension System

According to Bohidar et al., (2015), suspension system is a mechanical system of spring and shock absorber that mounted on the wheel and axle to the chassis of wheeled vehicle. The main functions of the suspension system are for protect chassis from road irregularities, keep wheel camber and wheel direction, react to forces from tyre in longitudinal, lateral and torque motion, carry weight of the vehicle, provide steering stability with better handling, and ensure the passenger's comfort. In the suspension system, there are a few main components with many functions which are steering knuckle, ball joint, control arm, shock absorber, control arm bushing and spring.

The main purpose of shock absorbers is to reduce overall vehicle body movement and to absorb or dissipate energy from the road disturbance without dissipate the vibration energy stored in the spring and dissipate the vibration energy stored in the spring (Poornamohan et al., 2012). When the vehicle through the uneven road, the vehicle body will be moving up and down or side to side to various degrees in response to driving and road condition. Shock absorber also acts as stabilizer to overall vehicle ride. It is because to preventing an excess of vehicle body to roll in any direction during cornering. Other function of suspension is to isolate sprung mass from the unsprung mass vibration. **Figure 2.1** shows the prototype and schematic diagram of the two degree of freedom quarter car model suspension system.

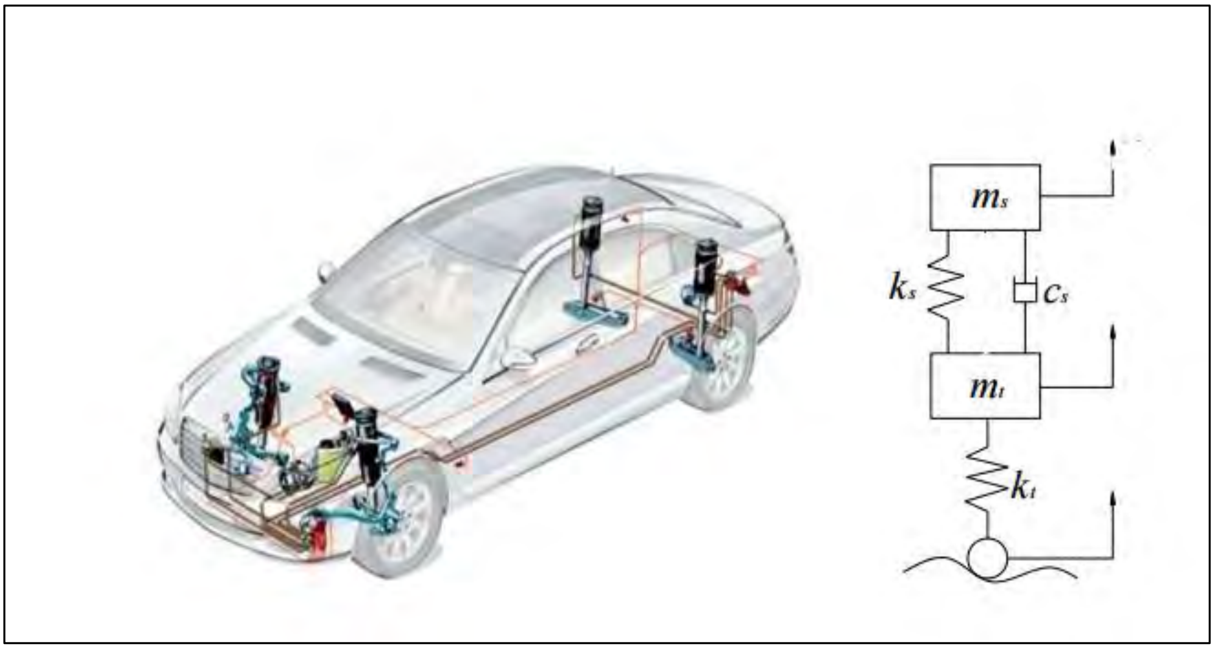


Figure 2.1: Prototype and Quarter Car Model Suspension System.
(Source: Liu et al, (2013))

The suspension is dividing by two catagories which are conventional suspension and advanced suspension. Conventional suspension system indicates the passive suspension system while advanced suspension system refer to active suspension and semi-active suspension system (Harun, 2008).

2.2 Conventional Suspension System

According to Hasan.,(1986), conventional suspension also known as passive suspension system. Most of the passenger vehicle used the passive suspension. A passive suspension system is one in which the qualities of the components which are springs and shock absorbers are fixed. The force versus velocity characteristic of shock absorber or damper usually nonlinear. The function of suspension system are to provide directional stability during cornering, to isolate sprung mass from the unsprung mass vibration and to maneuver and provide damping for the high frequency vibration induced fire excitations (Kumar & Vijayarangan, 2007).

A passive suspension system have been design to improve the ride comfort and handling of the vehicle. The shock absorber is dividing into two condition which are heavily damped suspension and lightly damped suspension. A heavily damped suspension will have good in handling but it will transmit a lot of road disturbance from the wheel to the vehicle body. When the vehicle is travelling at low speed through the uneven road surface or at high speed in the smooth road surface, it will be uncomfortable to the passenger and also will damage the vehicle part and component (Zhengke, 2015).

Moreover, a passive suspension system also have to control the vertical motion of the vehicle. A passive suspension do not produce an external energy produced by suspension element to the system. But it will controls the relative vertical motion of the vehicle by using different energy dissipating element for damper and an energy storing element for spring. The most important part in the passive suspension are spring and damper without containing any sensor, electronics or controls (Khajavi & Abdollahi, 2007).

The most important part in the passive suspension are spring and damper. Without these two important part, the vehicle difficult to control and the shock from road will disturb the passenger and damage the part of the vehicle.

2.2.1 Spring Theory

A suspension system is a mechanical device that have been designed to launch or damp shock impulse and dissipate energy. Basically, a spring is the main parts in the suspension system. In the system consist many type of spring which are leaf, torsion spring or coil spring. The function of the spring to support vehicle's weight and to suspend the vehicle's chassis without excessive sagging. When the vehicle is travelling on a level road and the wheels strike a bump, the spring will compressed quickly. The compressed spring will attempt to return its normal loaded lengthened and will rebound past to normal height, causing the body to lifted (Chavhan, 2014).

The suspension system has it own stiffness there are include the springs, motion ratio, and tire stiffness. The suspension stiffness can be apply to describe the force or displacement relationship between the road surface and the sprung mass. The wheel stiffness will be describe the relationship between the wheel and the sprung mass. Moreover, the tire stiffness is used to describe this relationship between the road and the wheel. It is the suspension stiffness that is of the most interest in controlling the vehicle's body. However, the vehicle suspension system is more practical to describe in terms of the natural frequency of vertical oscillation of the sprung mass or ride rate. The frequency of vertical oscillation will be more referred to as the heave frequency. It also will be describe by the pitch and roll motion of the vehicle. There is also a wheel frequecy that signifies between the natural frequency of wheel motion and the sprung mass of the vehicle. The presence of damping has an effect on the natural frequencies of the suspension system (Johnston, 2010).

2.2.2 Damper Theory

A damper is a device that disseminate energy in form of heat. The process of forcing a viscous fluid through an orifice will be transform the energy to heat. The energy will produce from the road since it will transmitted the road disturbances to the vehicle. The energy is transform into a temperature rise of the fluid inside of the damper. Basically, in the suspension system consist of various type of damper which are twin-tube hydraulic, monotube hydraulic, telescopic direct-acting and electromagnetic damper. The types of damper that commonly used in vehicular application is twin-tube hydraulic damper. The amplitude of the vibration of the vehicle should be reduce in order to increase the rate of comforts, improve the traction between wheel and road and vehicle's stability (Ferdek & Luczko, 2012).

The requirement of the damper is different due to the different vehicle which is has varies parameter that effect the vibration response on the vehicle body. It is desirable for the damper to exert large response of control forces to body interpret so that the vehicle exhibits a flat and level ride without proposing, wallowing or bouncing. Simultaneously, the damper should be able to absorb the energy from the wheel and not conducted to the vehicle body. Fundamentally, the low speed motion is controlled by the passage of damping oil through a precision orifice drilled in the damper piston. The high-speed motion is supported by a spring-loaded valve built into the piston. The change-over point occurs when the flow of hydraulic fluid through the low-speed orifice allows pressure to build, which triggers the spring-loaded high speed valve. This is usually called the “blow-off” point, because the high-speed valve pops open and vents the pressure. The low speed region exhibits one damping value, then the blow-off point is reached, after which the high-speed region shows a different, lower damping value, which is represented as a milder slope of the force-velocity curve (Titurus et al., 2010).

Unfortunately, the spring in the high-speed valve must have a preload such that it cannot activate until the low speed orifice flow is at a maximum, meaning that the blow-off point occurs at a minimum velocity, with an associated minimum force. A damper which shows the blow-off point as a knee in the curve is said to be “Bilinear”. There is one slope for the low speed damping, and a second slope for the high-speed damping (Johnston, 2010).

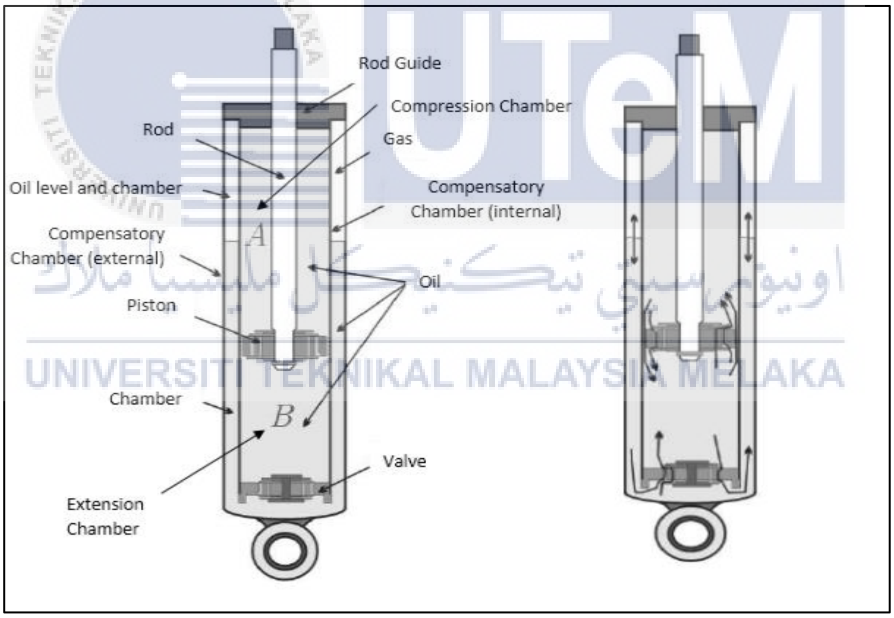


Figure 2.2: Model of the hydraulic damper
(Source: Johnston, 2010))

2.3 Advances Suspension System

Active and semi-active suspension systems are advanced suspension system. There are new innovations of suspension system has been developed and these system is controlled by electronic system. There are several factor the passive suspension system have been improved to advances suspension system is to improve the performance of ride comfort, ride handling and stability of the vehicle. Semi-active is a possible way to a fully active suspension system to considerably improve suspension performance (Rijumon et al., 2013).

According to Kumar & Vijayarangan, (2007), the advances suspension system has been inspiring and motivates by many researchers and academicians due to the lack of altitude control of the vehicle body and demand for better ride comfort and ride handling in the automotive field to consider the use of active suspension system. Other than that, the electronic system that used in active suspension has a potential in order to improve the ride comfort as well as the road handling and vehicle stability for passenger car. A better suspension system with soft and hard suspension should be controlled electronically in order to get "soft" against road disturbance and "hard" against load disturbance.

2.3.1 Semi-Active Suspension System

Semi-active suspension system is quite similar with the passive suspension system. It consists of spring and controllable damper in which the spring element is used to store the energy. Meanwhile, the controllable damper is used to dissipate the energy (Harun, 2008).

One of the researchers is from Zehsaz & Javash, (2013) was describe about definition of semi-active. Semi-active suspension systems provide controlled real-time dissipation of energy. For an automotive suspension, it is accomplished through a mechanical device called an active damper used in parallel with an ordinary spring. There are two general classifications of semi-active control which are continuously variable semi-active control and on/off semi-active control. The continuously variable semi-active control requires the electromechanical active damper valve to modulate its orifice to any effective size. While for on/off semi-active control requires a simpler valve which can switch between a large orifice area (off-state damping) and a small orifice area (on-state damping). The on-state damping characteristic can be made nonlinear same with the existing suspension. The advantages of using semi-active suspension are the operational cost is less than active suspension and only small amount of the energy is consumed (Rijumon et al., 2013).

2.3.2 Full Active Suspension System

Active suspension system uses hdraulic actuator to reduce the amount of external power necessary to achieve the desired performance characteristics and be able to exert an independent force on the suspension to improve the riding characteristics. Figure , shows a schematic view of the active suspension system. From the **Figure 2.3**, the force actuator replaces the suspension spring and damper in passive system. Sensors continuously monitor the operating conditions of the vehicle body. Based on the signals obtained by the sensors and prescribed control strategy the force in the actuator is modulated to improved ride comfort and ride handling (Rijumon et al., 2013).

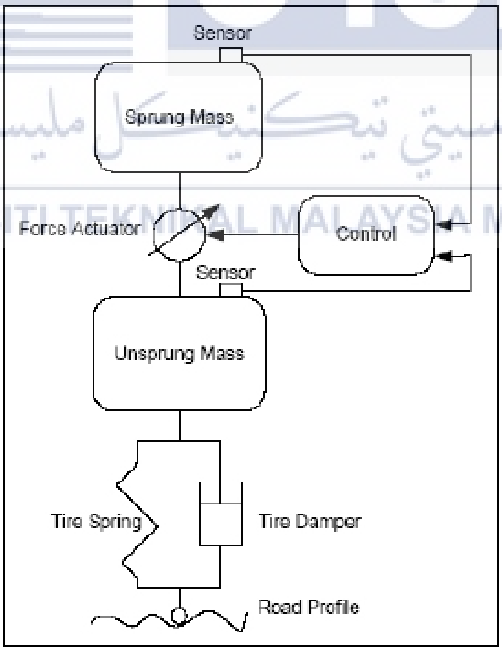


Figure 2.3: Schematic of a full active suspension system.
(Source: Khajavi & Adollahi, 2007))

2.4 Vibration Comfort for Passenger and Vehicle

Vibration phenomena occuring in vehicles will affect the safety and comfort of the vehicle.The vibration phenomena is an important issue for method of transport. It will be exposed to many disadvantage such as increase of fuel consumption, damages elements of vehicle and causing vibration of roadside building. Suspension parameter of the vehicle will effect the driving safety and comfortably when the vehicle engine is running or the vehicle in motion. Vibration transmits to a passenger has a large affect on comfort, performance and health (Sitnik et al., 2013).

A vibration comfort of a vehicle is essential for a vehicle to obtain passenger satifaction. There are several range of vibration as shown in **Table 2.1** that can be support by human body which are between 4 to 12 Hz. Basically, the vibration occur in each part of vehicle but in the low-frequency range such as the tire rolling over an uneven road will produce vibration frequency about 4 to 6 Hz of cyclic motion. The vibration more to 12 Hz will affect on the human organs and reduce the vehicle's ride comfort (Fouladi & Mohd Nor, 2009).

The mechanical damage will affect the vehicles parts such as the engine mounting and shock absorber mounting. It is because the vibration part of vehicle will produce a collision and friction between one part with another part. So, the effect of collision between the part may damage the vehicle parts. Other than that, the vibration of vehicle also will produce effect of physiological on humans. The physiological effect such as increase in heart rate, increase in muscle tension in long term with the vibration effect can damage to human body such as disk to spine, damage on digestive system peripheral veins and female reproductive organ. The different parts of human body will have different effects of vibrations. To reduce the vibration of the vehicle are difficult because it is depending on many factors such as the road condition, unbalance of the engine and whirling of the shafts. Moreover, the vibration of frequency range between 10 to 20 Hz also will cause a headache, eye strain and irritations in the intestines and bladder. Most of the people have vertical vibration' sensitivity in between 5 to 16 Hz and to the lateral vibration between 1 to 2 Hz. So that, to tuning the suspension with optimal comfort, it need to select the suitable stiffness of spring and damping value which is can reduce the vibration of vehicle that transmit to the passenger (Katu, 2016).

Table 2.1: Range for Comfort

(Source: Katu, (2016))

Vibration	**Reaction**
Less than 0.315 m/s^2	Not uncomfortable
0.315 to 0.63 m/s^2	A little uncomfortable
0.5 to 1.0 m/s^2	Fairly uncomfortable
0.8 to 1.6 m/s^2	Uncomfortable
1.25 to 2.5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

2.5 Ride Comfort for Passenger and Vehicle

Ride comfort is defined as the overall comfort including of the passenger during travel which is also known as ride quality. Suspension of the vehicle is the main factor to increase the ride comfort for passenger and vehicle. When the vehicle travel through unevenness road surface, the vehicle body will produce vibration isolation effect. The vibration isolation of the vehicle should be reducing in order to improve the ride comfort for passenger and vehicle. There are several steps to reduce the vibration which are improved the quality of the road condition, select suitable type of tyre for the vehicle and tuning the suspension with optimal parameter. It is because there are plays an important factor as an elastic components and damping element to absorb the vibration energy. Moreover, the elastic components also can buffer the impact, reduce vibration and transmit force respectively. It is known as the soul of chassis design which is an important component to ensure ride comfort and handling stability (Banerjee et al., 2016).

The rigidity and damping parameter of the suspension system are selected through empirical design or optimization method. Since the vehicle ride comfort and handling stability are contradicting the suspension system, a compromise must be made to fulfil the requirement of both performances. The parameters of its suspension characteristic cannot be adjusted to the vehicle's operational states and incentive changes. Hence, the further improvement of its vibration reduction performance is restrained. In order to get an optimal damping parameter for suspension system, it need to observe the vertical displacement of vehicle body, road input and ratio of wheel to indicate the comfort level for the passenger. A damping coefficient of 1000 *N.s/m* will produce the lowest transmissibility which are vibration isolation, suspension travel and road holding (BalaRaju, 2014).

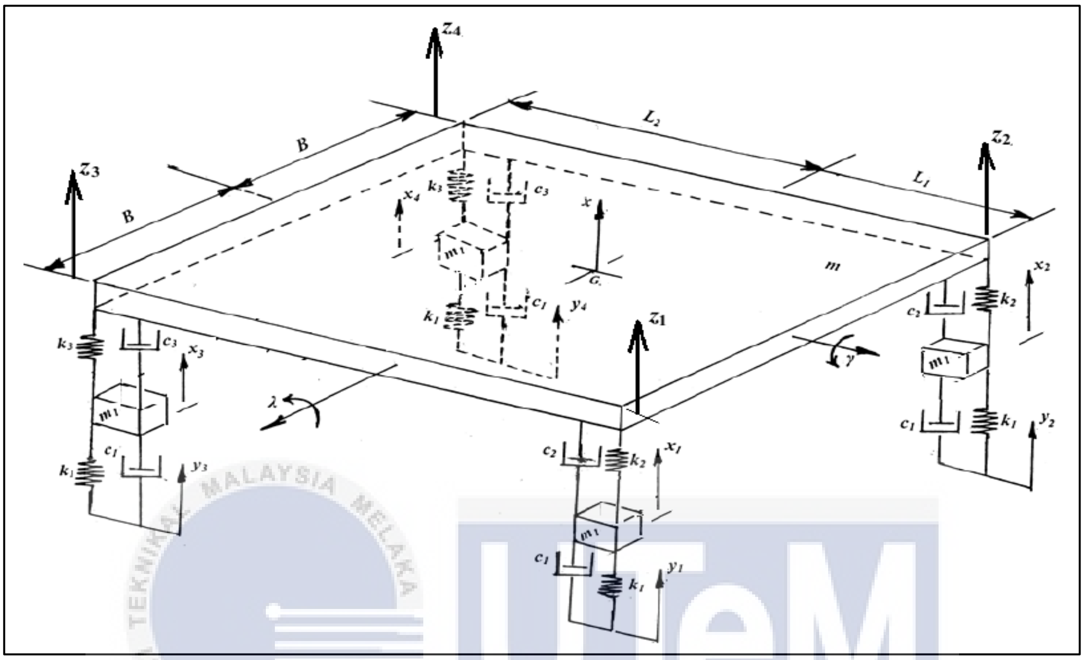


Figure 2.4: Schematic arrangement of full car model.

(Source: BalaRaju, 2014)

2.6 Pitch Motion of Vehicle Axis System

In a vehicle system modelling, the vehicle dynamic behaviour can be determined when the forces exerting to the vehicle from the tires, gravity and aerodynamics. All of the movement will be effect on the comfort of vehicles. In order to achieve vehicle comfort, many aspects should consider such as the translational motion and moments of the vehicle system. Basically, a vehicle system consists of three translational motions and three moments which are the longitudinal motion through x-axis where the direction to the front of the vehicle is positive value, the lateral motion through the y-axis where the direction to the right side of the vehicle is the positive value, the vertical motion through z-axis where the upward direction is positive value, the roll moment about the x-axis where clockwise direction is positive, the pitch moment about the y-axis where clockwise is positive and the yaw moment about the z-axis where clockwise direction is positive. This report only will be cover pitch motion of the vehicle (Abdullah et al., 2016).

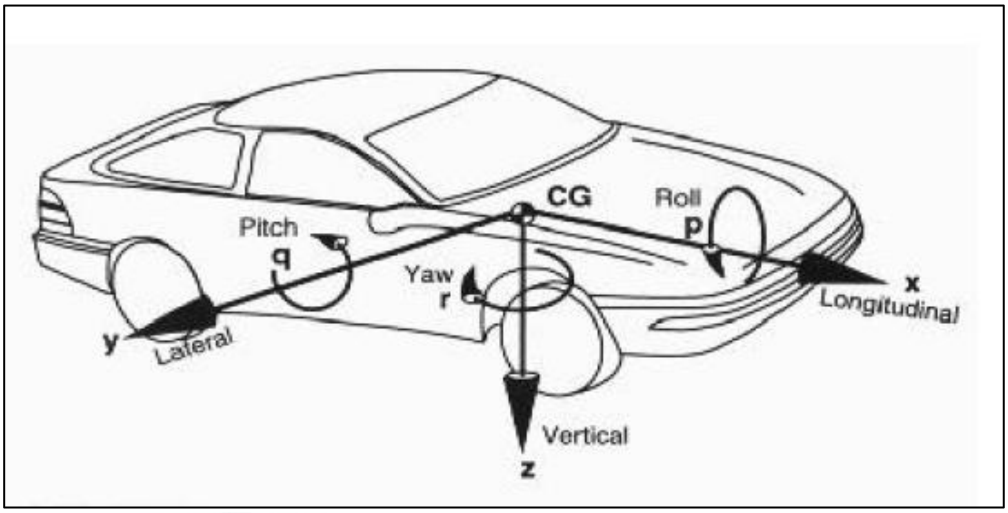


Figure 2.5: Vehicle axis system.
(Source: Abdullah et al., 2016)

Most of the vehicle has a problem among the comfort of the vehicle when through the uneveness road. The vehicle will stimulate a harmonic response in the pitch mode due to road disturbance. Pitch motion of the vehicle will occur more rapidly compare to the heave motion in response to the vertical disturbances. Pitch motion and heave motion are related linked through the concept of "centres of oscillation". The centres of oscillation may be determined by solving the Eigenvectors of two degree of freedom "Bounce-Pitch Model". The interaction between pitch motion and heave motion may be examining the heave-pitch coupling term in the total stiffness matrix. Actually, pure pitch motion does not only effect the load transfer across on one axle but the load tranfer will be support by both axle of the vehicle. This is because of rotational acceleration about the y-axis, through this effect is generally very small owing to the small pitch angles and low rotational acceleration. Mostly, the load transfer situation may be occur during the vehicle braking, accelerate or through uneveness road surface. When these situation happen, the pitch acceleration may be large, but in response to vertical disturbances this effect is likely to be small. The recovery of that pitch condition back to ride height results in weight transfer due to pitch (Johnston, 2010).

CHAPTER 3

METHODOLOGY

In this chapter, the whole project implementation involving the step from modelling process until the final result of analysis will be explained. The modelling of half-car for passive suspension system were design. To develop the modelling, the MATLAB R2016a software will be used. A few simulation analyses will be carry out on these model. The mathematical modelling also will validate with the CarSimEd to make sure the mathematical model is representing the real vehicle ride model. The parameter of the vehicle will be design and select the accurate values in order to reduce the pitch motion of the vehicle in passive suspension system.

3.1 Modelling Assumption

There are some assumption was done in order to verify the result. The vehicle body is referred to as a sprung mass. The roll center assumed located below body center of gravity. The four wheel was assumed as an unsprung mass. The effect of aerodynamics and cross wind effect are neglect. For this report, it need to improve the ride comfort of the half-car pitch ride model. So that, main factor that need to take for analyse are pitch motion and vertical acceleration of the vehicle body by using both software which are Matlab/Simulink and CarSimEd. There are four equation consist in four degree of freedom of pitch ride model that produce from the motion of the vehicle which are vertical motion of vehicle body, rotational motion of vehicle body, vertical motion of right wheel and vertical motion of left wheel. The derivation of the equation will be shown in this chapter.

3.2 Project Flow Chart

The methodology of this project can easily be described by the flowchart in the figure below. The **Figure 3.1** shows the flow chart of the process in order to completing this project.

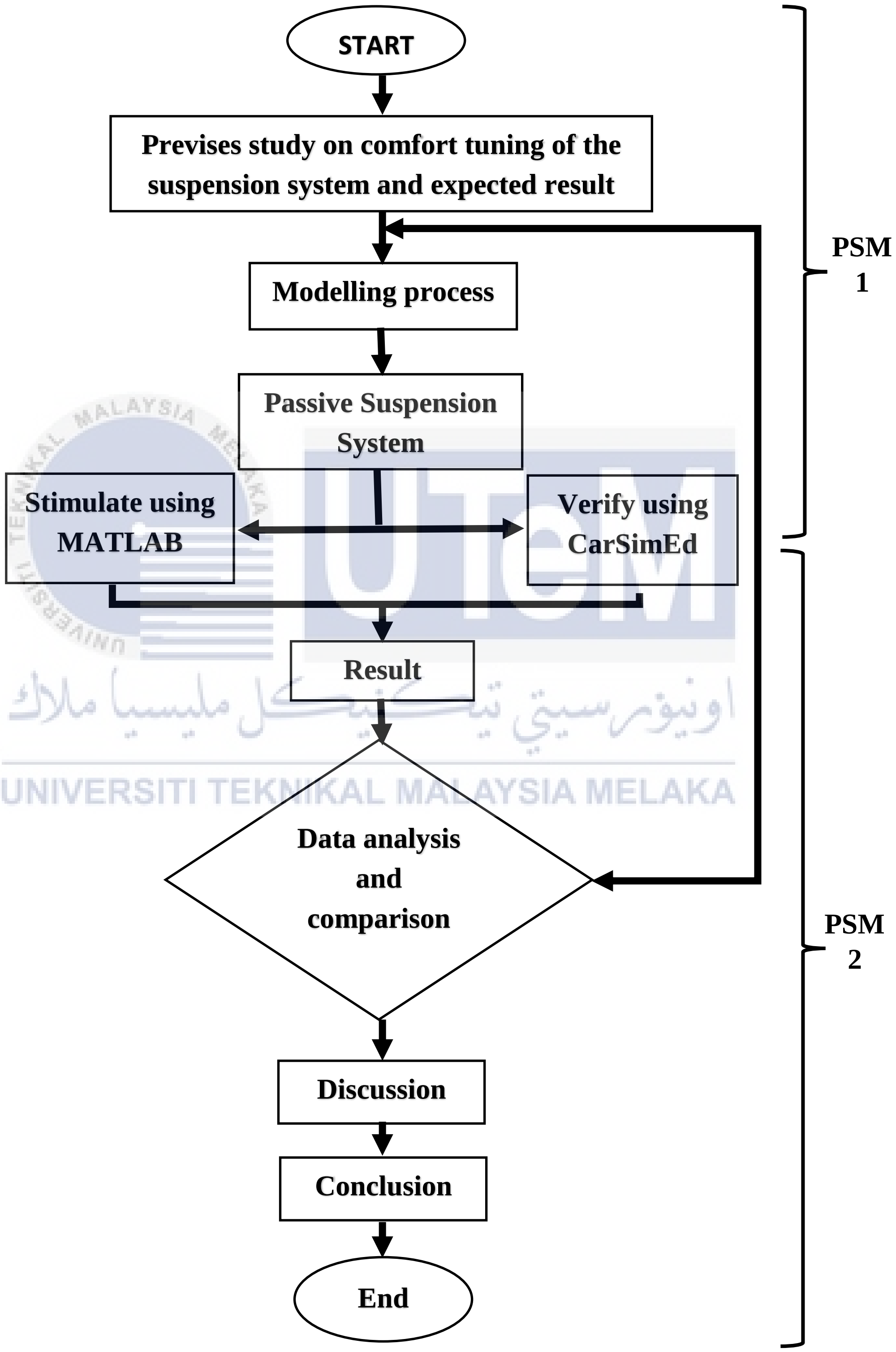


Figure 3.1: Project Methodology Flowchart

3.3 Vehicle Suspension System

Primary vehicle suspension is the term used to designate those suspension components that connecting the axle and wheel assemblies of a vehicle to the frame of the vehicle. This is in contrast to secondary suspensions, which are the elements connecting other components to the frame or body of a vehicle: such as engine mounts, seat suspensions, and cab mounts. There are two basic types of elements in conventional suspension systems. These elements are springs and dampers. The role of the spring in a vehicle's suspension system is to support the static weight of the vehicle body. The role of the damper is to dissipate vibration energy and control the input from the road that is transmitted to the vehicle. For the report, it need to analyse and stimulate the pitch motion' effect to the vehicle.

3.3.1 Schematic Model of Vehicle

This is beginning of the step to design a suspension modelling of vehicle after review, analyse and understand the literature review as stated in chapter two above. It will involve establishing the design requirement and equation of motion of the motorcycle. This report only will be cover pitch dynamics motion of the vehicle. The purpose of this phase is to make clearly about the physical setup of half-car model of vehicle with its suspension. In order to be useful the mathematical model must be sufficiently complex to accurately include the dynamics of the vehicle, yet be reasonably simple to manipulate. In order to examine the pitch dynamics of a vehicle, the simplest model that can be used is a four degree-of-freedom pitch plane model.

Firstly, the sprung mass usually will be a reference for the mass of the vehicle body whereas the unsprung mass will be a reference for the mass of the wheel of the vehicle. The formula has been studied from the vibration characteristics of the vehicle to get the equations of motion based on Newton's second law for each mass. The response can be determined by solving the equation of motion after the excitation of the system is known. By using the 4 DOF model as shown in **Figure 3.2** a study can be made to review the up and down linear motion and the pitch angle of the motorcycle body and the motion of the wheel.

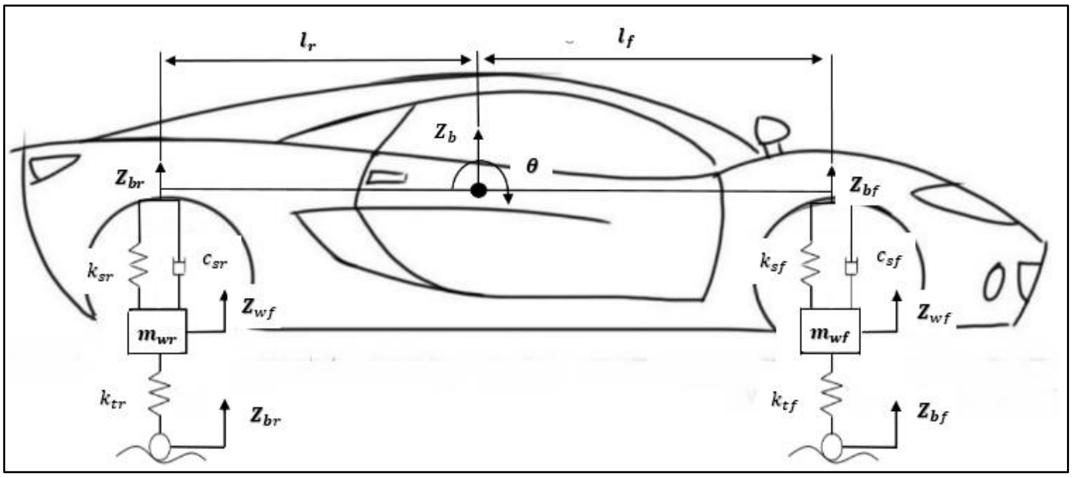


Figure 3.2: 4 DOF Half-Car Pitch Plane Ride Model

3.3.2 Mathematical Model of Vehicle

In this report will be cover 4 DOF half-car pitch plane ride model. It is to analyse the pitch motion of vehicle in order to achieve the comfort of vehicle. In this model, the vehicle body is allowed to move in vertical and pitch direction and each wheel is allowed to move in vertical direction. The spring in **Figure 3.2** were assumed to be linear motion. This means that the load in the spring is directly proportional to the deflection produce, with the spring constant, k being the proportionality constant. The road excitation on the front and rear wheels are represented by Z_{wf} and $Z_{wr.}$ Due to this being only a 2-D, two-wheeled model, the roll and yaw motion of the vehicle were not taken into account.

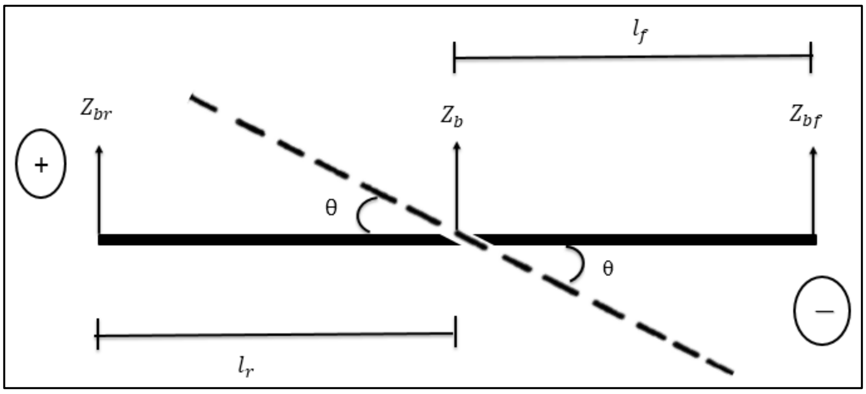


Figure 3.3: Pitch motion of the vehicle

There are several cases that affect the sprung mass in half car model. The cases are front and rear of pitch motion. From **Figure 3.3**, these cases will be observe from right and left side of the vehicle and will be able to interpret the equation from the pitch motion form. The equation of the vehicle pitch motion:

$$Z_{br} = Z_b + l_r \sin\theta \quad \text{and} \quad \dot{Z}_{br} = \dot{Z}_b + l_r \sin\dot{\theta}$$

$$Z_{bf} = Z_b - l_f \sin\theta \quad \text{and} \quad \dot{Z}_{bf} = \dot{Z}_b - l_f \sin\dot{\theta}$$

Since the value of θ is very small. So that, the value of $\sin\theta$ can be neglect and from θ only.

So,

$$Z_{br} = Z_b + l_r\theta \quad \text{and} \quad \dot{Z}_{br} = \dot{Z}_b + l_r\dot{\theta}$$
$$Z_{bf} = Z_b - l_f\theta \quad \text{and} \quad \dot{Z}_{bf} = \dot{Z}_b - l_f\dot{\theta} \tag{1}$$

1) The vertical motion of the vehicle (Sprung Mass)

$$\ddot{Z}_b = \frac{1}{m_b}[\, -c_{sr}(\dot{Z}_{br} - \dot{Z}_{wr}) - k_{sr}(Z_{br} - Z_{wr}) - c_{sf}(\dot{Z}_{bf} - \dot{Z}_{wf})$$
$$- k_{sf}(Z_{bf} - Z_{wf}) \,] \tag{2}$$

Substitute equation (1) into equation (2),

$$\ddot{Z}_b = \frac{1}{m_b}[\, -c_{sr}(\dot{Z}_b + l_r\dot{\theta} - \dot{Z}_{wr}) - k_{sr}(Z_b + l_r\theta - Z_{wr}) - c_{sf}(\dot{Z}_b - l_f\dot{\theta} - \dot{Z}_{wf}) -$$
$$k_{sf}(Z_b - l_f\theta - Z_{wf}) \,] \tag{3}$$

2) The rotational motion of vehicle body (Pitch)

$$\ddot{\theta} \;=\; \frac{1}{I_\theta}\,\{(-l_f\;[\,-c_{sf}(\dot{Z}_{bf}-\dot{Z}_{wf}) - k_{sf}(Z_{bf}-Z_{wf})]$$

$$-[-l_r\;(c_{sr}(\dot{Z}_{br} - \dot{Z}_{wr})\;-k_{sr}(Z_{br} - Z_{wr})]\} \tag{4}$$

Substitute equation (1) into equation (4),

$$\ddot{\theta} \;=\; \frac{1}{I_\theta}\,\{(-l_f\;[\,-c_{sf}(\dot{Z}_b-l_f\dot{\theta}-\dot{Z}_{wf}) - k_{sf}(Z_b-l_f\theta-Z_{wf})]\,-$$

$$[-l_r\;(c_{sr}(\dot{Z}_b+l_r\dot{\theta} - \dot{Z}_{wr})\;-k_{sr}(Z_b+l_r\theta - Z_{wr})]\} \tag{5}$$

3) The vertical motion of rear wheel (Tyre)

$$\ddot{Z}_{wr} \;=\; \frac{1}{m_{wr}}\,[\,-c_{sr}(\dot{Z}_{wr} - \dot{Z}_{br}) - k_{sr}(Z_{wr} - Z_{br})\;-\;k_{tr}(Z_{wf} - Z_{rr})] \tag{6}$$

Substitute equation (1) into equation (6),

$$\ddot{Z}_{wr} \;=\; \frac{1}{m_{wr}}\,[\,-c_{sr}(\dot{Z}_{wr} - l_r\dot{\theta} - \dot{Z}_b) - k_{sr}(Z_{wr}+l_r\theta - Z_b)\;-\;k_{tr}(Z_{wf} - Z_{rr})\;] \tag{7}$$

4) The vertical motion of front wheel (Tyre)

$$\ddot{Z}_{wf} \;=\; \frac{1}{m_{wf}}\,[\,-c_{sf}(\dot{Z}_{wf} - \dot{Z}_{bf}) - k_{sf}(Z_{wf} - Z_{bf})\;-\;k_{tf}(Z_{wf} - Z_{rf})\;] \tag{8}$$

Substitute equation (1) into equation (8),

$$\ddot{Z}_{wf} \;=\; \frac{1}{m_{wf}}\,[\,-c_{sf}(\dot{Z}_{wf} + l_f\dot{\theta} + \dot{Z}_b) - k_{sf}(Z_{wf}+l_f\theta - Z_b)\;-\;k_{tf}(Z_{wf} - Z_{rf})\;] \tag{9}$$

3.4 Matlab Simulation

From the equation that shows above, each equation will be used to create a 4 DOF ride model by using Matlab/Simulink. The 4 DOF ride model will be verify and simulate on different type of vehicle which are Sedan, Hatchback and SUV, Full size car.

