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"Not what we give,
But what we share,
For the gift
without the giver
Is bare."
- James Russell Lowell

ABSTRACT

The suspension systems are designed to be effectively isolate the vibration and absorb the shock of the obstacles on the road and improving the ride comfort of the car passengers. There are several types of suspension used in a vehicle. Recent developments in multivariable control and microprocessor have led to implementation of modern control algorithms to be used on vehicle suspension systems and control the suspension behavior electronically. This kind of development has potential to increase the overall performance.

Such suspension has advanced concepts where the suspension system is controlled using sensing device and servomechanisms. This type of suspension is controlling the conventional passive suspension system and because of that, the suspension system is called active suspension system. However, passive suspensions are found on most of the conventional vehicles. Thus, half car model passive suspension system is studied so that the behavior of passive suspension system during travelling on a rough terrain can be analyzed and a working model and simulation of passive suspension system can be provided for educational purpose.

Generally, passive suspension system is formed by combination of two components. The first component is an energy dissipating element, which is the damper, and the second component is an energy-storing element, which is the spring. Since energy cannot be added into the system by any of these two components, this type of suspension systems is called passive.

This paper presents the study and simulation of passive suspension system with the utilization of MATLAB Simulink to build the model. The response of the vehicle body, pitch angle, sprung masses, and unsprung masses are simulated and analyze to create better understanding on passive suspension system performance.

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CHAPTER 1
INTRODUCTION

1.1 Project Background

Transportation is well established as one of the basic services for human society. Successive research and development in improving transportation facilities have participated considerably in bringing mobility to most segments of the population around the world and accelerated the industrial commercial success. The needs for efficient and fast transportations are rising and together with that, several means of system installed in the vehicle have been either proposed or developed. As the transportation system serves humanity, safety must come first before comfortability and economically feasible. The transportation facilities should be built more efficiently. Thus, advanced research is needed in different aspects of transportation such as reliability, maintenance in vehicle structures, vibration, and shock effects in transportation.

Passenger's comfort, maintenance and repair costs of the vehicle are greatly influenced by mechanical vibrations. A vehicle travelling on a certain road profile is subjected to a disturbance at each wheel with random function of time taken for the vehicle body to go back to its initial condition. The vehicle system which responds to such disturbance is called a suspension system. One of the main objectives of a vibration engineer is to design the vehicle suspension system to be able to achieve the acceptable and appropriate response. Among the requirements for the suspension system to be considered appropriate are acceptable passenger comforts, small suspension deflections and good road holding ability. Good vibration isolation is required to secure the occupants comfort, whereas good road holding is important for vehicle holding and enhancing the safety of vehicle occupants. Key design constraint for a suspension system are represented by the acceleration of vehicle body, maximum allowable relative displacement between the vehicle and various suspension components, including wheels, vehicle and other unsprung masses. Additional constraints are

imposed by the overall system robustness, reliability, power and cost requirements.

Conventionally, road vehicle system was passive devices consisting of energy storage and dissipative elements tuned to one particular design point. The fixed characteristics inherent in the passive suspensions have led to a compromise in performance between sprung mass isolation, suspension level, and tire-road contact variation. Recent developments in multivariable control design methodology and microprocessor implementation of modern control algorithms open a new era for the design of electronically controlled vehicle suspension systems, with potential increase in overall performance. Such advanced suspension concepts include actively controlled systems that use sensing devices and servomechanisms and externally controlled passive systems called semi-active suspensions. However, passive suspensions are found on most of the conventional vehicles. Roughly, they are characterizes by the absence of external power sources, whereas the active suspensions require additional energy sources, such as compressors or pumps to achieve superior ride and holding performance[1].

The modern approaches in design demand not only acceptable performance but optimal performance. Considerable efforts have been devoted over the last two decades to determine the optimum suspension design for a vehicle travelling on randomly profiled roads. These studies realized that optimum passive suspension design is essentially a compromise between the several competing requirements of the suspension itself. Before proceeding on optimizing the suspension performance, the response of the system must be first observed and analyzed.

1.2 Problem Statement

Increasing the performance of the suspensions in motor vehicles has always been an interest of many automotive and vibrations engineers. When the vehicle is travelling over rough terrain, there will be bouncing motion, pitching motion and rolling motion exhibits by the vehicle. The bouncing motion is the up and down motion of the vehicle, pitching motion is the rotation about the center of gravity along the vehicle's length and the rolling motion is the rotation about the center of gravity along the vehicle's width.

Some engineers are resorting to active suspensions which have more superior performance compared to conventional passive type with respect to road handling and holding under all conditions including straight roads, rough roads, broken roads and the ride quality of the vehicle. Such superior performance is obtained at the expense of increase system complexity since the vehicle must be fitted out with a series of devices such as sensors, force actuators, and accessories for realizing the desired control law; more expensive and heavier vehicles result on the one hand, and less reliable ones on the other, owing to the greater number of parts that are liable to break down [1].

However, active suspension system is also rather complex, since it requires components such as actuators, high pressure tanks for the control fluid, sensors for detecting the system state, etc. which makes itself heavier and more energy consumptive than a passive suspension system. Hence there rises an increasing concern about whether the pursuit of higher performance of active system is worth that much cost and complexity. Compared to the active suspensions system, the passive suspensions system is cost economical, reliable and it requires no power consumption which is why it is gaining more attention in consumer's automobile industry.

1.3 Objectives

The objective of the proposed research is to investigate the responses of passive vehicle suspension models in order to obtain better understanding of their performance limits. It is also proposed to model the passive suspension system using MATLAB Simulink and analyze it to obtain the suspension parameters that will produce certain desirable responses.

Specifically, there are several objectives of this project which are:

- To study the response of passive suspension system to obtain better understanding of the performance limit
- To develop a model of passive suspension system using MATLAB Simulink
- To analyze the behavior of passive suspension system during travelling on a rough terrain
- To provide working passive suspension system model and simulation for educational purpose

CHAPTER 2
LITERATURE REVIEW

2.1 Suspension Components

The main components of a passive suspension system are springs and shock absorbers. The most commonly found spring types in a suspension system are the coil springs, torsion bars and leaf springs. Coils springs are the typical helical springs applied to absorb the shock when the vehicle travelling on a rough terrain and making sure the tires are on the road the whole time by maintaining the force between the tire and the road. The torsion bar spring has almost the same performance but a bit different placement compared to coiled spring. One axle is attached to one end of steel shaft while the other end is slotted into a tube and held there by splines. As the suspension moves, the shaft is twisted along its length and coiled up. As the top of the coil is pressed, the pressing force is actually inducing a twisting in the shaft all the way down to the coil. Examples of cars implementing this type of spring in their suspension are Volkswagen Beetles, Porches and Peugeot 205s. The leaf springs can be on most heavy duty vehicles. In the appearance, they look like a layer of metal connected to the axle. The layers a called leaves and the spring system is called leaf springs.

The main function of shock absorbers or most of the time referred as dampers is dampen the vertical motion induced when a car is travelling on a rough terrain. Without dampers, the car which operates with only springs as the component of a suspension system would wallow along the road until the passengers will feel uncomfortable and physically sick. Generally, shock absorbers have two functions. Firstly, they absorb the vibration transmitted to the car chassis when the car is travelling or encountered a bumper. Secondly, dampers keep the tires planted on the road which improves the vehicle handling. The dampers work in conjunction with the springs. The springs absorb the shock during travelling and transformed it into kinetic energy which later dissipated by the damper.

2.2 Model Selection

Suspension system plays significant role when it comes to ride comfort of a car. Passenger's ride comfort is quite subjective as it is judged by the car passengers themselves. As the ride comfort of the passengers are concerned, designing a suspension system which provides good ride comfort should be a priority for vibration engineers without ignoring the safety factor of a car.

The passive suspension system installed in the vehicle must be studied and analyzed to create higher understanding of the vehicle vibration. For the studies and detail investigation to be carried out, a vehicle model must be selected. The pitch, bounce and roll motion of the vehicle must be taken into consideration. Thus, half car vehicle model will be used for the purpose of analyzing the response of the vehicle.

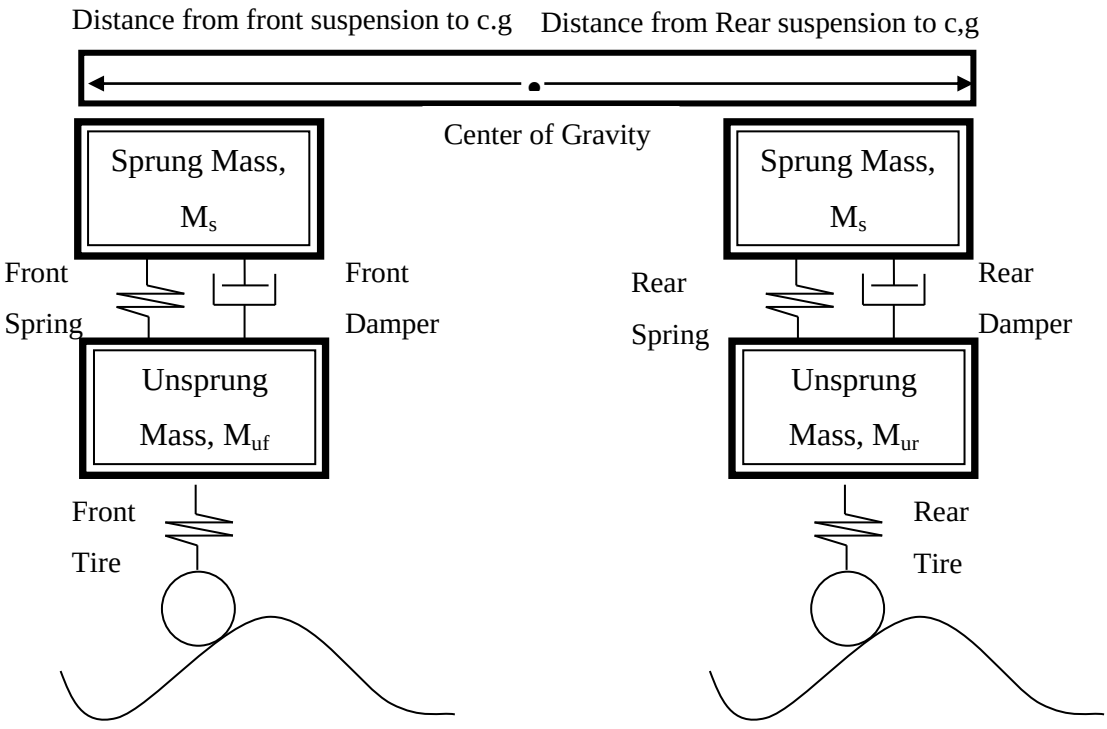


Figure 2.1: Half Car Passive Suspension Model

Sprung mass is a portion of vehicle's total mass. It is mass that is supported above the suspension and half of the weight of the suspension itself in most applications. Typically, it includes the vehicle body weight, the car chassis, internal components, passengers and other weight carried on the vehicle but the mass of the components suspended below the suspensions component is not included.

Unsprung mass is the mass of the components that is not supported by the suspension system. It is the mass of the suspension components, wheels and other components such as the wheel axles, wheel bearings, wheel hubs, tires and a portion of the weight of drive shafts that is connected directly to the wheels rather than supported by the suspension.

2.3 Vehicle Dynamics

Vehicle dynamics can be referred as the study of vehicle body motion. The forces acting on a system can be divided into two types of forces; internal forces and external forces. Internal forces are the forces acting between several connected bodies while the external forces are forces acting from outside of the system. Examples of external forces are the contact force, which described by the traction force at the tireprint of a driving wheel and body force, which referred to the gravitational force on the vehicle's body [2]. The vehicle accelerates, maneuvers through corner, and stops are greatly depending on the amount of grip or friction between the road and the tires. In simpler way, the greater the friction, the faster the car accelerates.

Suspension system directly affected the handling of the vehicle. A suspension system that functions properly allows the car chassis to experience minimal vibration and less disturbed when travelling on a rough terrain. This is achieved by the combination of several components in the system such as bushings, springs and dampers.

When a bump is encountered by the travelling vehicle, the energy is absorbed by the bushing while the springs compress and store the kinetic energy. When the kinetic energy is released, the vehicles weight will rebound. The rate at which the springs compress and rebound is controlled using a hydraulic damper, such as a shock absorber or strut. The result of this action is decreasing the amount of vibration felt in the passenger compartment [2].

2.4 Moment of inertia and Radius of Gyration

Moment of inertia can be expressed as $I = Mk^2$ where M is the total sprung mass of a car while k is the radius of gyration of the mass. Figure 2.2 shows the radius gyration of a car.