3.4.1 Ride Model Simulink

The ride model will develop in Matlab Simulink based the four equation above. The design will represent different input and output. From this ride model, we can analyse the effect on the both suspension and wheel when hit 0.1 m bump on road in order to improve the comfort of the vehicle. To improve the comfort of the vehicle, stiffness of spring and damping coefficient are an important role. So that, the parameter of spring stiffness and damping coefficient for the system need to change until the analysis on comfort will be achieve. The 4 DOF ride model are shown in Appendices.

3.4.2 Validation of 4 DOF Half-Car Pitch Plane Ride Model Using CarsimEd

The 4 DOF ride model will be verify by comparing the result between 4 DOF model and CarsimEd. It is to make sure the both result have similar pattern to make the 4 DOF ride model is acceptable to run the simulation. After that, the 4 DOF ride model will be run on three type of vehicle which are sedan, hatchback and SUV, Full size car to produce a result on pitch motion and vertical body acceleration. The parameter of each vehicle will be shown in **Table 3.1, Table 3.2** and **Table 3.3** and will be simulated on various spring stiffness and damping value. **Figure 3.4** shows the layout of CarSimEd that will be simulate for various vehicle on bounce sine sweep test to produce the pitch motion of vehicle.

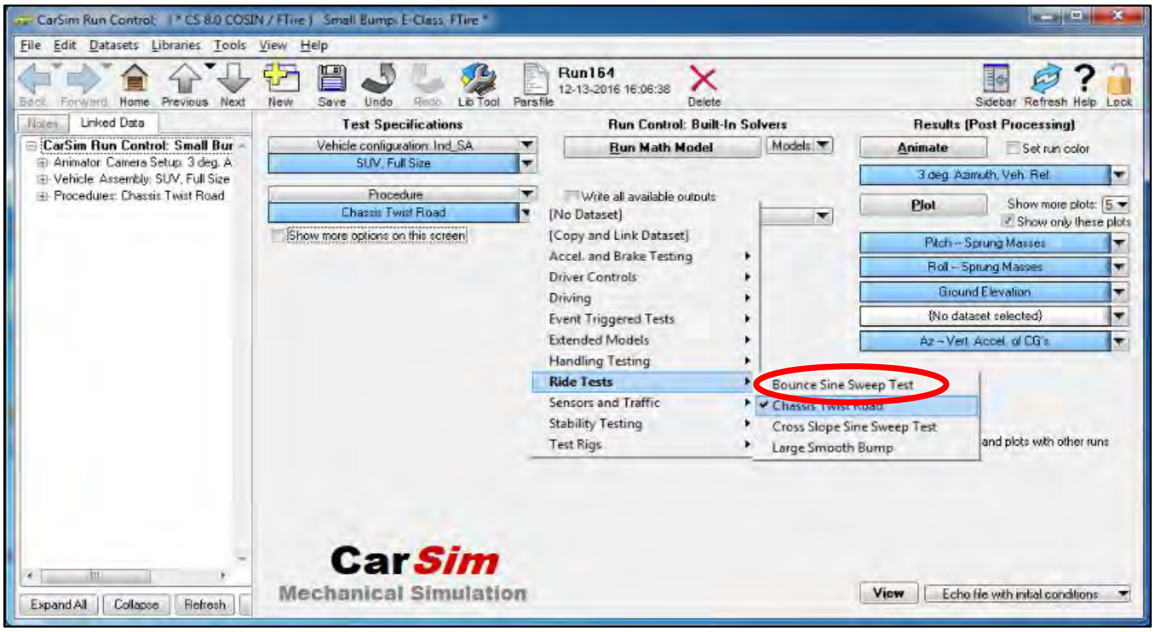


Figure 3.4: Layout of CarSimEd

The result from the simulation will be obtained such as pitch motion, roll motion, vertical body acceleration and ground elevation of the vehicle as shown in **Figure 3.5**.

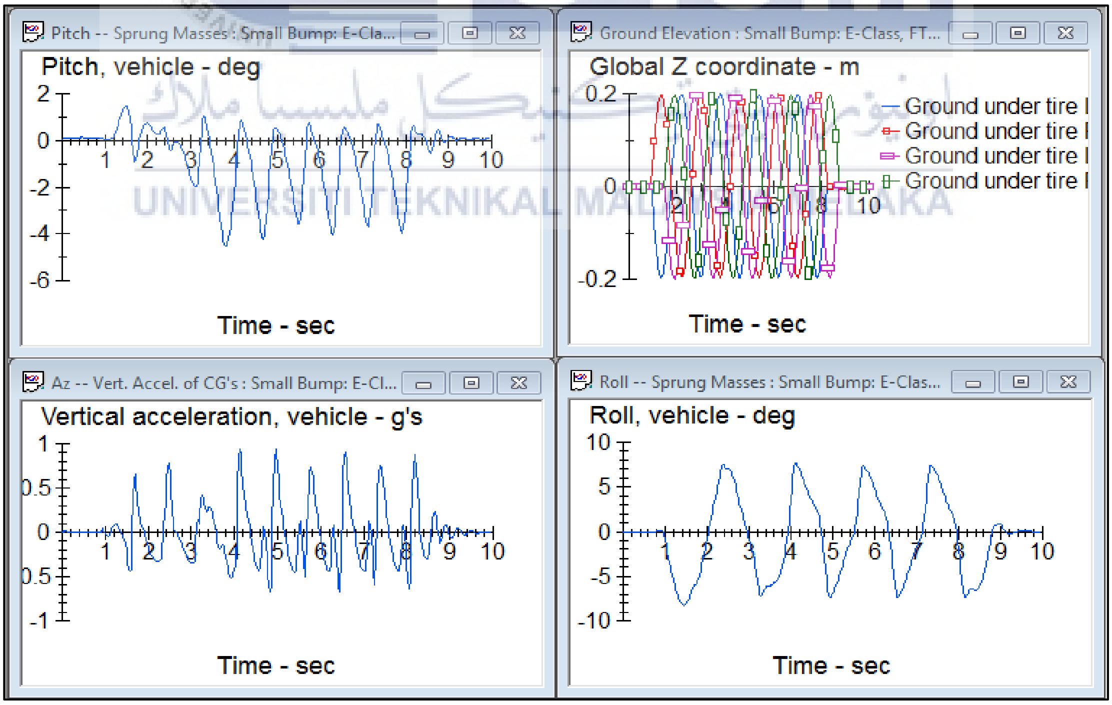


Figure 3.5: Result for the vehicle motion using CarSimEd

3.5 Data Analysis

For the next of this project, data analysis and parameter will be taking from the selective car which are SUV, Full size car, sedan and hatchback. All the parameter will be take out from CarSimEd as shown in **Table 3.1, Table 3.2 and Table 3.3**. The parameter that have been state in the thesis including chassis, stiffness, mass body and mass unsprung. All the parameter of the vehicle below will be apply different value of spring stiffness(k) which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m while for damping value (c) which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m to select the suitable suspension on each vehicle. In addition, **Figure 3.6, Figure 3.7 and Figure 3.8** shows that the animation of each vehicle when through the bounce sine sweep test.

Table 3.1: Parameter for SUV, Full size car

Parameter	Symbol	Value
Mass of Vehicle Body (Kg)	m_b	2257
Mass of Front Wheel (Kg)	m_{wf}	125
Mass of Rear Wheel (Kg)	m_{wr}	150
Distance between CG and Front Axle (m)	l_f	1.33
Distance between CG and Rear Axle (m)	l_r	1.62
Vehicle Body Mass Moment of Inertia ($Kg \cdot m^2$)	I	3524.9

Figure 3.6: Animation of bounce sine sweep (SUV)

Table 3.2: Parameter for Sedan

Parameter	Symbol	Value
Mass of Vehicle Body (Kg)	m_b	1340
Mass of Front Wheel (Kg)	m_{wf}	80
Mass of Rear Wheel (Kg)	m_{wr}	80
Distance between CG and Front Axle (m)	l_f	1.10
Distance between CG and Rear Axle (m)	l_r	1.67
Vehicle Body Mass Moment of Inertia ($Kg \cdot m^2$)	I	4192

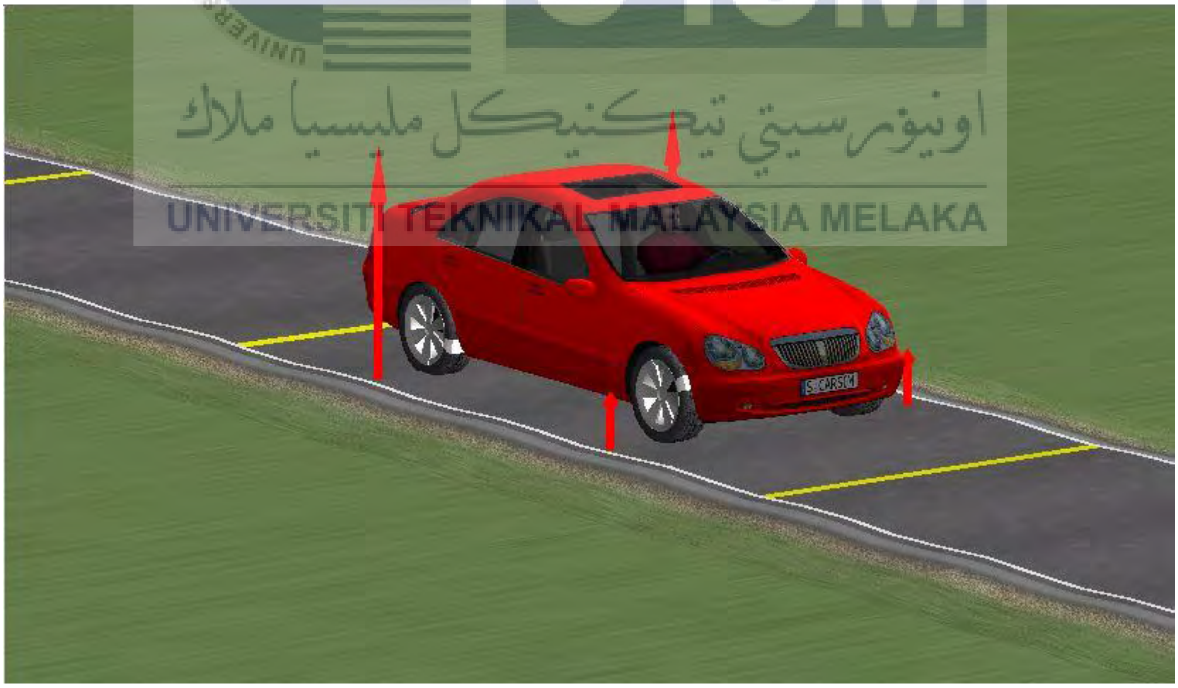


Figure 3.7: Animation of bounce sine sweep (Sedan)

Table 3.3: Parameter for Hatchback

Parameter	Symbol	Value
Mass of Vehicle Body (Kg)	m_b	1270
Mass of Front Wheel (Kg)	m_{wf}	71
Mass of Rear Wheel (Kg)	m_{wr}	71
Distance between CG and Front Axle (m)	l_f	1.02
Distance between CG and Rear Axle (m)	l_r	1.56
Vehicle Body Mass Moment of Inertia ($Kg \cdot m^2$)	I	1523

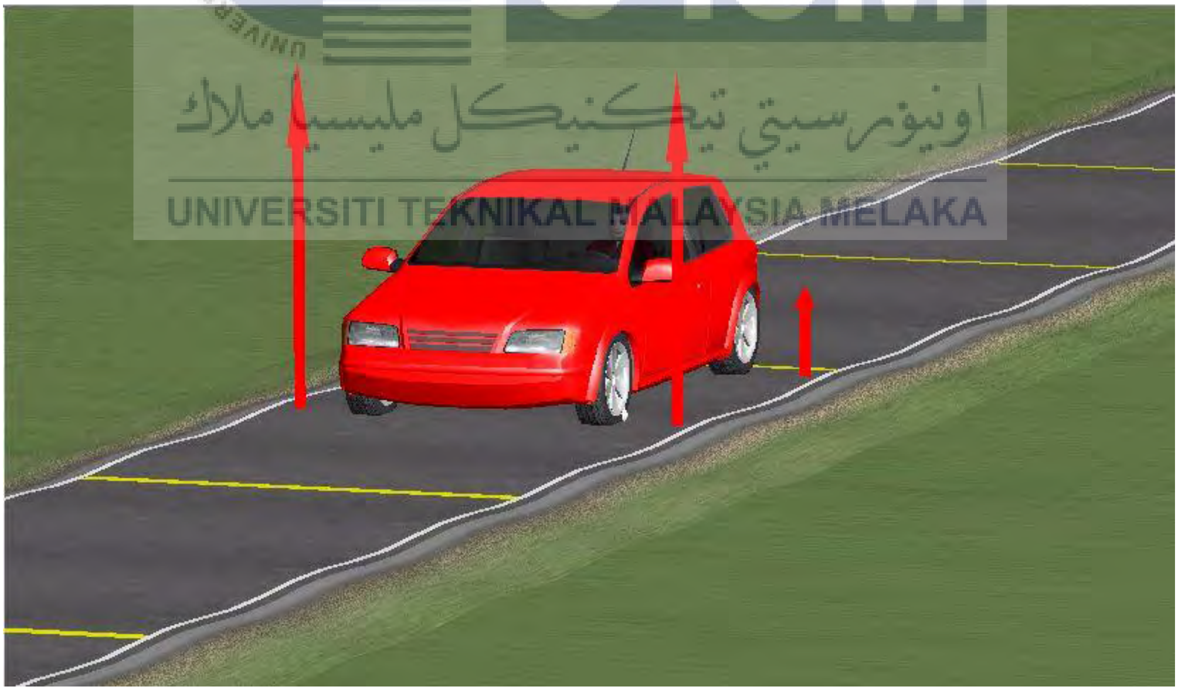


Figure 3.8: Animation of bounce sine sweep (Hatchback)

CHAPTER 4

RESULT AND DISCUSSION

4.1 Verification of 4 DOF Ride Model Using Carsimed

The 4 DOF ride model are verified using CarSimEd for ride over bump test. It can be seen that the 4 DOF ride model simulation result for body vertical acceleration and body pitch displacement closely follow the trends of the responses from CarSimEd with acceptable error. This error is due to the simplification of the 4 DOF ride model compared to CarSimEd. For this verification of 4 DOF ride model, the parameter of the vehicle will be select from CarSimEd which is SUV, Full size car model. The 4 DOF ride model will be verify by using five different spring stiffness (k) which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m while for damping value (c)which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m. The parameter in **Table 3.1** will be stimulating by using Matlab/Simulink and CarSimEd software in order to validate and verify the 4 DOF ride. **Figure 4.1 and Figure 4.2** shows that the response of the pitch body and vertical body acceleration in 4 DOF ride model are similarly follow the response in CarSimEd simulation

From the result, the difference in magnitude between the 4 DOF ride model and CarsimEd in pitch motion and vertical body acceleration response may be due to the compliance effect in suspension. Meanwhile the 4 DOF ride model were neglected the kinematic effect and compliance effect in suspension. The trajectory is not purely vertical if the kinematic effect taken into consideration. The wheel moves out laterally and longitudinally when the suspension is compressed and expanded. This contributes to the difference between the 4 DOF ride model and CarSimEd pitch displacement responses. The verification of 4 DOF ride model will be stimulate with various spring stiffness and damping value in order to determine the difference of magnitude for verified the 4 DOF ride model. For the other verification result with different spring stiffness and damping value will be shown in Appendix.

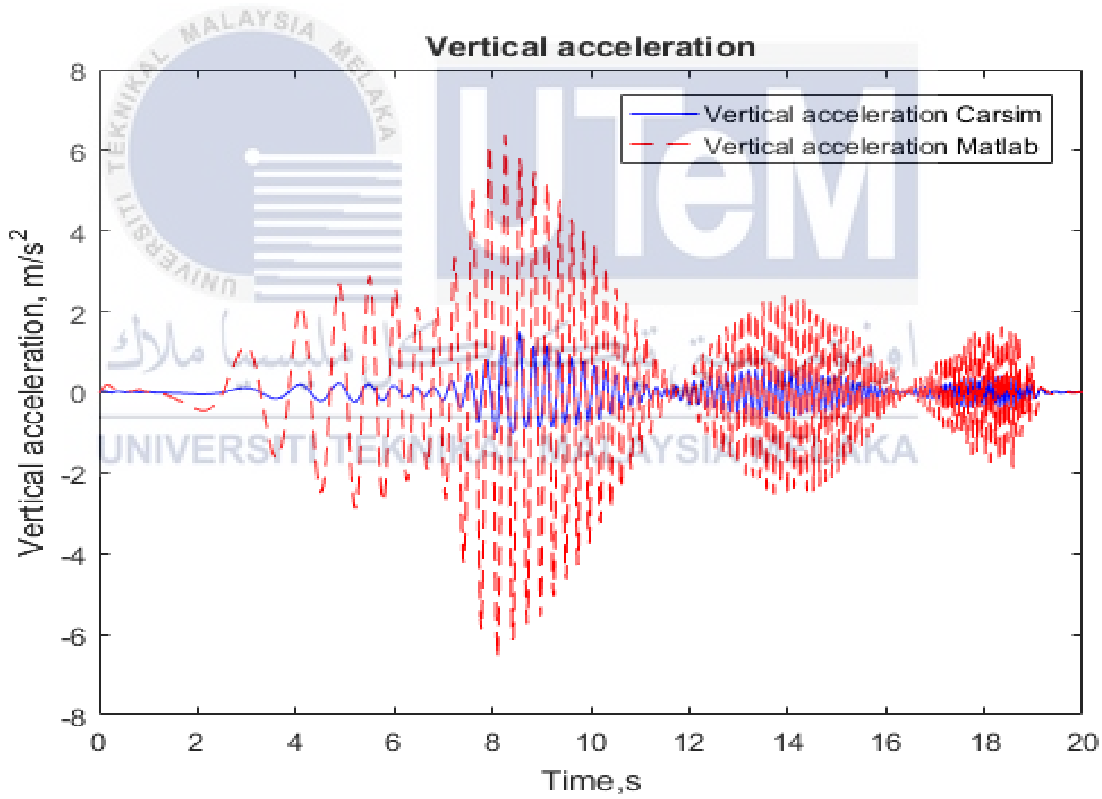


FIGURE 4.1: Verification of 4 DOF ride model on C = 30 kNs/m and K = 189 kN/m

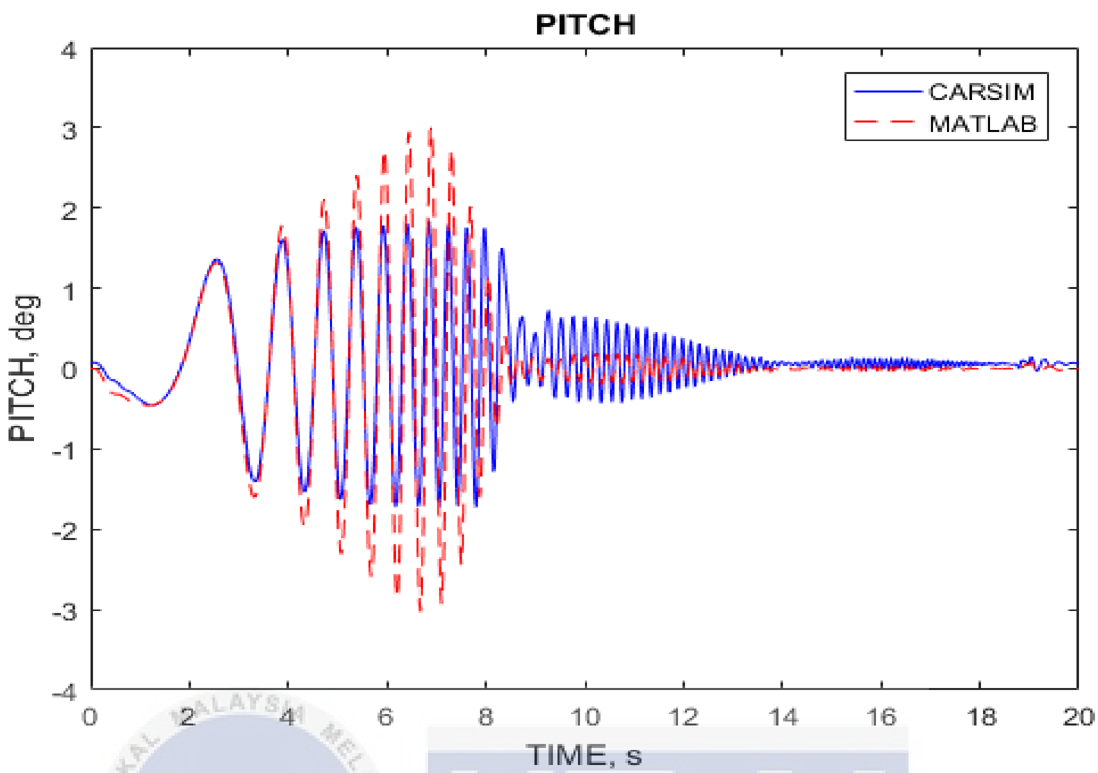


FIGURE 4.2: Verification of 4 DOF ride model on C = 30 kNs/m and K = 189 kN/m

Figure 4.3 and **Figure 4.4** shows the average difference between 4 DOF ride model and CarSimEd on pitch motion and vertical body acceleration with five different spring stiffness and five different damping value. From the both result, the difference magnitude between 4 DOF ride model and CarSimEd are very small range. So, it can be neglected the kinematic and compliance effect on suspension and can be proceed the simulation on three different type of vehicle which are SUV, full size, Sedan and Hatchback by using 4 DOF ride model in order to achieve the objectives.

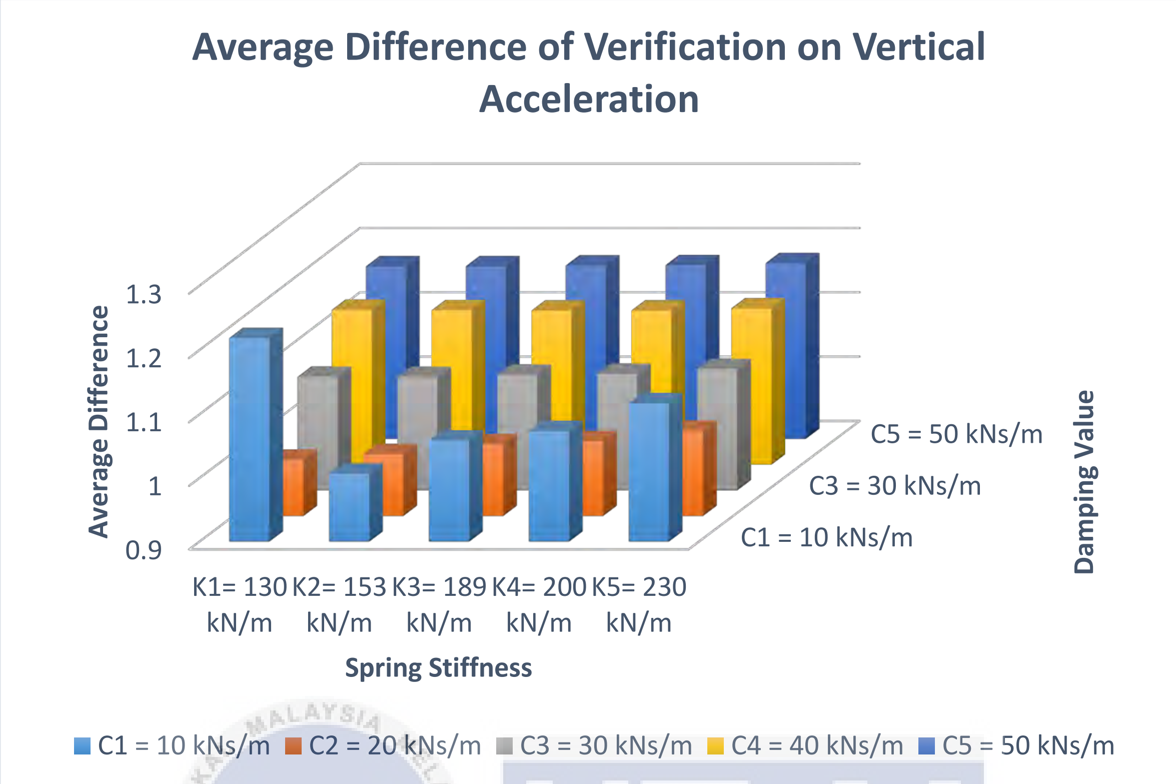


Figure 4.3: Average difference of verification (Vertical Acceleration)

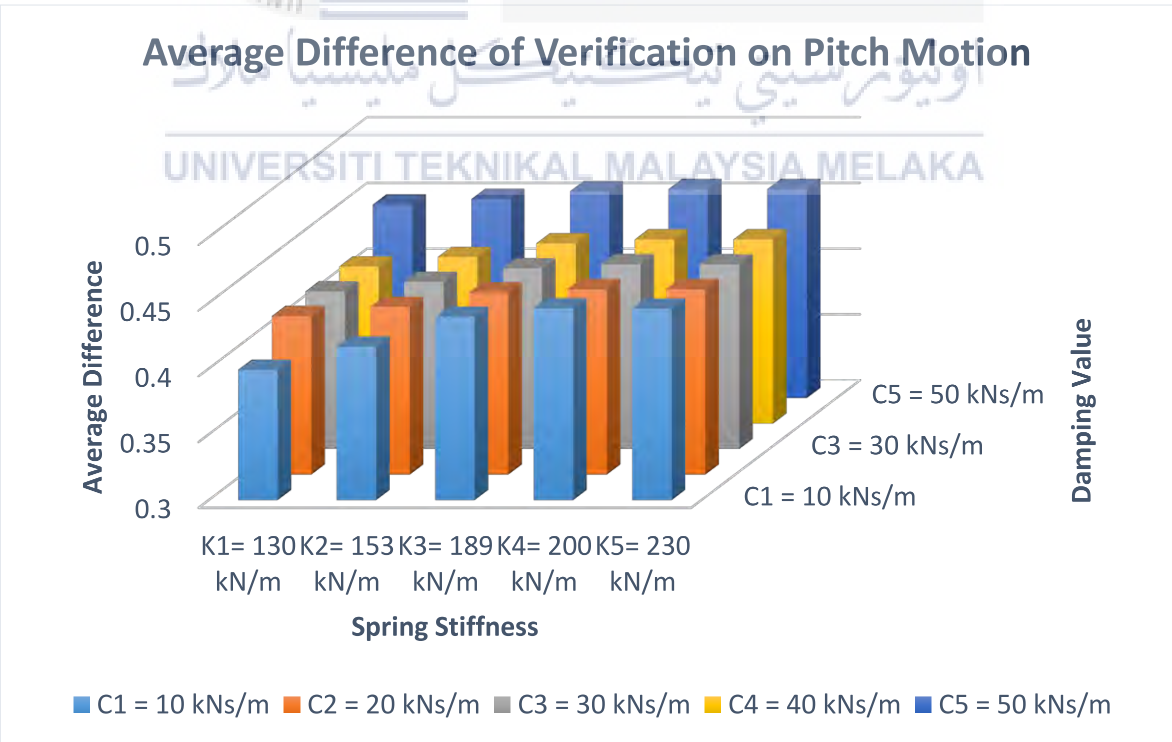


Figure 4.4: Average difference of verification (Pitch Motion)

4.2 Simulation by Using 4 DOF Ride Model

After the 4 DOF ride model have been verify, the experimental work will be conduct on three different type of vehicle which are Sedan, Hatchback and SUV, Full size car with five different spring stiffness and damping value in order to observe which parameter are most suitable for each of vehicle. The parameter randomly selected from CarSimEd with suitable range for each of the vehicle. The step input will be applied about 0.1m height of bump on the rear tire of 4 DOF ride model. The 4 DOF ride model will produce a different result of overshoot amplitude and settling time depends on the parameter of the vehicle, spring stiffness and damping value. From the result of overshoot amplitude and settling time, it can be select the optimal value of spring stiffness and damping for a vehicle in order to improve the comfort of vehicle.

4.2.1 Simulation for SUV, Full Size Car

In order to determine the most suitable value of spring stiffness and damping value for SUV, Full size car, it need to run the parameter of SUV, Full size car as shown in **Table 3.1** in the 4 DOF ride model with various spring stiffness and damping value to produce the schematic result which are representing the pitch body and vertical body acceleration. To improve the comfort of the vehicle, it need to analyse the amplitude of pitch body and vertical body acceleration. From the **Figure 4.5** until **Figure 4.9** shows that the result of pitch body effect when the vehicle hit the bump about 0.1m high on the road surface with different pattern of graph for five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five constant value of damping which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m .

Based on the result, the overshoot will happen when the tire of the vehicle hit the bump and will cause the impact to entire vehicle body. It can be noted that amplitude decreasing with respect to time which means the overshoot decreasing with settling time. Further, it seen that the amplitude overshoot of pitch body effect will increasing when the spring stiffness is stiffer. When the overshoot is higher, it will affect the settling time of vehicle body become longer to reduce the bounce. The lowest the amplitude response overshoot of the pitch body effect, the vehicle will more comfort when driving. To improve the comfort of the vehicle, it need to select the optimal spring stiffness and damping value that suitable with the SUV, Full car size. **Figure 4.5** and **Figure 4.6** shows the data cursor on each line to represent the overshoot value and settling time to tabulate the data in **Table 4.1** and **Table 4.2** for all figure.

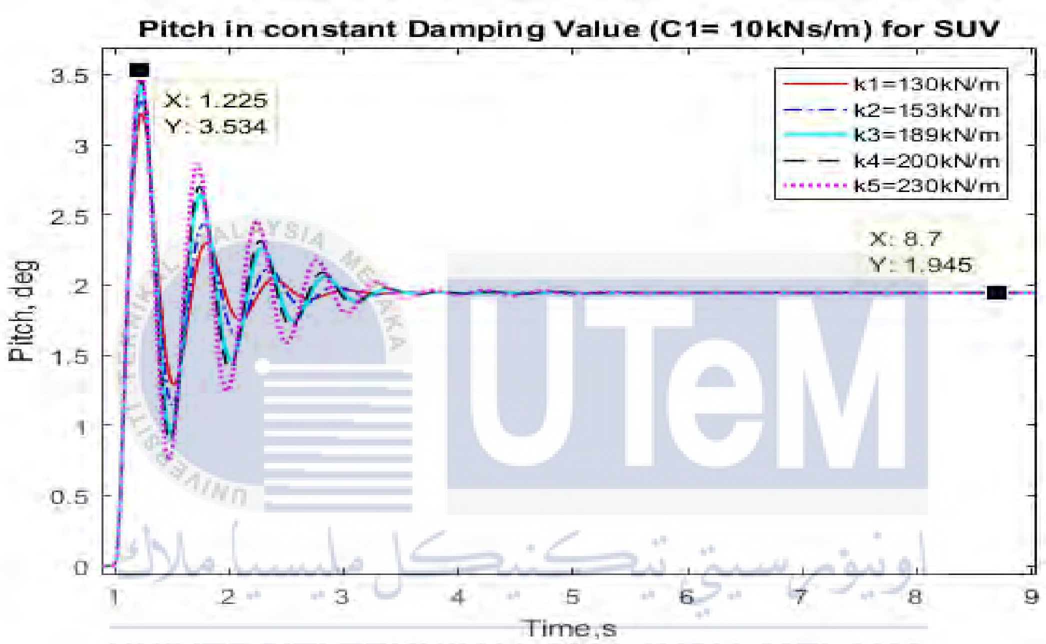


Figure 4.5: Pitch in constant damping value (C1 = 10 kNs/m) for SUV

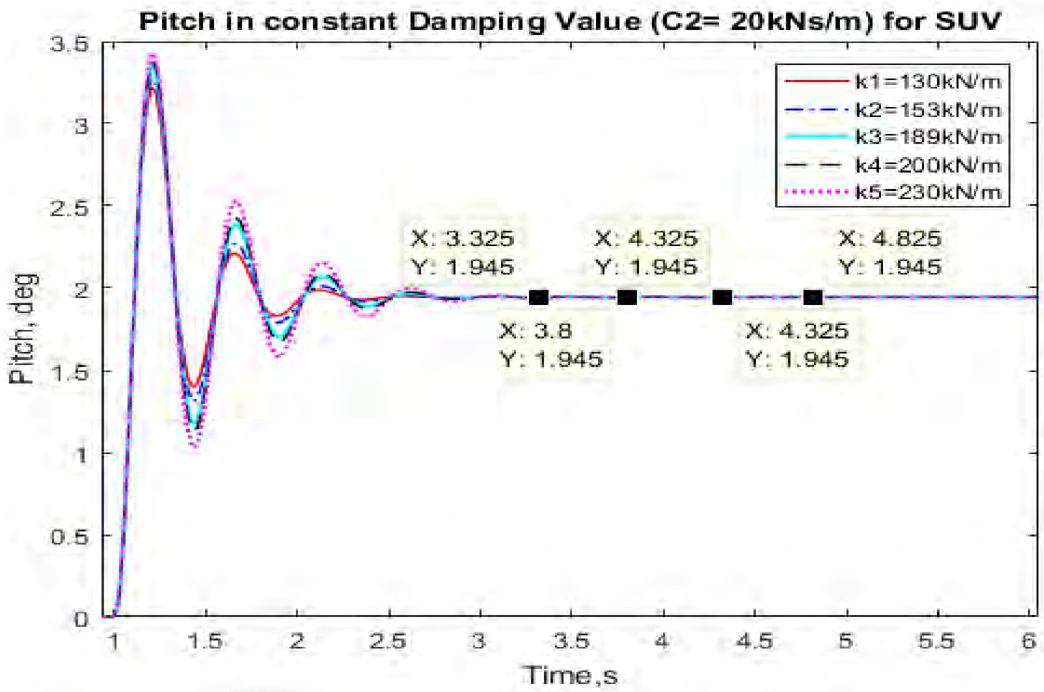


Figure 4.6: Pitch in constant damping value (C2 = 20 kNs/m) for SUV

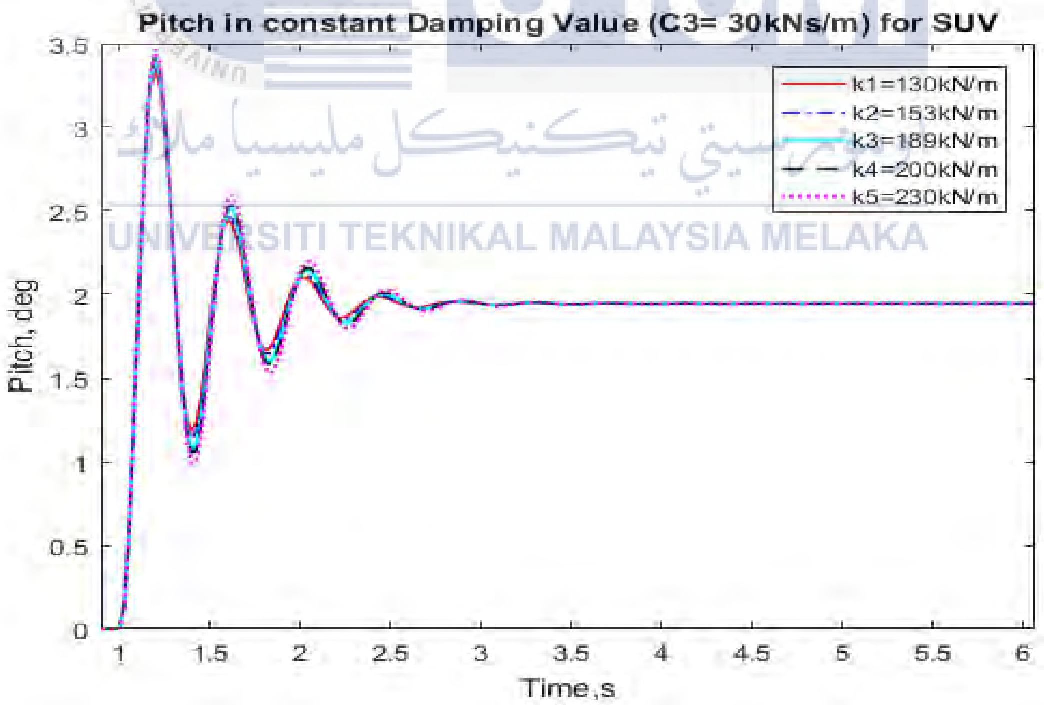


Figure 4.7: Pitch in constant damping value (C3 = 30 kNs/m) for SUV

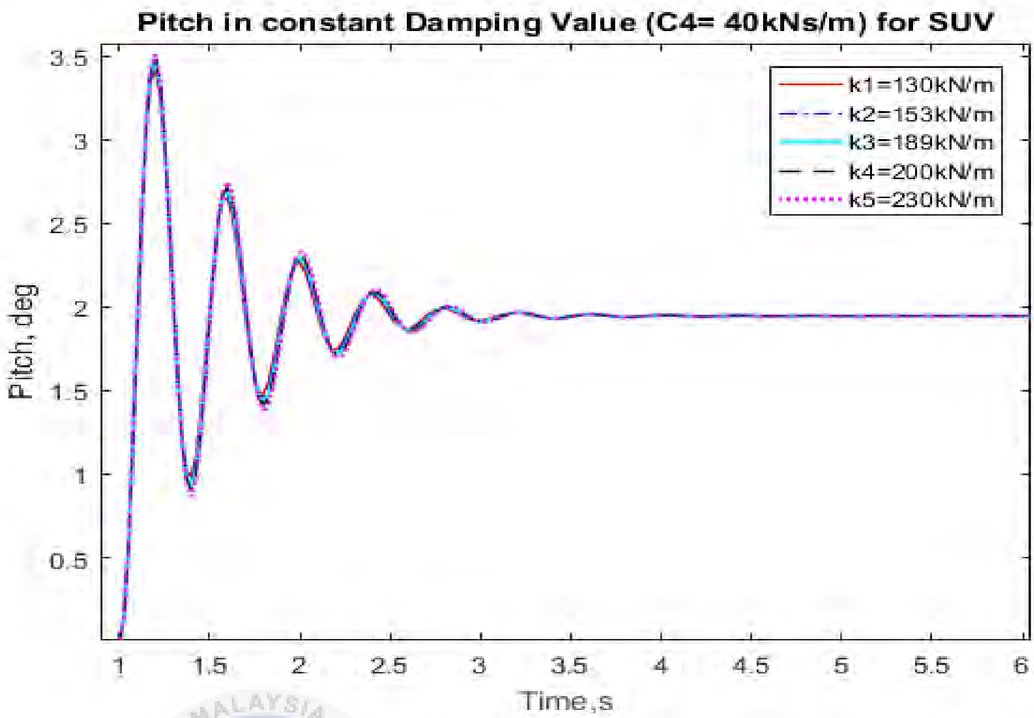


Figure 4.8: Pitch in constant damping value (C4 = 40 kNs/m) for SUV

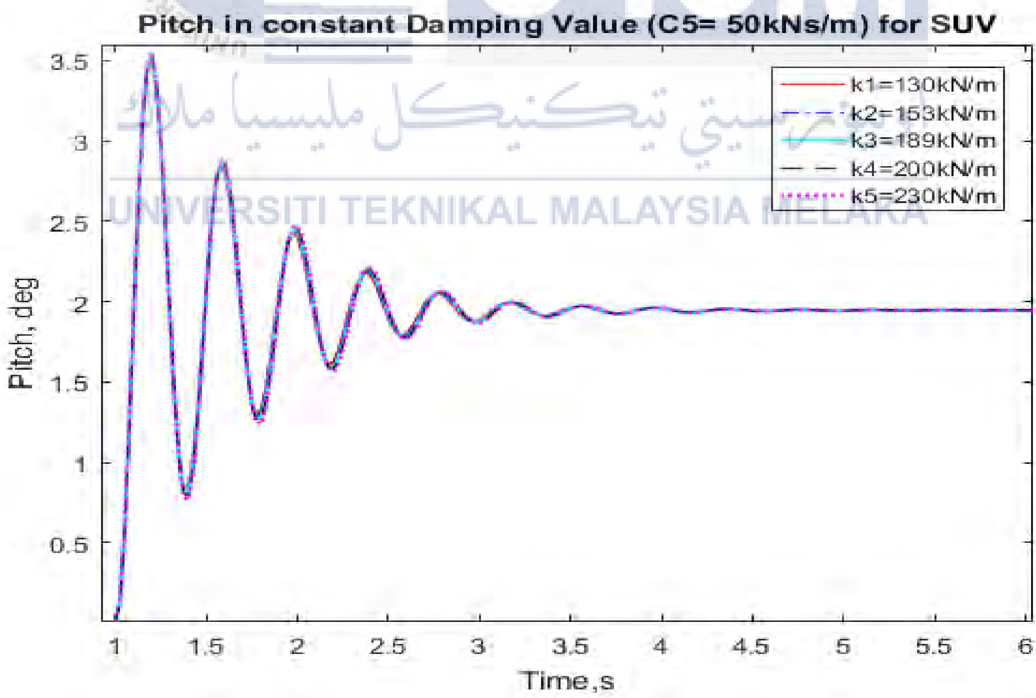


Figure 4.9: Pitch in constant damping value (C5 = 50 kNs/m) for SUV

From the **Figure 4.10** until **Figure 4.14** shows that the result of pitch body effect with five constant value of spring stiffness on five different value of damping which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m . When the vehicle hit the bump about 0.1m high on the road surface, it will produce a result of amplitude overshoot and settling time with various pattern depends on parameter of vehicle, spring stiffness and damping value.

Based on figure below, it can be observed that the overshoot and settling time of the pitch body effect on each value of spring stiffness and damping value. Further, it is seen that settling time is decreasing with very less drop in overshoot, which is undesirable for good ride and handling of the vehicle. So, the lower the value of damping, the overshoot of pitch body effect value become smaller with shortest settling time that able to reduce the bounce from the vehicle body. It can be noted that when no damping is provided the amplitude of overshoot is increased with time which means passenger will be getting lots of vibration and also it can be damage to the vehicles with a lot of wear and tear in the system. The highest the value of damping will provide the vehicle more comfort during driving through an uneven road. So, to improve the comfort of the vehicle, it need to select the optimal spring stiffness and damping value that suitable with the SUV, Full car size.

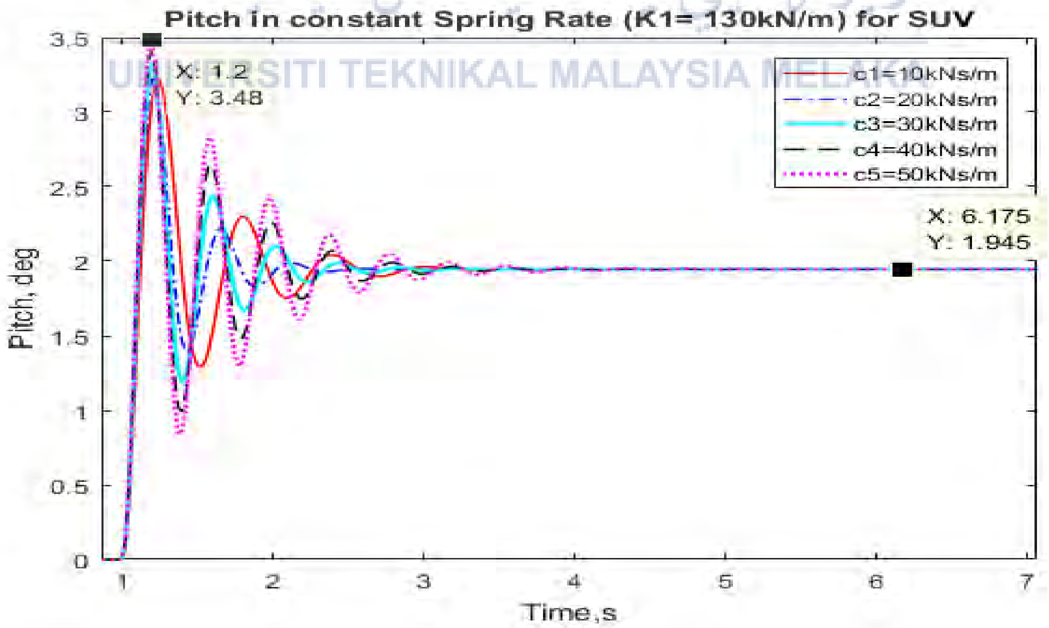


Figure 4.10: Pitch in constant spring rate (K1 = 130 kN/m) for SUV

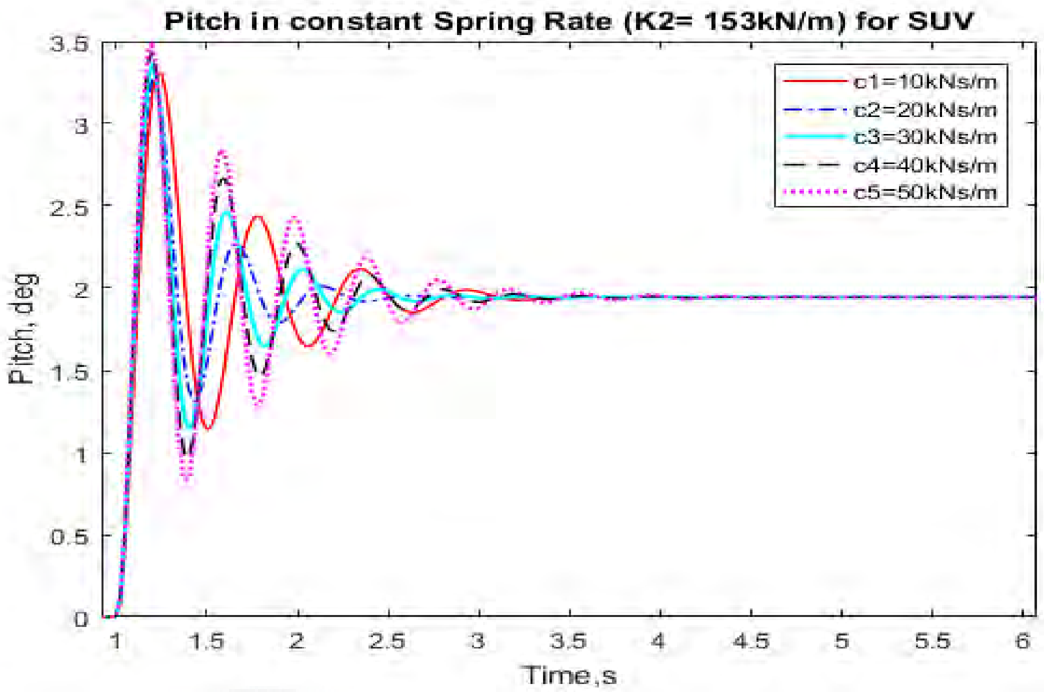


Figure 4.11: Pitch in constant spring rate (K2 = 153 kN/m) for SUV

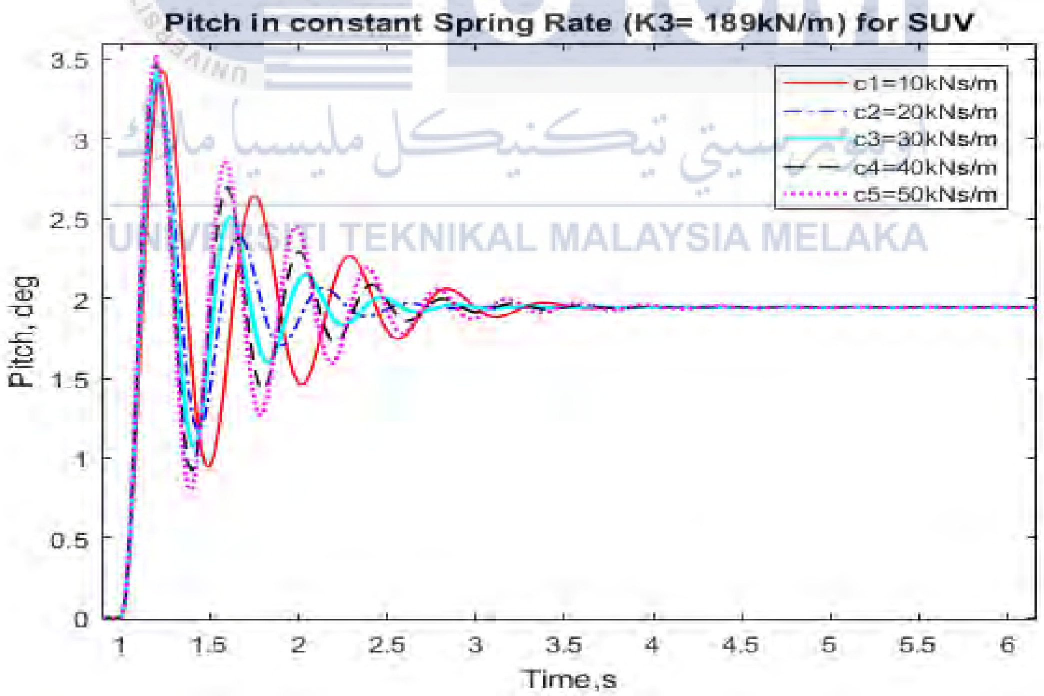


Figure 4.12: Pitch in constant spring rate (K3 = 189 kN/m) for SUV

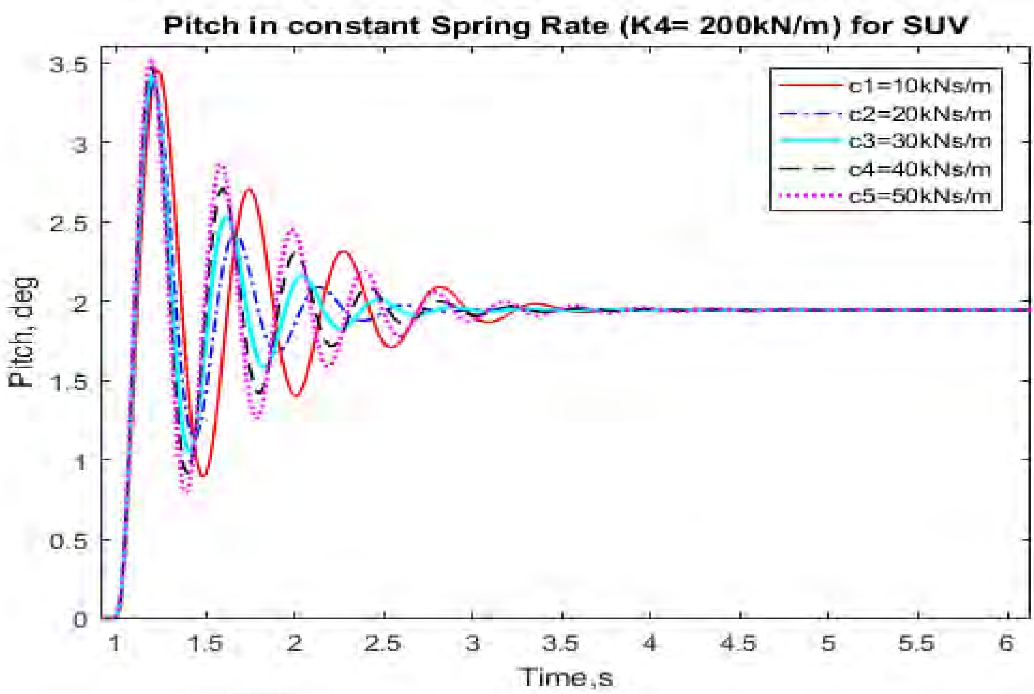


Figure 4.13: Pitch in constant spring rate (K4 = 200 kN/m) for SUV

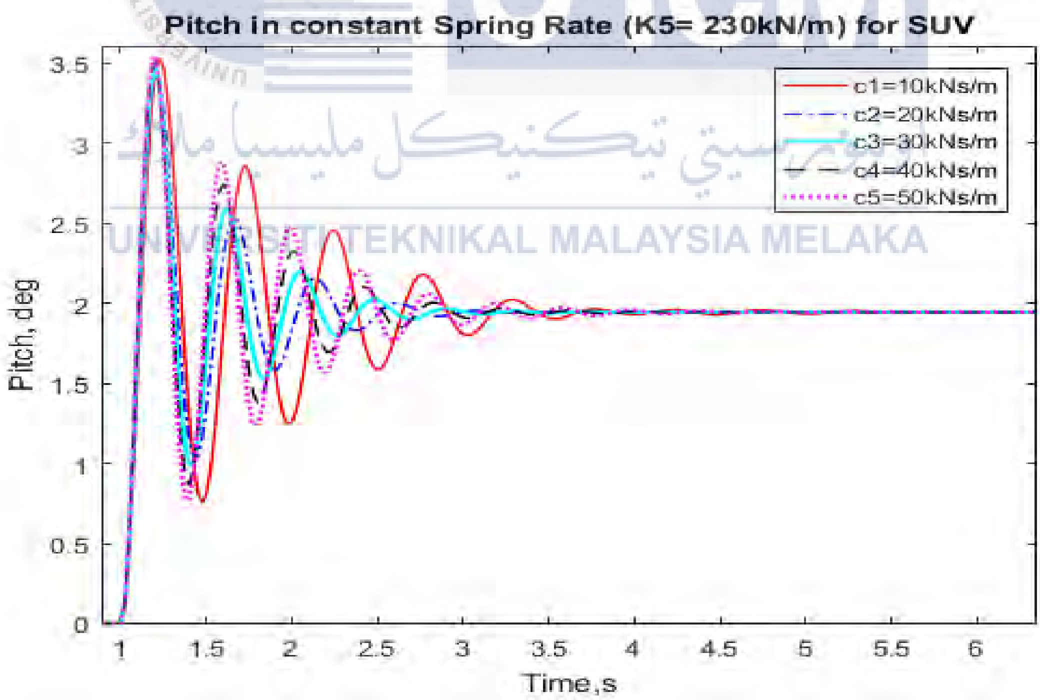


Figure 4.14: Pitch in constant spring rate (K5 = 230 kN/m) for SUV

Table 4.1 and Table 4.2 show that the value of amplitude overshoot and settling time from all the simulation below on the SUV, Full size car with five different value of spring stiffness on five different value of damping. From the table below, it can analyse the different overshoot value of pitch body effect and settling time from the vehicle body. From the simulation result of SUV, Full Size car, when apply damping value about 20 kNs/m and spring stiffness about 130 kN/m, it will produce the smallest amplitude of overshoot and shortest settling time.

Table 4.1: Overshoot (deg) for SUV on different spring stiffness and damping value.

		Damping Value				
	kNs/m kN/m	C1 = 10	C2 = 20	C3 = 30	C4 = 40	C5 = 50
Spring Stiffness	K1 = 130	3.221	3.224	3.335	3.418	3.480
	K2 = 153	3.307	3.278	3.370	3.442	3.498
	K3 = 189	3.429	3.354	3.419	3.476	3.523
	K4 =200	3.460	3.375	3.433	3.486	3.530
	K5 = 230	3.534	3.428	3.469	3.511	3.549

Table 4.2: Settling Time (s) for SUV on different spring stiffness and damping value.

		Damping Value				
	kNs/m kN/m	C1 = 10	C2 = 20	C3 = 30	C4 = 40	C5 = 50
Spring Stiffness	K1 = 130	5.050	3.325	4.350	5.425	6.175
	K2 = 153	6.100	3.800	4.375	5.450	6.200
	K3 = 189	6.575	4.325	4.800	5.500	6.600
	K4 =200	7.700	4.325	4.825	5.500	6.600
	K5 = 230	8.700	4.825	4.900	5.900	6.625

Figure 4.15 and **Figure 1.6** shows that the overall result for SUV, Full size car with same parameter and various value spring stiffness and damping against to overshoot and settling time for pitch body effect. It can be noted that the different spring stiffness and damping value the performance of the vehicle suspension system. Basically, the spring stiffness and damping value of suspension system will be selected depending on the vehicle parameter. If the vehicle has a heavy mass on the vehicle body, the spring stiffness and damping value should be higher to support the vertical motion of the vehicle body when hit a bump or driving through an uneven road. It is because suspension spring able to support the weight of vehicle body and passenger while a damper able to absorb and reduce the bounce force that exerted on the vehicle body. From overall simulation result for SUV, Full size car, it can be noted that damping value is more important in vehicle compare to spring stiffness. It is because the damper will absorb the vertical force that affect the pitch motion on the vehicle body and reduce the bounce force from the road surface transmit to vehicle body while the spring of suspension only hold the vehicle body from the shock impact. So, in order to achieve the comfort of the vehicle, it need to select the optimal value of spring stiffness and damping which are suitable with the parameter of the SUV, Full size car.

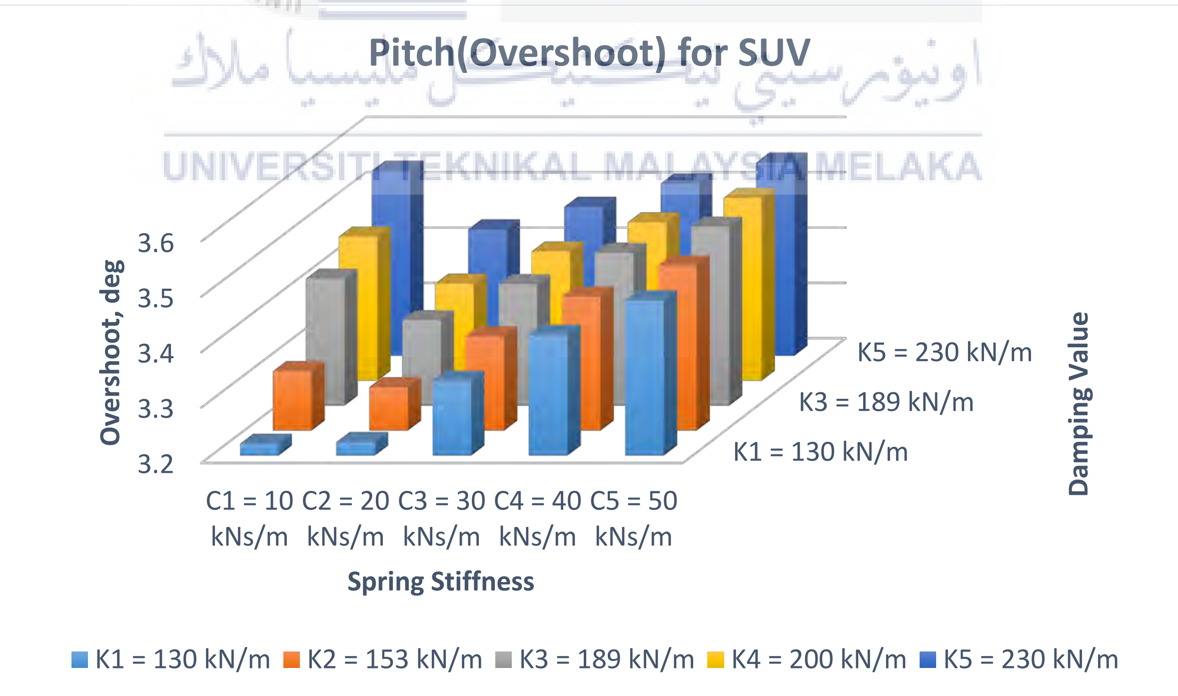


Figure 4.15: Overall result of pitch motion for SUV (Overshoot,deg)

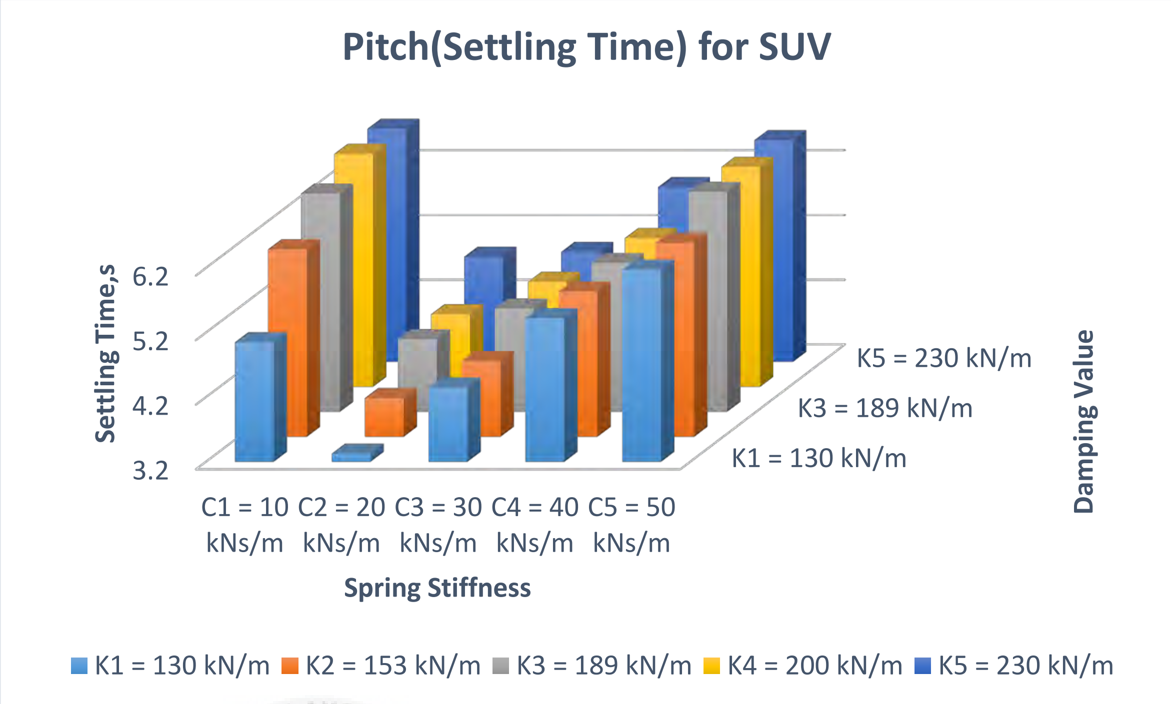


Figure 4.16: Overall result of pitch motion for SUV (Settling Time,s)

Figure 4.17 until **4.21** shows that the result of vertical acceleration happens of SUV, Full size car in five constant damping value which are on five different value of spring stiffness. It can be noticed that the effect of five different value of spring stiffness and damping due to the vertical acceleration of the vehicle body. Basically, vertical acceleration is the movement of centre of gravity on the vehicle body when hit the bump or driving through an uneven road. The vertical acceleration also the important factor to improve the comfort of the vehicle.

For this simulation, the vehicle body also will experience the overshoot when hit the bump with 0.1m height. Based on the result, it can be noticed that the higher value of spring stiffness, it will affect the overshoot on vertical body acceleration of vehicle body. when the overshoot on vertical body acceleration is higher, it will reduce the comfort of the vehicle and able to damage the system. So, it need to run the result with different value of spring stiffness in order to determine the optimal value for spring stiffness that suitable with the SUV, Full size car. **Figure 4.17** shows the data cursor on overshoot for each of the result in order to tabulate the data in **Table 4.3**.

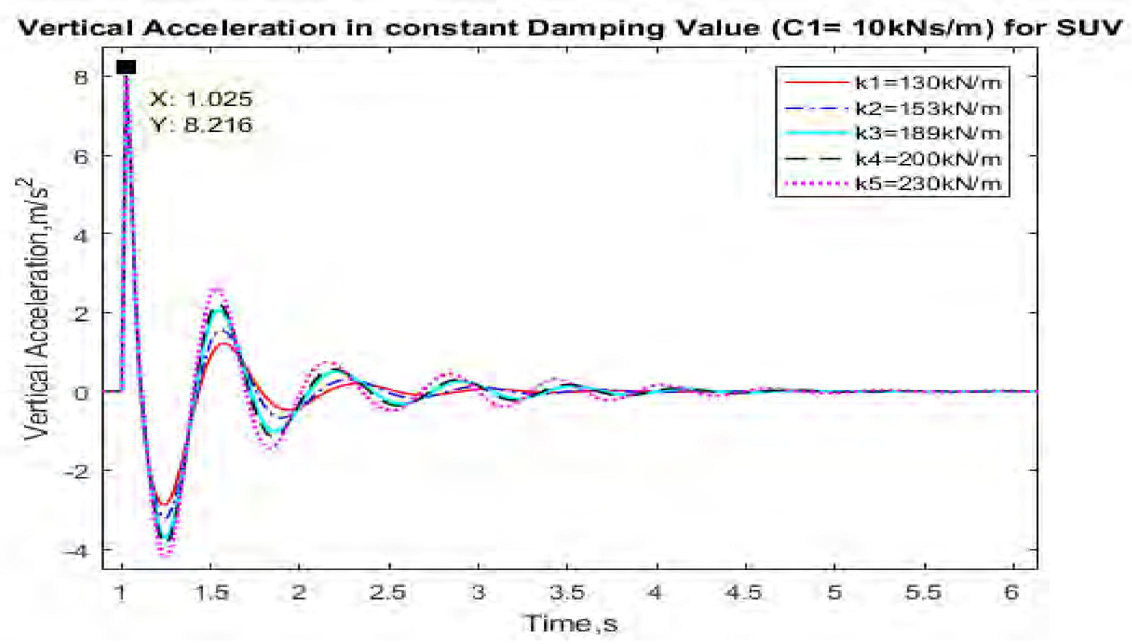


Figure 4.17: Vertical acceleration in constant damping value (C1 =10 kNs/m) for SUV

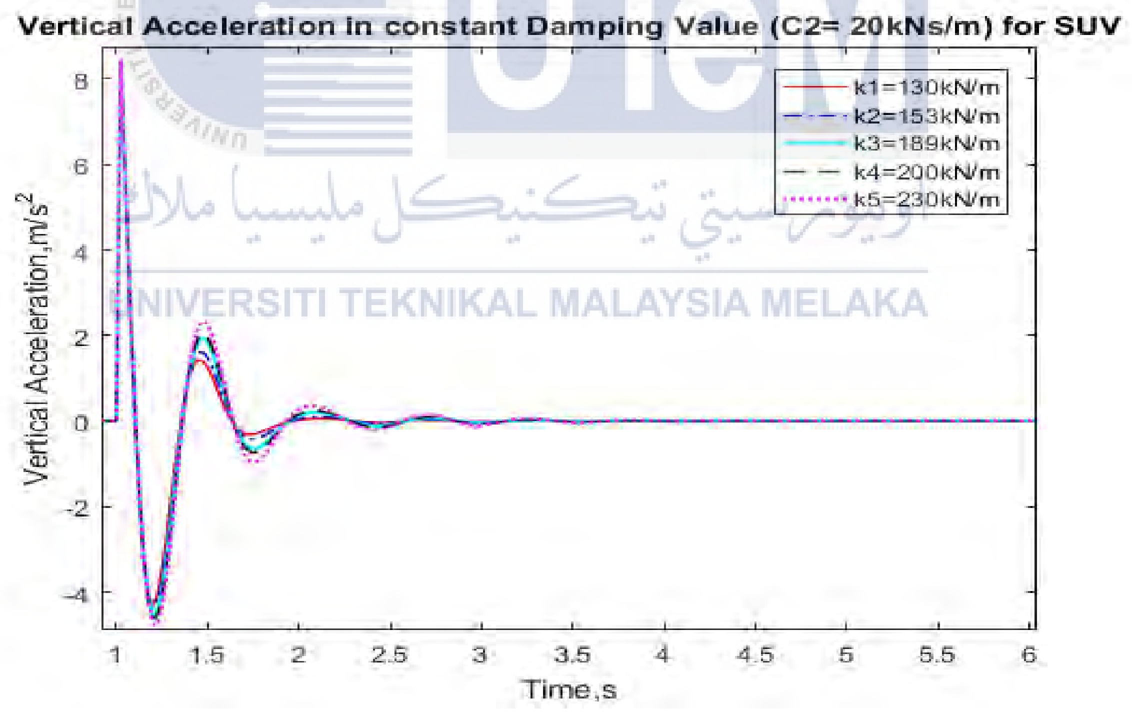


Figure 4.18: Vertical acceleration in constant damping value (C2 =20 kNs/m) for SUV

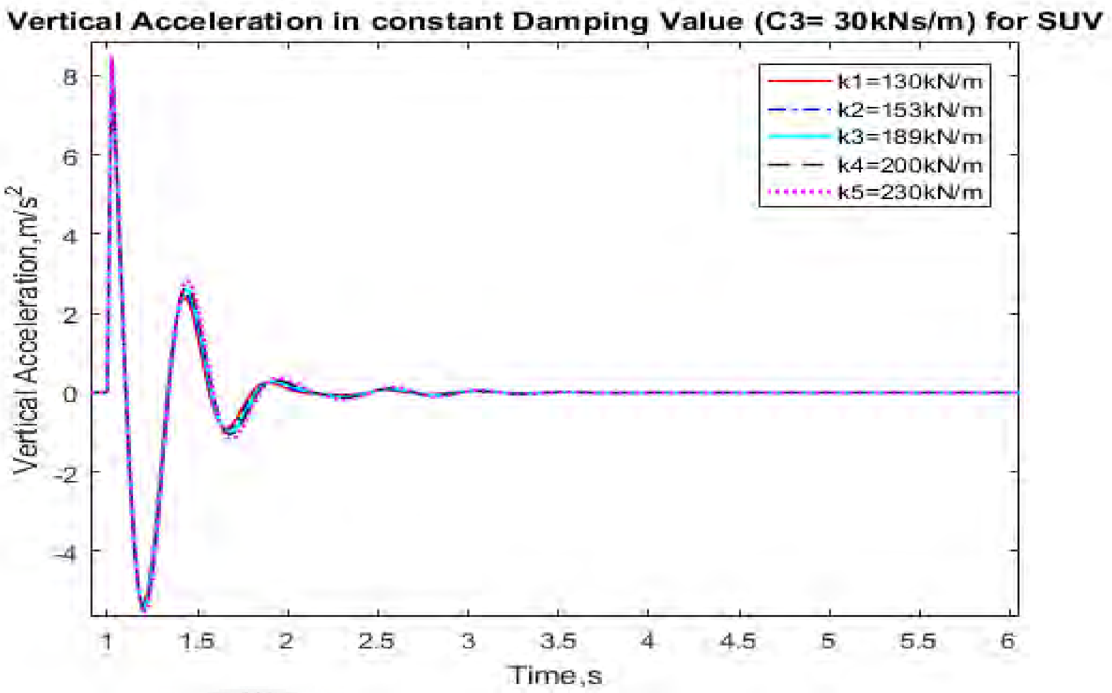


Figure 4.19: Vertical acceleration in constant damping value (C3 =30 kNs/m) for SUV

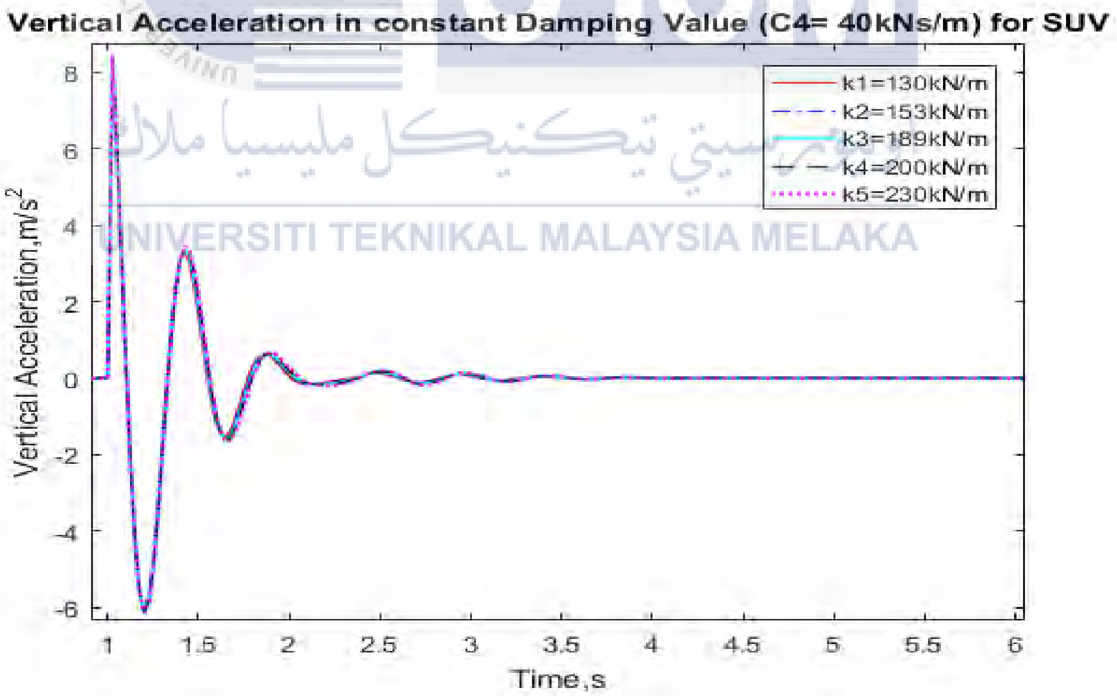


Figure 4.20: Vertical acceleration in constant damping value (C4 =40 kNs/m) for SUV

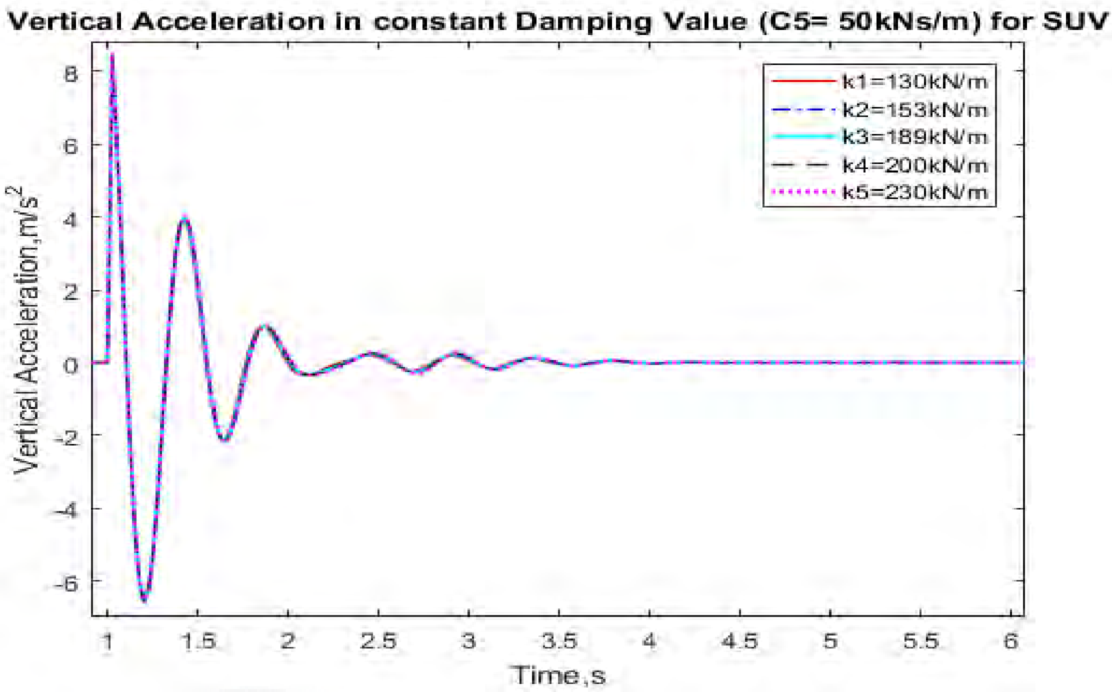


Figure 4.21: Vertical acceleration in constant damping value (C5 =50 kNs/m) for SUV

Figure 4.22 until 4.26 shows that the result of vertical acceleration happens of SUV, Full size car in five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five constant damping value which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m.