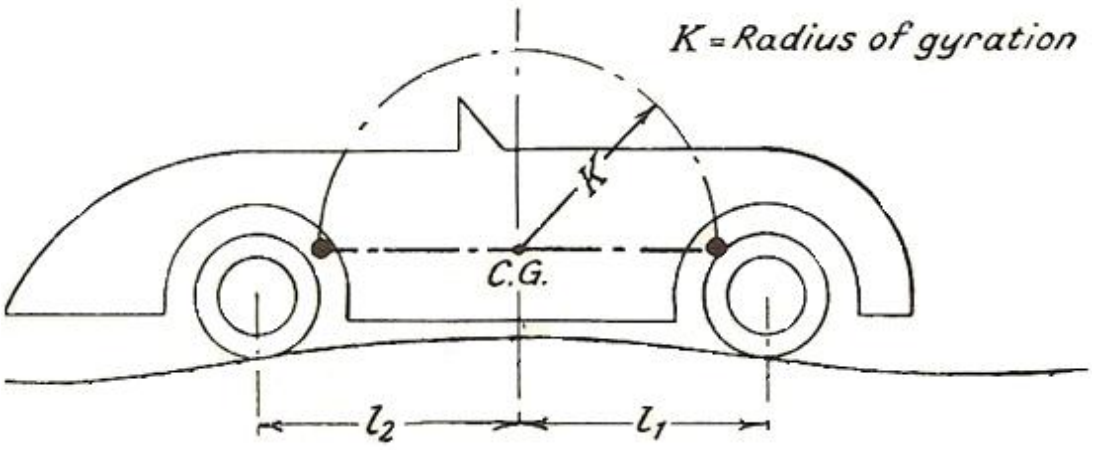


Figure 2.2: Radius of Gyration of a car [3]

Assuming that the rear vehicle mass and the front vehicle mass are concentrated in the front and rear axle, the moment of inertia will gives [3]:

$$I_{yy=M_f.l_2{}^2+M_r.l_1{}^2}$$

Assuming $l_1 = l_2$, and $M_f = M_r$, we get [3]:

$$I_{yy} = M_f.l_1(l_1 + l_2)$$

From the diagram, we know that $M_f = \frac{M_T.l_2}{l_1+l_2}$, substituting into the earlier equation gives [3]:

$$I_{yy} = \frac{M_T.l_2.l_1(l_1+l_2)}{(l_1+l_2)} = M_T.l_2.l_1$$

2.5 Bounce, Pitching motion

Bounce is a motion which both ends of vehicle move up and down together. Pitch motion is a bit similar to bounce but different in the pattern of oscillation. One end goes up while the other goes down. Pitching motion is quite disturbing and undesirable in vehicle movement compared to bouncing motion.

During travelling on a straight line, bouncing and pitching motion can be experienced. Basically, bounce occurred when sprung masses of front and rear vehicle are equal while pitch occurred when the vehicle is travelling on more than one road disturbance in a short distance.

2.6 Damped Oscillation

No springs will oscillate forever; it is the fact that has been proved. The frictional forces will diminish the amplitude of oscillation until eventually the system is at rest. However, in most cases the oscillation of the spring is treated as ideal which means there is no friction or damping. In suspension system, damping forces is needed to aid the spring slowly come to rest. Damping forces is the combination of kinetic friction, which tends to be independent of the speed and various fluid drag forces, which tend to be dependent on speed, which make the damping forces become quite complicated.

There may be other forces involved in damping that has not been specified. To describe the damping force in qualitative way, the damping force can be assumed as:

$$F_d = -bv$$

Where, b is the damping constant or usually known as the damping coefficient. Considering the spring force and the damping force in the Newton's second law, we get the suspension force.

$$F = ma = -kx - bv = m\frac{d^2x}{dt^2}$$

Manipulating the equation gives:

$$\frac{d^2x}{dt^2} + \frac{b}{m}\frac{dx}{dt} + \frac{k}{m}x = 0$$

Simplifying the equation by substituting and cancelling out the common $x(t) \neq 0$, we get:

$$\alpha^2 + \frac{b}{m}\alpha + \frac{k}{m} = 0$$

Solving for α,

$$\alpha = \frac{\frac{-b}{m} \pm \sqrt{\frac{b^2}{m^2} - \frac{4k}{m}}}{2}$$

Factoring $-4/km$ out from under radical,

$$\alpha = \frac{-b}{2m} \pm i\omega_0 \sqrt{1 - \frac{b^2}{4km}}$$

Two solutions are obtained from the equation, one of them gives:

$$x \pm (t) = X_{0\pm} e^{\frac{-b}{2m}t} e^{\pm i\omega' t}$$

Where,

$$\omega' = \omega_0 \sqrt{1 - \frac{b^2}{4km}}$$

Take the real part of their sum and get:

$$x \pm (t) = X_0 e^{\frac{-b}{2m}t} \cos(\omega' t + \emptyset)$$

Where,

X_0 = real initial amplitude

$\emptyset$ = relative phase of the oscillator

CHAPTER 3
METHODOLOGY

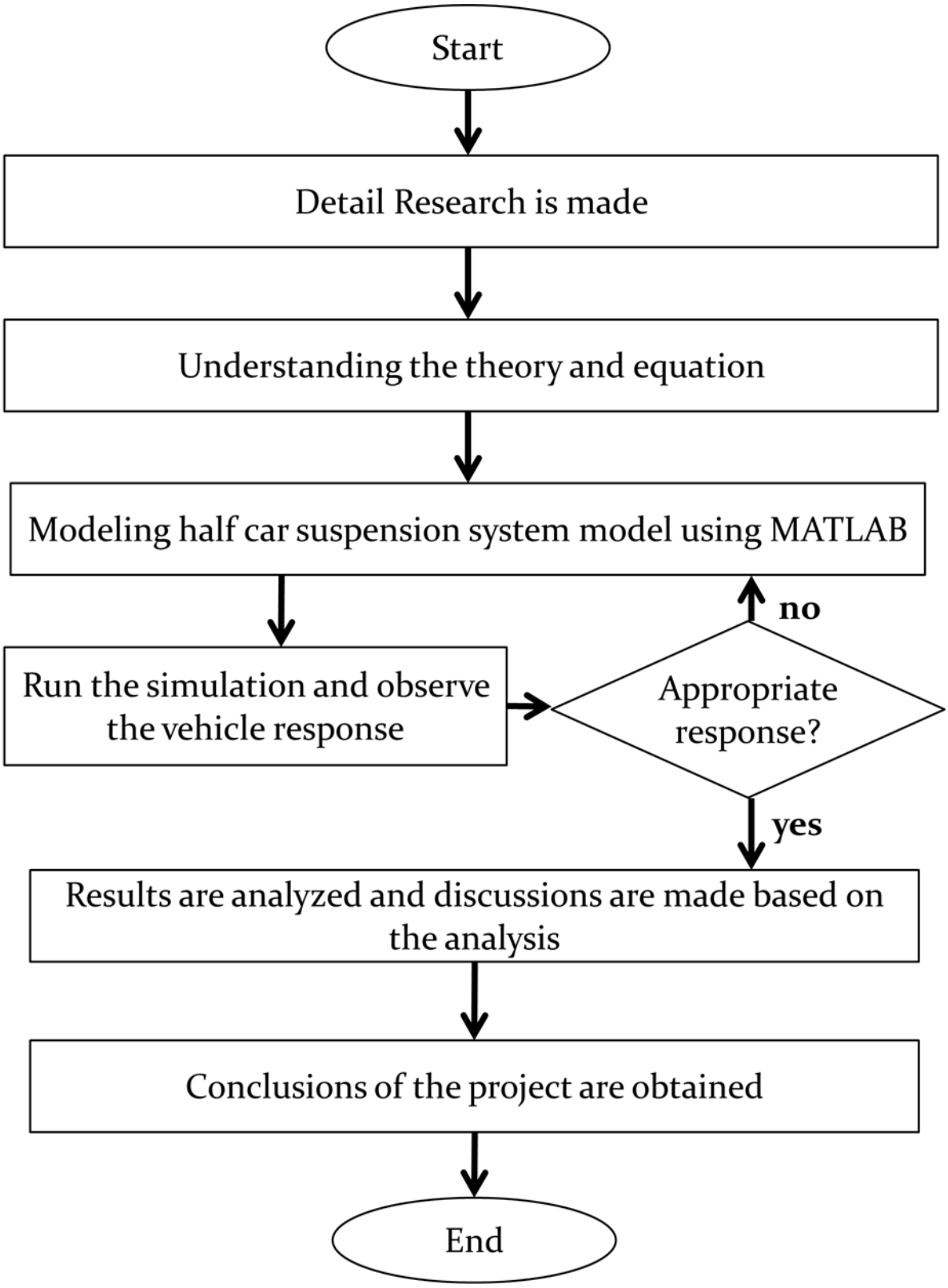
3.1 MATLAB Simulink software

MathWork has developed the MATLAB Simulink software which is an environment for multidomain simulation ad Model – Based design for dynamic and embedded system. Furthermore, Simulink contains interactive graphical environment and sets of block library which can be customize in order to design, simulate, implement and test a variety of time-varying systems, with a large variety of block diagram to be chose for example, communications, controls, signal processing, video processing, and image processing. Besides, more designing option can be used such as multiple modeling domains, as well as tools for design, implementation, and verification and validation tasks with installing the add-on products [5].

MATLAB is computer software with high-level technical computing language and interactive environment to develop algorithm. It also can be used to visualize data, analyze the data and do numeric computation. MATLAB is very useful in this project as it can compute mathematical problem faster than any other traditional programming languages.

Simulink is part of MATLAB software which provides an immediate access to some useful tools when developing algorithms and equations. The algorithms will then be visualized in simulation based. The software allows the user to customize the modeling environment and defining the model signal and parameters before the validity of the data can be tested.

3.2 Project Planning



3.3 Project Milestone

Every project has its own milestone that should be followed to ensure good progress and keep the project to be completed within the time limit. Followed are the milestone suggested by the Mechanical Engineering Final Year Project Coordinator and the personal project milestone:

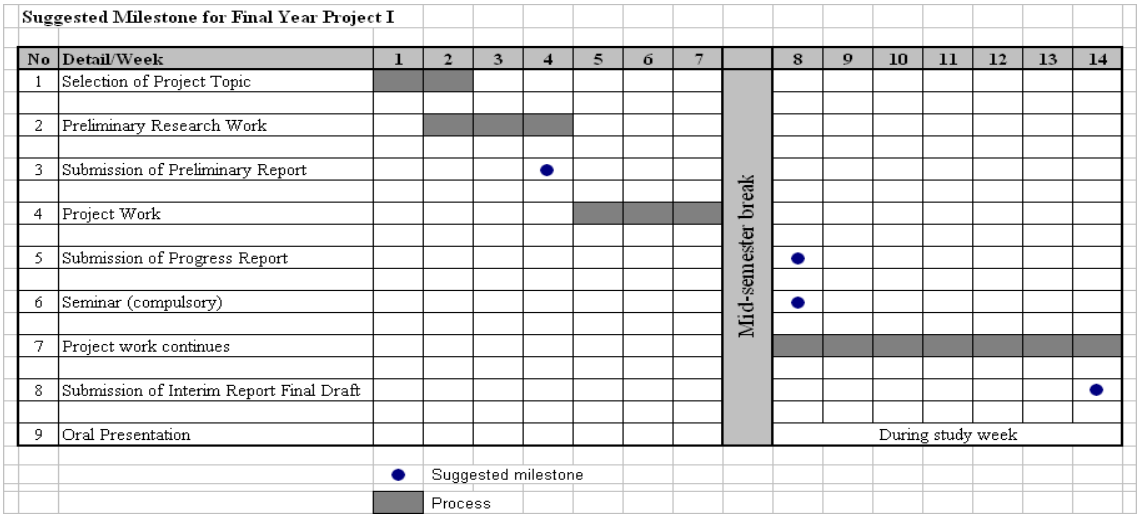


Figure 3.1: Suggested Milestone for FYP 1

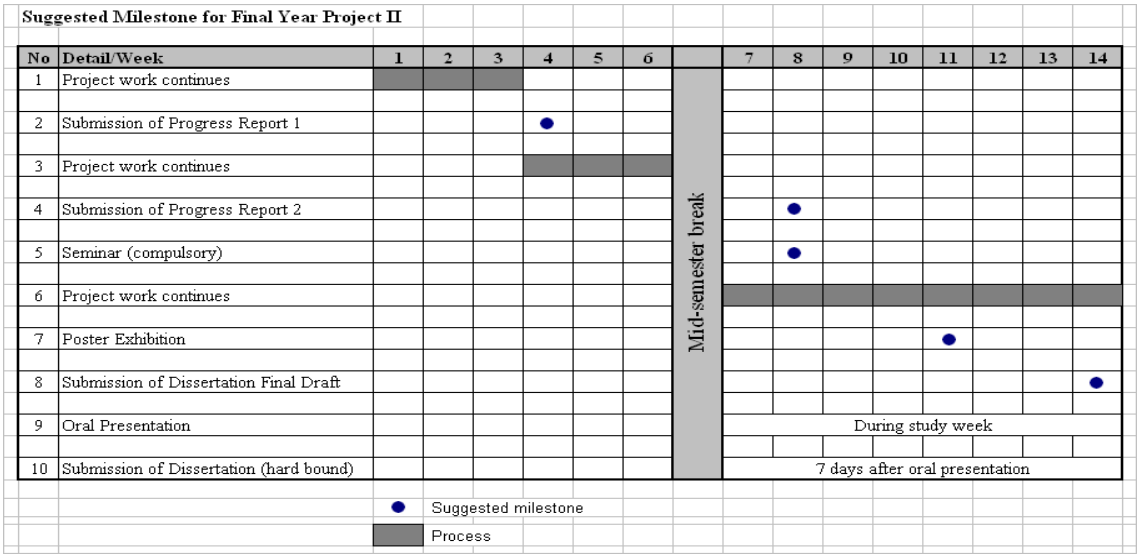


Figure 3.2: Suggested Milestone for FYP 2

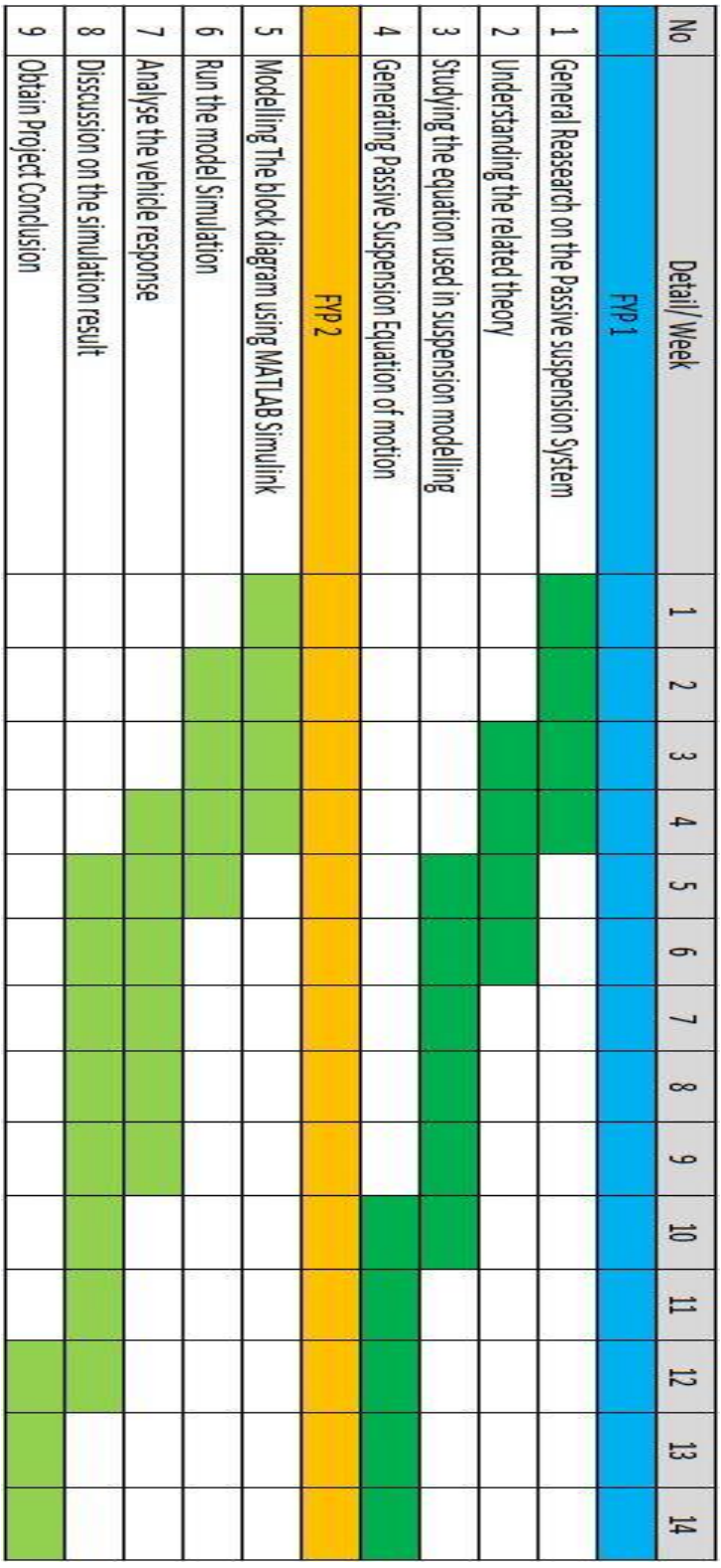


Figure 3.3: Personal Final Year Project Milestone

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Vehicle Parameters

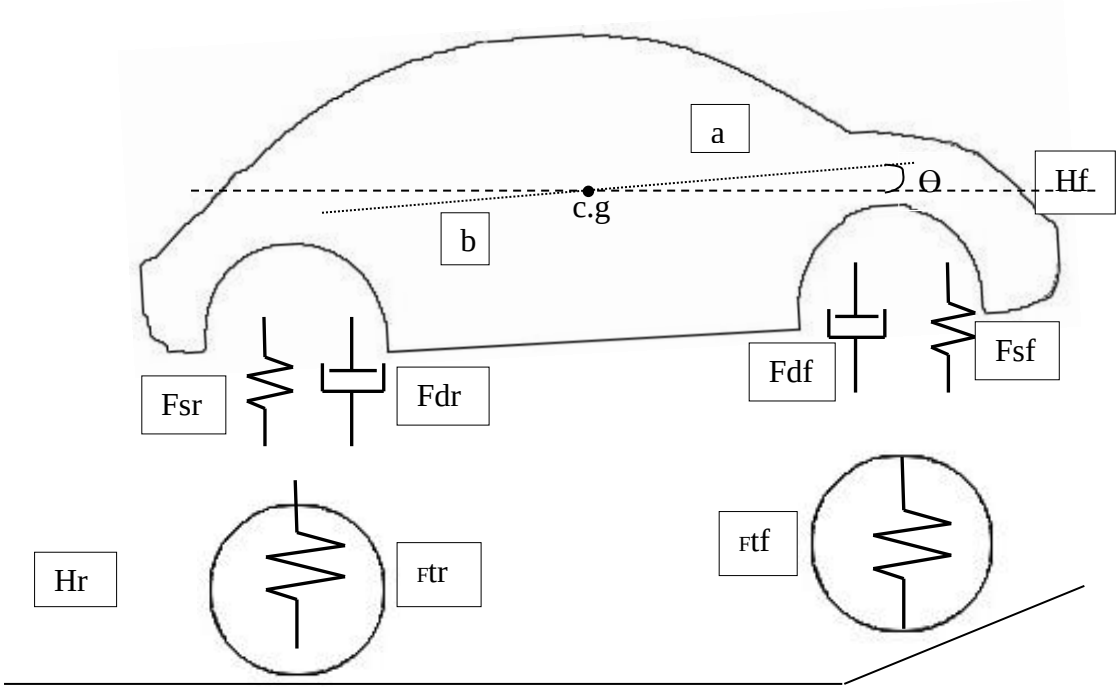


Figure 4.1: Half Car Model

Parameters for modeling half car suspension are as follows:

```
>> Mb = 635; %half car body mass (kg)
>> Msf = 299; %half car body front sprung mass (kg)
>> Msr = 220; %half car body rear sprung mass (kg)
>> Muf = 58; %half car body front unsprung mass (kg)
>> Mur = 58; %half car body rear unsprung mass (kg)
>> Kt = 180000; %tire stiffness (N/m)
>> Ksr = 17800; %rear spring stiffness (N/m)
>> Ksf = 18900; %front spring stifness (N/m)
>> Cdr = 2350; %rear damping coefficient (Ns/m)
>> Cdf = 2460; %front damping coefficient (Ns/m)
>> Iyy = 1066.8; %vehicle body moment of inertia (kgm2)
>> a = 1.4; %distance of font suspension from c.g (m)
>> b = 1.2; %distance of rear suspension from c.g (m)
>> Hf = 0.15; %front road height (m)
>> Hr = 0; %rear road height (m)
>> g = 9.81; %rear road height (m/s2)
```

4.2 Equation of Motion

Before equation of motion can be generated, the free body diagram of the vehicle must be first considered.

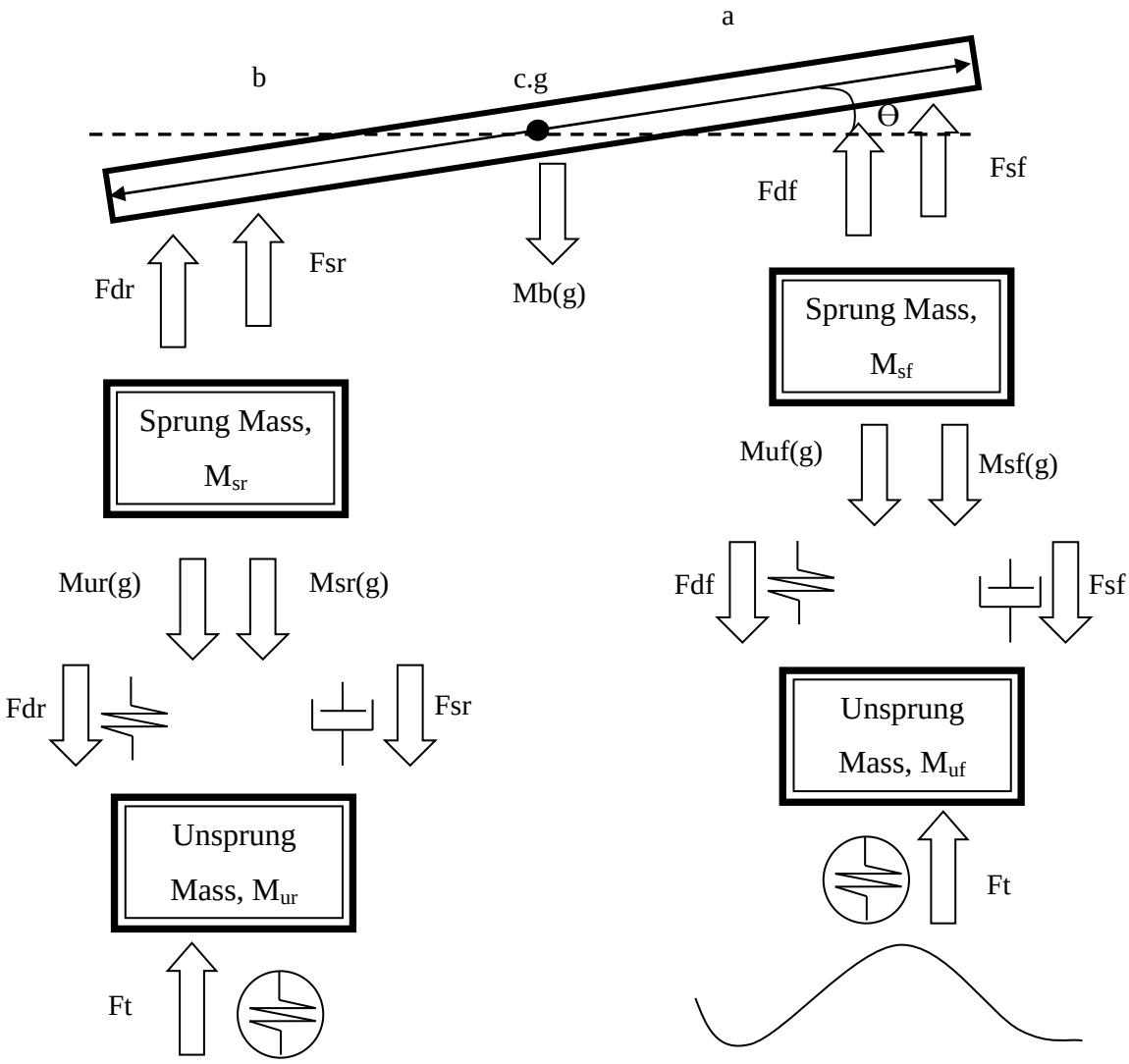


Figure 4.2: Half Car Vehicle Model Free Body Diagram

Front and rear vehicle body displacement when the vehicle wheels hit an obstacle:

$$Z_{sf} = Z_b + a\ sin\theta$$

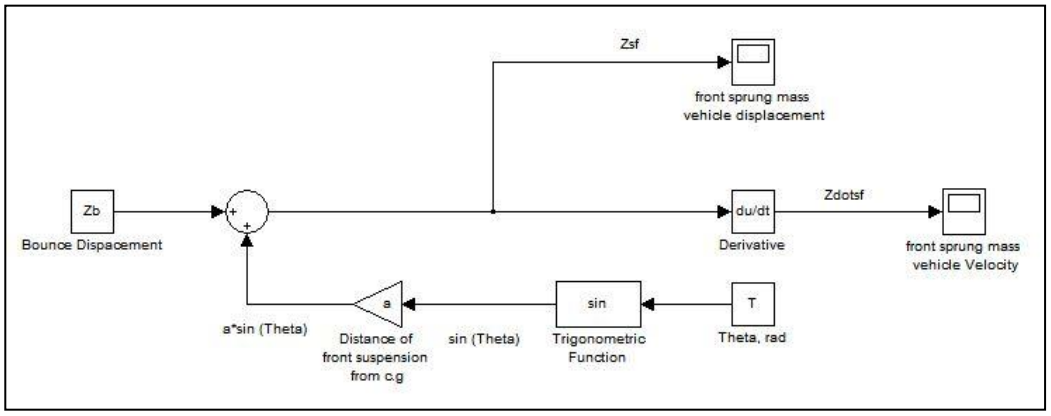


Figure 4.3: Front Sprung Mass Displacement

$$Z_{sr} = Z_b - b\ sin\theta$$

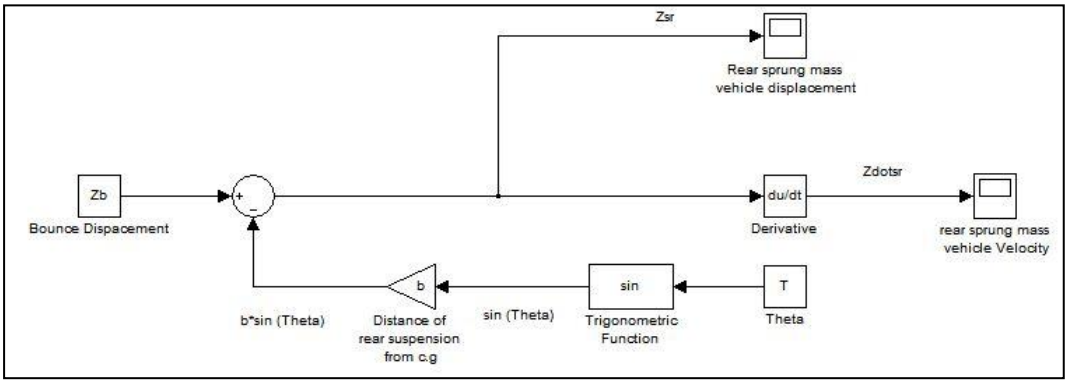


Figure 4.4: Rear Sprung Mass Displacement

Vehicle body acceleration × Half car body mass:

$$F = ma$$

$$F_f + F_r - M_b(g) = M_b\ddot{Z}_b$$

$$\left(F_{sf} + F_{df}\right) + (F_{sr} + F_{dr}) - M_b(g) = M_b\ddot{Z}_b$$

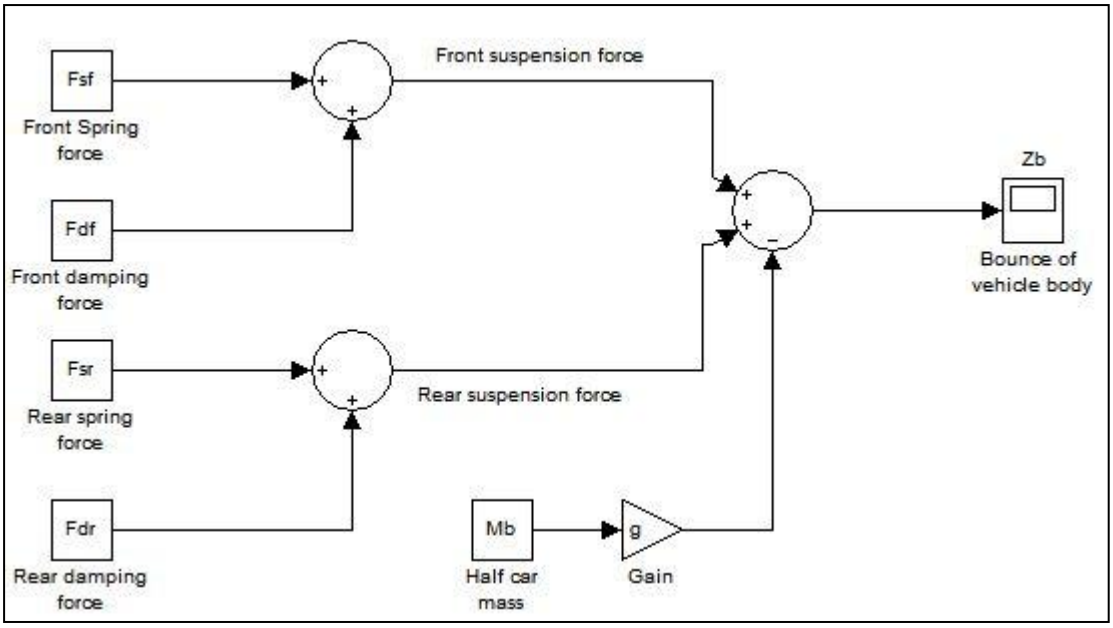


Figure 4.5: Vehicle body acceleration times Half car body mass

Vehicle body moment of inertia × Pitch acceleration

$$F_f(a) - F_r(b) = I_{yy}\ddot{\theta}$$

$$(F_{sf} + F_{df})(a) - (F_{sr} + F_{dr})(b) = I_{yy}\ddot{\theta}$$

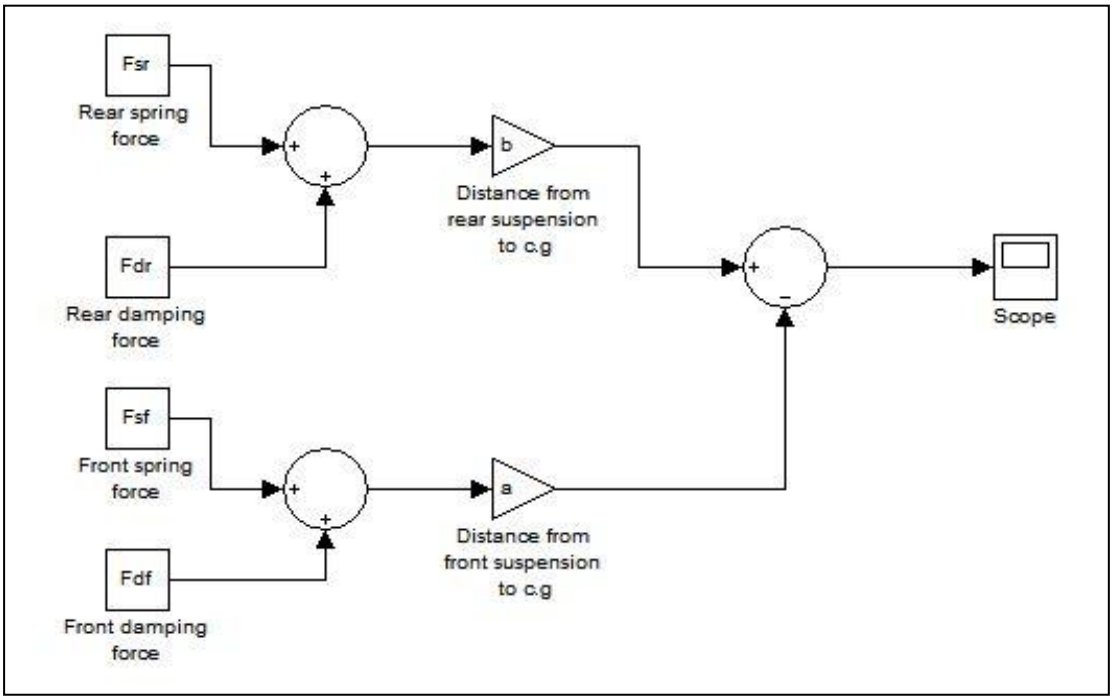


Figure 4.6: Vehicle body moment of inertia times Pitch acceleration

Vehicle Unsprung mass × Unsprung vehicle body acceleration:

$$F_{tf} + F_f - M_{sf}(g) = M_{uf}\ddot{Z}_{uf}$$

$$F_{tf} + (F_{sf} + F_{df}) - M_{fb}(g) = M_{uf}\ddot{Z}_{uf}$$

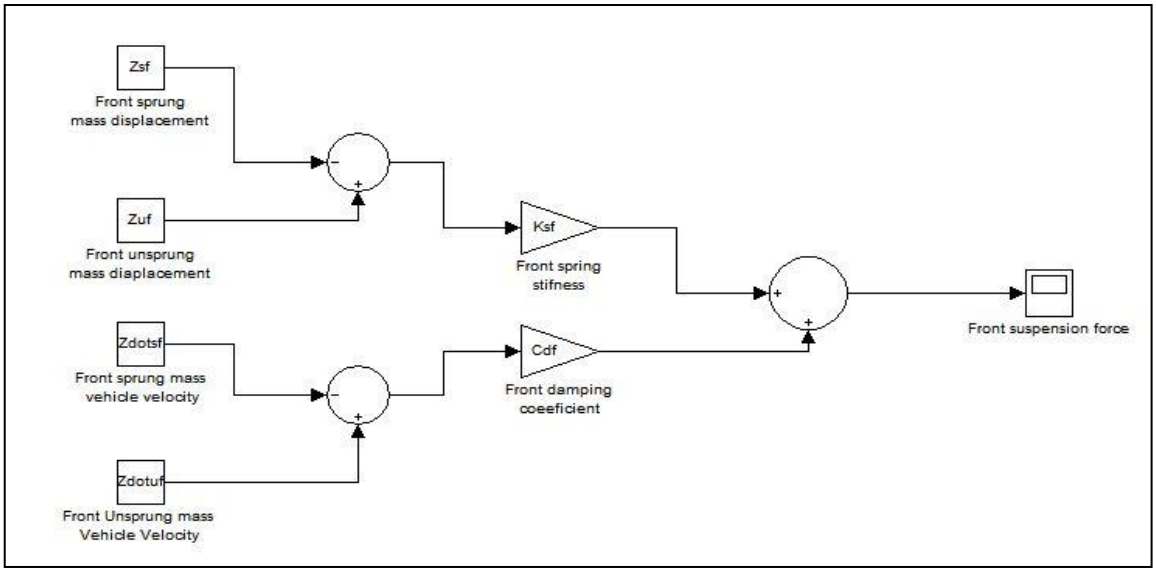


Figure 4.7: Front Vehicle Unsprung mass times Unsprung vehicle body acceleration

$$F_{tr} + F_r - M_{sr}(g) = M_{ur}\ddot{Z}_{ur}$$

$$F_{tr} + (F_{sr} + F_{dr}) - M_{sr}(g) = M_{ur}\ddot{Z}_{ur}$$

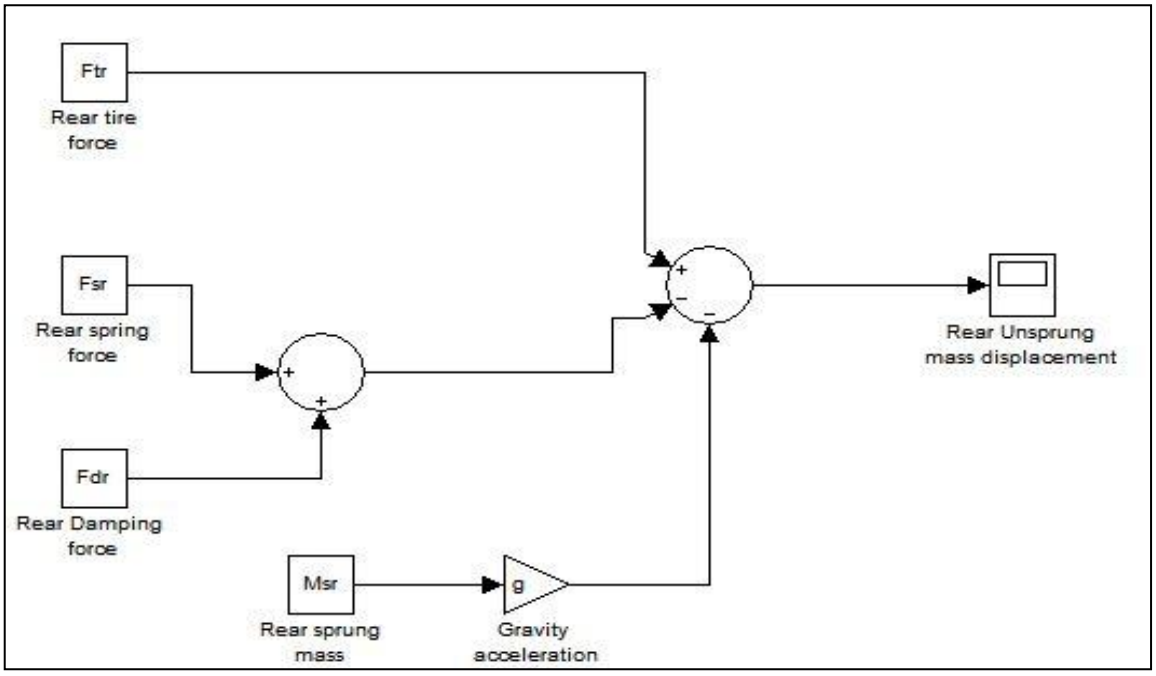


Figure 4.8: Rear Vehicle Unsprung mass times Unsprung vehicle body acceleration

Front and Rear Suspension force:

$$F_{sf} = k_{sf}(Z_{uf} - Z_{sf}) + C_{sf}(\dot{Z}_{uf} - \dot{Z}_{sf})$$

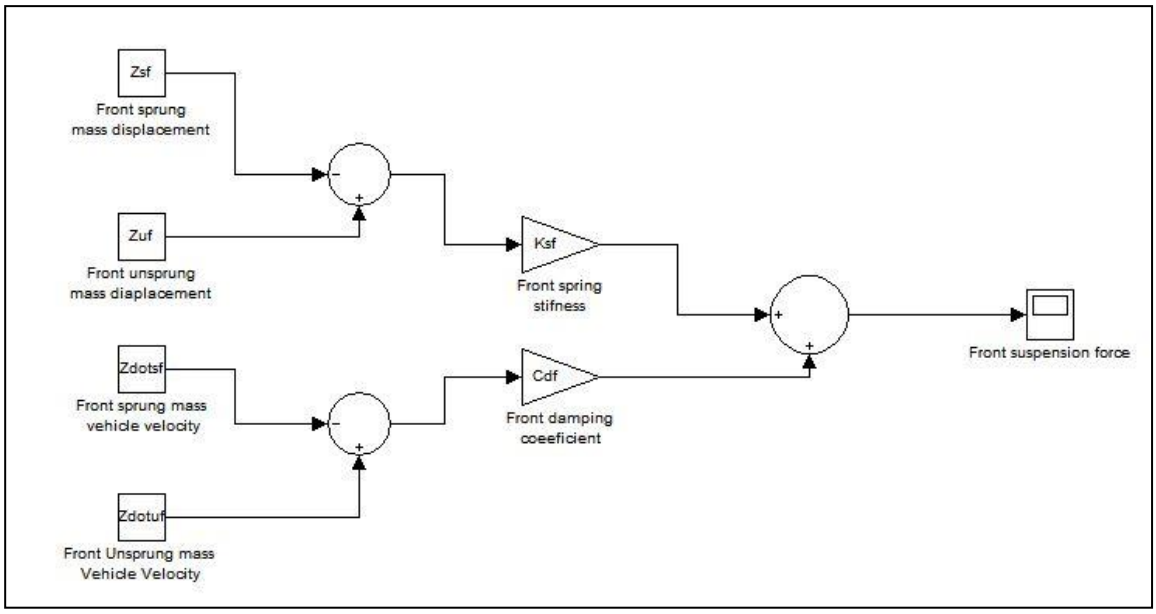


Figure 4.9: Front Suspension Force

$$F_{sr} = k_{sr}(Z_{uf} - Z_{sf}) + C_{sr}(\dot{Z}_{ur} - \dot{Z}_{sr})$$

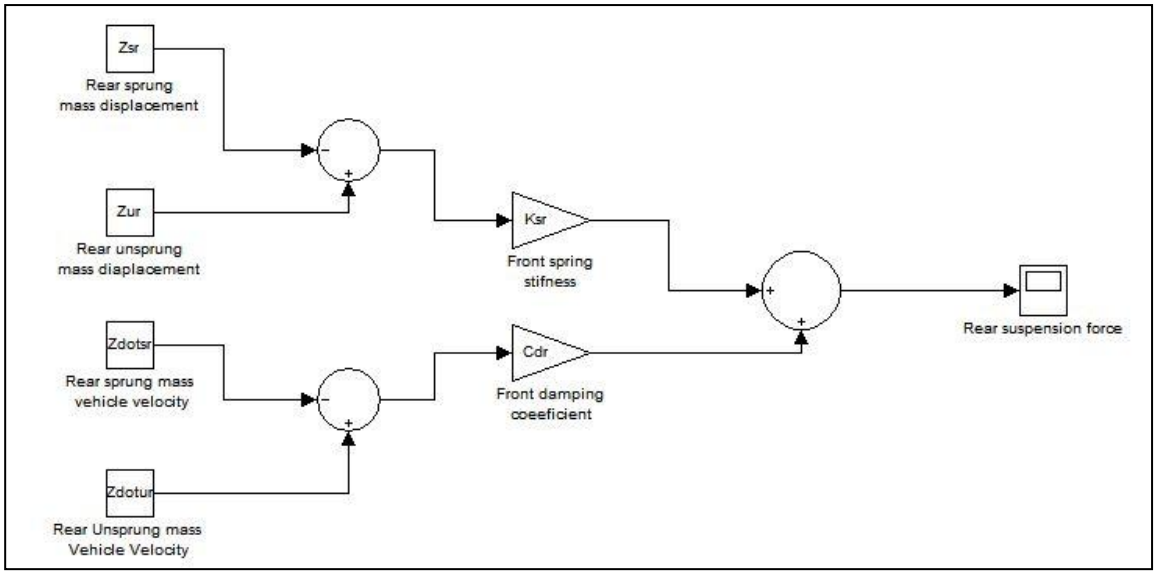


Figure 4.10: Rear Suspension Force

Front and Rear tire force:

$$F_{tf} = k_t(H_f - Z_{uf})$$

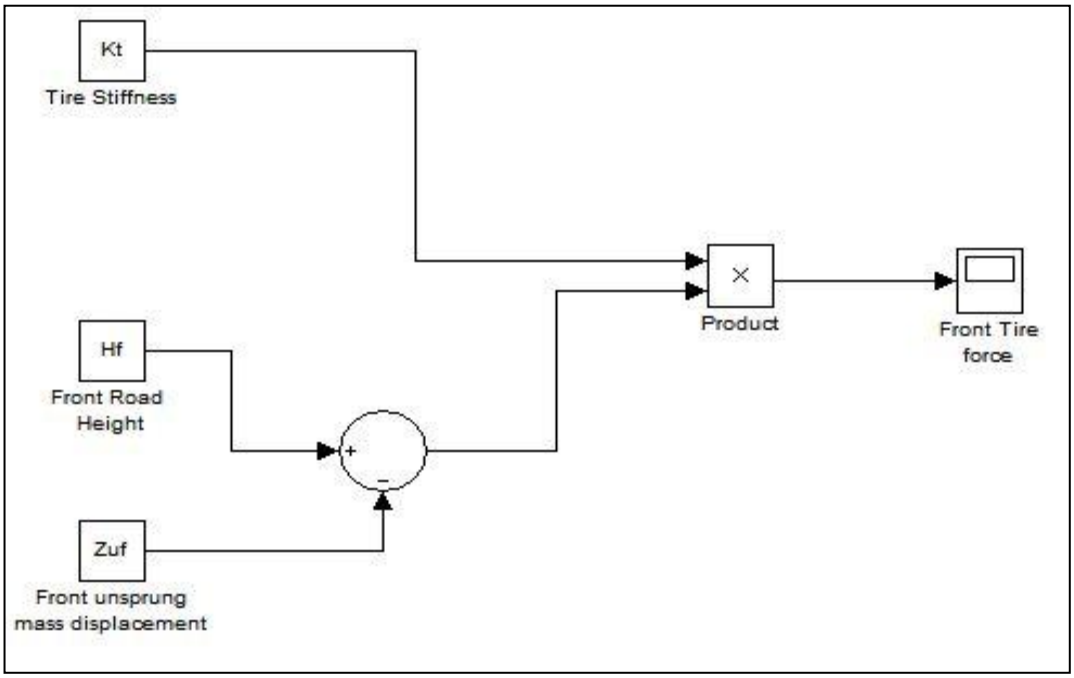


Figure 4.11: Front Tire force

$$F_{tr} = k_t(H_r - Z_{ur})$$

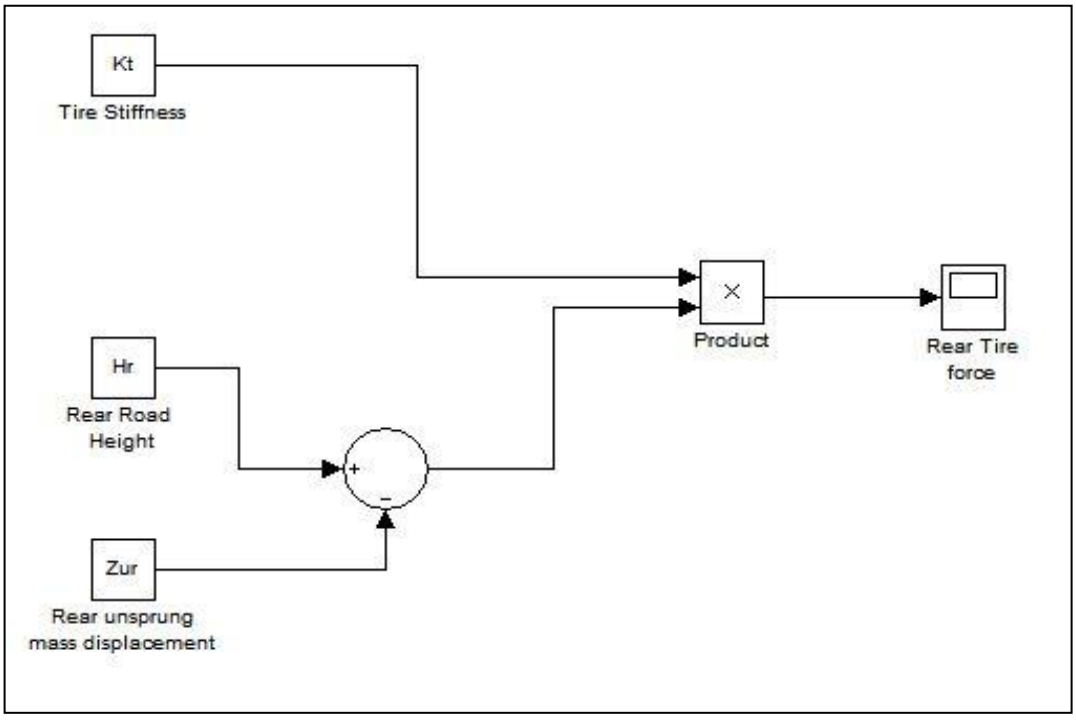


Figure 4.12: Rear Tire force

4.3 Half Car Passive Suspension Model

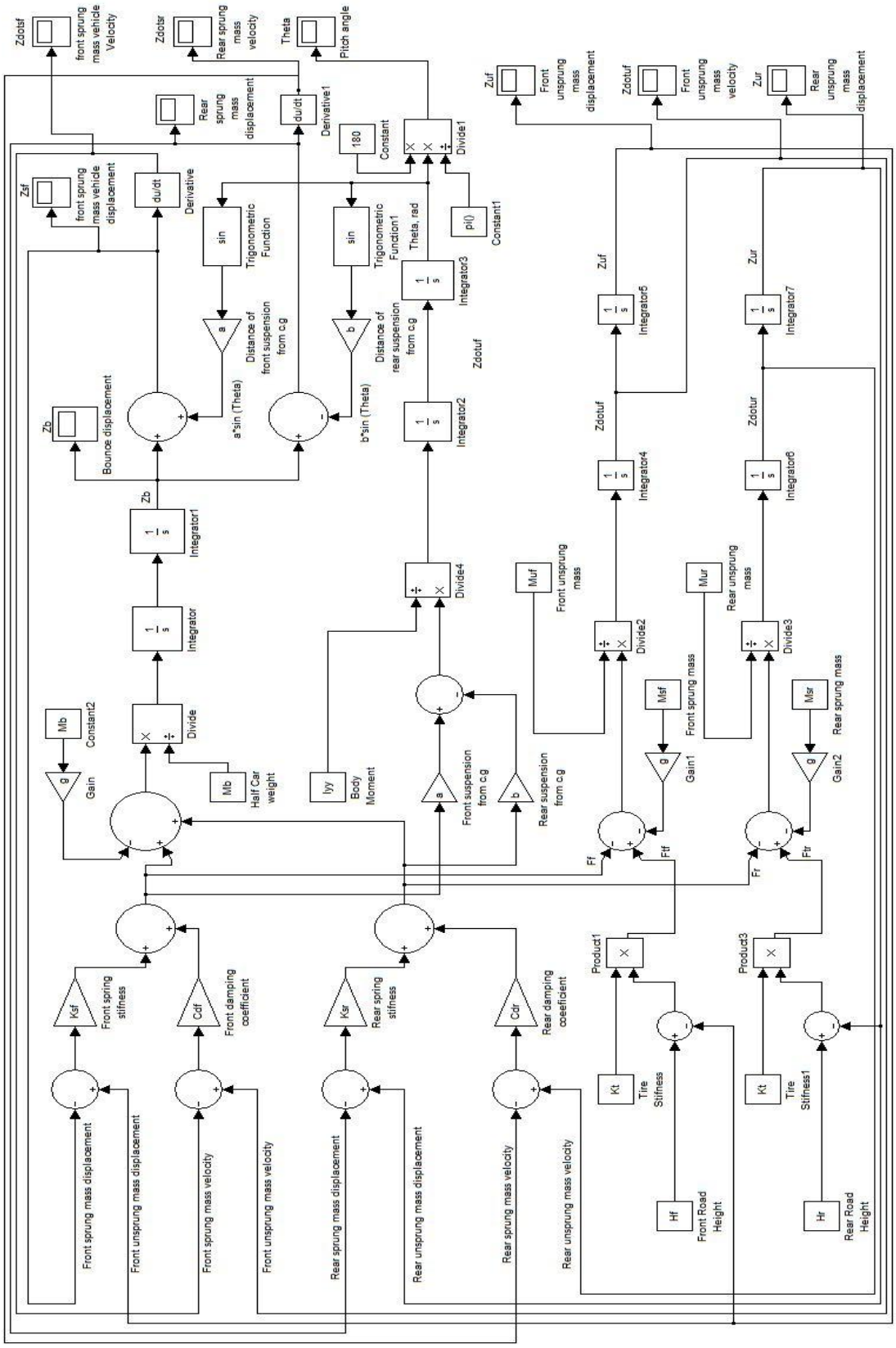


Figure 4.13: Half Car Passive Suspension System

4.4 MATLAB Simulink Simulation

The vehicle is subjected to 0.15 m of road disturbance. Through MATLAB Simulink, the response of the travelling vehicle can be observed. The response is grouped into the vehicle body displacement, vehicle pitch angle, the sprung mass response and unsprung mass response for better presentation.

i) Vehicle Body Displacemet, Z_b:

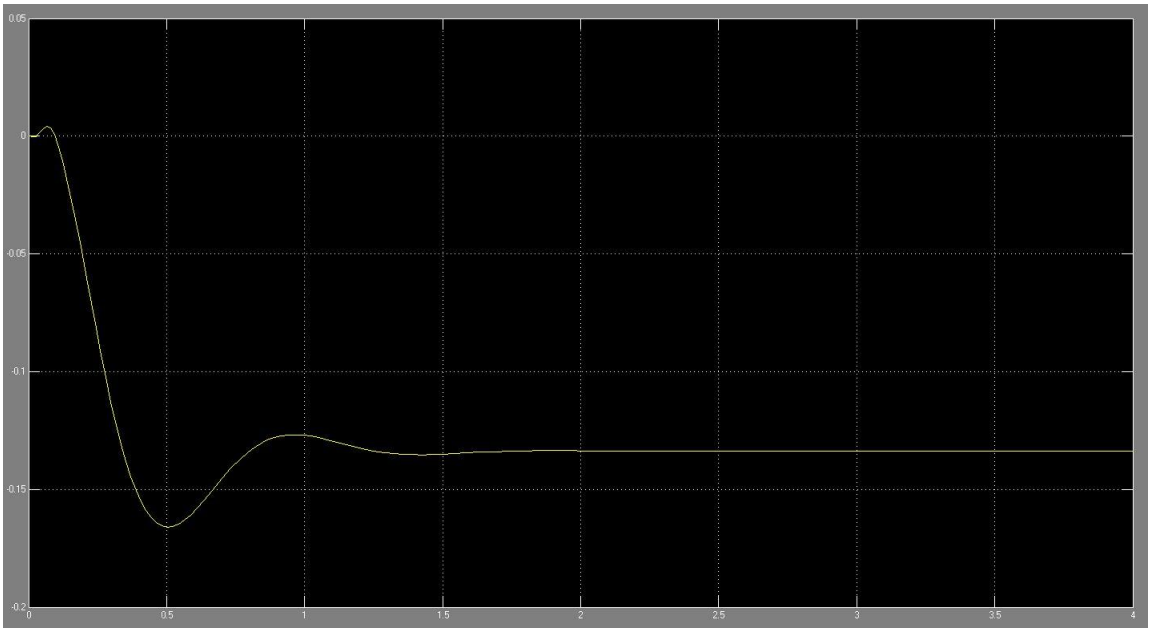


Figure 4.14: Vehicle Body Displcement

ii) Vehicle Pitch angle, θ:

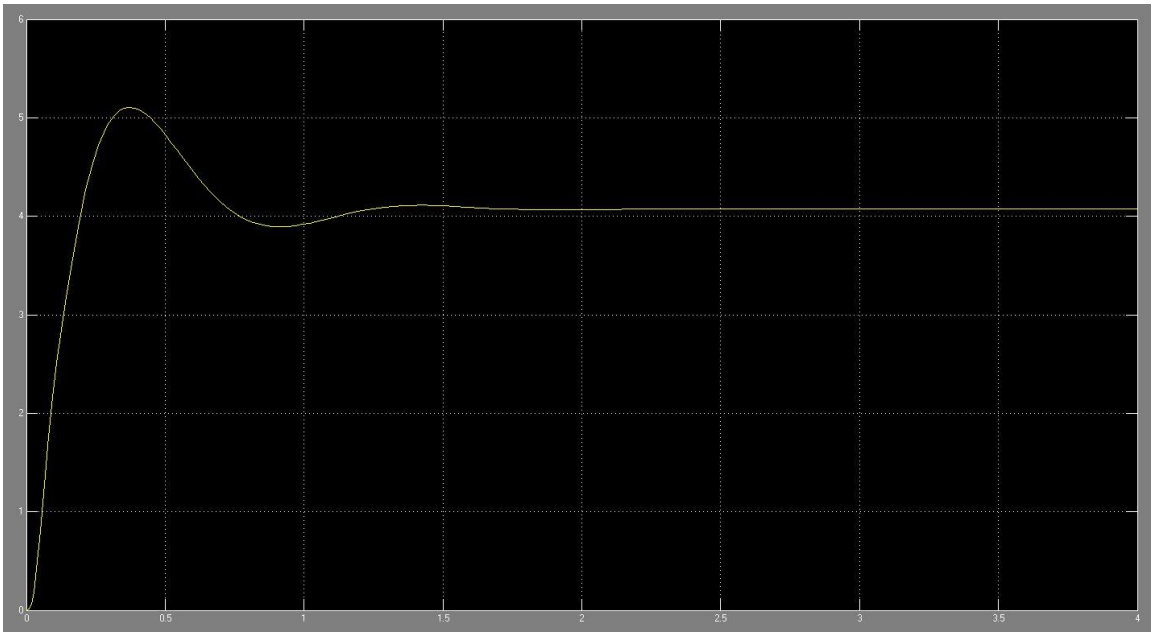


Figure 4.15: Vehicle Pitch angle

iii) Sprung Mass Response, $Z_{sf}, \dot{Z}_{sf}, Z_{sr}, \dot{Z}_{sr}$:

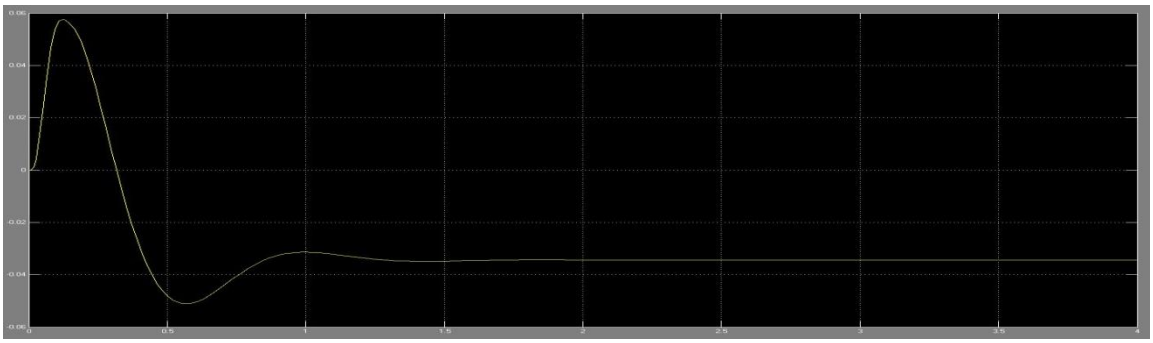


Figure 4.16: Front Sprung mass Displacement

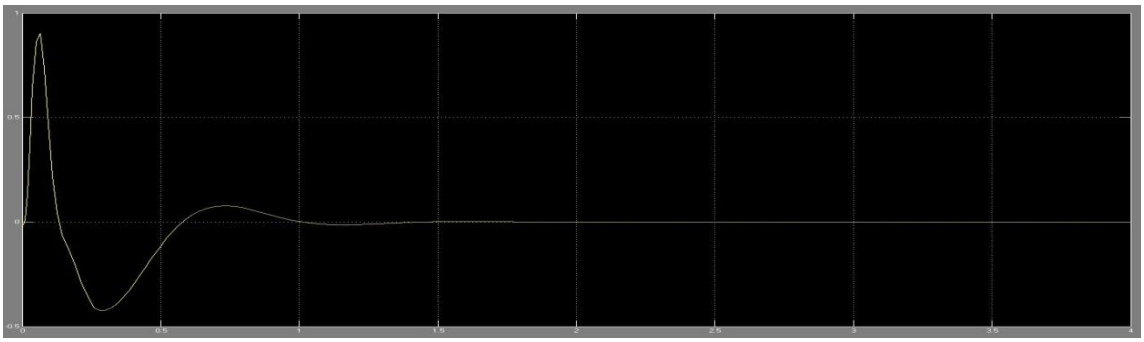


Figure 4.17: Front Sprung mass Velocity

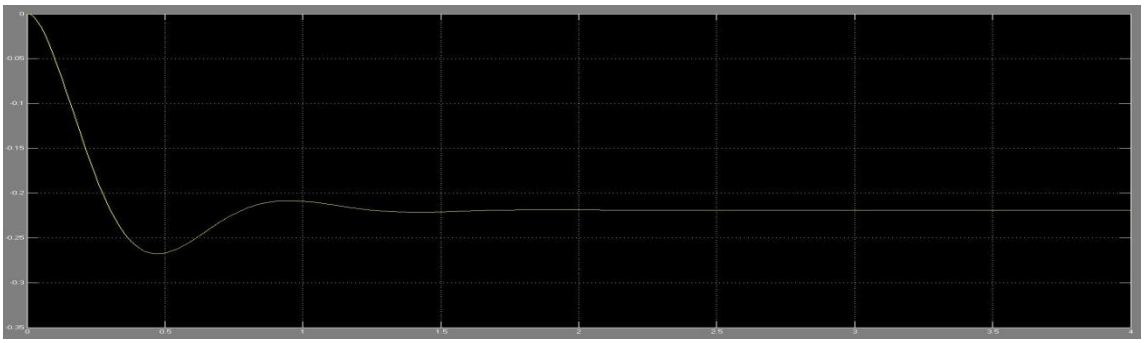


Figure 4.18: Rear Sprung mass Displacement

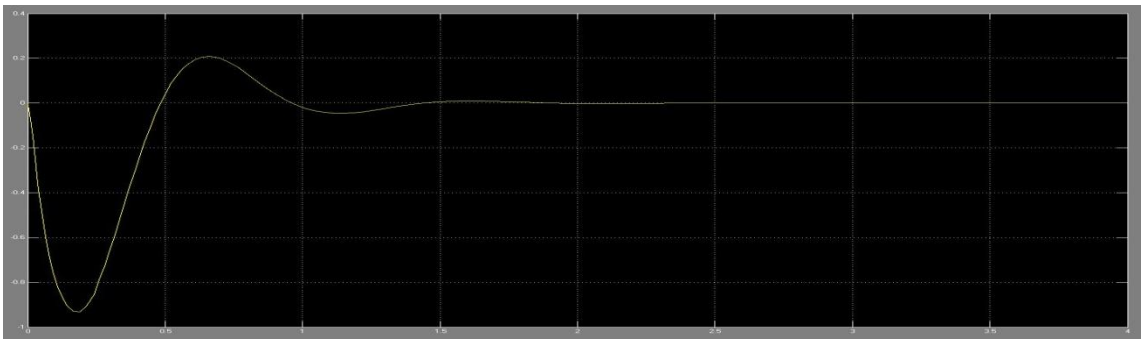


Figure 4.19: Rear Sprung mass Velocity

iv) Sprung Mass Response, $Z_{uf}, \dot{Z}_{uf}, Z_{ur}, \dot{Z}_{ur}$:

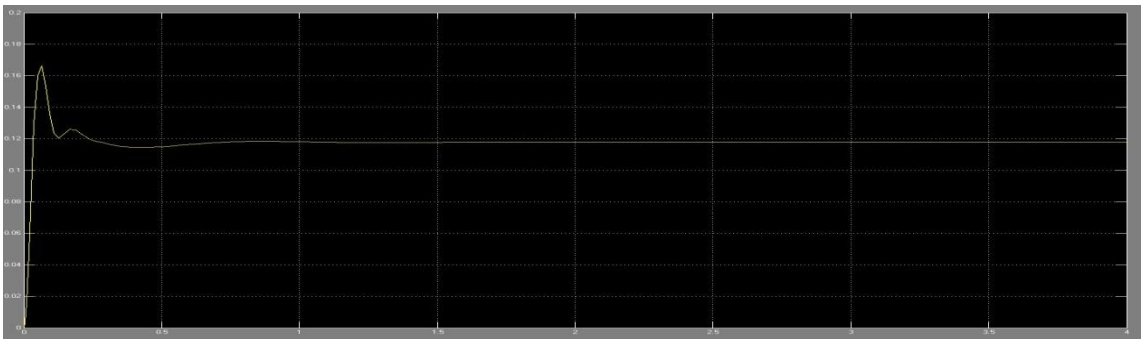


Figure 4.20: Front unsprung mass displacement

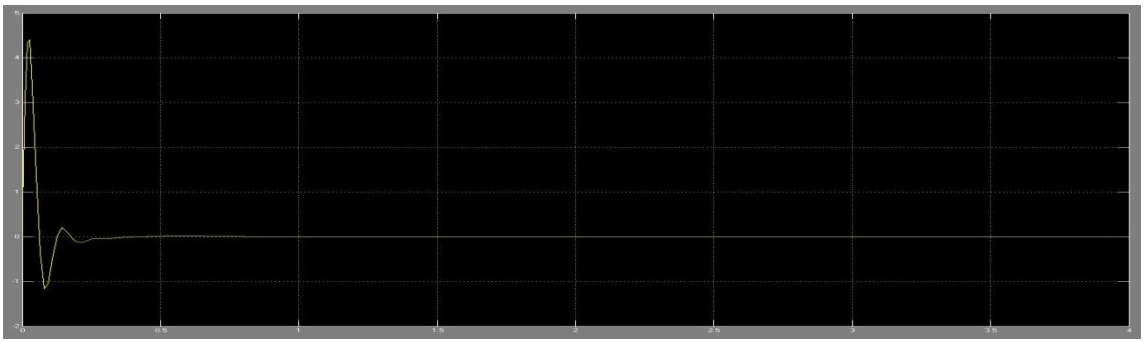


Figure 4.21: Front Unsprung mass Velocity

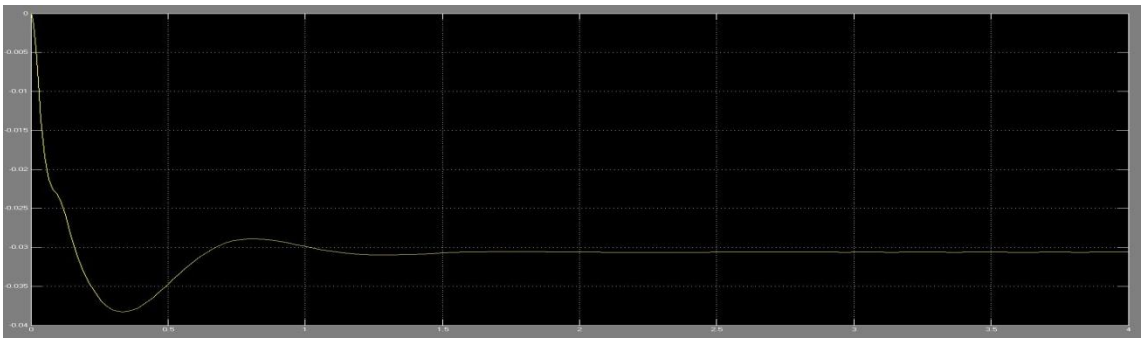
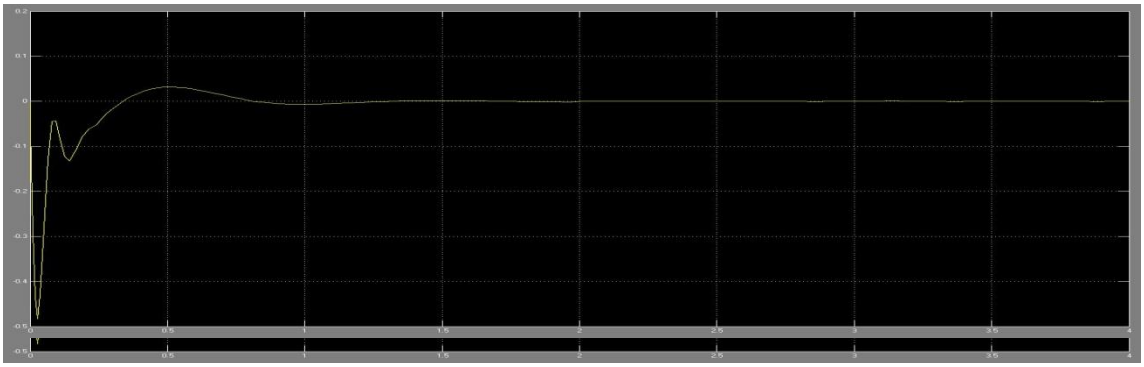


Figure 4.22: Rear Unsprung mass Displacement



4.22: Rear Unsprung mass Displacement

4.5 Discussion

The response of the travelling vehicle which runs on passive suspension system can be effectively simulated using MATLAB Simulink. The movements of the vehicle body are stated clearly with the graph generated. Z_b represents the bounce displacement of vehicle body movement. As the vehicle travel on a 15cm bumper, the body is displaced by 5 degree upward.

The velocity of the sprung mass and unsprung mass are going back to zero after the car has stabilized. The zero value represents the initial condition of the vehicle body.

Note that the simulation result for the displacement did not return to the initial condition of the vehicle body as the graph did not return to value zero after the vehicle is stable. This is because the modeling was done using constant block diagram. The simulation gives the exact vehicle response on exact road height inputted into the Simulink model. As there is no command send to the Simulink that the bumper height will be zero again with the function of time, the displacement of the vehicle body will not become zero after the car has stabled.

Alternatively, other type of block diagram such as pulse generator or sine wave function can be used. However, as the study involve only the vehicle response at exact time and there is no input in vehicle velocity. Thus, the experiment is preceded using the constant block as the input.