It can be observed the effect of vertical body acceleration based on the five-different value of damping with constant spring stiffness on the SUV, Full size car. Damper is the important component of the suspension system to absorb the undesirable force from the road exerted on the vehicle body. So, in order to improve the comfort of SUV, Full size car, it need to determine the optimal damping value that are able to reduce the overshoot value of vertical body acceleration and shorten the settling time on vehicle body. It can be noted that from the simulation, the higher the value of damping on the SUV, it will reduce the overshoot and settling time of the vertical body acceleration.

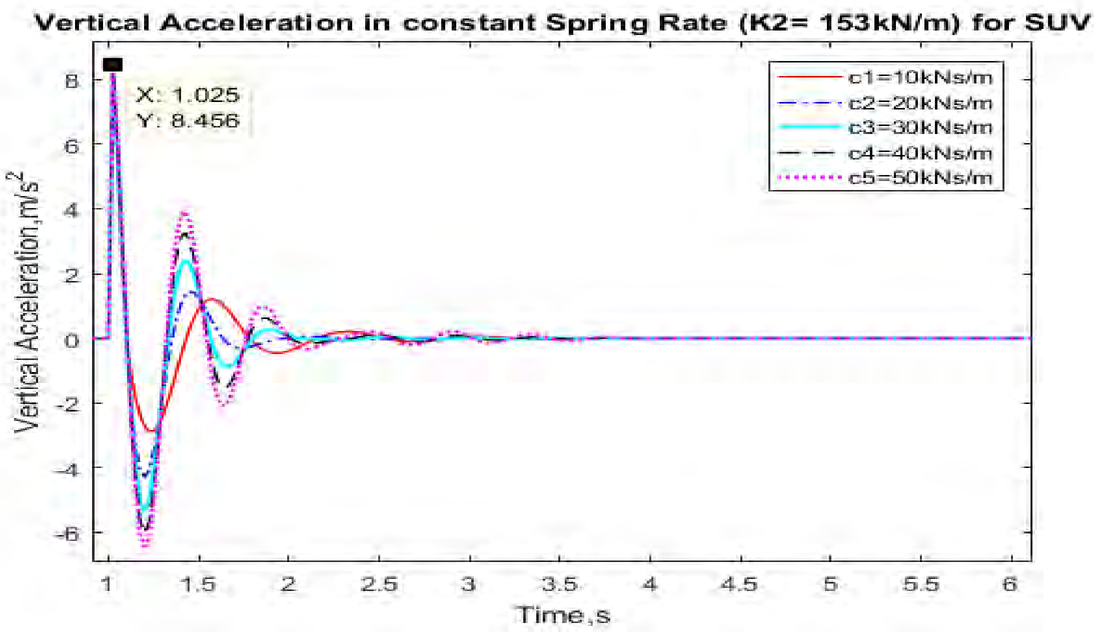


Figure 4.22: Vertical acceleration in constant spring rate (K1 =130 kN/m) for SUV

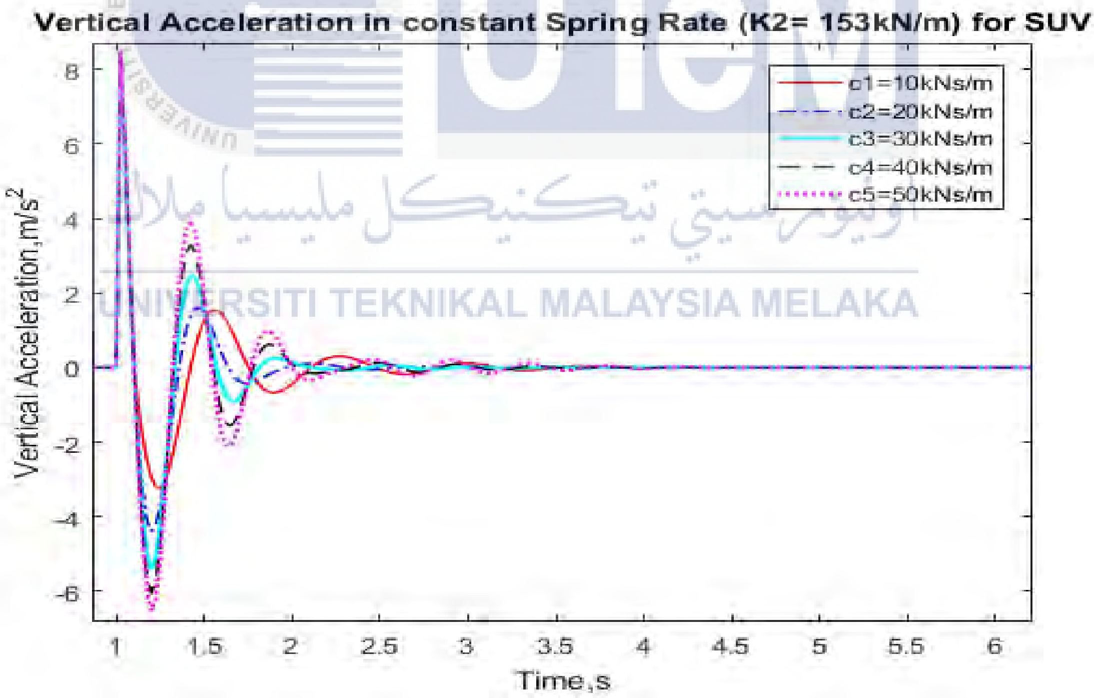


Figure 4.23: Vertical acceleration in constant spring rate (K2 =153 kN/m) for SUV

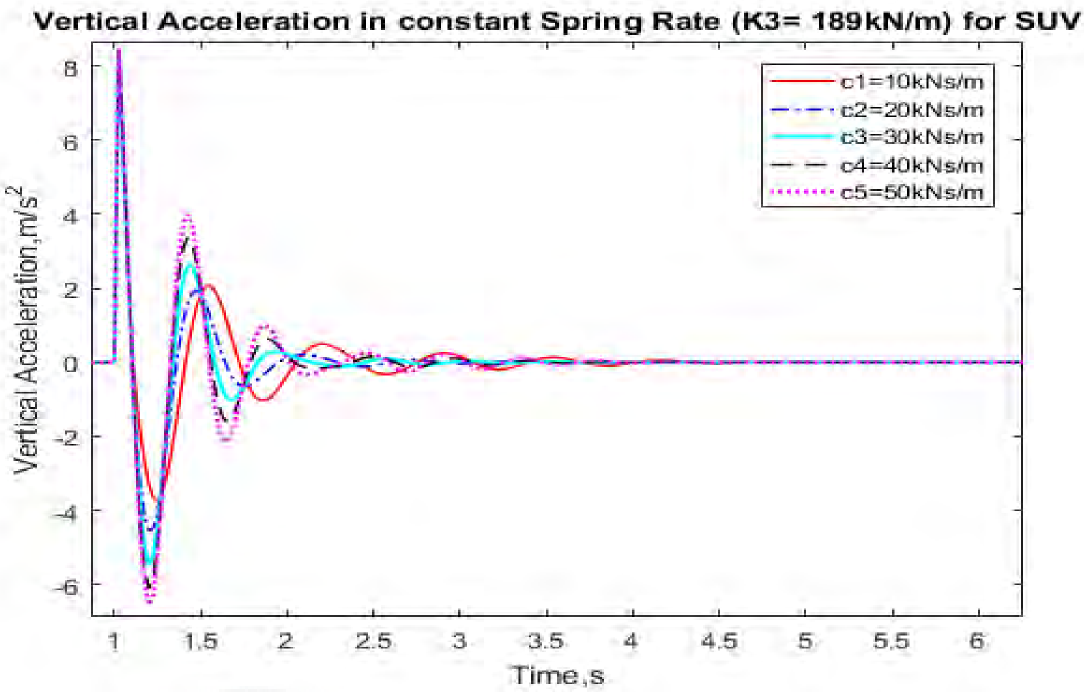


Figure 4.24: Vertical acceleration in constant spring rate (K3 =189 kN/m) for SUV

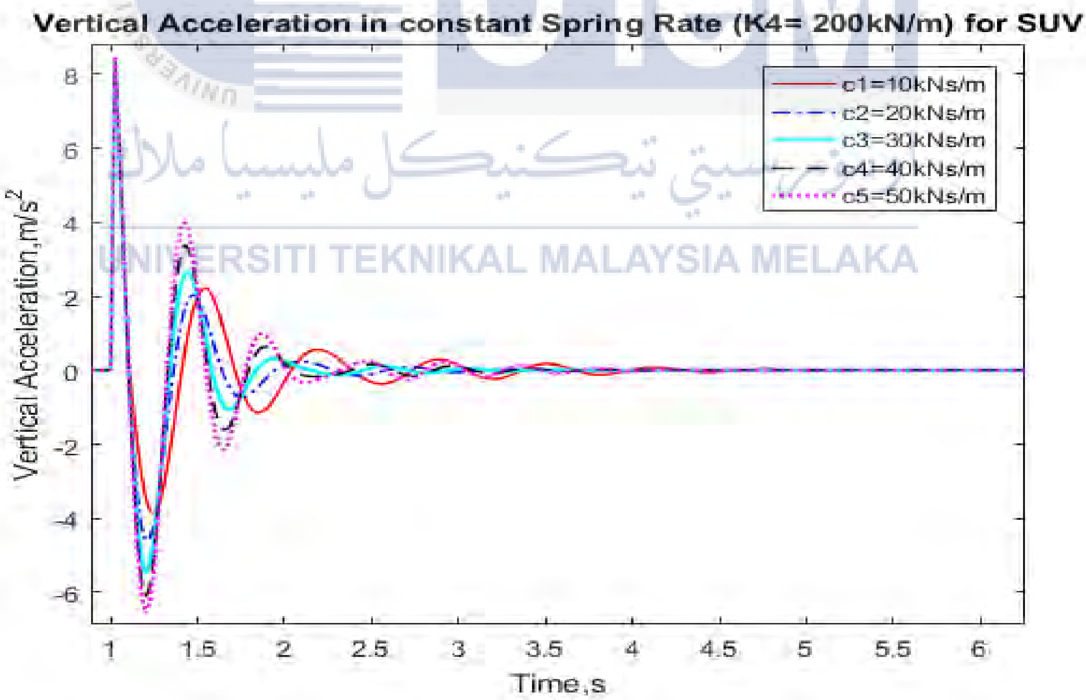


Figure 4.25: Vertical acceleration in constant spring rate (K4 =200 kN/m) for SUV

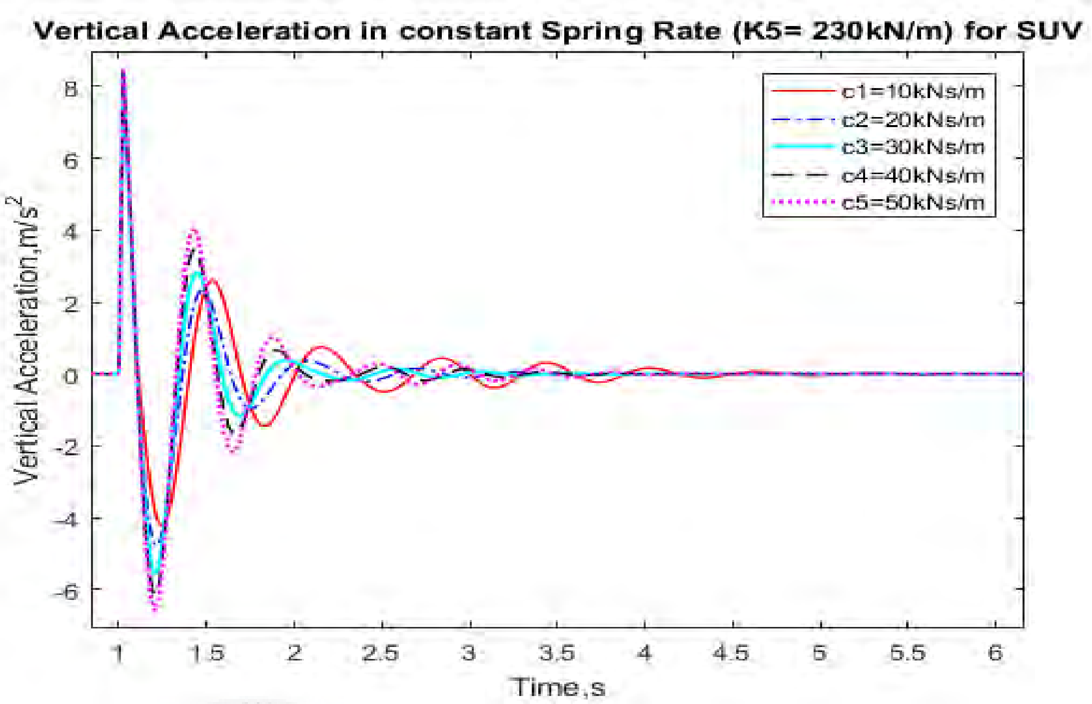


Figure 4.26: Vertical acceleration in constant spring rate (K5 =230 kN/m) for SUV

Table 4.3 shows that the value of overshoot that experienced on vertical body acceleration with various spring stiffness and damping value. It can see that the lowest overshoot value that experienced on vertical body acceleration on the SUV, Full size car with spring stiffness about 130 kN/s and damping value about 10 kNs/m.

Figure 4.27 shows that the overall result of overshoot vertical body acceleration on the SUV, Full size car with various value of spring stiffness and damping. So, it can be concluded that the most suitable range value of spring stiffness between 130 kN/m to 153 kN/m while for damping value between 10 kNs/m and 20 kNs/m on the SUV, Full size car.

Table 4.3: Overshoot for SUV on different spring stiffness and damping value.

	kNs/m / kN/m	Damping Value				
		C1 = 10	C2 = 20	C3 = 30	C4 = 40	C5 = 50
Spring Stiffness	K1 = 130	7.467	8.470	8.338	8.400	8.456
	K2 = 153	7.783	8.403	8.367	8.417	8.468
	K3 = 189	7.989	8.378	8.410	8.444	8.485
	K4 =200	8.051	8.293	8.423	8.452	8.491
	K5 = 230	8.216	8.238	8.458	8.473	8.505

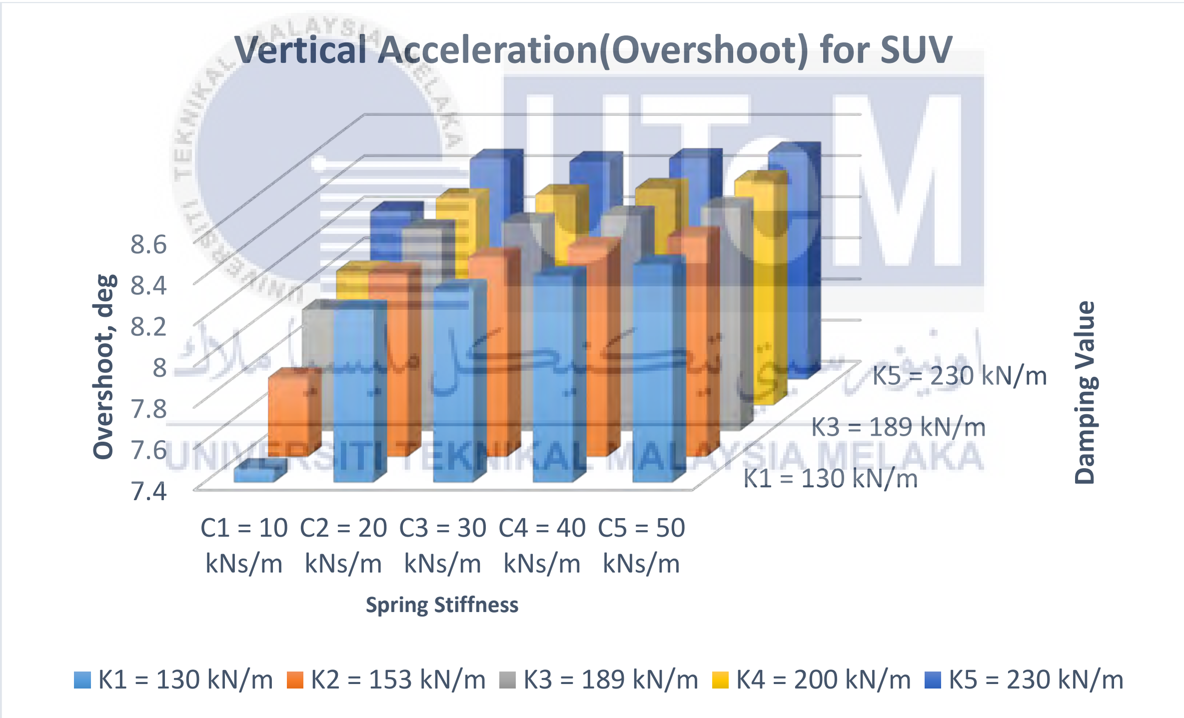


Figure 4.27: Overall result of vertical acceleration for SUV (Overshoot, deg)

4.2.2 Simulation for Sedan

The 4 DOF ride model will simulated the parameter of Sedan car as shown in **Table 3.3** with the five different value of spring stiffness and damping in order to observe the pitch body effect and vertical body acceleration of Sedan car. In order to determine the most suitable value of spring stiffness and damping value for Sedan car, it need to run the parameter of Sedan car in the 4 DOF ride model with various spring stiffness and damping value to produce the schematic result which are representing the pitch body and vertical body acceleration. To improve the comfort of the vehicle, it need to analyse the amplitude of pitch body and vertical body acceleration.

From the **Figure 4.28** until **Figure 4.32** shows that the result of pitch body effect when the vehicle hit the bump about 0.1m high on the road surface with different pattern of graph for five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five constant value of damping which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40kNs/m and c_5=50 kNs/m .

Based on the result, it can be analysed that the pattern of pitch motion for Sedan car with five constant value of damping on five different spring stiffness. It can be observed that the overshoot and settling time of the pitch body effect on each value of spring stiffness on constant damping value. The overshoot will happen when the tire of the vehicle hit the bump and will cause the impact to entire vehicle body. It can be noted that amplitude decreasing with respect to time which means the overshoot decreasing with settling time. Further, it seen that the amplitude overshoot of pitch body effect will increasing when the spring stiffness is stiffer. When the overshoot is higher, it will affect the settling time of vehicle body become longer to reduce the bounce. The lowest the amplitude response overshoot of the pitch body effect, the vehicle will more comfort when driving. To improve the comfort of the vehicle, it need to select the optimal spring stiffness and damping value that suitable with the SUV, Full car size.

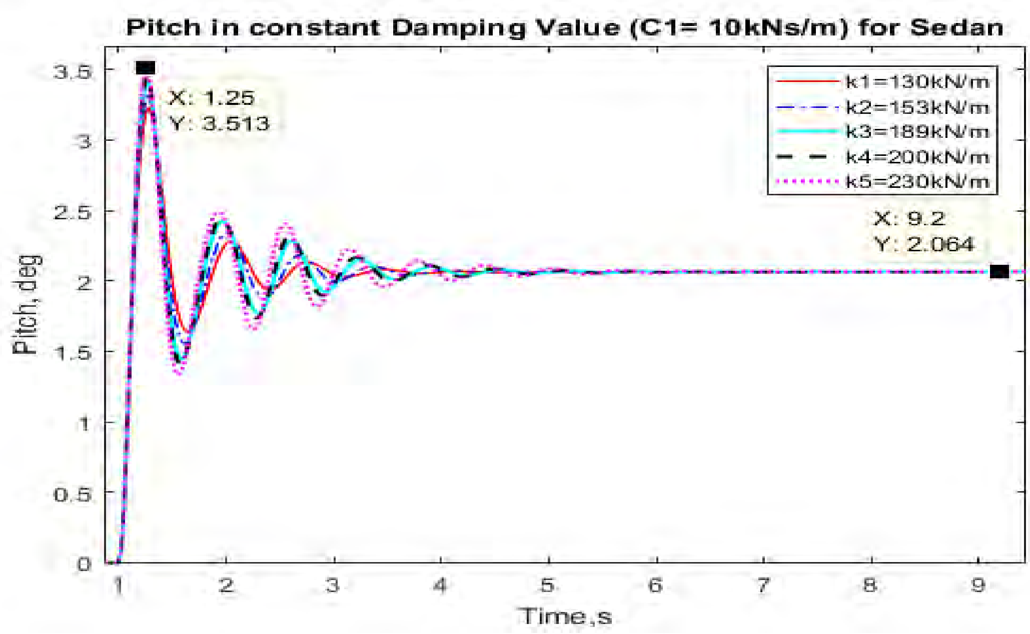


Figure 4.28: Pitch in constant damping value (C1 = 10 kNs/m) for Sedan

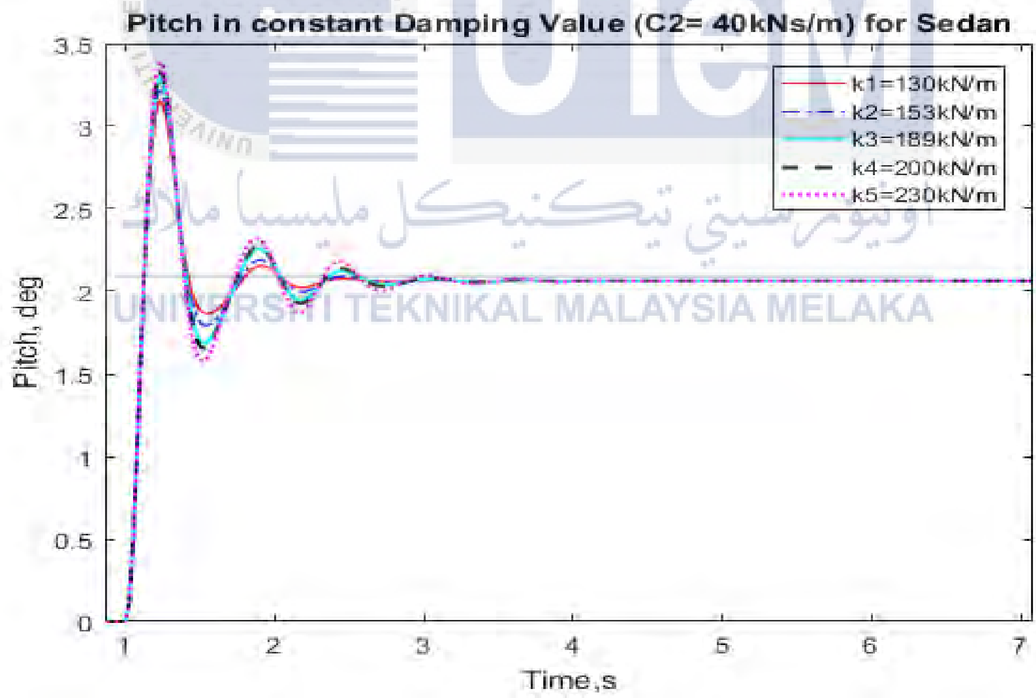


Figure 4.29: Pitch in constant damping value (C2 = 20 kNs/m) for Sedan

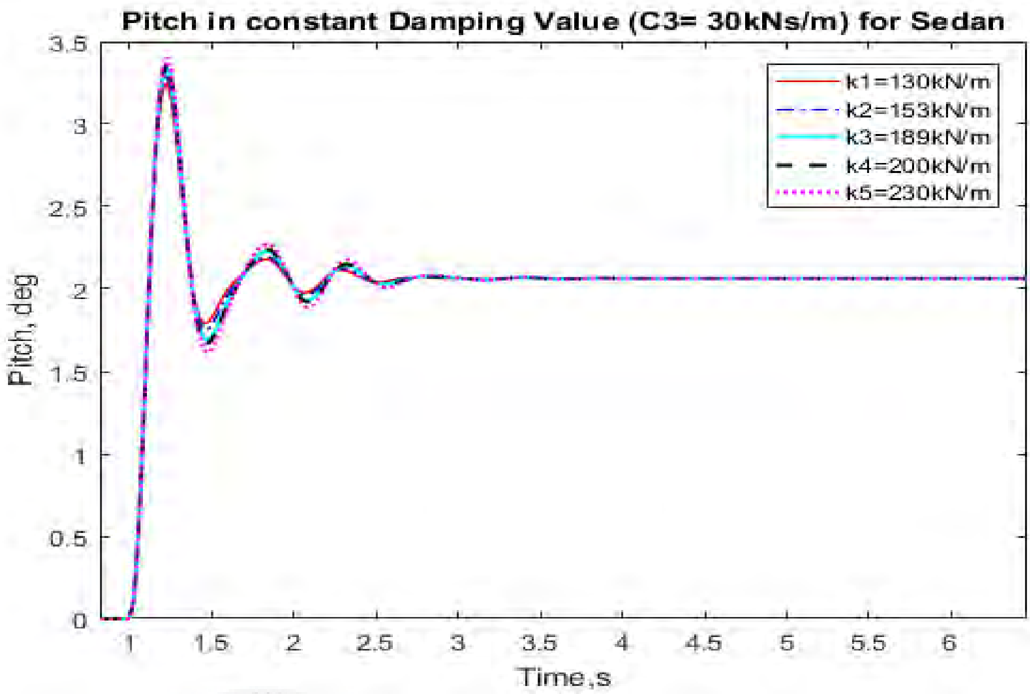


Figure 4.30: Pitch in constant damping value (C3 = 30 kNs/m) for Sedan

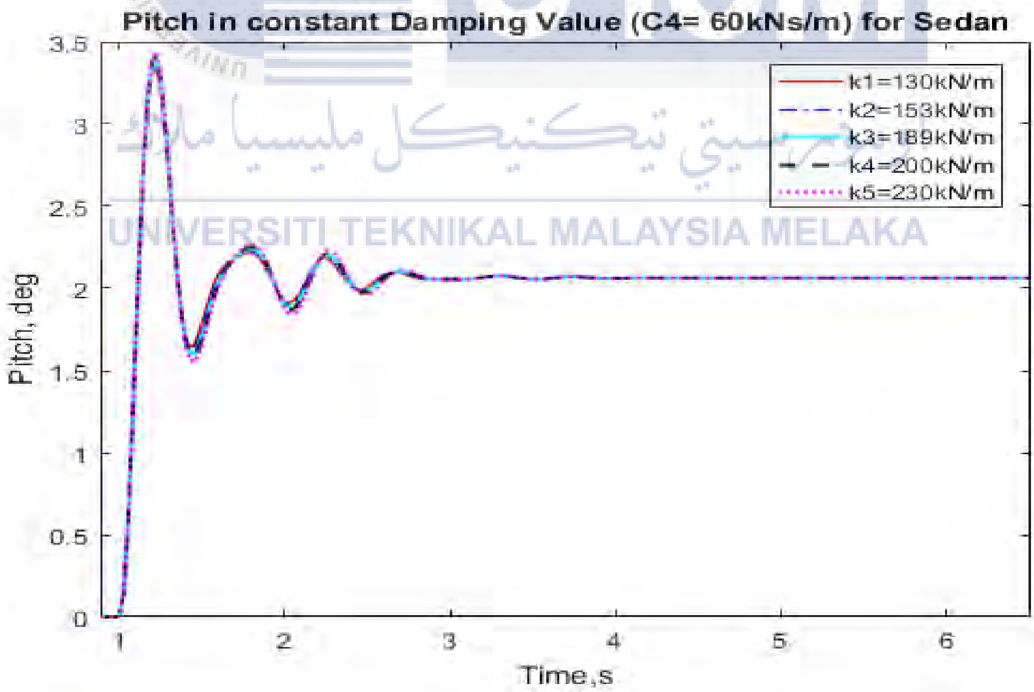


Figure 4.31: Pitch in constant damping value (C4 = 40 kNs/m) for Sedan

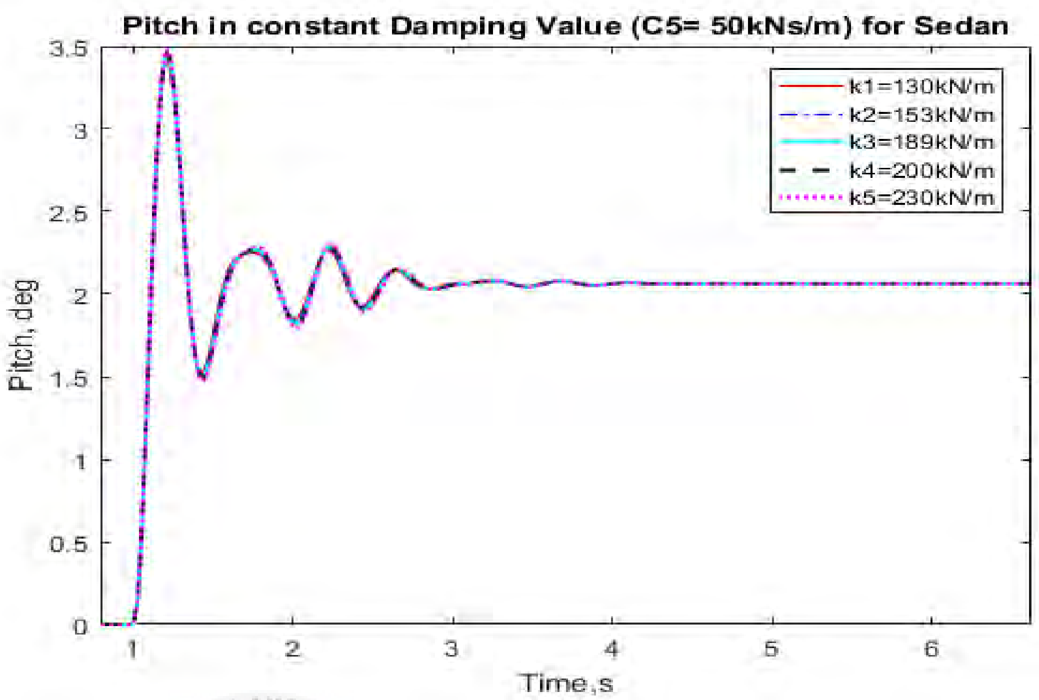


Figure 4.32: Pitch in constant damping value (C5 = 50 kNs/m) for Sedan

From the **Figure 4.33** until **Figure 4.37** shows that the result of pitch body effect with five constant value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five different value of damping which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m . It seen that the various value of damping will be more affected the amplitude overshoot and settling time of pitch motion.

From the result, it can noted that damper allow a significant effect compare to the spring of suspension. It is because damper of suspension acts as a mechanism that absorb the vertical force from the force transmit to vehicle body. Other than that, damper also acts as a mechanism that reduce the bounce force when the vehicle tire hit the bump and directly affecting the vehicle body. So, the higher value of damping will be provided better performance to the suspension system because able to reduce more vertical force and bounce force when the vehicle tire hit the bump. But, in order to improve the passenger comfort, the damper stiffness of the suspension need to be matched with the spring stiffness depends on the parameter of the vehicle.

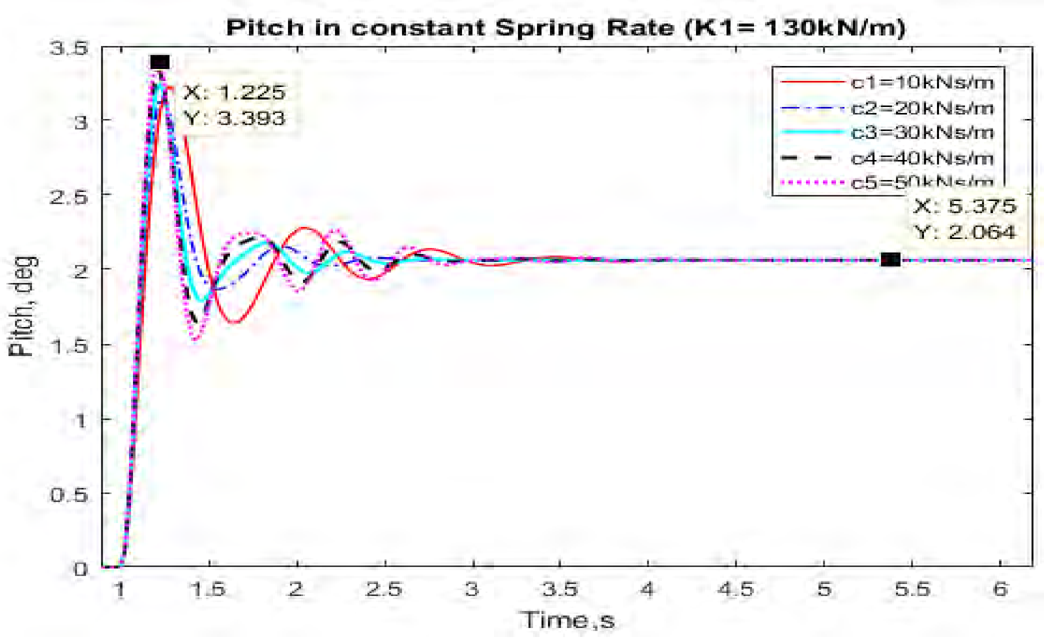


Figure 4.33: Pitch in constant spring rate (K1 = 130 kN/m) for Sedan

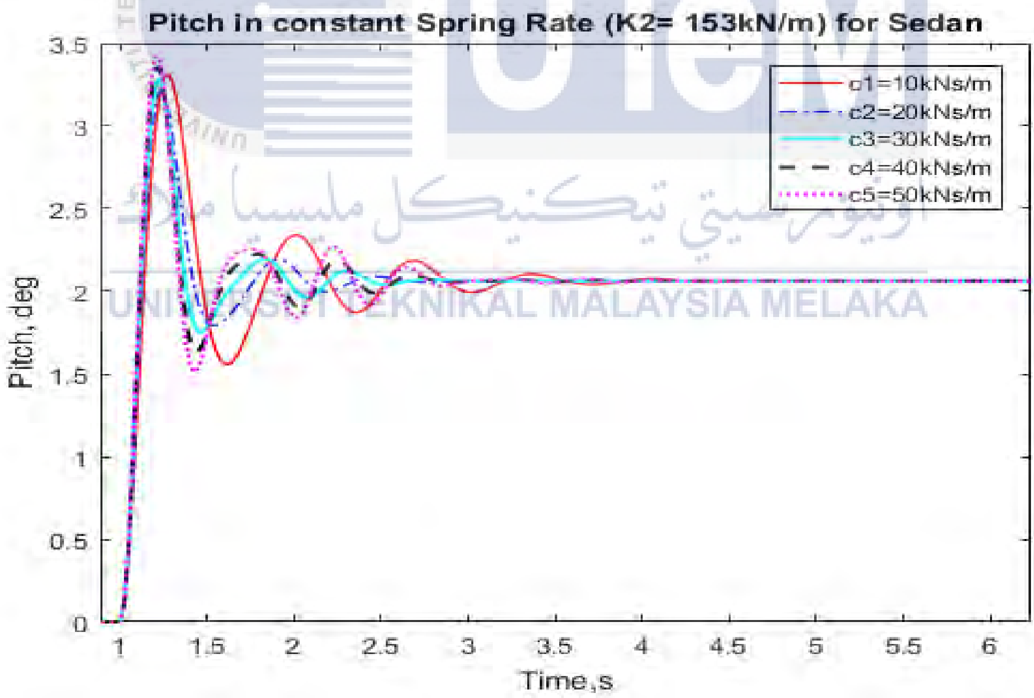


Figure 4.34: Pitch in constant spring rate (K2 = 153 kN/m) for Sedan

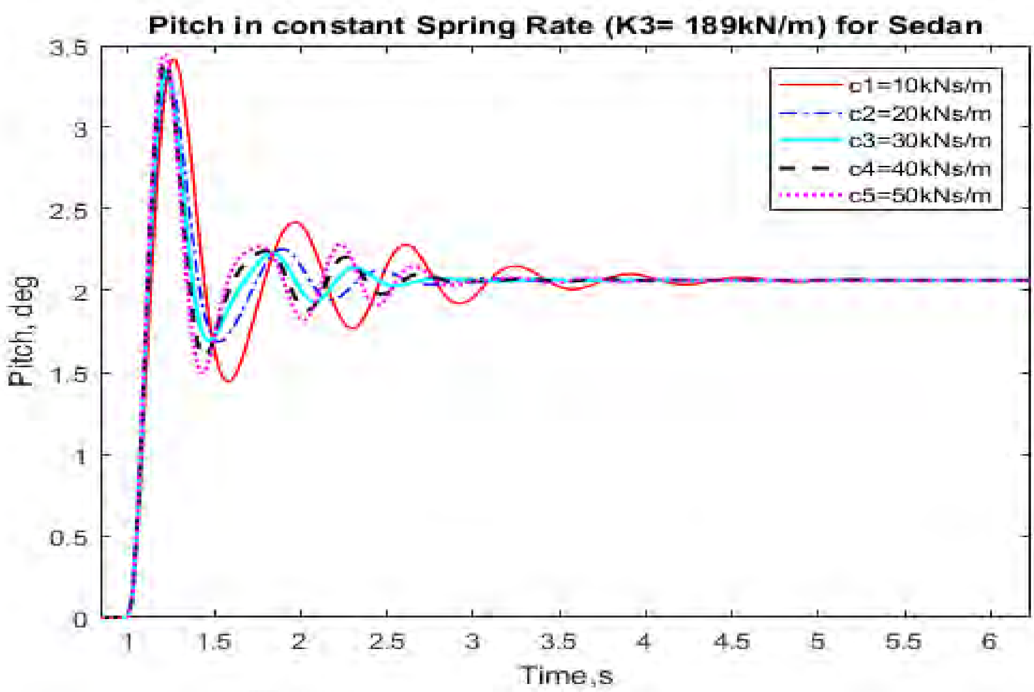


Figure 4.35: Pitch in constant spring rate (K3 = 189 kN/m) for Sedan

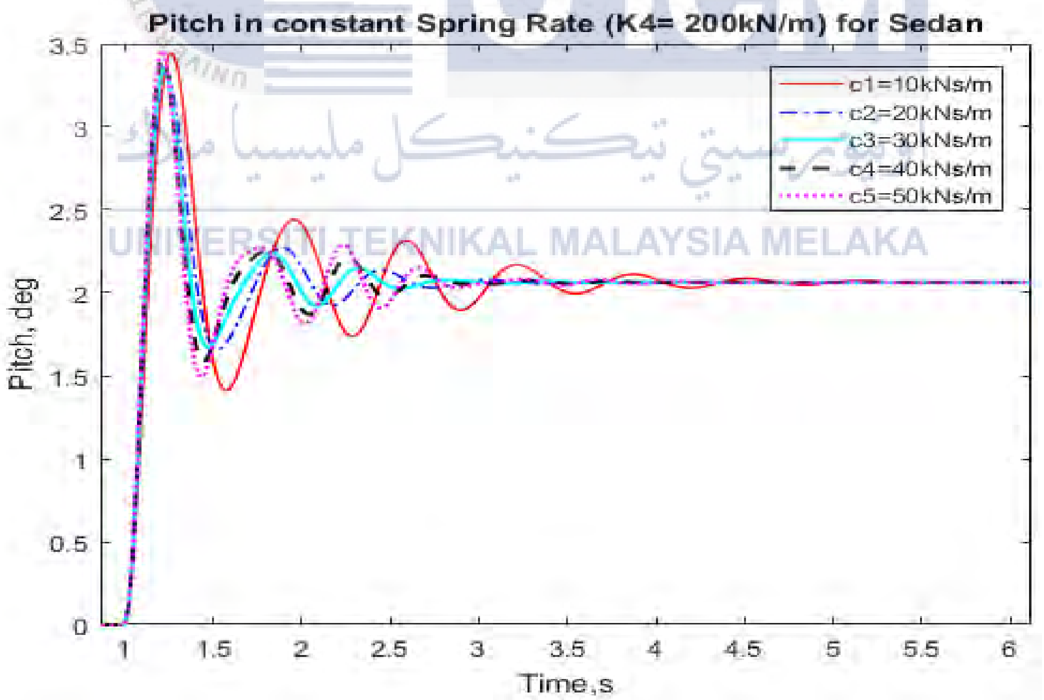


Figure 4.36: Pitch in constant spring rate (K4 = 200 kN/m) for Sedan

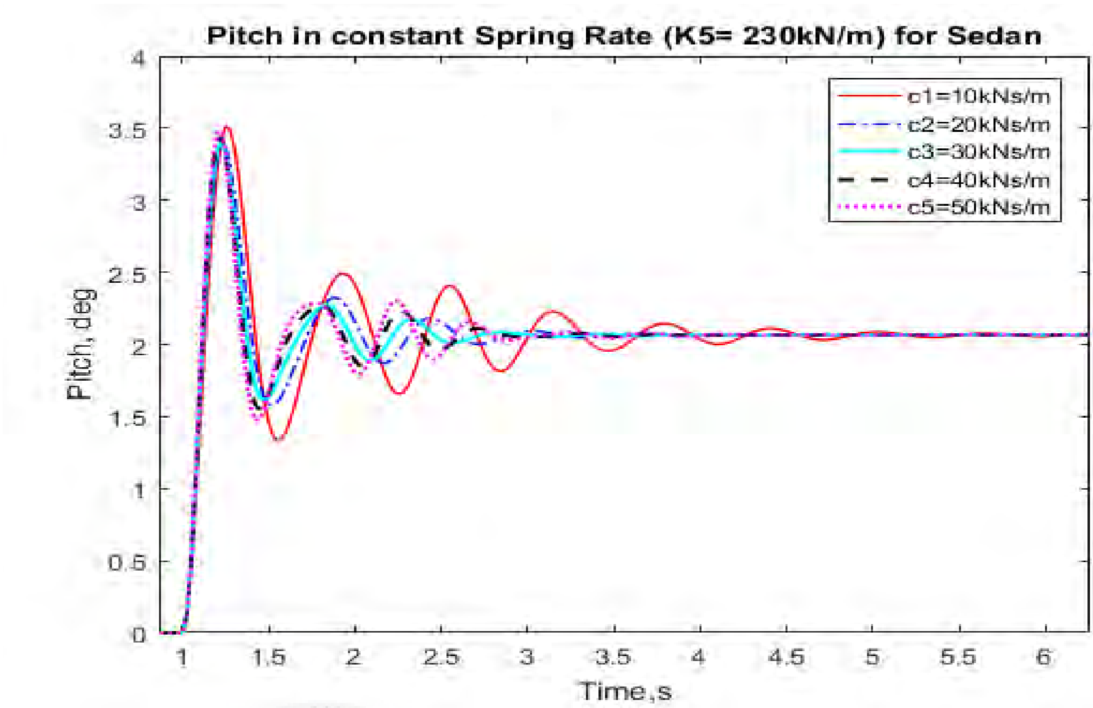


Figure 4.37: Pitch in constant spring rate (K5 = 230 kN/m) for Sedan

Table 4.4 and **Table 4.5** show that the value of amplitude overshoot and settling time from all the simulation below on the Sedan car with five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five different value of damping which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m .

Table 4.4: Overshoot (deg) for Sedan on different spring stiffness and damping value.

Spring Stiffness	kNs/m \ kN/m	Damping Value				
		C1 = 10	C2 = 20	C3 = 30	C4 = 40	C5 = 50
	K1 = 130	3.231	3.155	3.250	3.330	3.403
	K2 = 153	3.317	3.217	3.291	3.358	3.420
	K3 = 189	3.416	3.303	3.349	3.399	3.446
	K4 =200	3.441	3.326	3.365	3.411	3.454
	K5 = 230	3.513	3.385	3.407	3.442	3.477

Table 4.5: Settling Time (s) for Sedan on different spring stiffness and damping value.

	kNs/m / kN/m	Damping Value				
		C1 = 10	C2 = 20	C3 = 30	C4 = 40	C5 = 50
Spring Stiffness	K1 = 130	6.025	3.525	3.700	4.975	5.375
	K2 = 153	6.575	4.075	3.725	5.025	5.400
	K3 = 189	7.625	4.125	4.275	5.075	5.425
	K4 =200	7.550	4.675	4.300	5.100	5.425
	K5 = 230	9.200	5.700	4.850	5.125	5.475

Figure 4.38 and 4.39 the overall result of overshoot and settling time from the simulation of 4 DOF ride model on Sedan car with various value of spring stiffness and damping. It can be observed that the different value of spring stiffness and damping will produce different effect on overshoot and settling time on the result.

From the result, it can be noted that the different spring stiffness and damping value the performance of the vehicle suspension system will produce different effect on the vehicle. Basically, the spring stiffness and damping value of suspension system will be selected depending on the vehicle parameter. For the sedan, it has a medium mass on the vehicle body. So, the spring stiffness and damping value for Sedan car should be in medium value to support the vertical motion of the vehicle body when hit a bump or driving through an uneven road. It is because suspension spring able to support the weight of vehicle body and passenger while a damper able to absorb and reduce the bounce force that exerted on the vehicle body. From overall simulation result for Sedan car, it can be noted that damping value is more important for Sedan car compare to spring stiffness. So, in order to achieve the comfort of the vehicle, it need to select the optimal value of spring stiffness and damping which are suitable with the parameter of the Sedan car.

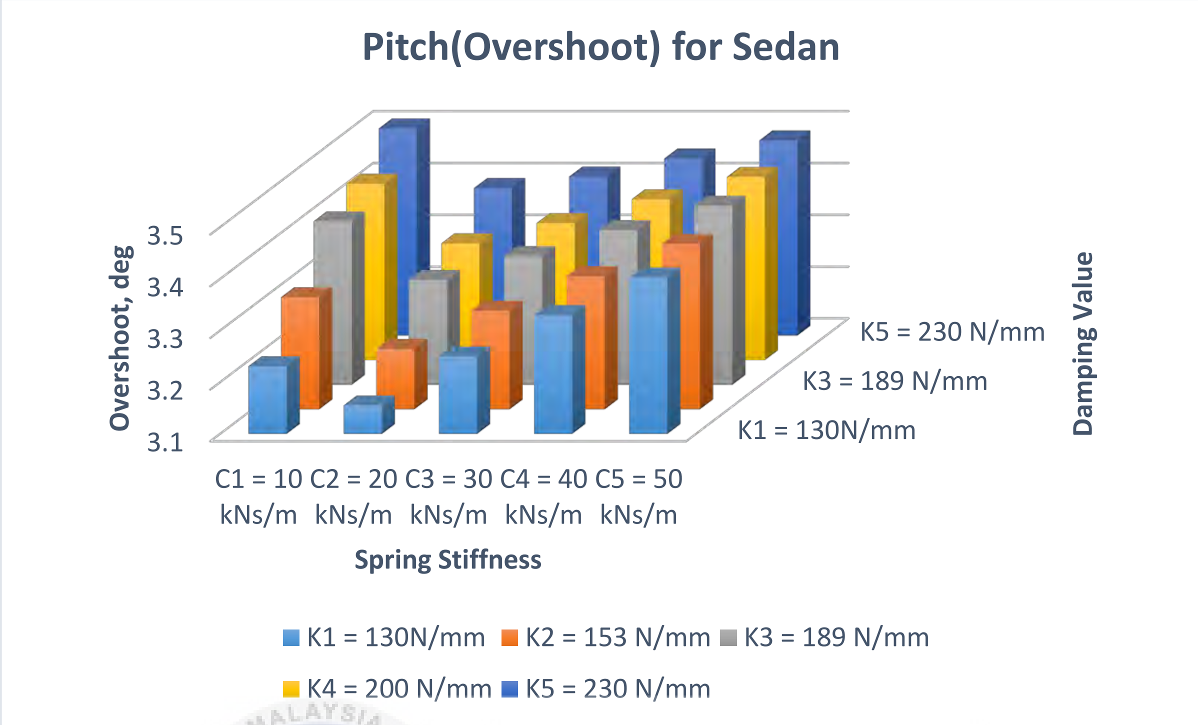


Figure 4.38: Overall result on pitch motion for Sedan (Overshoot)

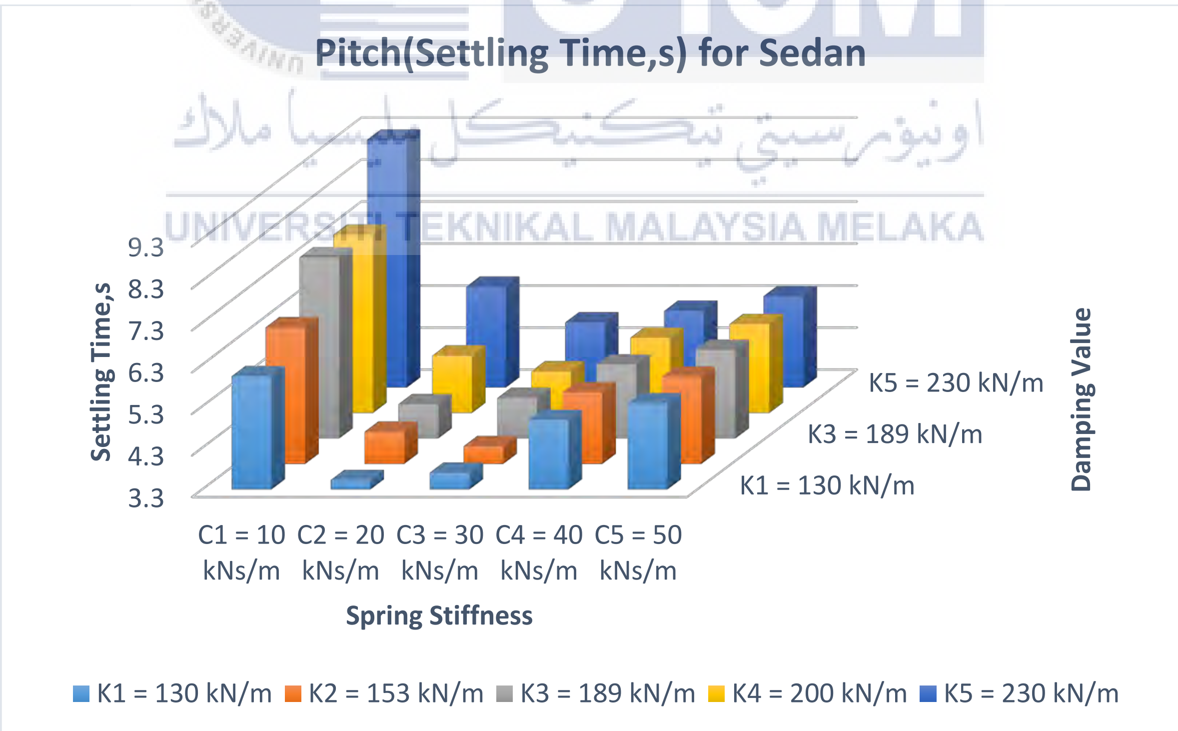


Figure 4.39: Overall result on pitch motion for Sedan (Settling Time,s)

Figure 4.40 until **4.44** shows that the result of vertical acceleration happens of Sedan car with five constant damping value which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m on five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m.

From the result, it can be observed that the spring stiffness of the suspension system only has a minor effect due to the vehicle comfort on the vehicle body acceleration. Based on the simulation on Sedan car for vertical body acceleration, the stiffer the spring stiffness will cause the amplitude overshoot and settling time of vertical body acceleration become higher and longer. It is because when spring of suspension system is stiffer, the suspension system will transmit more shock from the tire to the vehicle body that can lost the vehicle comfort to passenger. In order to determine the optimal value of spring stiffness, it need to select the spring stiffness that provide the lower overshoot of vertical body acceleration and shortest settling time. But, the spring stiffness of suspension should be match with value of damper based on the parameter of the Sedan car.

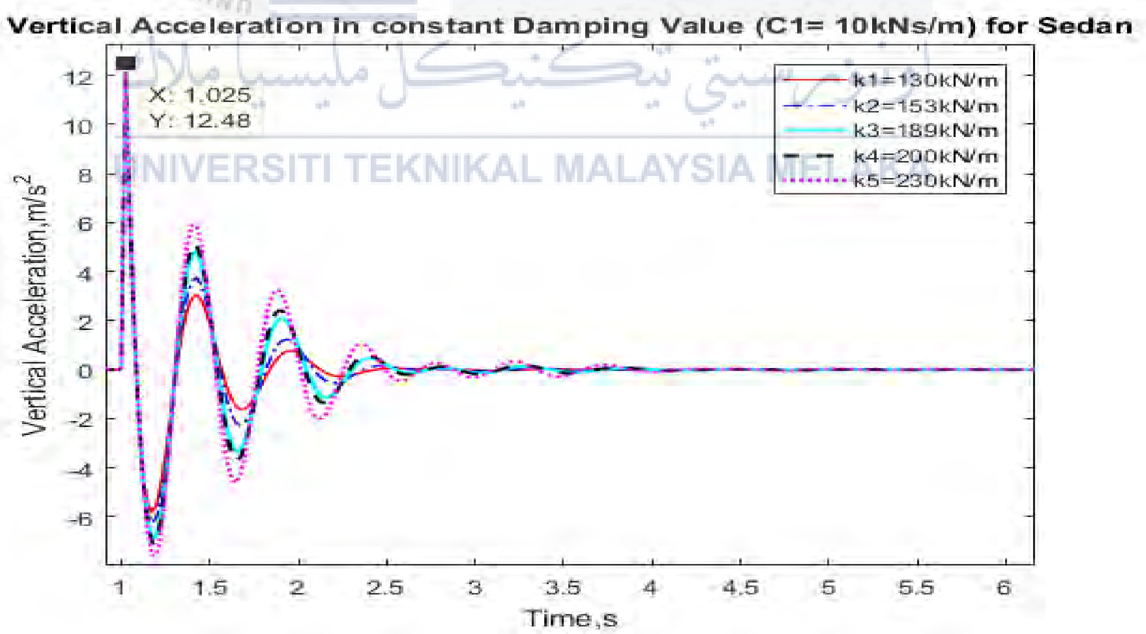


Figure 4.40: Vertical acceleration in constant damping value (C1 = 10 kNs/m) for Sedan

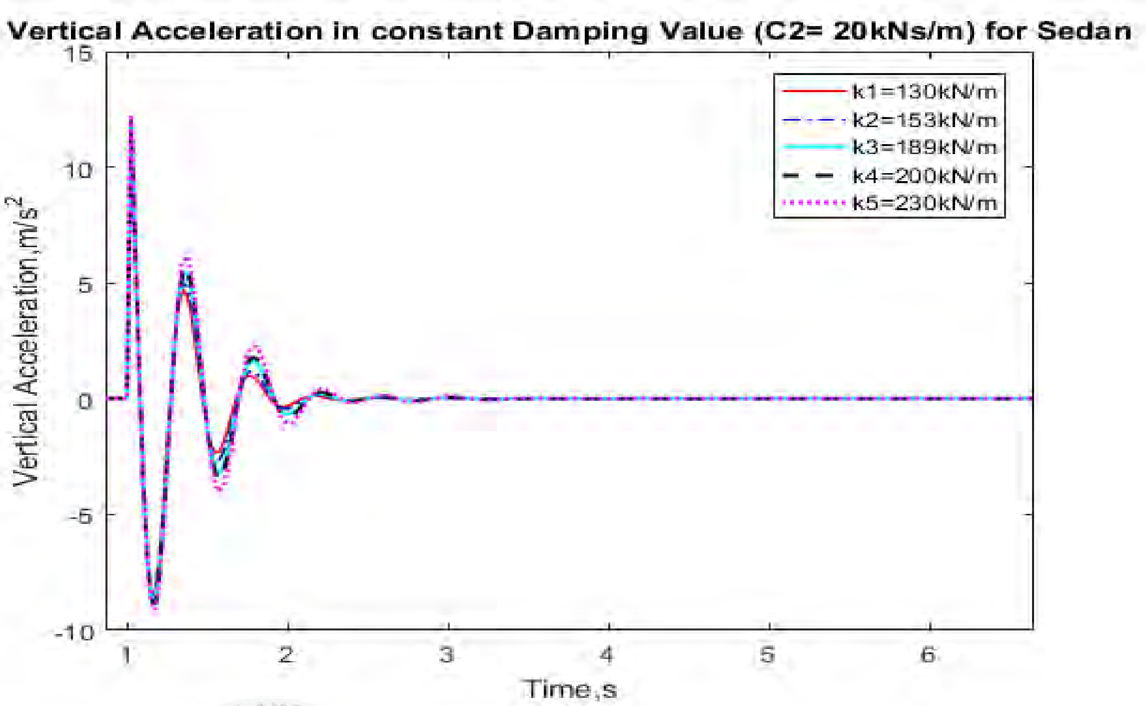


Figure 4.41: Vertical acceleration in constant damping value (C2 = 20 kNs/m) for Sedan

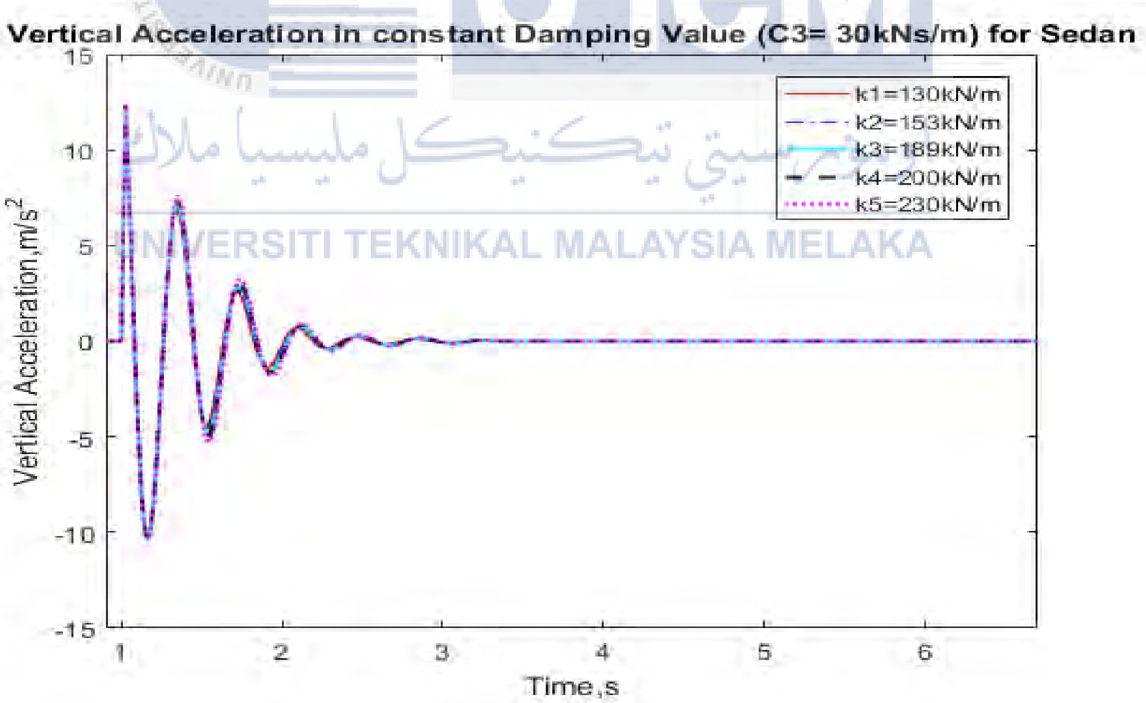


Figure 4.42: Vertical acceleration in constant damping value (C3 = 30 kNs/m) for Sedan

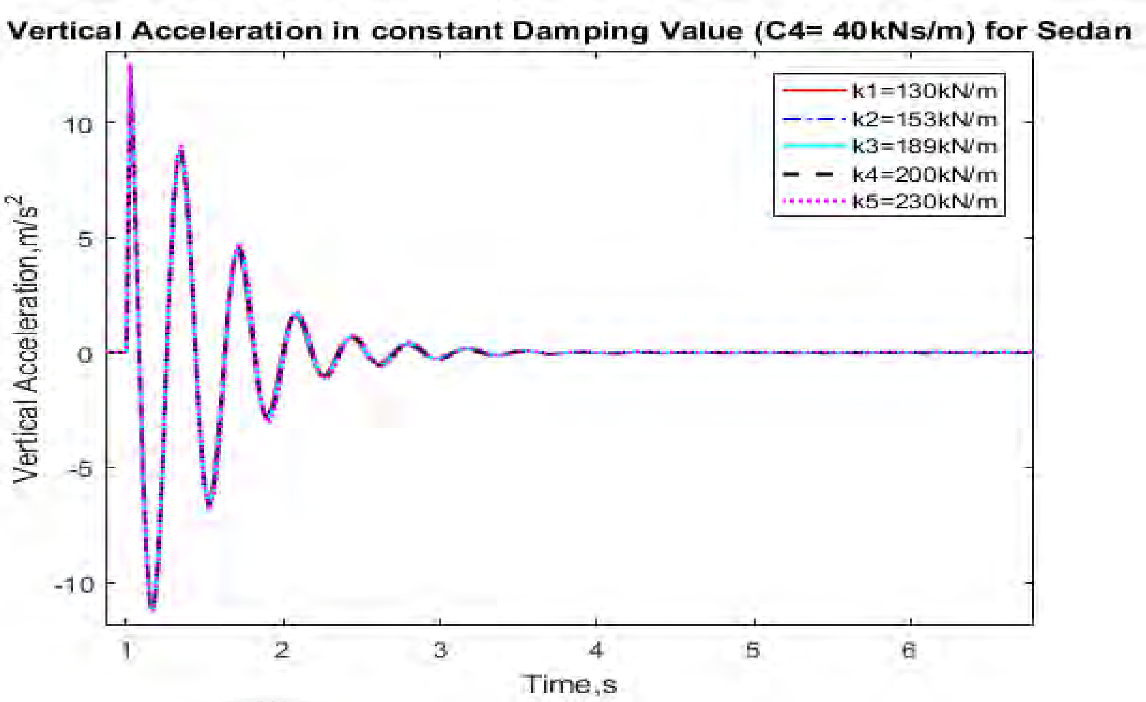


Figure 4.43: Vertical acceleration in constant damping value (C3 = 30 kNs/m) for Sedan

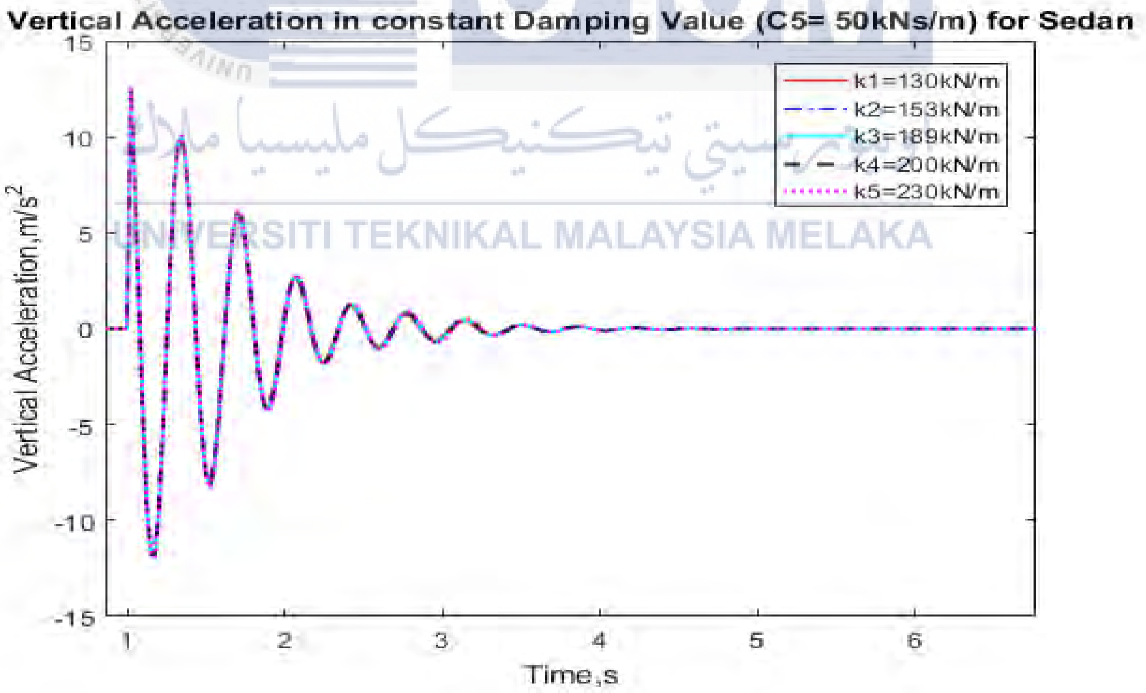


Figure 4.44: Vertical acceleration in constant damping value (C5 = 50 kNs/m) for Sedan

Figure 4.45 until 4.49 shows that the simulation result of vertical acceleration happens of Sedan car in five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five constant damping value which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m.

Damper is the important component of the suspension system to absorb the undesirable force from the road exerted on the vehicle body. From the result, it can observe that the effect of damper of suspension system on the vertical body acceleration of vehicle body. It can be noticed that, the lower value of the damping, it will reduce the amplitude overshoot and settling time for the vertical acceleration. It is because the damper will absorb more vertical force from the tire when apply higher value of damping on the suspension system So, in order to improve the comfort of Sedan car, it need to determine the optimal damping value that are able to reduce the overshoot value of vertical body acceleration and shorten the settling time on vehicle body.

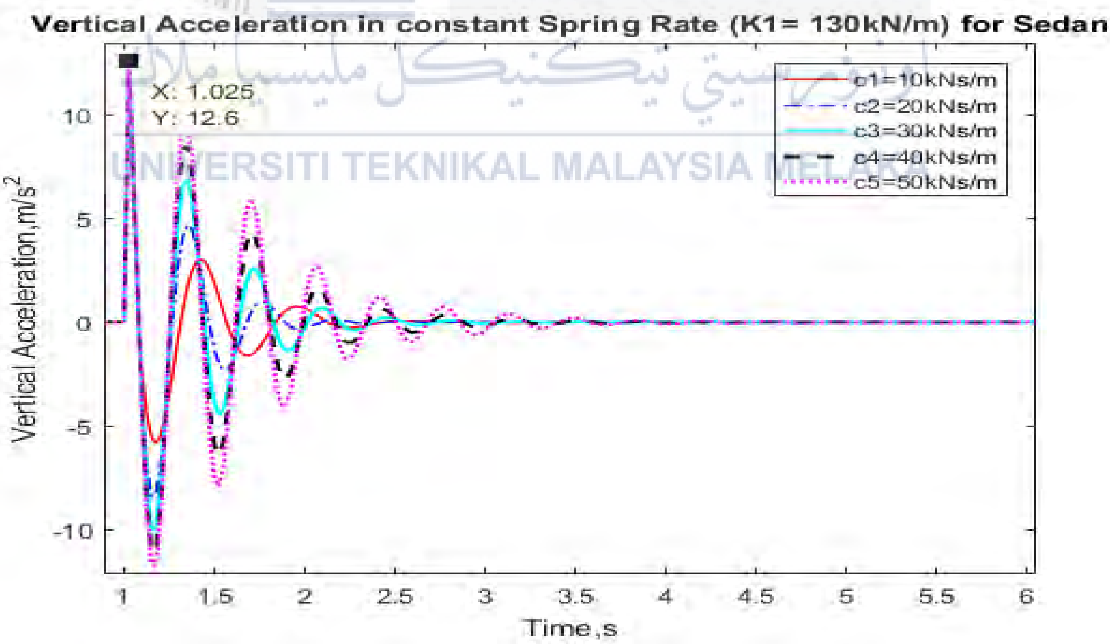


Figure 4.45: Vertical acceleration in constant spring rate (K1 = 130 kNs/m) for Sedan

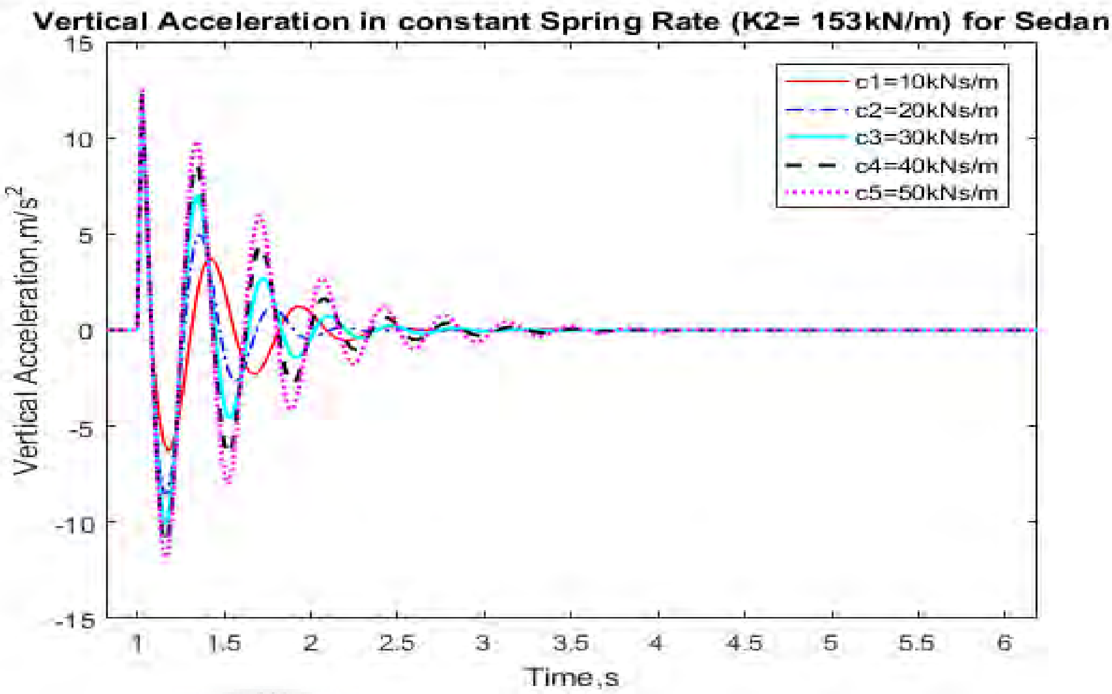


Figure 4.46: Vertical acceleration in constant spring rate (K2 = 153 kNs/m) for Sedan

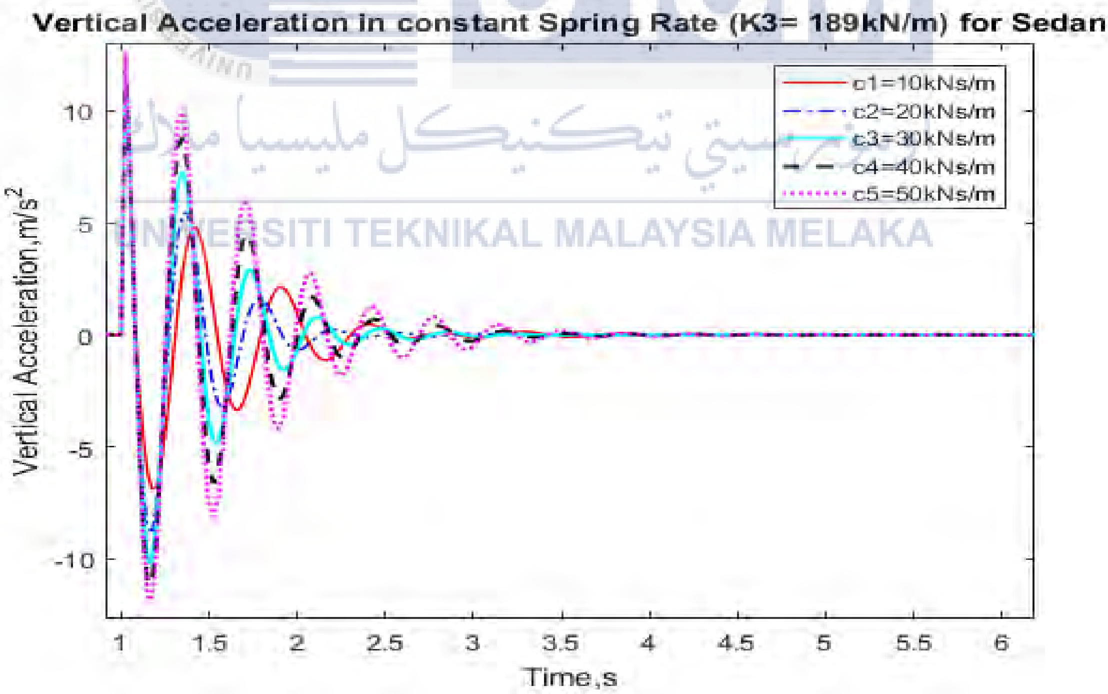


Figure 4.47: Vertical acceleration in constant spring rate (K3 = 189 kNs/m) for Sedan

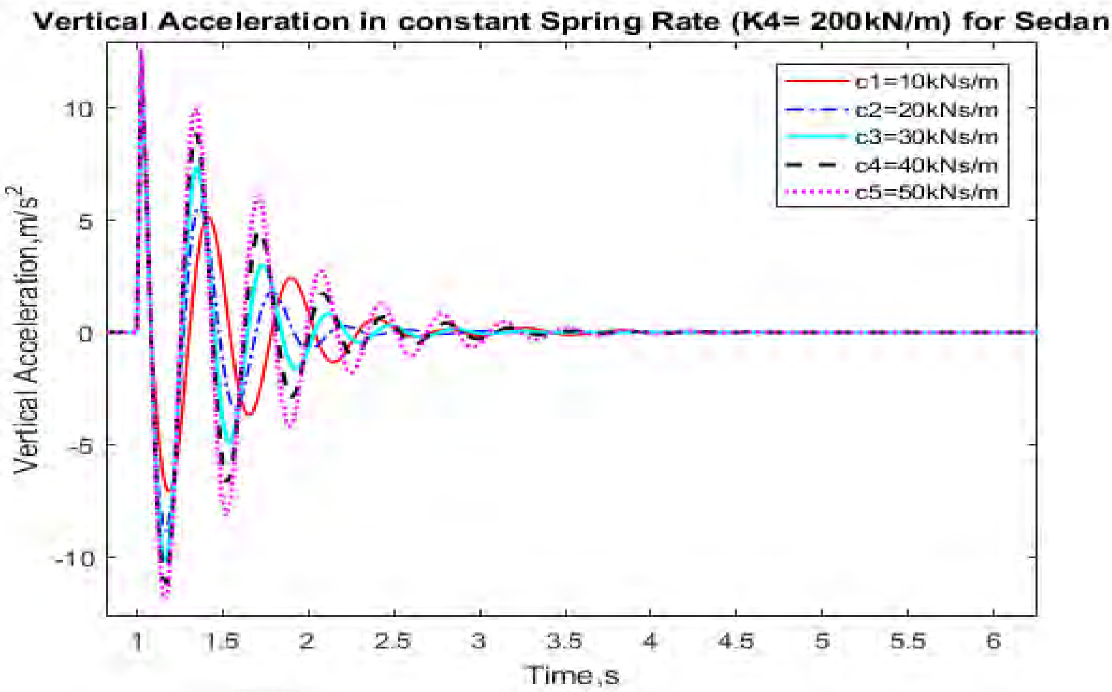


Figure 4.48: Vertical acceleration in constant spring rate (K4 = 200 kNs/m) for Sedan

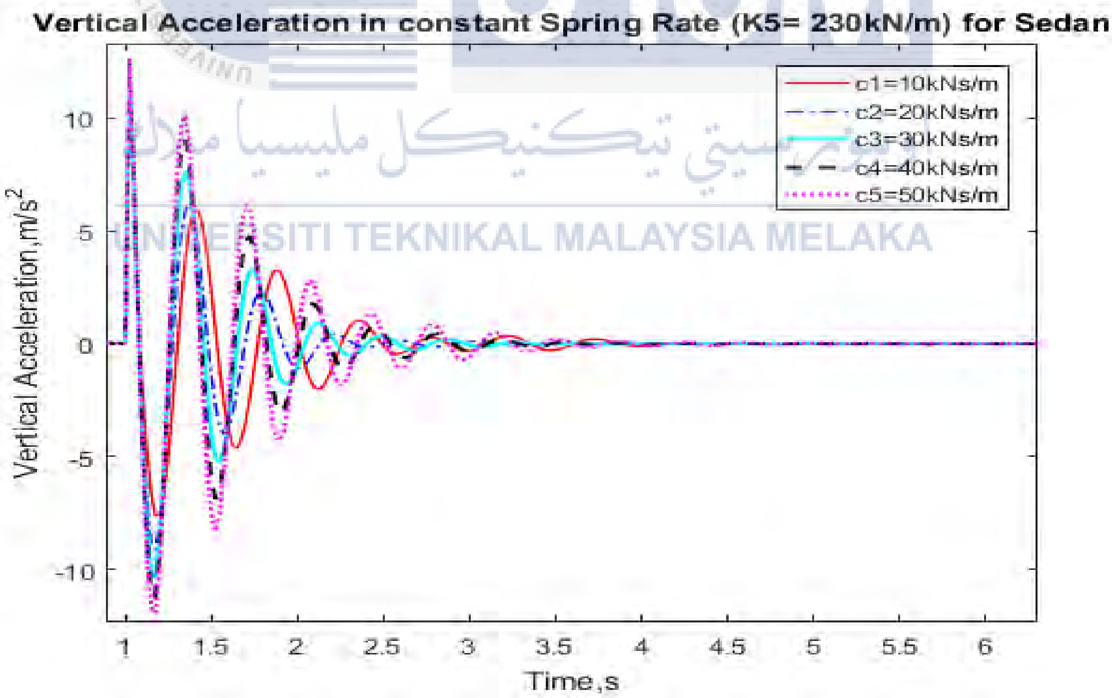


Figure 4.49: Vertical acceleration in constant spring rate (K5 = 230 kNs/m) for Sedan

Table 4.6 show that the value of amplitude overshoot that experienced on vertical body acceleration from all the simulation on the Sedan car with five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five different value of damping which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m .