4.6 Modification of Parameters

Designing a passive suspension system with good ride comfort of a car has never been an easy task. However, as the response of the suspension system can be simulated, some modification can be done to the system for the purpose of studying whether the vehicle ride comfort can be improvised. The damping coefficient of the passive suspension system is manipulated and the vehicle response is recorded.

```
>> Cdr = 1600; %rear damping coefficient (Ns/m)
>> Cdf = 1700; %front damping coefficient (Ns/m)
```

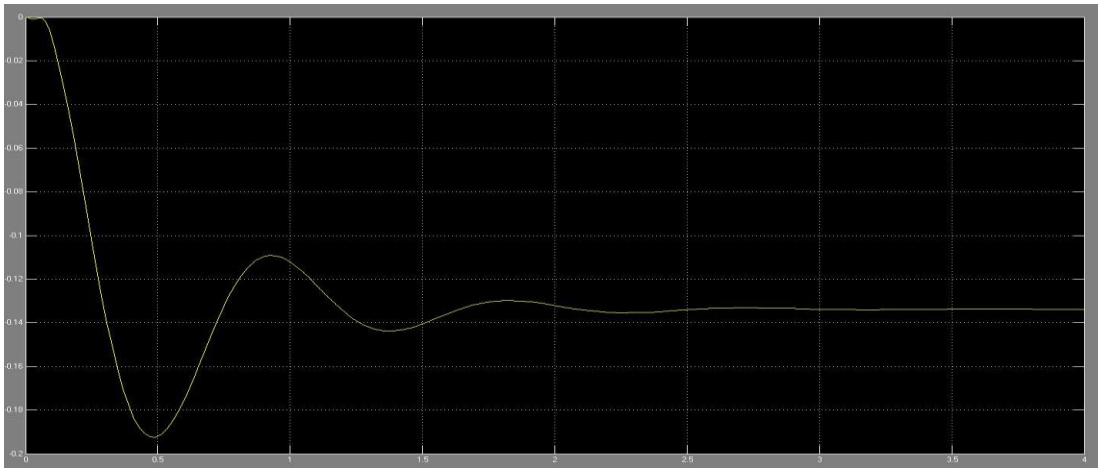


Figure 4.23: Bounce Displacement of Vehicle Body for Lower C_d

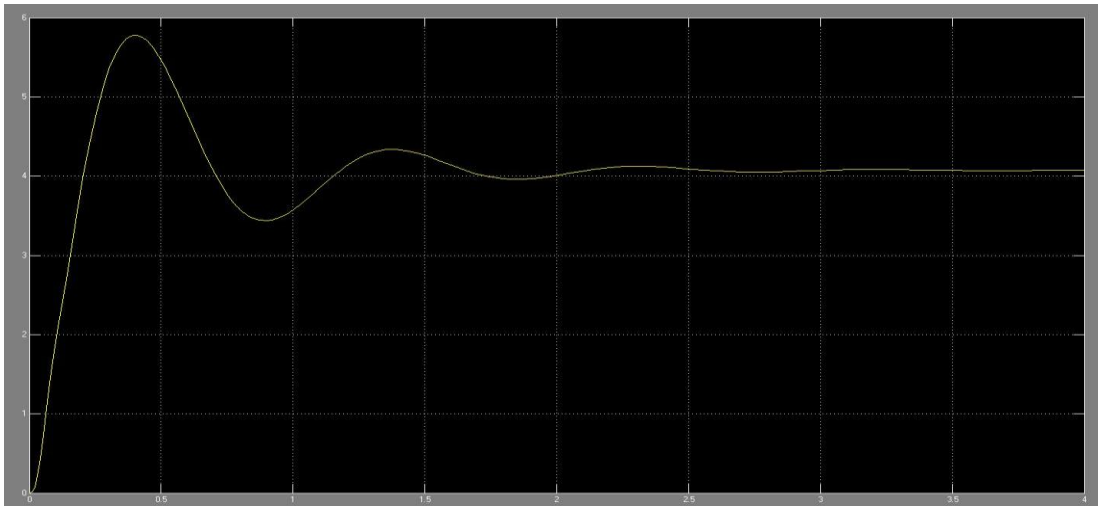


Figure 4.24: Pitch Angle of Vehicle Body for Lower C_d

```
>> Cdr = 2700; %rear damping coefficient (Ns/m)
>> Cdf = 2800; %front damping coefficient (Ns/m)
```

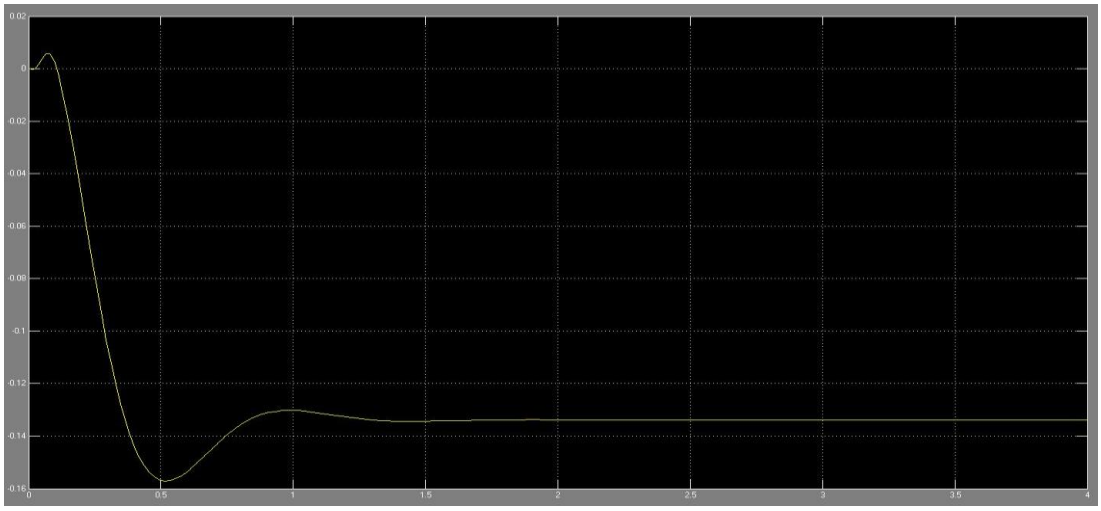


Figure 4.25: Bounce Displacement of Vehicle Body for Higher C_d

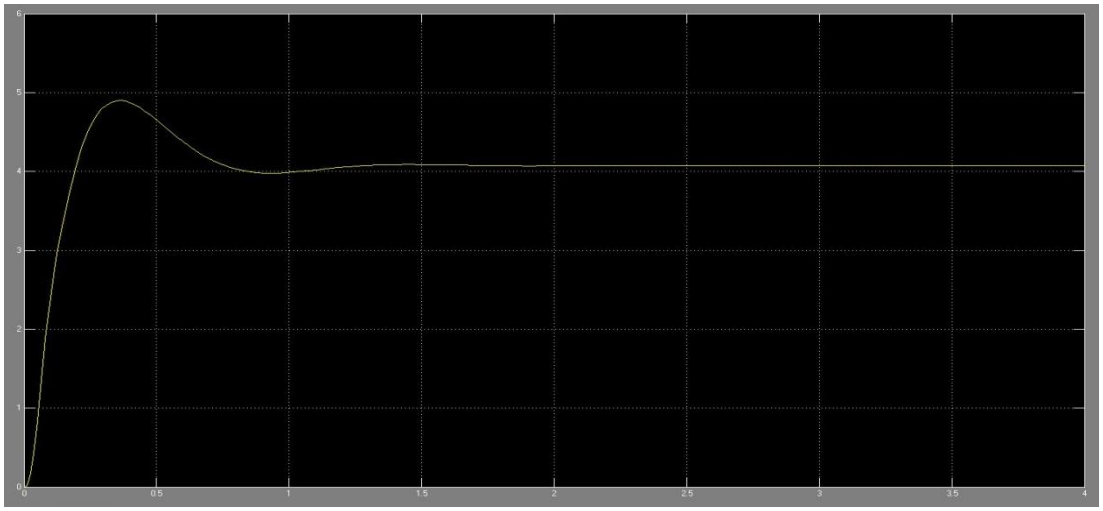


Figure 4.26: Pitch Angle of Vehicle Body for Higher C_d

Lower damping coefficient makes the suspension softer and has higher bounce displacement and pitch angle. The time taken for the vehicle to stable is longer. Vice versa, higher damping coefficient gives lower bounce displacement and shorter time for vehicle to stable as the suspension become harder.

CHAPTER 5
CONCLUSION

Passive suspension system can be considered as the conventional technique of decreasing the vibration and bumps experienced by the vehicle occupants besides improving the vehicle handling and keeping the tire of the vehicle in contact with the road. Active vehicle suspension system will do a very good job especially in term of the overall suspension performance and the ability of isolating the vibrations from the vehicle occupants. However, such type of suspension requires more electrical equipment which making the suspension system to be consumed a lot of power and that is not desirable. In addition, most suspension system that is found in most vehicles is passive suspension system and it is ideal for an engineer to develop and optimize this type of suspension system in order to improve the ride comfort of a vehicle occupants.

Based on the study made, when a vehicle is travelling on 0.15m of road disturbance, the vehicle body will be displaced about 0.166m on the pitch angle 5.1 degree. Other vehicle response can be seen clearly with the help of MATLAB Simulink software. High damping coefficient will make the damper become harder and gives less bouncing motion while lower damping coefficient will make the suspension become softer with longer time taken to stabilize.

Thus, the objectives of the project are met. As the suspension system is modeled using MATLAB Simulink, the response of the suspension system is studied and better understanding on the performance limit is obtained. The behavior of the suspension during travelling on a rough terrain is recognized and the model build and the simulation can be considered working and suitable to be used for educational purpose.

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APPENDICES

APPENDIX A (QUARTER CAR VEHICLE MODEL DEVELOPED IN FYP 1)

Quarter Car Vehicle model

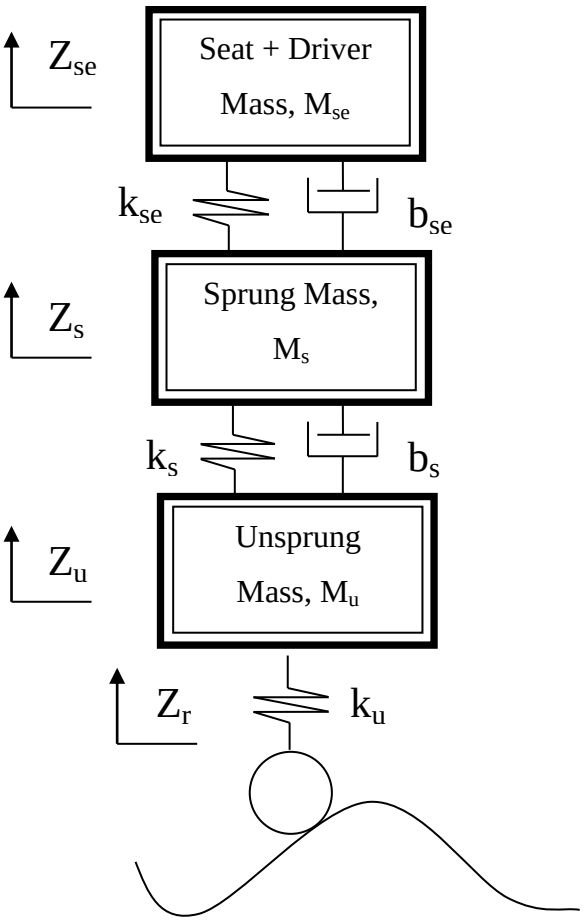


Figure: Passive suspension quarter car vehicle model

The parameters of the vehicle are as follow:

- Mass of the driver and the car seat, Mse = 92 kg
- Mass of sprung, Ms = 260 kg
- Mass of unsprung, Mu= 45 kg
- Damping ratio for sprung mass, bs = 2100
- Damping ratio for seat mass, bse = 3200
- Stiffness of the sprung mass, Ks = 29000 N/m
- Stiffness of Unsprung mass, Ku = 130000 N/m
- Stiffness of seat mass, Kse = 8000 N/m
- Road disturbance, Zr = 0.3
- Zr, Zu Zs, Zse = vertical displacement of road

Equation of Motion

1) The car seat and driver mass:

$$\ddot{Z}_{se} = \frac{-k_{se}(Z_{se} - Z_s) - b_{se}\left(\dot{Z}_{se} - \dot{Z}_s\right)}{M_{se}}$$

2) Sprung Mass:

$$\ddot{Z}_s = \frac{k_{se}(Z_{se} - Z_s) + b_{se}\left(\dot{Z}_{se} - \dot{Z}_s\right) - k_s(Z_s - Z_u) - b_{se}\left(\dot{Z}_s - \dot{Z}_u\right)}{M_s}$$

3) Unsprung Mass:

$$\ddot{Z}_u = \frac{k_s(Z_s - Z_u) + b_s\left(\dot{Z}_{se} - Z_u\right) - k_s(Z_u - Z_r)}{M_u}$$