Figure 4.50 shows that the overall result of overshoot vertical body acceleration on the SUV, Full size car with various value of spring stiffness and damping. So, it can be concluded that the most suitable range value of spring stiffness between 130 kN/m to 153 kN/m while for damping value is 10 kNs/m are suitable for Sedan car.

Table 4.6: Overshoot for Sedan on different spring stiffness and damping value.

	kNs/m / kN/m	Damping Value				
		C1 = 10	C2 = 20	C3 = 30	C4 = 40	C5 = 50
Spring Stiffness	K1 = 130	11.83	12.03	12.28	12.48	12.60
	K2 = 153	11.99	12.08	12.31	12.50	12.61
	K3 = 189	12.23	12.17	12.35	12.53	12.63
	K4 =200	12.30	12.19	12.36	12.53	12.64
	K5 = 230	12.48	12.26	12.40	12.56	12.65

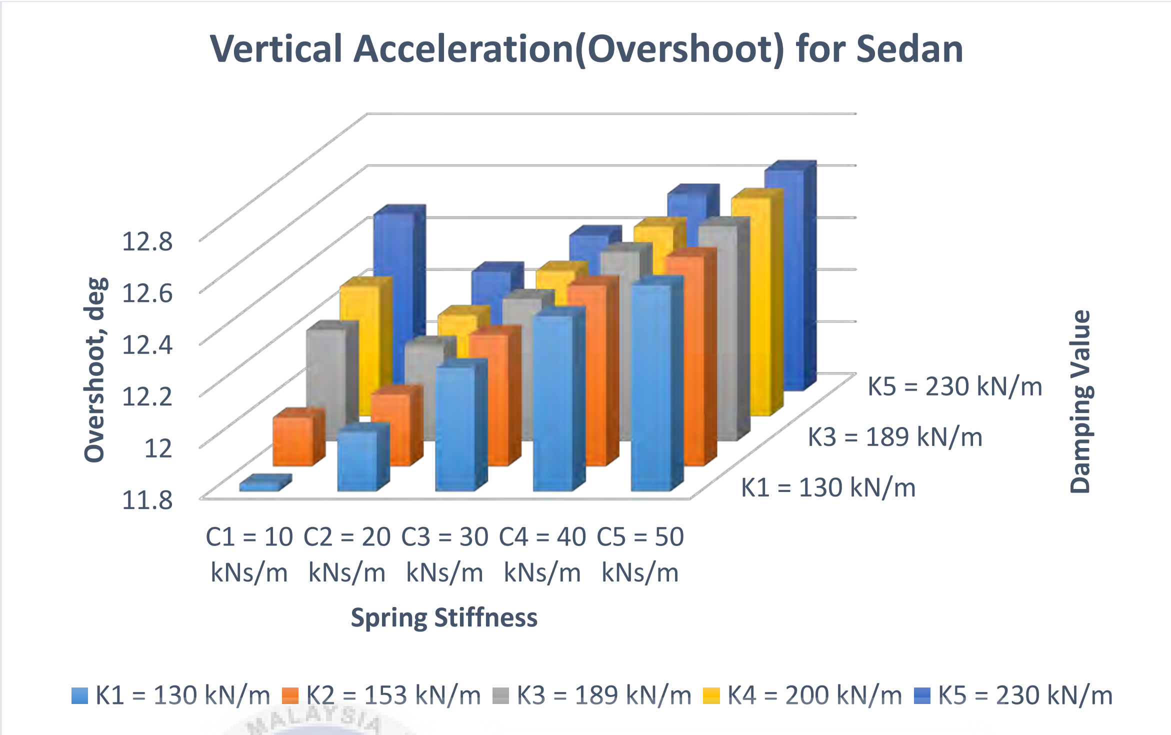


Figure 4.50: Overall result on vertical acceleration for Sedan (Overshoot)

4.2.3 Simulation for Hatchback

In order to determine the most suitable value of spring and damping value for Hatchback car, it need apply the parameter of Hatchback car as shown in **Table 3.4** on the 4 DOF ride model with 5 different value of spring stiffness and 5 different value of damping to observe which one suitable to apply on Hatchback car. Furthermore, to improve the comfort of the Hatchback car, it need to determine the lowest value of overshoot and settling time for the pitch body effect and vertical body acceleration. In this simulation for Hatchback car, the 4 DOF ride model will be apply about 0.1 m height of bump as an input on the rear tire to observe the effect on pitch body motion and vertical body acceleration.

Figure 4.51 until 4.55 shows the result from the simulation for Hatchback car with five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five constant value of damping which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m. The result shows that the effect of the spring stiffness and damping value on pitch body motion and vertical body acceleration for Hatchback car.

From the result, it can be observed the pattern on the schematic result of simulation for Hatchback car on five constant value of damping and five different spring stiffness. The schematic result will represent the amplitude overshoot and settling time for the pitch motion body. It can be noticed that the higher the value of the spring stiffness with higher damping value, it will produce higher value of overshoot and longer settling time of Hatchback car that can reduce the comfort to the passenger on the vehicle. Further, it seen that for the simulation result, the amplitude overshoot of pitch body is corresponding with the vertical body acceleration. It means that when the amplitude of overshoot is higher, it will affect the settling time of vehicle body become longer to reduce the bounce. So, in order to improve the comfort of the Hatchback car, it need to select the optimal value of spring stiffness that matching with the damping value. **Figure 4.51** shows the data cursor that represent the value overshoot and settling time in order to tabulate in **Table 4.7** and **Table 4.8**.

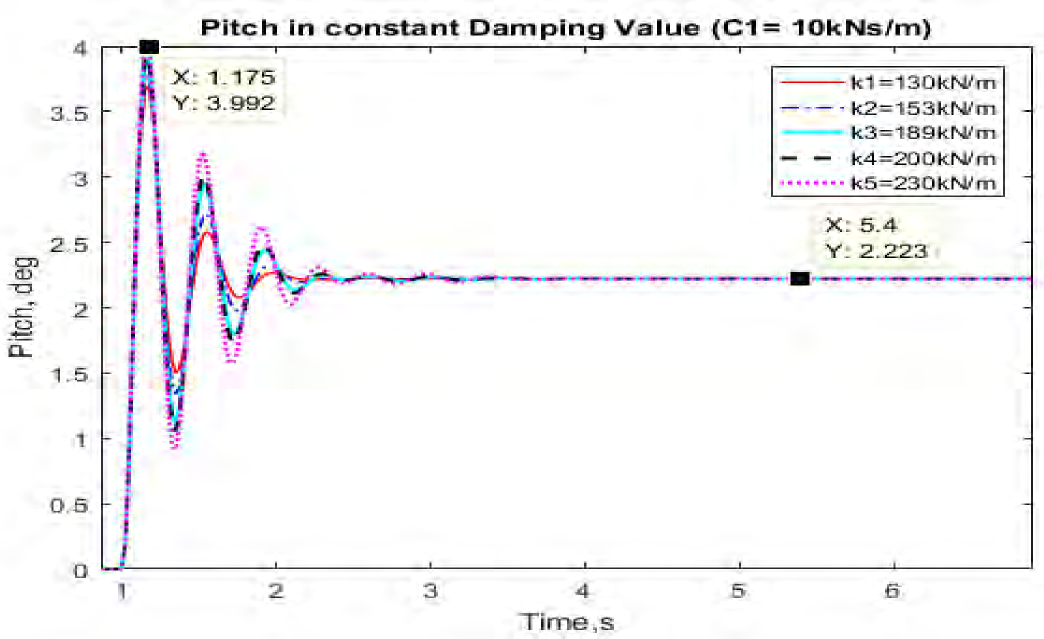


Figure 4.51: Pitch in constant damping value (C1 = 10 kNs/m) for Hatchback

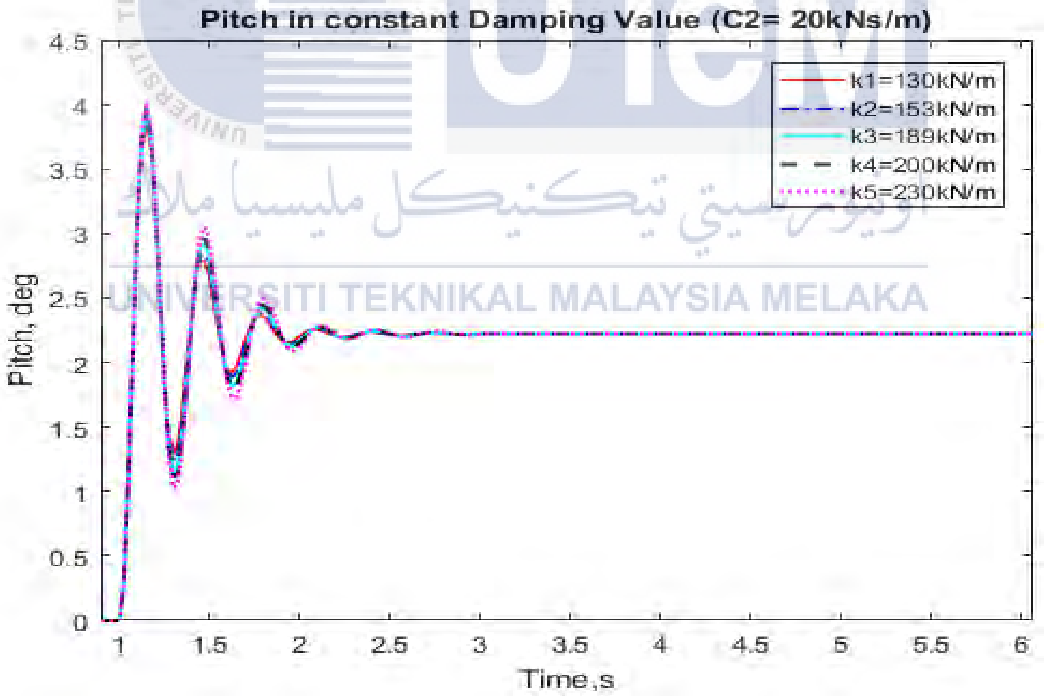


Figure 4.52: Pitch in constant damping value (C2 = 20 kNs/m) for Hatchback

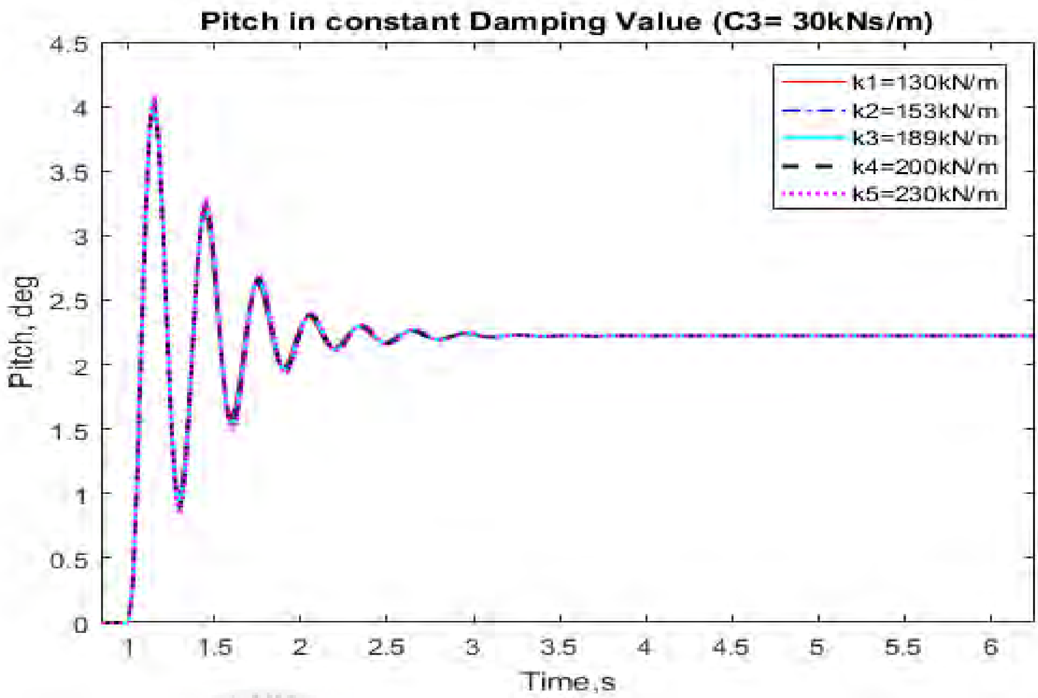


Figure 4.53: Pitch in constant damping value (C3 = 30 kNs/m) for Hatchback

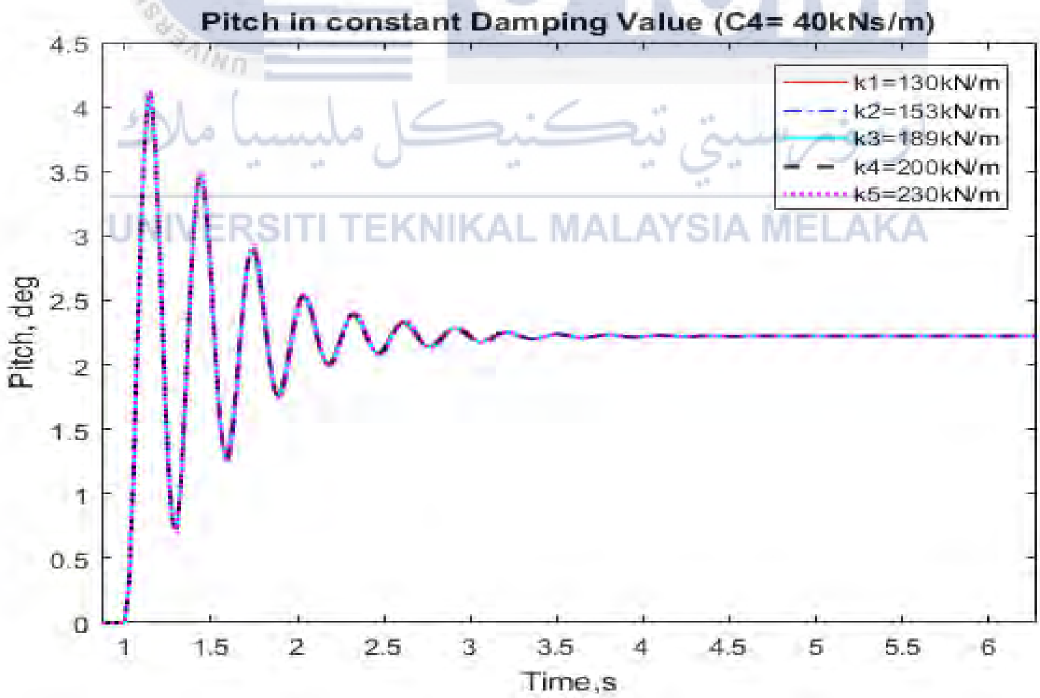


Figure 4.54: Pitch in constant damping value (C4 = 40 kNs/m) for Hatchback

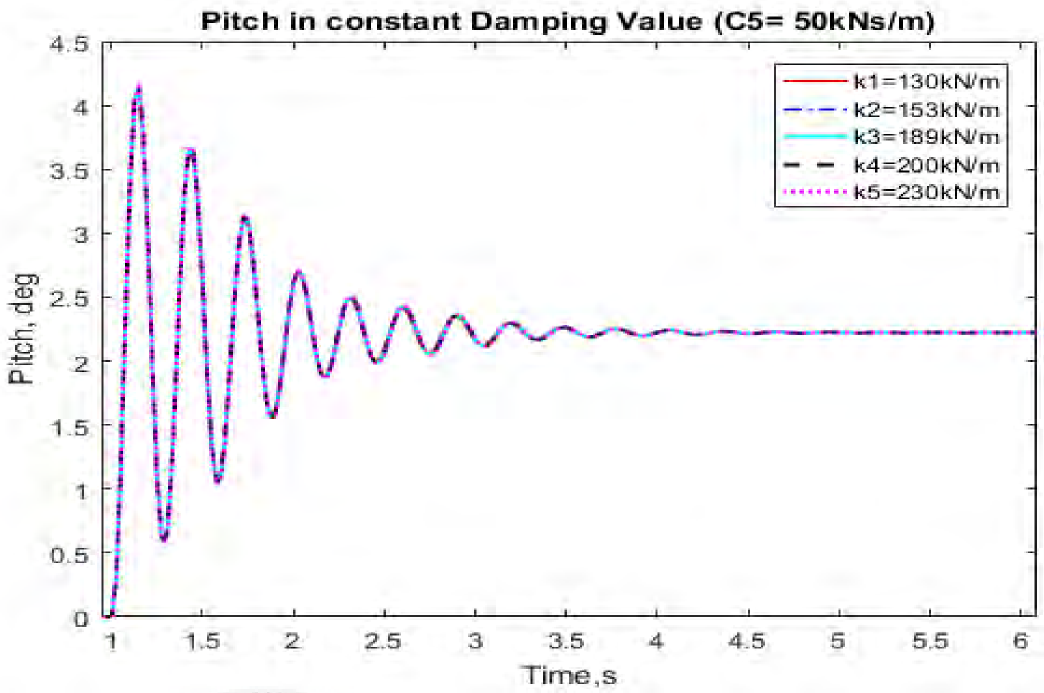


Figure 4.55: Pitch in constant damping value (C5 = 50 kNs/m) for Hatchback

From the **Figure 4.56** until **Figure 4.60** shows that the result of pitch body effect with five constant value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five different value of damping which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m . When the vehicle hit the bump about 0.1 m high on the road surface, it will produce a result of amplitude overshoot and settling time with various pattern depends on parameter of vehicle, spring stiffness and damping value.

Based on the result, it seen that the overshoot and settling time of the pitch body effect on each value of spring stiffness and damping value. The lower the value of damping, the overshoot of pitch body effect become smaller with shortest settling time due to the damper will absorb the vertical force from the tire that transmit to vehicle body. Theoretically, in order to improve comfort of the hatchback car, the value of damping should be suitable with the parameter of the hatchback car and the spring stiffness. It is because when the tire of the vehicle hit the bump, it will produce undesirable force on the vehicle body. So, the damper should be matching with the spring stiffness in order to absorb more the vertical force and reduce the bounce of the vehicle. It can be noted that when no damping is provided the amplitude of overshoot is increased with time which means passenger will be getting lots of vibration and also it can be damage to the vehicles with a lot of wear and tear in the system.

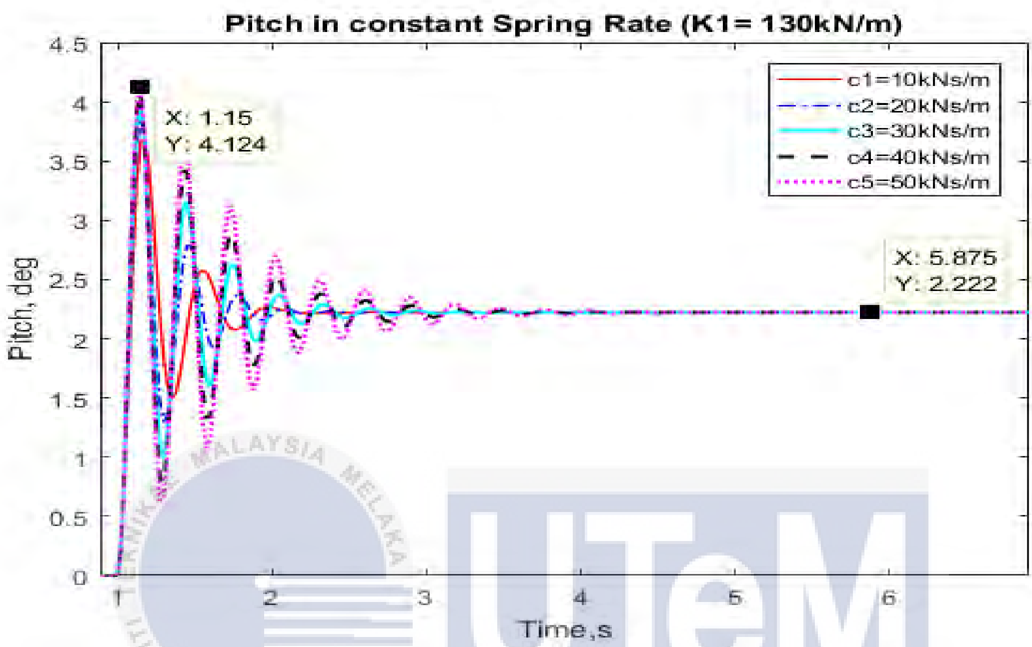


Figure 4.56: Pitch in constant spring rate (K1 = 130 kN/m) for Hatchback

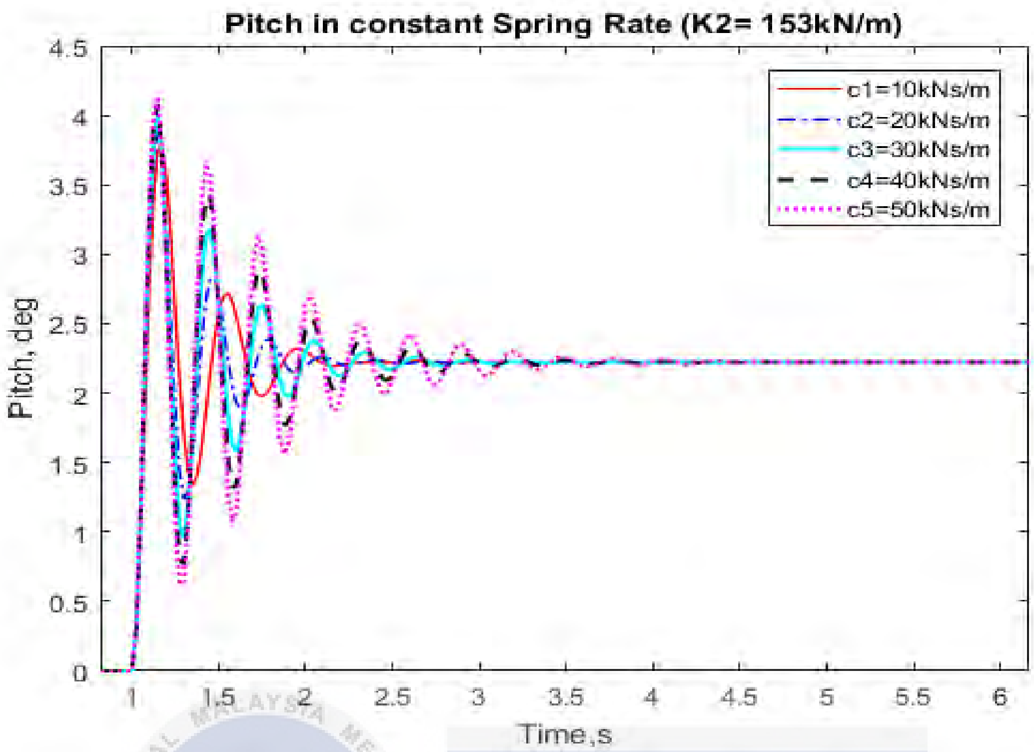


Figure 4.57: Pitch in constant spring rate (K2 = 153 kN/m) for Hatchback

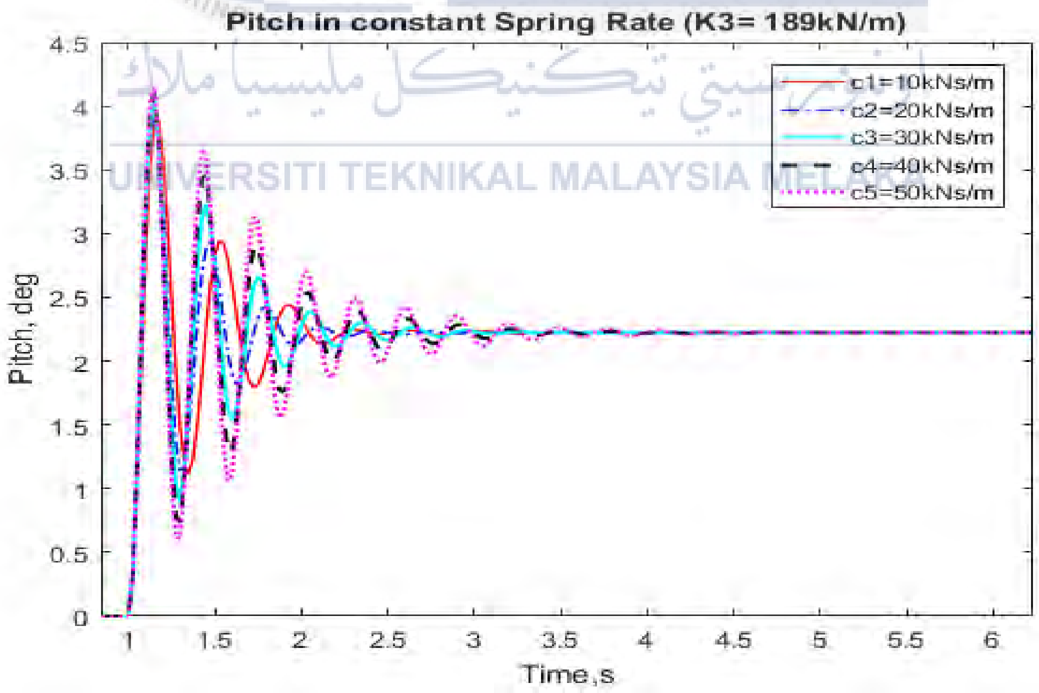


Figure 4.58: Pitch in constant spring rate (K3 = 189 kN/m) for Hatchback

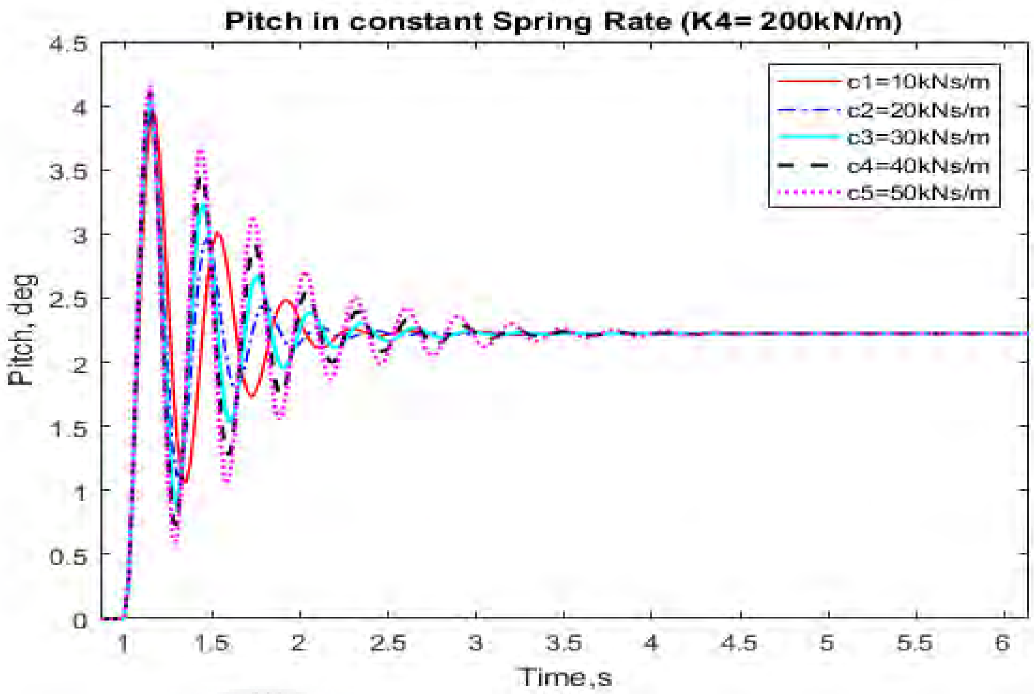


Figure 4.59: Pitch in constant spring rate (K1 = 200 kN/m) for Hatchback

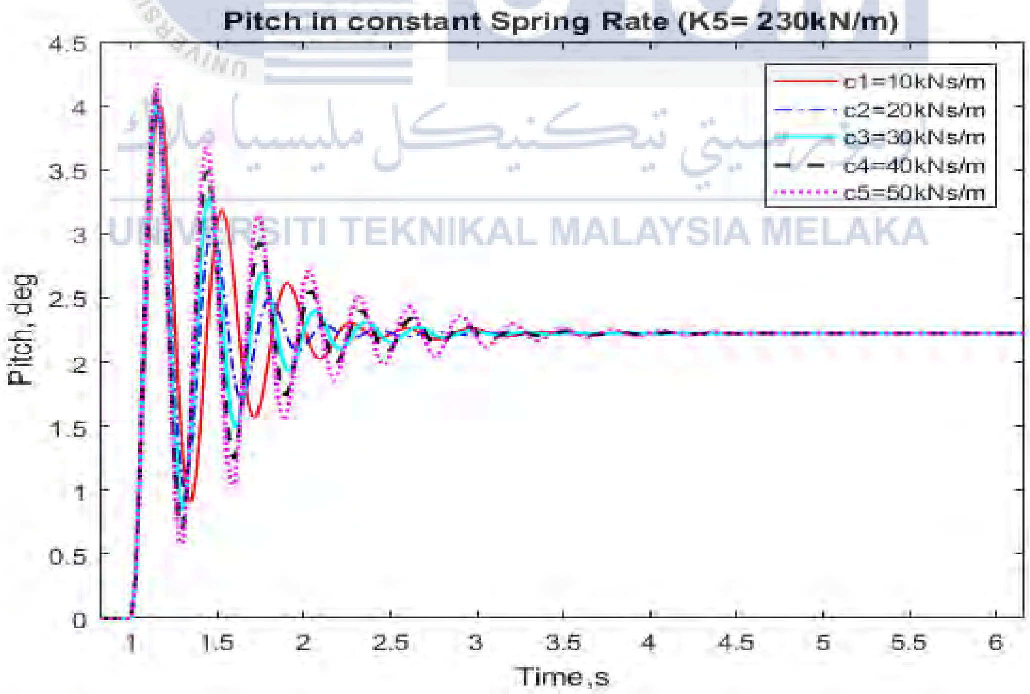


Figure 4.60: Pitch in constant spring rate (K5 = 230 kN/m) for Hatchback

Table 4.7 and **Table 4.8** show that the overall value of amplitude overshoot and settling time from all the simulation on the Hatchback car with five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 189 kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five different value of damping which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m .

Based on the table below, it can analyse the different value of overshoot and settling time for pitch motion of Hatchback car with various value of spring stiffness and damping. It can be noticed that the lowest value of overshoot for pitch motion is 3.071 when apply 130 kN/m of spring stiffness and 10 kNs/m of damping value. While for the shortest settling for Hatchback car from this simulation is 3.1 second when apply about 130 kN/m of spring stiffness and 20 kNs/m of damping value.

Table 4.7: Overshoot (deg) for Hatchback on different spring stiffness and damping value.

		Damping Value				
	kNs/m kN/m	C1 = 10	C2 = 20	C3 = 30	C4 = 40	C5 = 50
Spring Stiffness	K1 = 130	3.701	3.850	3.976	4.062	4.124
	K2 = 153	3.787	3.893	4.001	4.079	4.136
	K3 = 189	3.897	3.955	4.039	4.104	4.154
	K4 =200	3.926	3.973	4.049	4.111	4.159
	K5 = 230	3.992	4.017	4.077	4.130	4.173

Table 4.8: Settling Time(s) for Hatchback on different spring stiffness and damping value.

Spring Stiffness (kN/m) \ Damping Value (kNs/m)	C1 = 10	C2 = 20	C3 = 30	C4 = 40	C5 = 50
K1 = 130	3.300	3.100	4.175	5.300	5.875
K2 = 153	3.725	3.400	4.200	5.300	6.150
K3 = 189	4.600	3.725	4.475	5.325	6.450
K4 =200	4.600	3.750	4.500	5.350	6.175
K5 = 230	5.450	4.075	4.525	5.350	6.475

Table 4 : Settling Time (s) for Hatchback on different spring stiffness and damping value.

Based on the overall result for simulation of Hatchback car, it shows that the different value of spring stiffness and damping will produce different effect on the amplitude overshoot and settling time. Therefore, in order to improve the comfort for Hatchback car, it should be select based on the amplitude overshoot and settling time of pitch motion by choosing the lowest one. Therefore, the value of spring stiffness and damping basically depends on the parameter of vehicle which is the heavy the mass of the vehicle, the hard spring and damper should be apply on the vehicle. Other that, the spring stiffness of suspension and the damper should be matching in order to produce better performance from the suspension system. Based on the result, when the higher spring stiffness matched with the hard damper, it will produce higher amplitude of pitch body motion and longer settling time on the vehicle to reach a comfort situation. It is because damping value is more important in vehicle compare to spring stiffness. It is because the damper will absorb the vertical force that affect the pitch motion on the vehicle body and reduce the bounce force from the road surface transmit to vehicle body while the spring of suspension only hold the vehicle body from the shock impact.

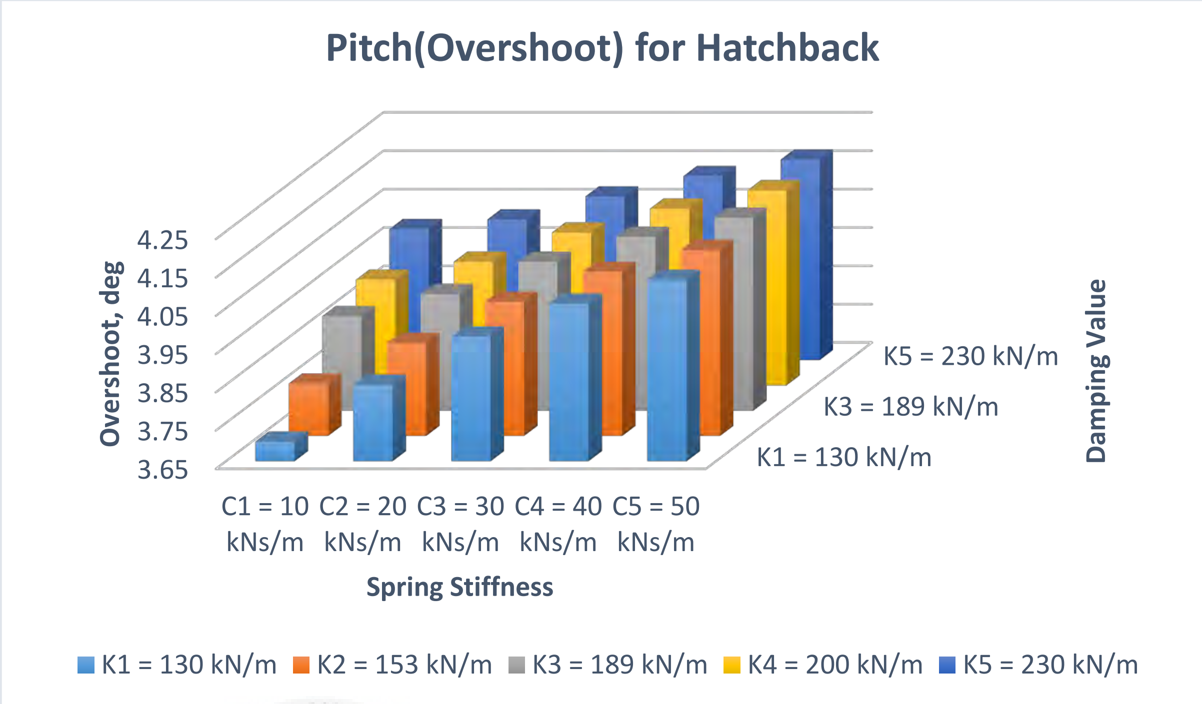


Figure 4.61: Overall result on pitch motion for Hatchback (Overshoot)

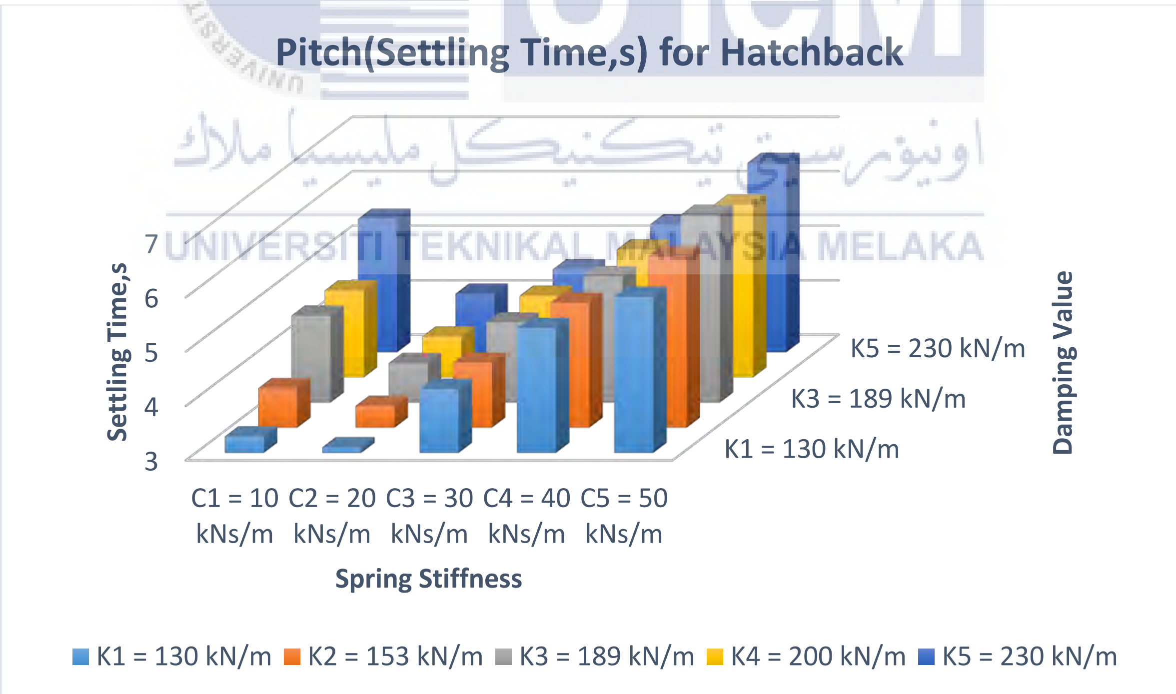


Figure 4.62: Overall result on pitch motion for Hatchback (Settling Time, s)

Furthermore, in order to improve the comfort of the vehicle, it also need to consider the vertical body acceleration of the vehicle. Based on **Figure 4.63 until 4.67**, it shows that the result of vertical acceleration happens of SUV, Full size car in five constant damping value m on five different value of spring stiffness.

From the result on constant value of damping with five different value of spring stiffness on the Hatchback car, it can be noticed that the effect on the result of amplitude overshoot with five different spring stiffness is very small. It is because spring of suspension only provide a small effect for the comfort of the vehicle due to its function which is to hold the tire with the vehicle body. So, it need to do a simulation on 4 DOF ride model with various value of spring stiffness in order to determine the optimal value for spring stiffness for Hatchback car. The data cursor in **Figure 4.63** represent the overshoot value of vertical acceleration each of the result in order to tabulate the data in **Table 4.9**.

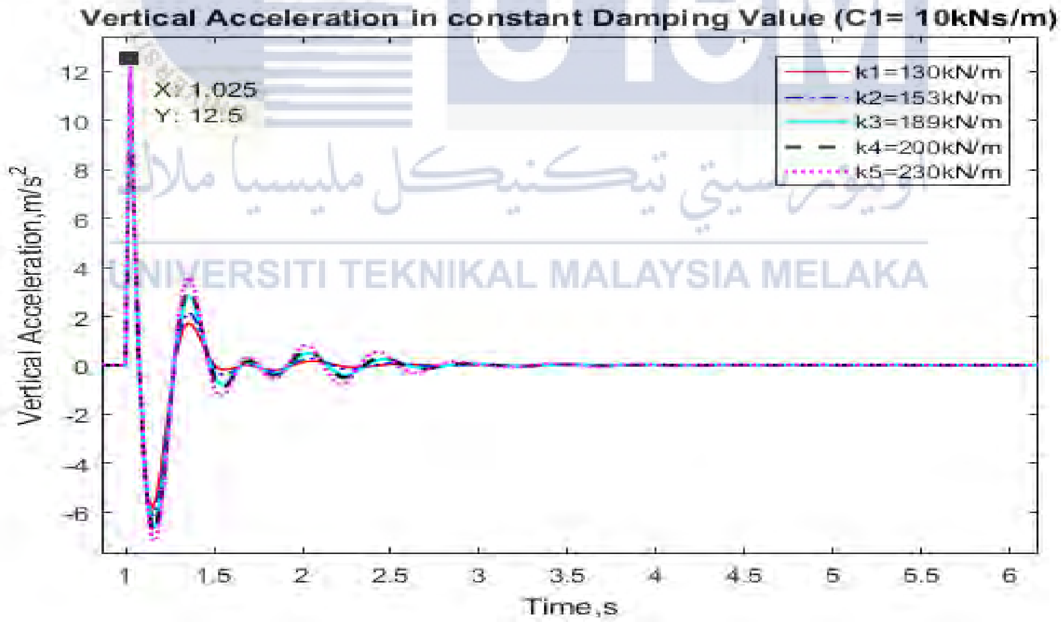


Figure 4.63: Vertical acceleration in constant damping value (C1 = 10 kNs/m) for Hatchback

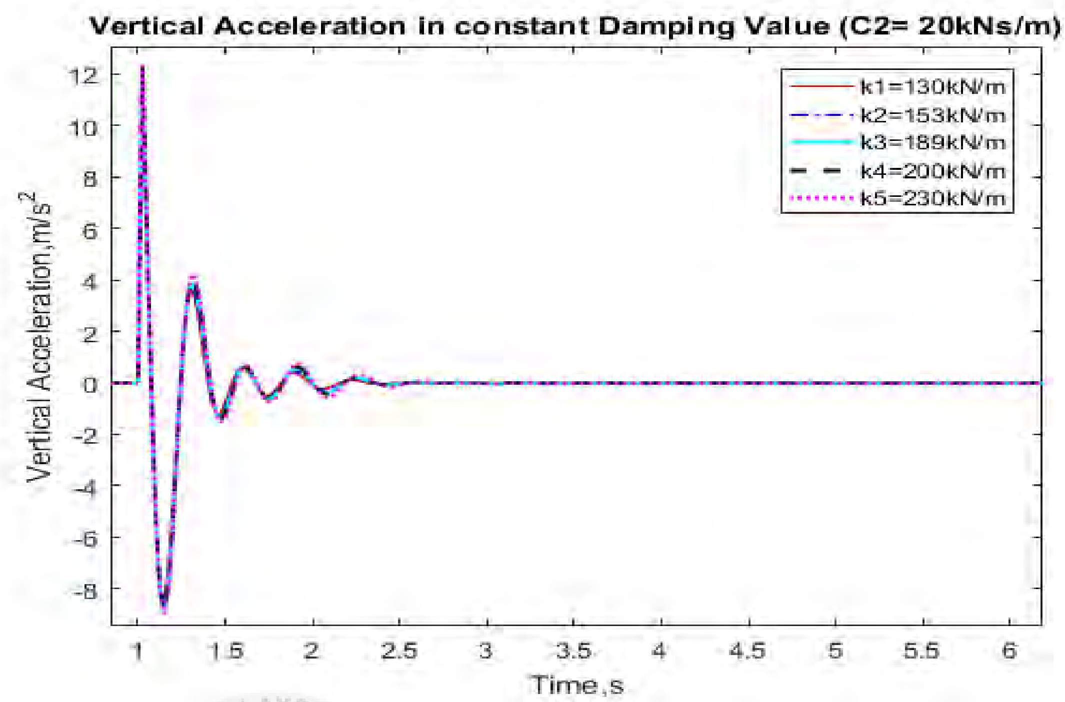


Figure 4.64: Vertical acceleration in constant damping value (C2 = 20 kNs/m) for Hatchback

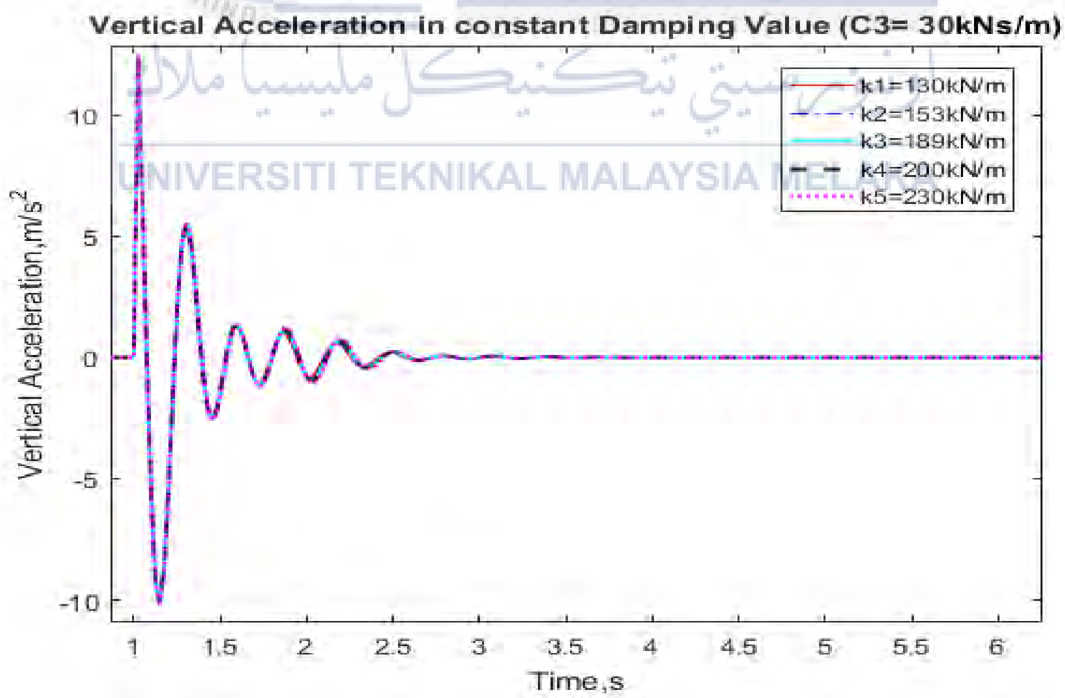


Figure 4.65: Vertical acceleration in constant damping value (C3 = 30 kNs/m) for Hatchback

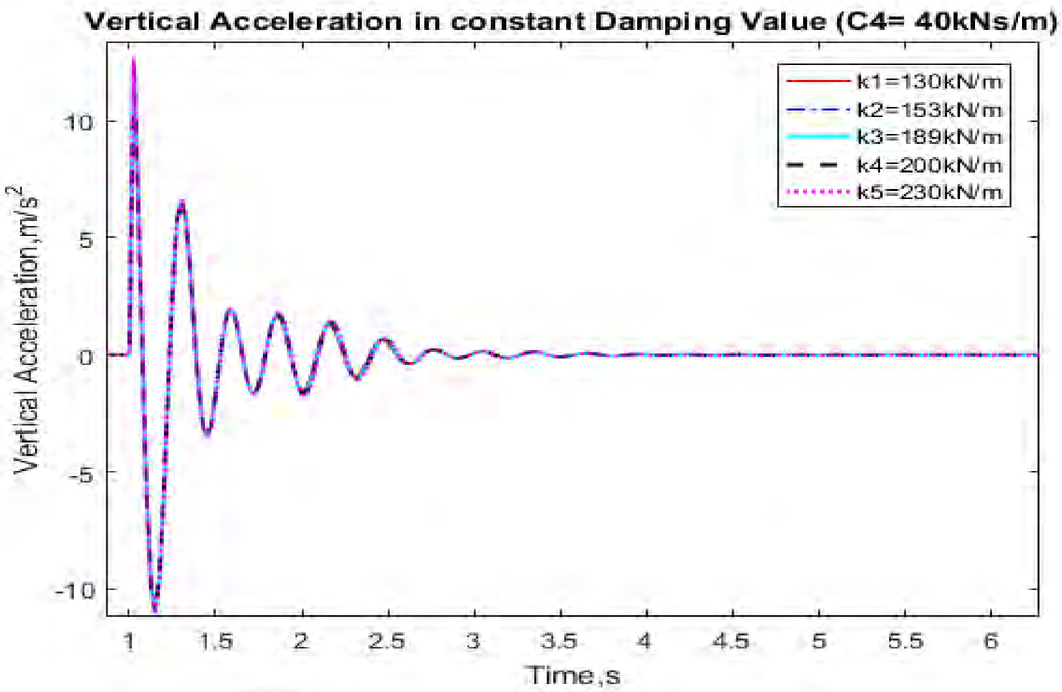


Figure 4.66: Vertical acceleration in constant damping value (C4 = 40 kNs/m) for Hatchback

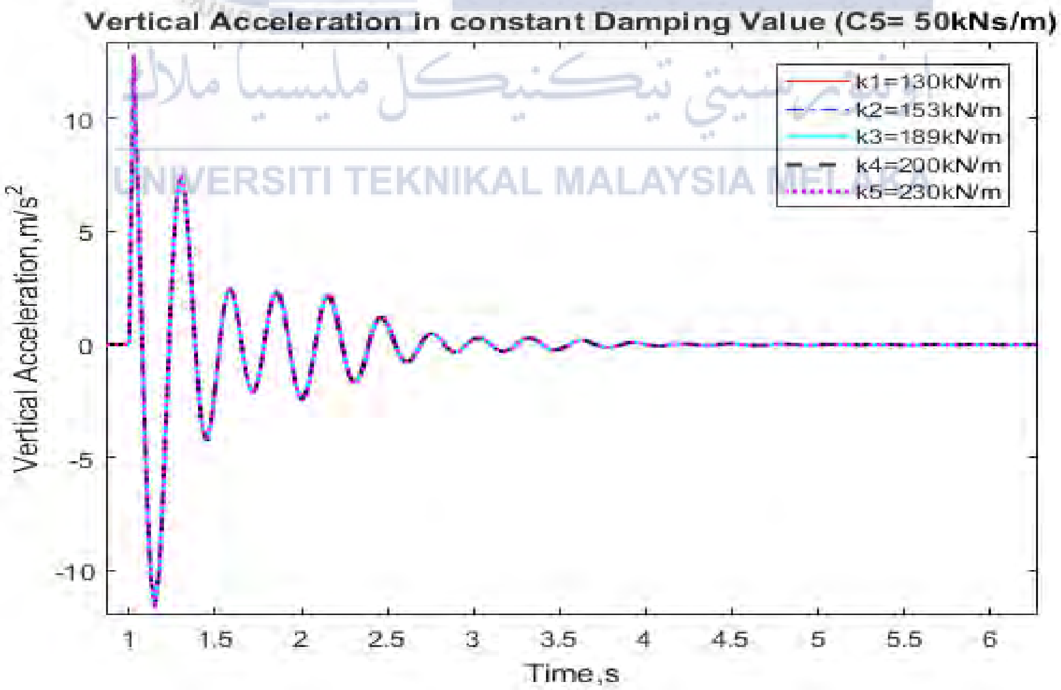


Figure 4.67: Vertical acceleration in constant damping value (C5 = 50 kNs/m) for Hatchback

Figure 4.68 until 4.72 shows that the result of vertical acceleration happens of Hatchback car in five different value of spring stiffness which are k_1= 130 kN/m, k_2= 153 kN/m, k_3= 18 9kN/m, k_4= 200 kN/m and k_5= 230 kN/m on five constant damping value which are c_1= 10 kNs/m, c_2= 20 kNs/m, c_3= 30 kNs/m, c_4= 40 kNs/m and c_5=50 kNs/m.

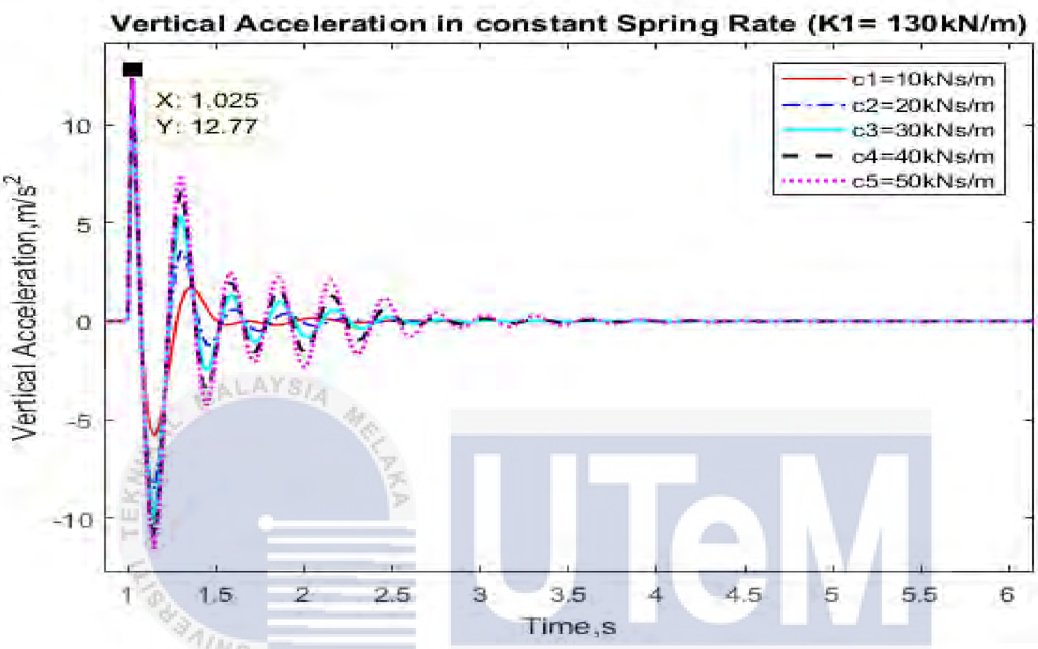


Figure 4.68: Vertical acceleration in constant spring rate (K1 = 130 kN/m) for Hatchback

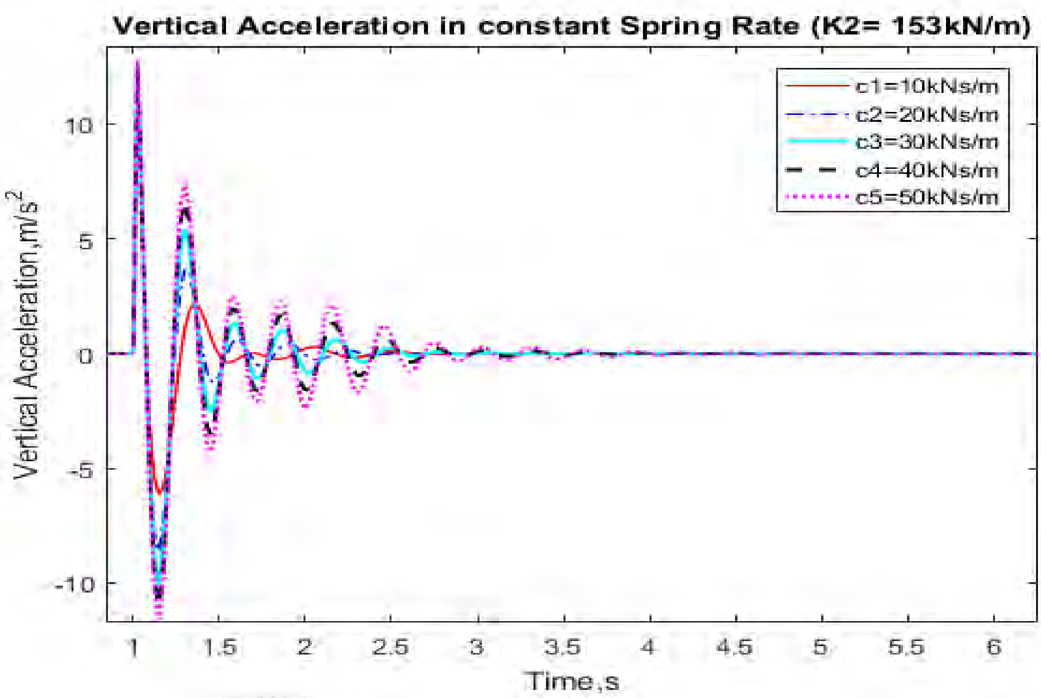


Figure 4.69: Vertical acceleration in constant spring rate (K2 = 153 kN/m) for Hatchback

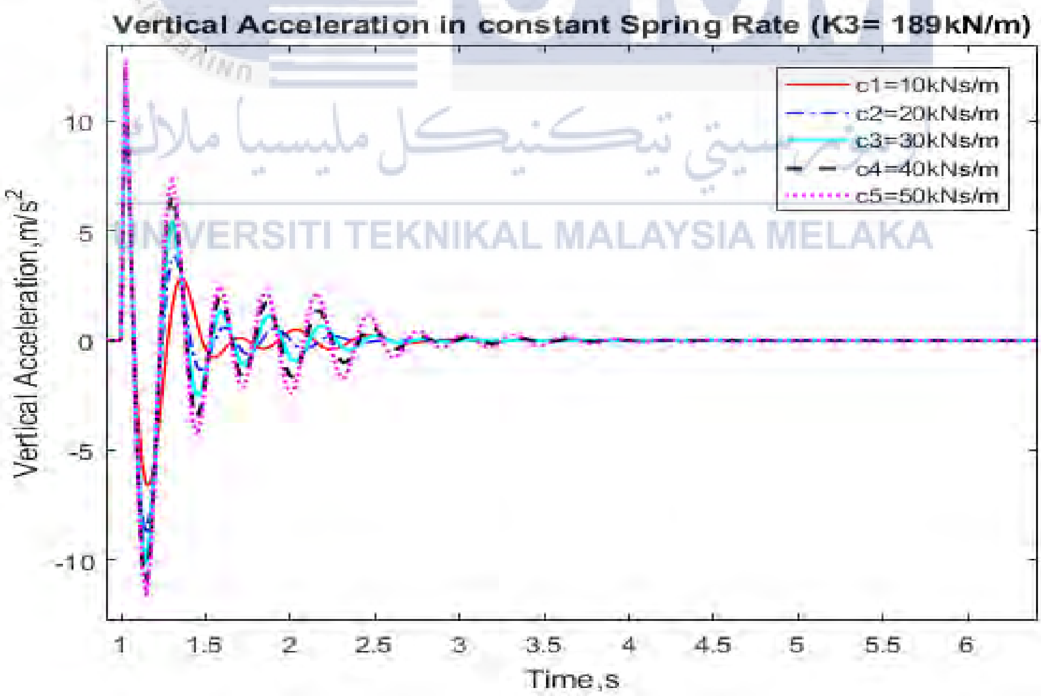


Figure 4.70: Vertical acceleration in constant spring rate (K3 = 189 kN/m) for Hatchback

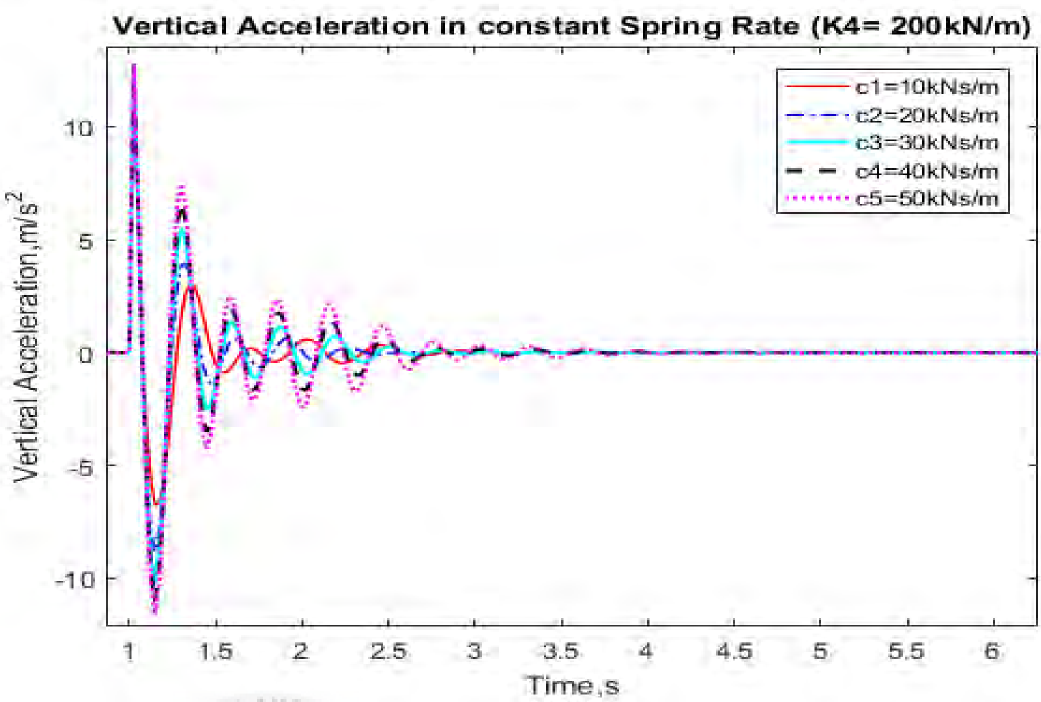


Figure 4.71: Vertical acceleration in constant spring rate (K4 = 200 kN/m) for Hatchback

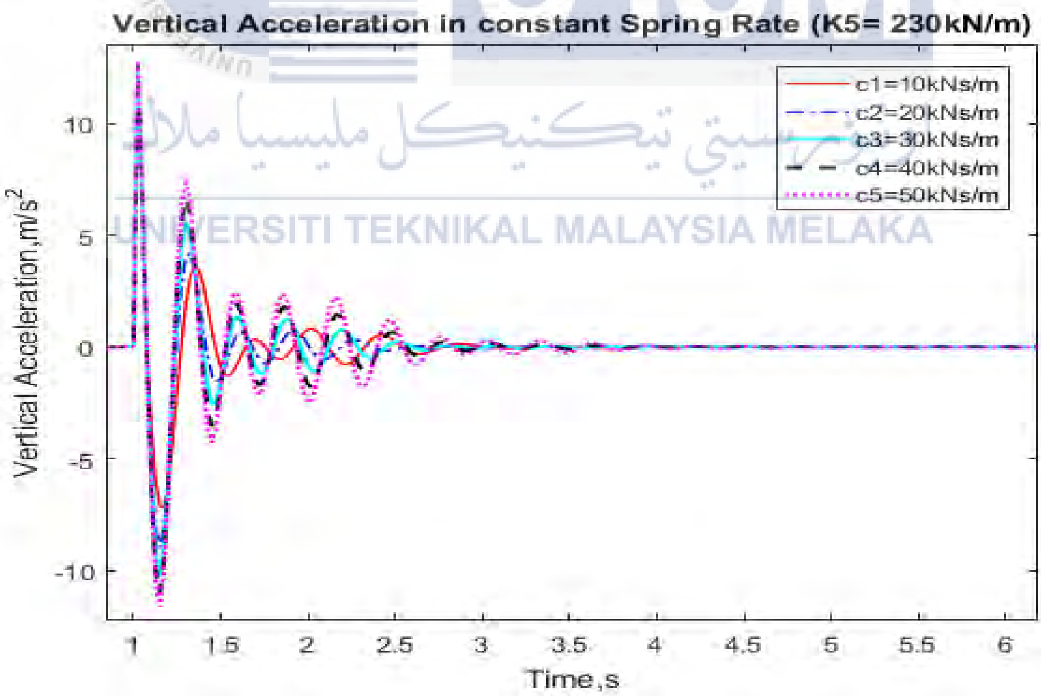


Figure 4.72: Vertical acceleration in constant spring rate (K5 = 230 kN/m) for Hatchback

Table 4.9 and **Figure 4.73** shows that the value of overshoot that experienced on vertical body acceleration with various spring stiffness and damping value. It can see that the lowest overshoot value that experienced on vertical body acceleration on the SUV, Full size car with spring stiffness about 130 kN/s and damping value about 10 kNs/m.

For overall simulation result on Hatchback car, it can analysed that the different effect of pitch body motion and vertical body acceleration on various value of spring stiffness. It can be noted that the damper of suspension is the main component that able to improve the comfort of the vehicle. It is because the damper of suspension is able to absorb the undesirable from the road that exerted on the vehicle body. So, the damper of suspension should be matching with the spring in order to produce a better performance on the suspension system before assemble to the vehicle. From the graph, it can be concluded that the most suitable spring stiffness and damping value for Hatchback car are 10 kNs/m for damping value while 130 kN/m for spring stiffness.

Table 4.9: Overshoot for Hatchback on different spring stiffness and damping value.

		Damping Value				
	kNs/m / kN/m	C1 = 10	C2 = 20	C3 = 30	C4 = 40	C5 = 50
Spring Stiffness	K1 = 130	11.90	12.11	12.40	12.62	12.77
	K2 = 153	12.05	12.17	12.43	12.63	12.78
	K3 = 189	12.27	12.25	12.47	12.66	12.80
	K4 =200	12.33	12.27	12.49	12.67	12.81
	K5 = 230	12.50	12.33	12.52	12.69	12.82

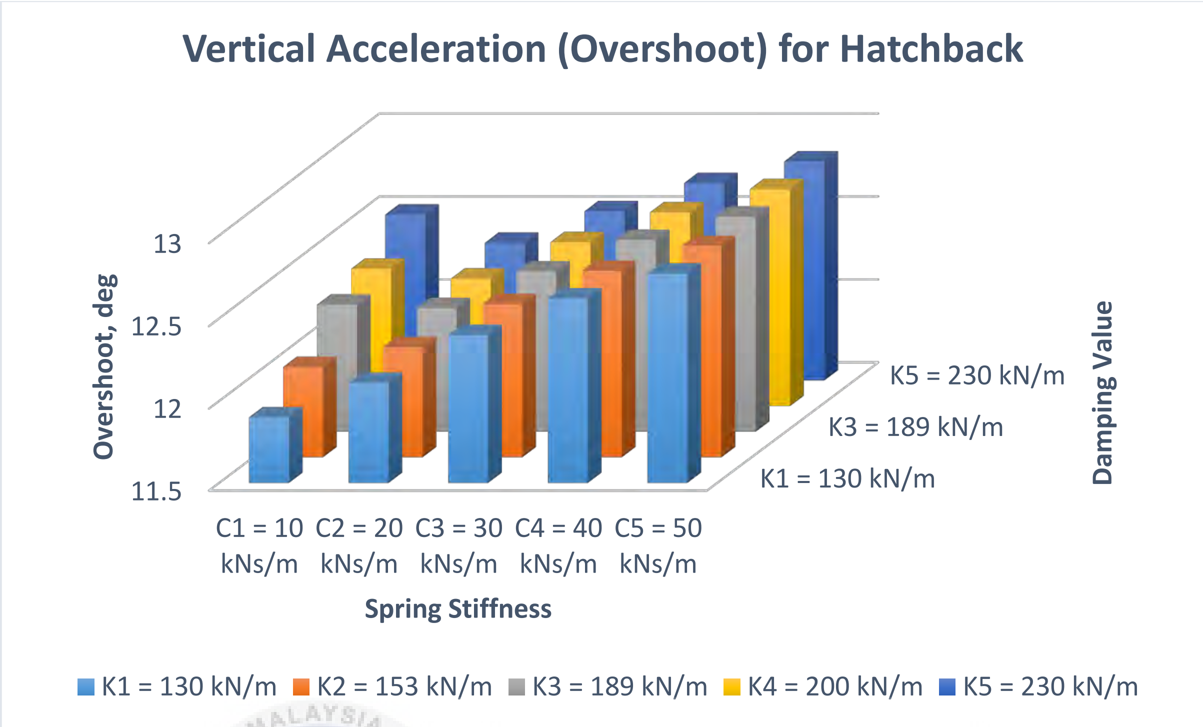


Figure 4.73: Overall result on vertical acceleration for Hatchback (Overshoot, deg)

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Pitch motion of the vehicle body represent the motion the vehicle between front body and rear body. The pitch motion can be simulated by using 4 DOF ride model or 7 DOF ride model. The 4 DOF ride model is the model used to simulate the half body of vehicle while 7 DOF ride model will be used to simulated the full body of the vehicle. A 4 DOF ride model was developed to simulate the dynamics behaviour of the vehicle ride over bumps. To make sure the 4 DOF ride model of simulation represent the real application on the vehicle, this 4 DOF ride model was verified with CarSimEd. After get the pattern of result between 4 DOF ride model and CarSimEd, the 4 DOF ride model are suitable to run the simulation on the various parameter of the vehicle which are Sedan, Hatchback and SUV, Full size car with five different value of spring stiffness and damping. From this simulation, it can determine the suitable spring stiffness and damping value on each vehicle in order to determine the optimal comfort on the vehicle and proved the minimum effect on pitch motion and vertical body acceleration.

5.2 Recommendation

To further study on suspension system for vehicle, this 4 DOF ride model are recommended to replace with 7 DOF ride model full car model. This full car model is required to validate first to make sure that this full car model representing real application on the vehicle. Other that, active and semi-active are recommended to use in the 4 DOF ride model simulation, it is because the tuning process on suspension system easier to improve the comfort of the vehicle. Last but not least, this 4 DOF simulation should apply on the real situation to proof that the theoretical result and real application are same. It is because the theoretical has neglected some effect on the vehicle.

REFERENCES

Liu , J., Shen, Y., & Yang, S. (2013). Parameters Optimization Of Passive Vehicle Suspension Based On Invariant Points Theory. *International Journal On Smart Sensing And Intelligent Systems*, 2182-2199.

Titurus, B., Bois, J. D., Lieven, N., & Hansford, R. (2010). A Method For The Identification Of Hydraulic Damper Characteristics From Steady Velocity Inputs. *Mechanical SystemsandSignalProcessing*, 2868-2887.

BalaRaju, A., Shruti, R. J., Venkatachalam, R. (2014). Effect of Damping on Comfort Level of a Fully Independent Suspension System of An Automobile. *International Journal of Innovative Research in Science, Engineering and Technology*, 13604-13609.

Abdullah, M. A., Jamil, J. F., & Mohan, A. E. (2016). Vehicle Dynamics Modelling And Simulation. *Malaysia: Centre For Advanced Research On Energy*.

Banerjee, S., Balamurugan, V., & Krishnakumar, R. (2016). Ride Comfort Analysis of Math Ride Dynamics Model of Full Tracked Vehicle with Trailing Arm Suspension. *12th International Conference on Vibration Problems*, 1110-1118.

Bohidar, S. K., Patel, G., & Sen, P. K. (2015). Suspension System: Review About Components, Principal And Classification. *International Journal of Advanced Technology in Engineering and Science*, 1606-1612.

Cao, D., Rakheja, S., & Su, C. Y. (2008). Heavy Vehicle Pitch Dynamics and Suspension Tuning. *Canada: CONCAVE Research Center*.

Ferdek, U., & Luczko, J. (2012). Modeling And Analysis Of A Twin-Tube Hydraulic Shock Absorber. *Journal Of Theoretical And Applied MechanicS*, 627-638.

Fouladi, M. H., & Mohd Nor, M. J. (2009). Evaluation of Whole-Body Vibration and Ride Comfort in a Passenger Car. *International Journal of Acoustics and Vibration*, 143-149.

Chavhan, G. R., Burande, S.W., Dhole, L. P. (2014). Analysis Of Shock Absorber Using Different Material Of Spring , *International Journal of Advanced Engineering Technology* , 19-21.

Gogaa, V. K. (2012). Optimization of vehicle suspension parameters with use of evolutionary. *Procedia Engineering 48*, 174-179.

Harun, M. H. (2008). Simulation An Active Suspension For Peugeot 206. Melaka: Universiti Teknikal Malaysia Melaka.

Johnston, M. J. (2010). Development and Evaluation of Vehicle Suspension Tuning Metrics. *Windsor, Ontario, Canada*.

Katu U.S., Desavale R.G & Kanai R.A. (2016). Effect Of Vehicle Vibration On Human Body – RIT Experience. *India: Department of Mechanical Engg.Rajarambapu Institute of Technology Sakharale*.

Khajavi, M. N., & Abdollahi , V. (2007). Comparison between Optimized Passive Vehicle Suspension System and Semi Active Fuzzy Logic Controlled Suspension System Regarding Ride and Handling . *World Academy of Science, Engineering and Technology*, 57-61.

Kumar, M. S., & Vijayarangan, S. (2007). Analytical and experimental studies on active suspension system of light passenger vehicle to improve ride comfort. 34-40.

Mitraa, A. C., Desaib, G. J., Patwardhanc, S. R., Shirked, P. H., Kurnee, W. M., & Banerjeef, N. (2016). Optimization Of Passive Vehicle Suspension System By Genetic. *12th International Conference on Vibration Problems, ICOVP 2015*, 1158 – 1166.