Passive Suspension Model using MATLAB Simulink

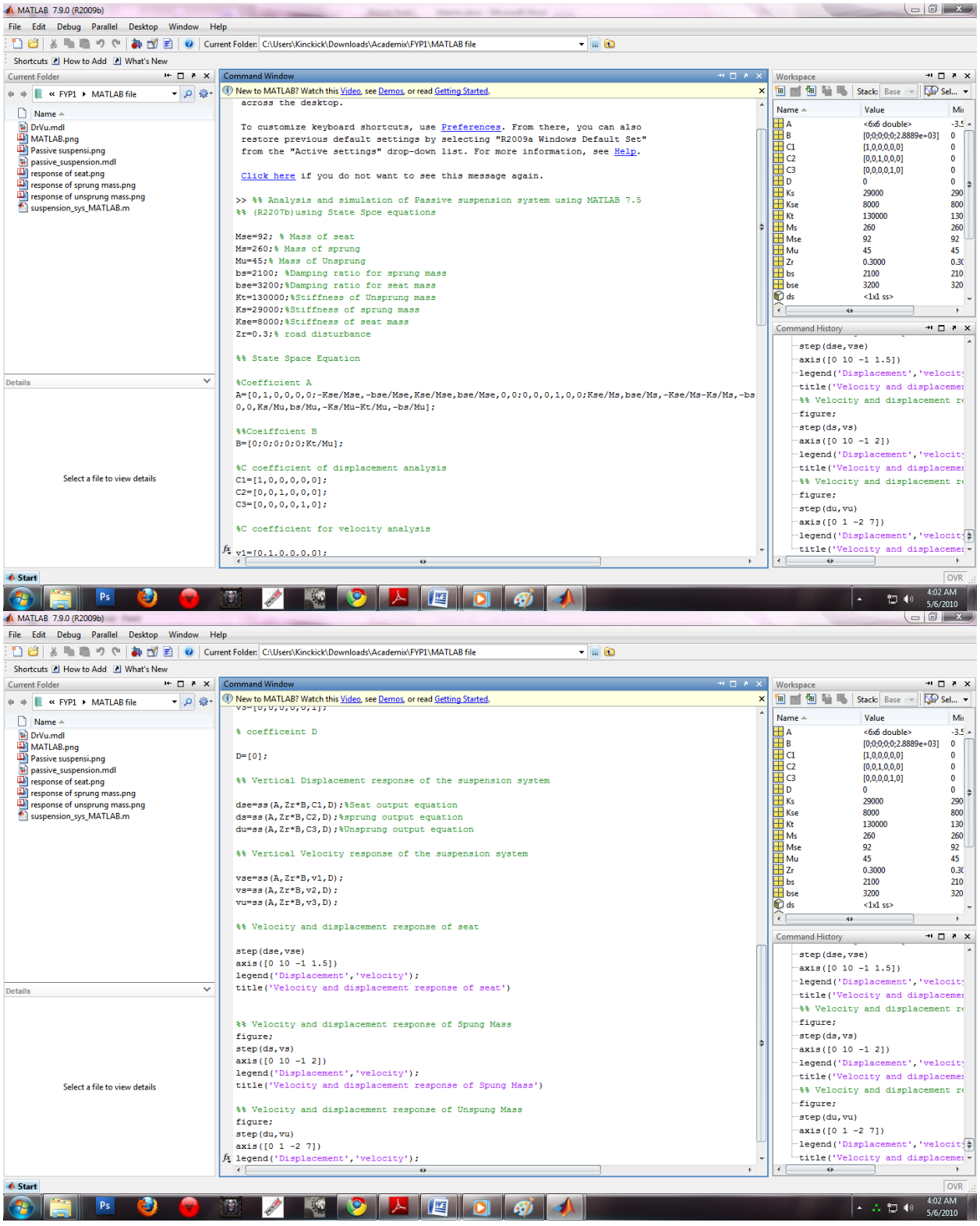
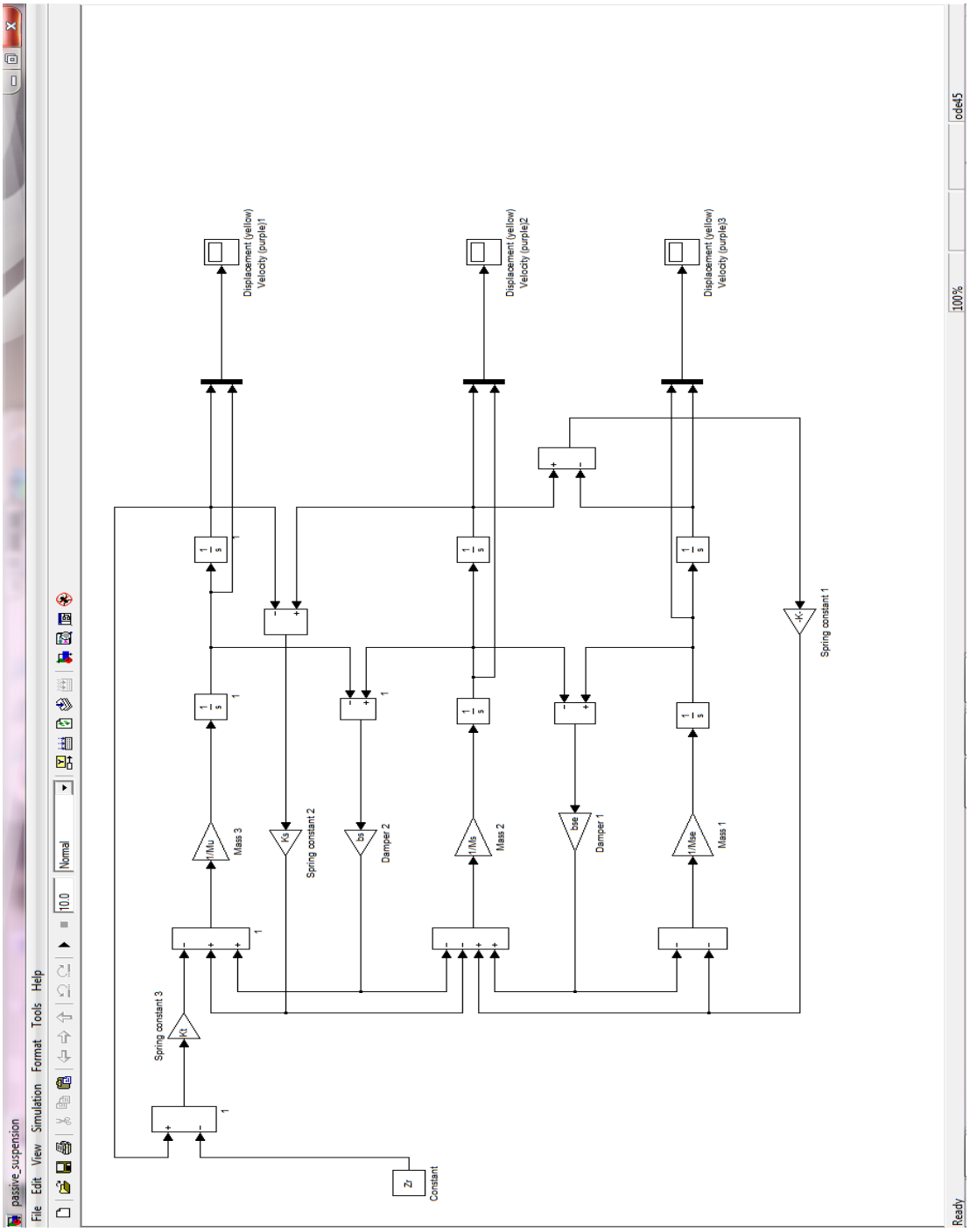


Figure: Car parameters are entered into MATLAB as input

Passive Suspension Block Diagram



Graph Generated

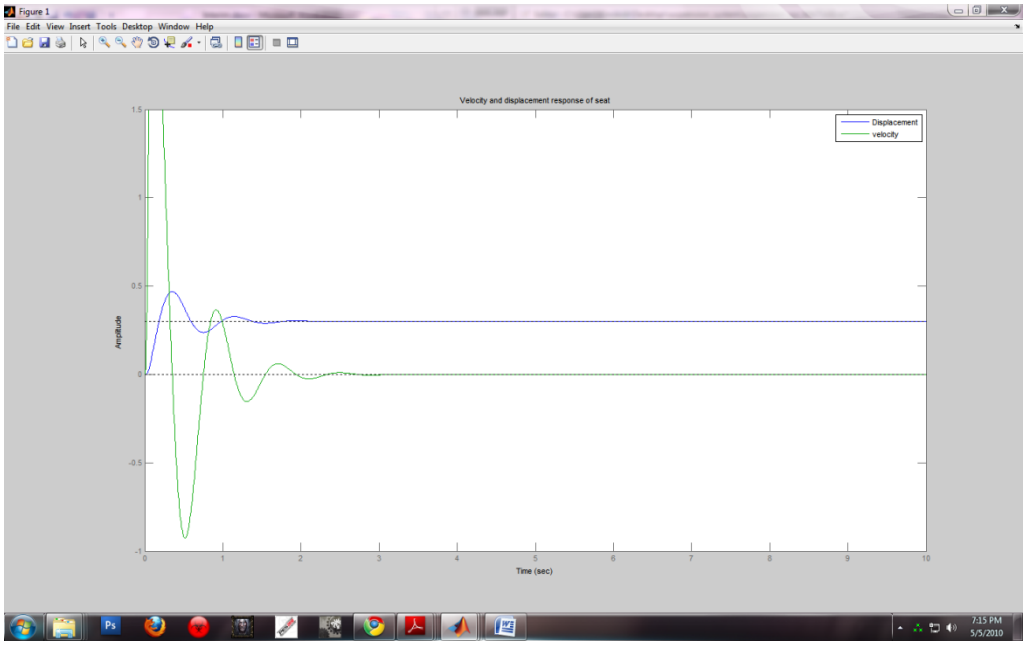


Figure: Response of car seat and driver

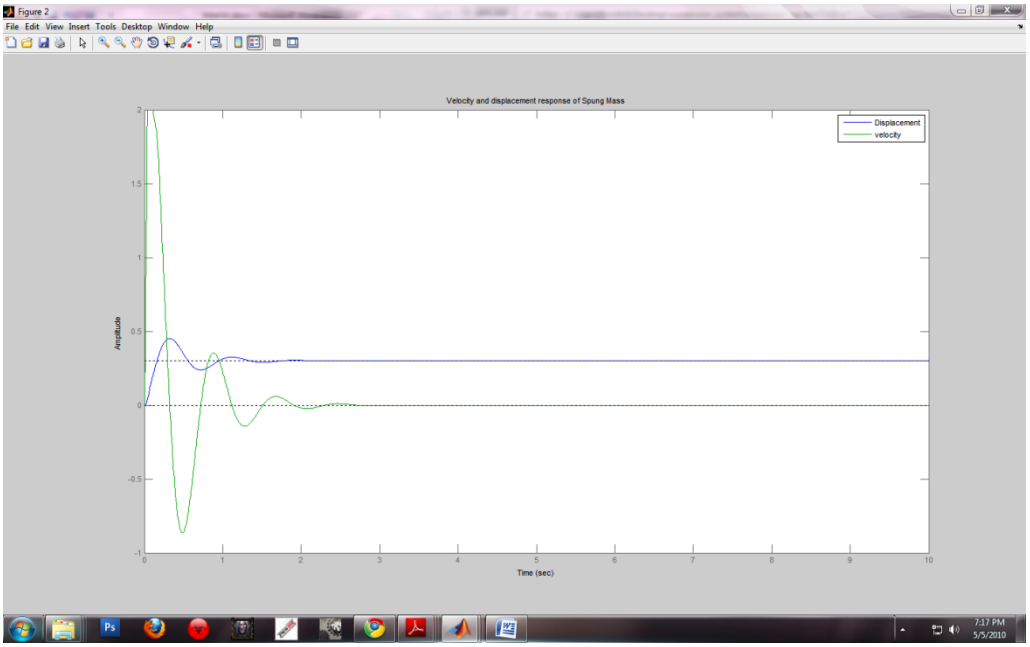


Figure: Response of Sprung Mass

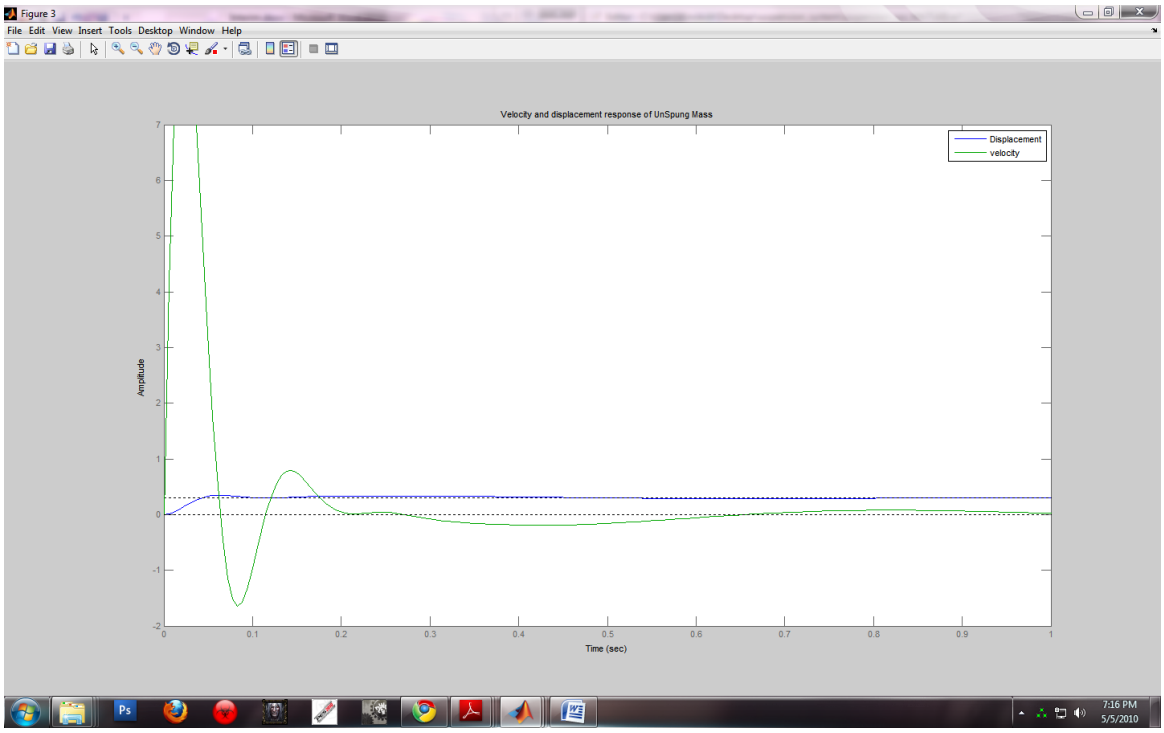


Figure: Response of Unsprung Mass