Oborne, D. (1978). Vibration and Passenger Comfort. *Applied Ergonomic*, 155-161.

Poornamohan, P., & Kishore.T, L. (2012). Design And Analysis Of A Shock Absorber. *International Journal of Research in Engineering and Technology* , 578-592.

Rijumon, K., Murtaza, M. A., & Krishnan, A. (2013). A Comparison Between Passive & Semi Active Suspension Systems. *International Journal of Innovative Research in Science, Engineering and Technology*, 2412-2416.

Salehpour, M., Jamali, A., & Nariman-zadeh, N. (2011). Optimal Selection of Active Suspension Parameters Using Artificial Intelligence. *International Journal of Automotive Engineering*, 244-255.

Shirahatti, A., Prasad, P., Panzade, P., & Kulkarni, M. (2008). Optimal design of passenger car suspension for ride and road holding. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*.

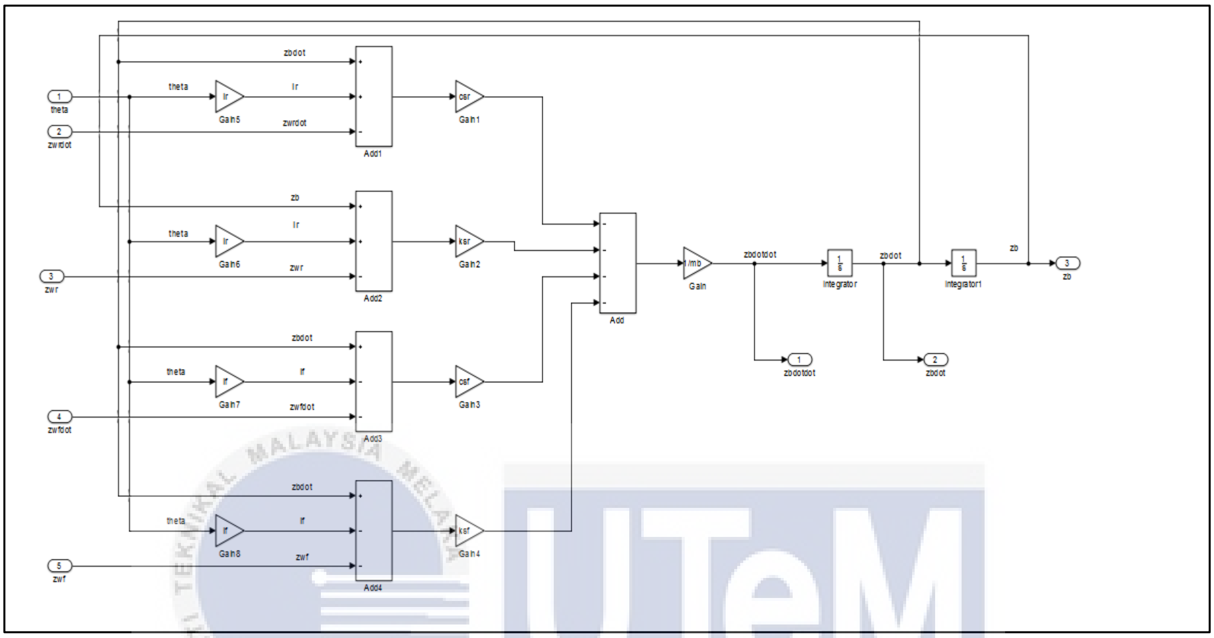
Sitnik, L. J., Tokowicz, M. M., Wróbel, R., & Kardasz, P. (2013). Vehicle Vibration In Human Health. *Journal of KONES Powertrain and Transport,*, 411-418.

Zehsaz, M., & Javash, M. S. (2013). Studying The Efficacy Of Road Disturbance Amplitude And Speed Increasing On Performance Of Semi Active Suspension System. *International Journal of Advances in Engineering & Technology*, 189-201.

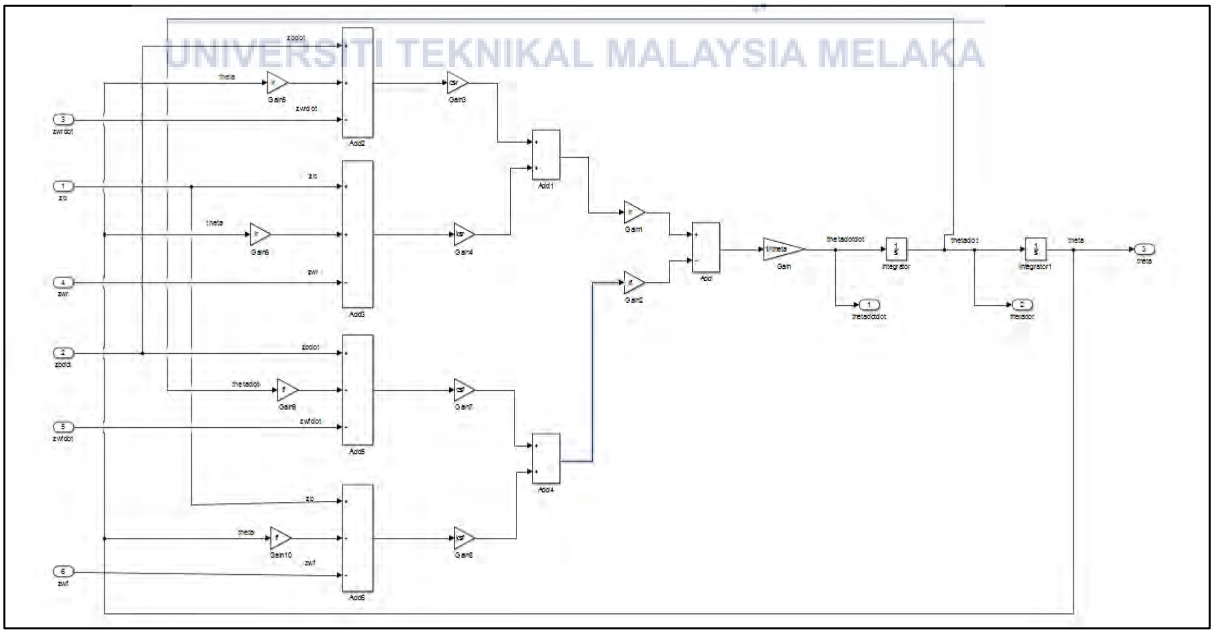
Zhengke, C. (2015). The research of vehicle's ride comfort in the nonlinear suspension system. *5th International Conference on Education, Management, Information and Medicine* (pp. 1392-1397). China: Automotive Engineering institute, Jiangxi University of Technology, Nanchang 330098,.

APPEDICES

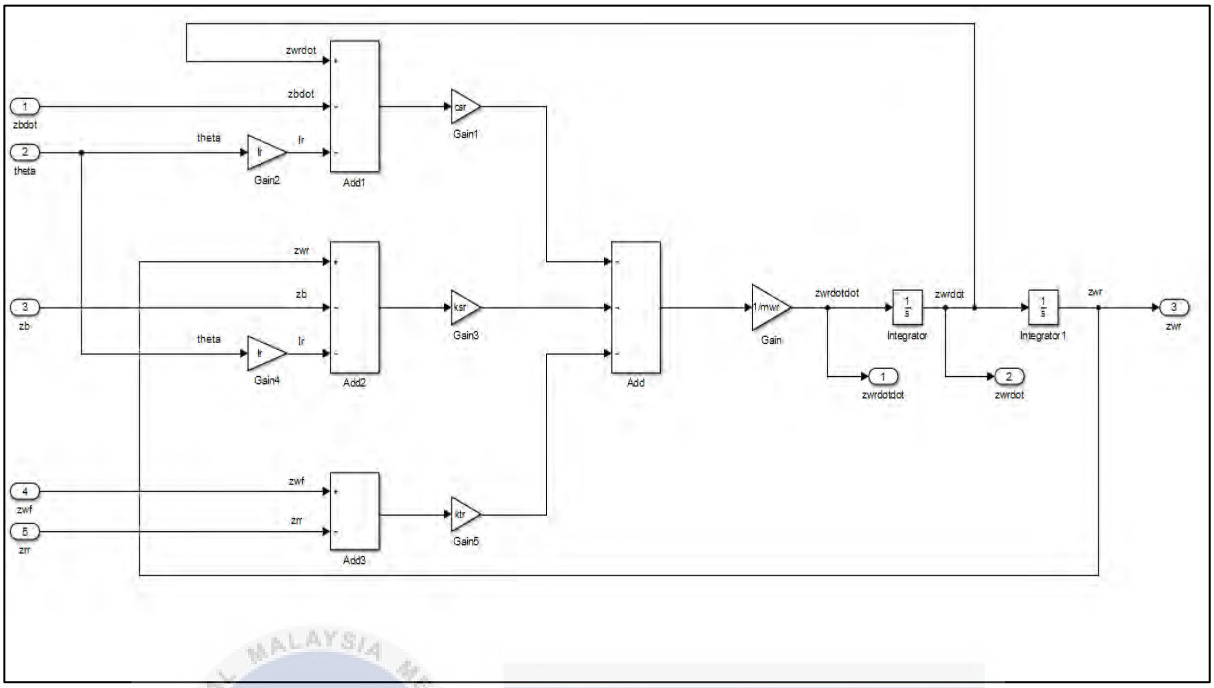
Appendix A: Simulink of the vertical motion of the vehicle (Sprung Mass)



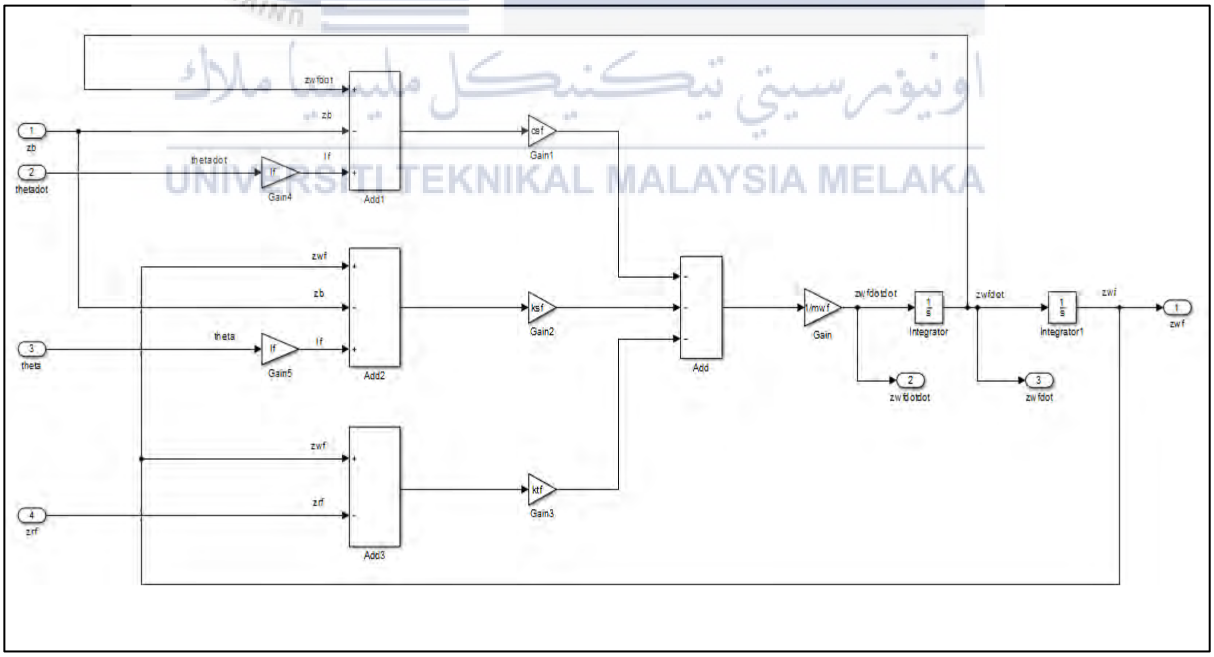
Appendix B: Simulink of the rotational motion of vehicle body (Pitch)



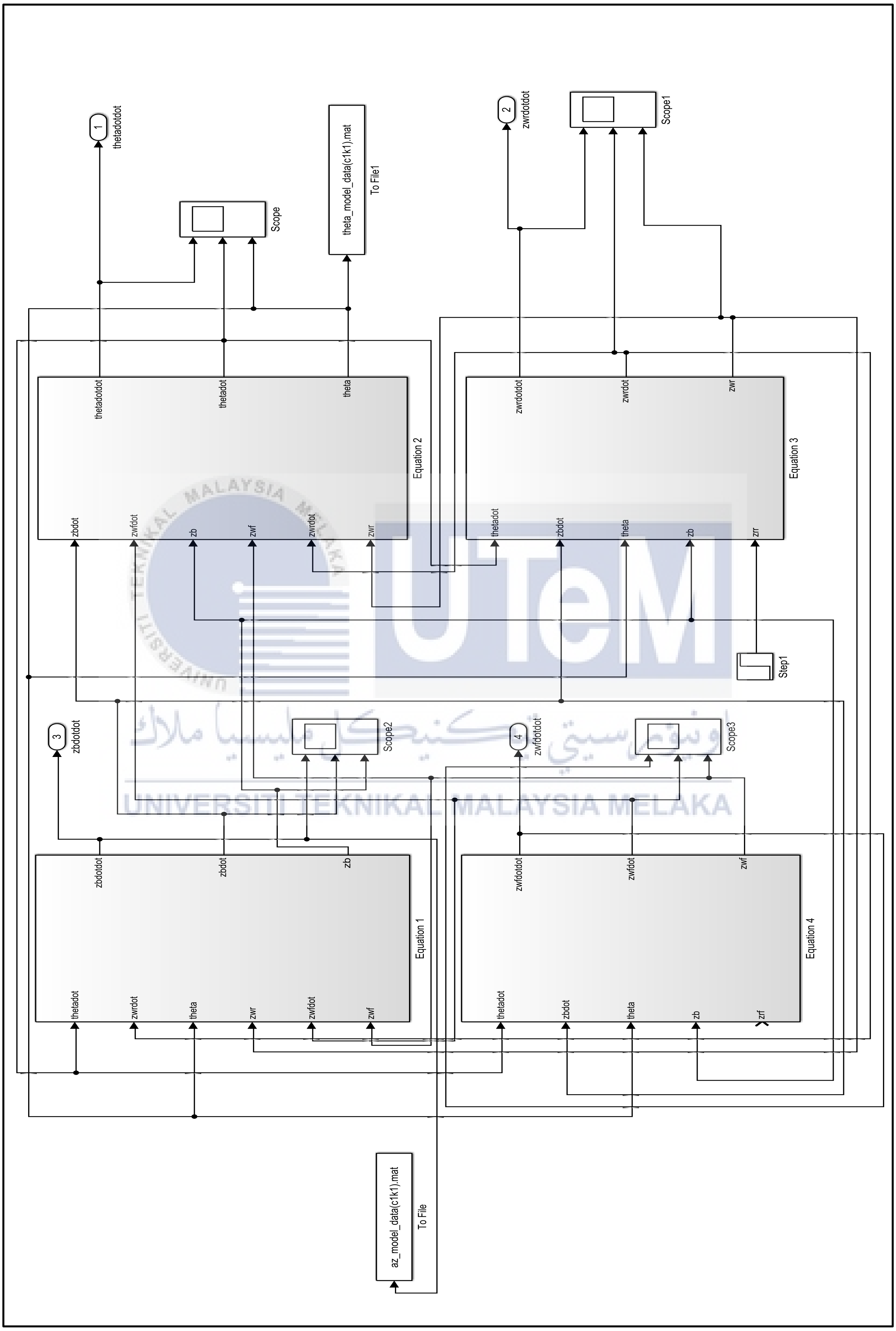
Appendix C: Simulink of the vertical motion of rear wheel (Tyre)



Appendix D: Simulink of the vertical motion of front wheel (Tyre)



Appendix E: 4 DOF ride model for pitch motion

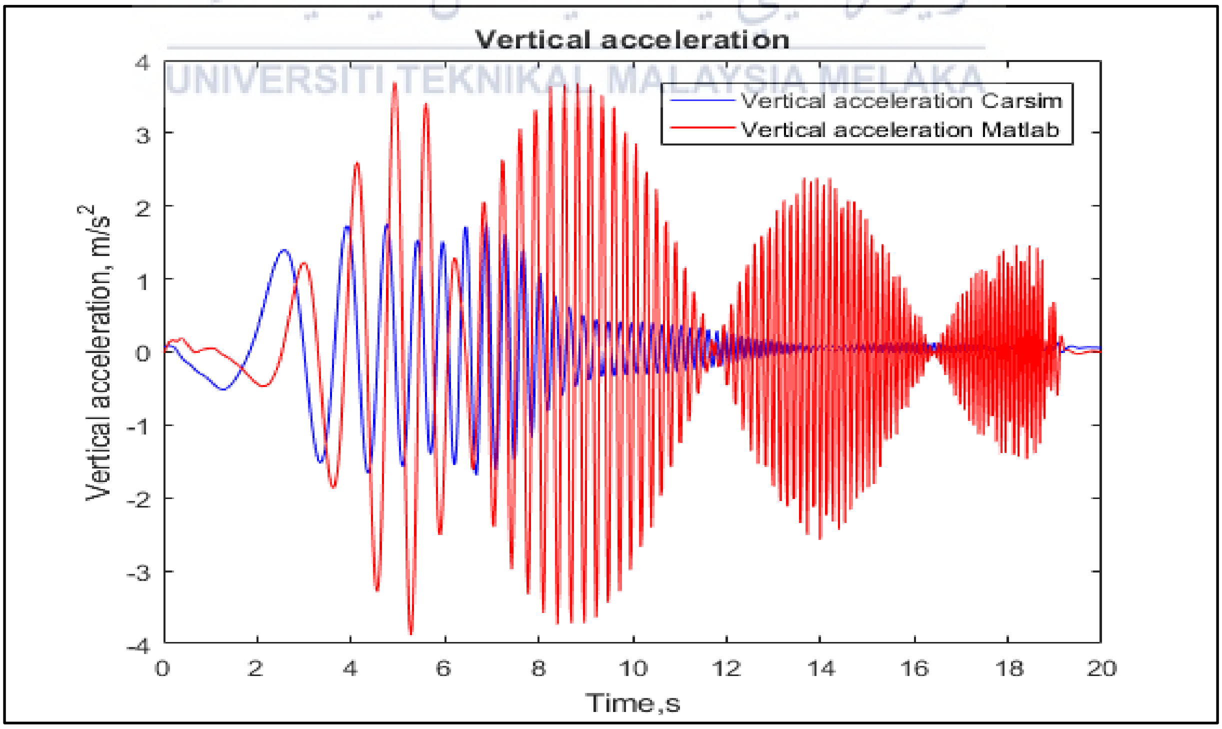


Appendix F: Coding on the Matlab

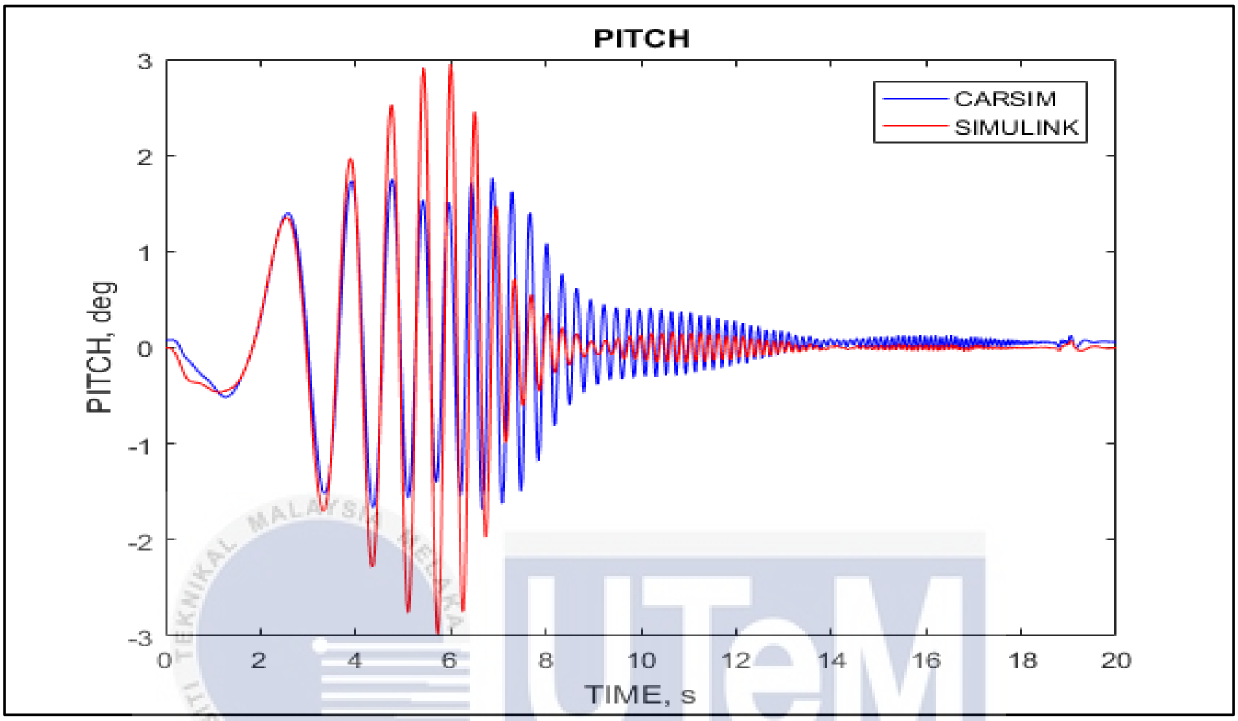
```
load data_pitch.mat;
load data_theta.mat;
figure(1)
plot(theta(1,:),theta(2,:)*180/3.142);
hold on;
plot(data_pitch(1,:),data_pitch(2,:));
xlabel('Time,s');
ylabel('Pitch angle');
title('Pitch Angle');
legend('Pitch model','Pitch Carsim')

load data_zbdotdot.mat;
load data_az.mat;
figure(2)
plot(zbdotdot(1,:),zbdotdot(2,:));
hold on;
plot(data_az(1,:),data_az(2,:));
xlabel('Time,s');
ylabel('Vertical acceleration, m/s^2');
title('Vertical acceleration');
legend('Vertical acceleration model','Vertical acceleration Carsim')
```

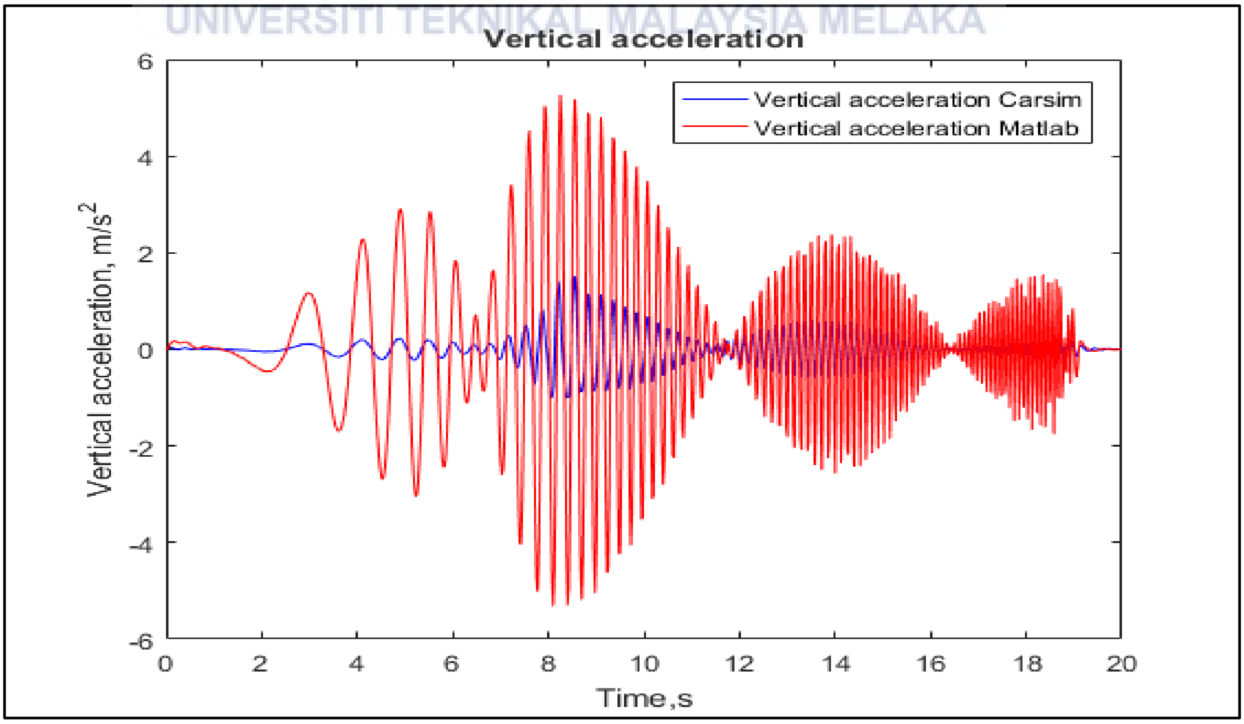

Appendix G: Verification of 4 DOF ride model on C = 10 kNs/m and K = 130 kN/m (Vertical Acceleration)



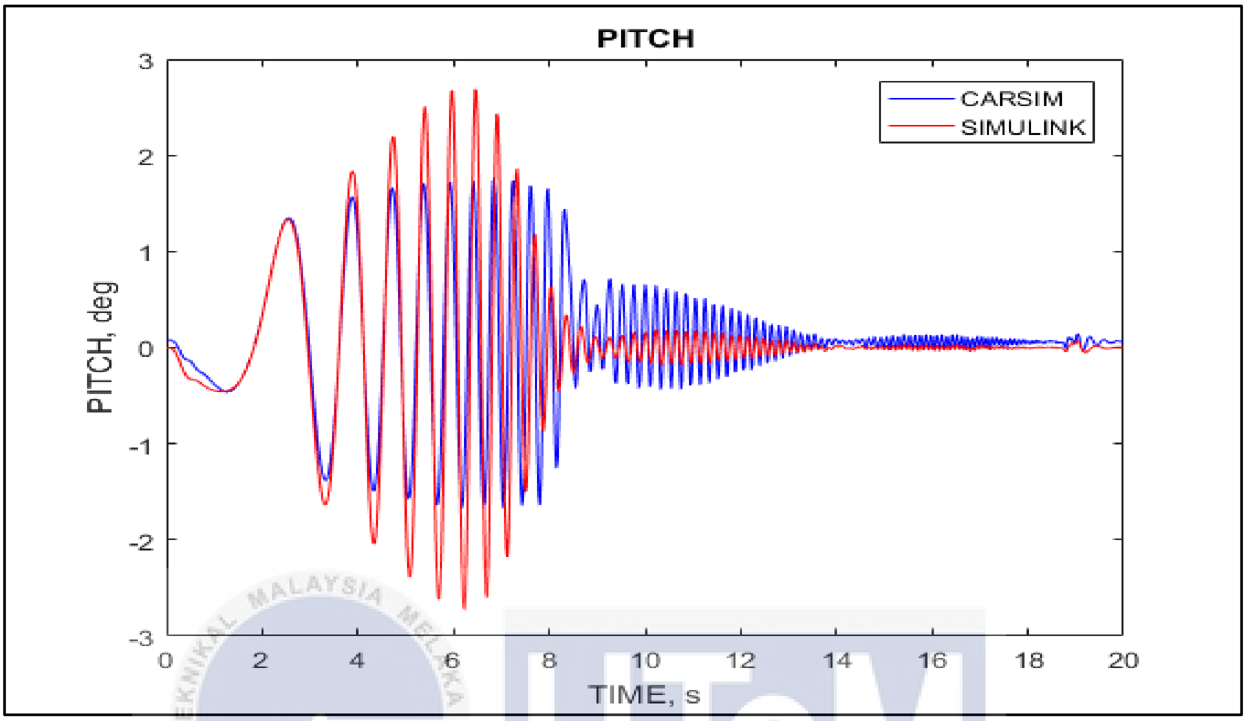
Appendix H: Verification of 4 DOF ride model on C = 10 kNs/m and K = 130 kN/m (Pitch Motion)



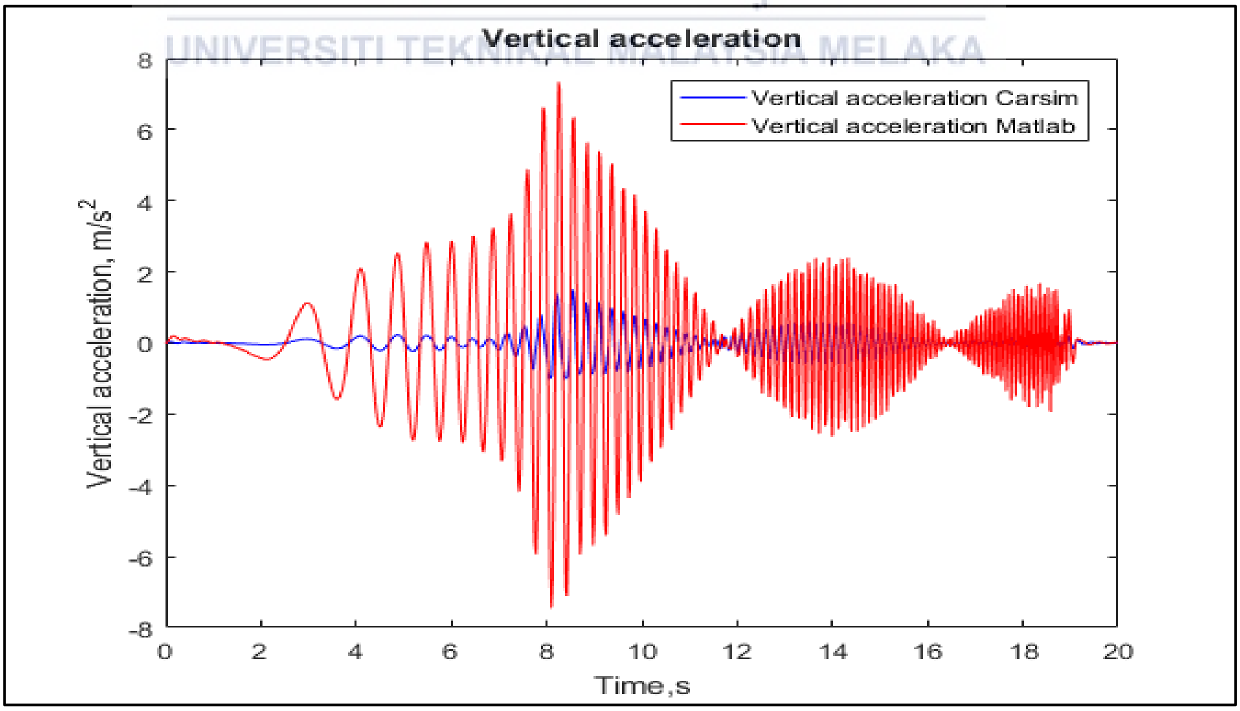
Appendix I: Verification of 4 DOF ride model on C = 20 kNs/m and K = 153 kN/m (Vertical Acceleration)



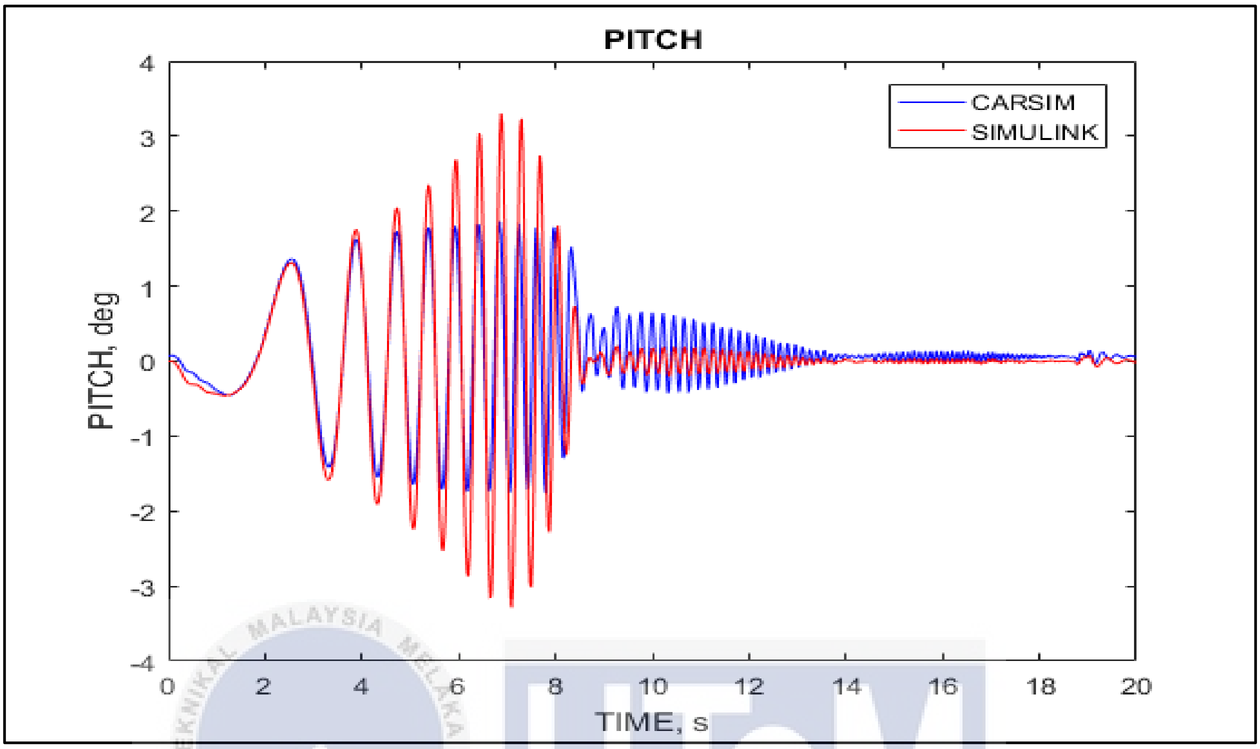
Appendix J: Verification of 4 DOF ride model on C = 20 kNs/m and K = 153 kN/m (Pitch Motion)



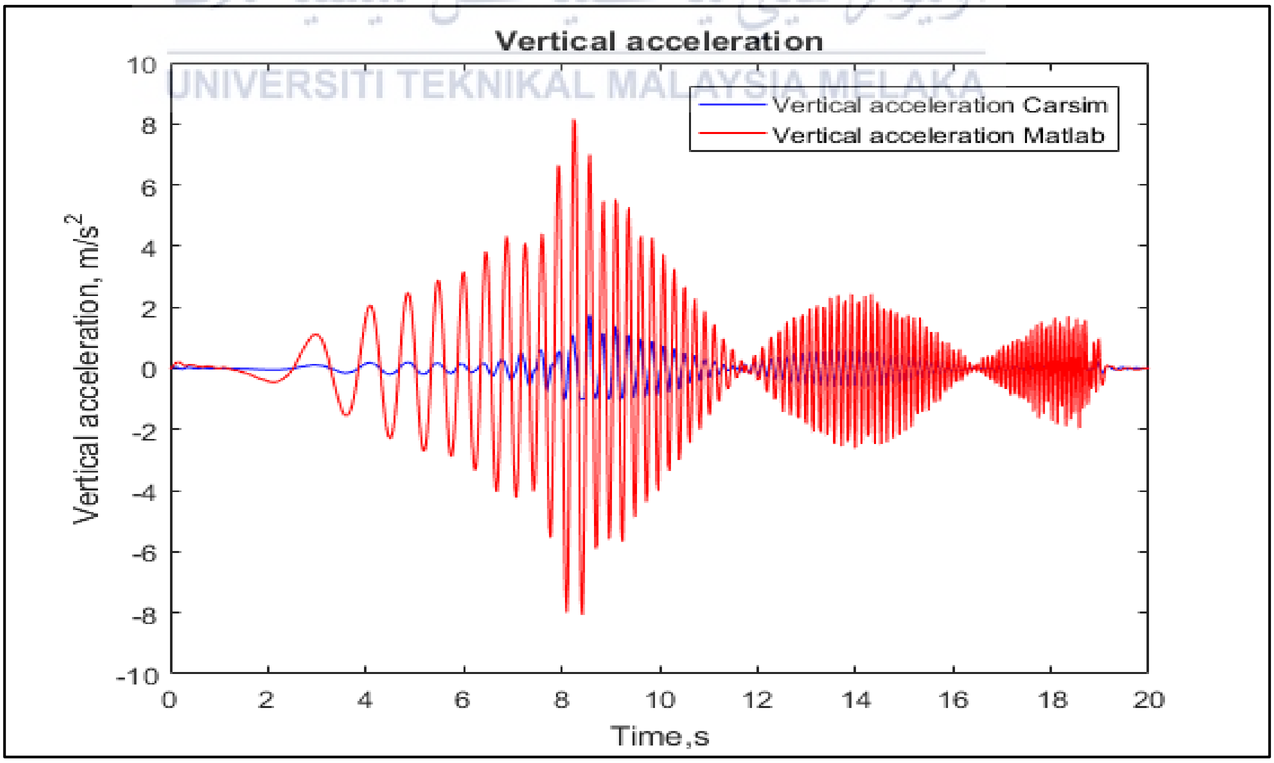
Appendix K: Verification of 4 DOF ride model on C = 40 kNs/m and K = 200 kN/m (Vertical Acceleration)



Appendix L: Verification of 4 DOF ride model on C = 40 kNs/m and K = 200 kN/m (Pitch Motion)



Appendix M: Verification of 4 DOF ride model on C = 50 kNs/m and K = 230 kN/m (Vertical Acceleration)



Appendix N: Verification of 4 DOF ride model on C = 50 kNs/m and K = 230 kN/m (Pitch Motion)