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B. ENG. (HONS) MECHANICAL ENGINEERING

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STUDIES AND SIMULATIONS OF SEMI-ACTIVE VEHICLE SUSPENSION SYSTEMS

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CERTIFICATION OF APPROVAL

STUDIES AND SIMULATIONS OF SEMI-ACTIVE VEHICLE SUSPENSION SYSTEM

By

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A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
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BACHELOR OF ENGINEERING (Hons)
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Approved by,

____

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Supervisor

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TRONOH, PERAK

November 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHAMAD HANIFF BIN ZAMAHSARI

ABSTRACT

A semi-active suspension system is considered to be one of the most realistic solutions for improving the ride quality of vehicles, because of its smaller energy consumption compared with that of active suspension systems. With applying equation of motion of a suspension, a simulation of the semi-active suspension is being done by using Simulink, MatLab. Various parameters being allocate to determine the better condition for the vehicle on different road surfaces. Fuzzy logic controller is being chosen to compute the simulation system. The basic understanding of suspension system and comparison between passive and semi-active suspension system will be shown in this report; from basic quarter model and end up with half model of suspension system.

ACKNOWLEDGEMENT

Praise to Almighty God, because of giving me this opportunity to complete this project. Then, to my project supervisor, Dr. Vu Trieu Minh, thanks a lot for the advice and useful tools for me along the progress of the project until the project completed.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Most of the vehicles today are rely on a number of electronic control systems. Usually, a stand-alone controllers fulfilling a particular function while others are co-ordinate by high-level of logic control. Those control system are breaking control, acceleration control, suspension control and so forth. Their aim are to enhance ride and handling, safety and of cause for driving comfort and pleasure.

Semi-active control devices offer reliability comparable to passive device, but still maintaining the versatility and adaptability of fully active system, without requiring large power source. Thus, semi-active device produce only a modulation of the damping forces in the controller system according to the control employed. Function for all suspension system is same that is to reduce chassis acceleration as well as dynamic tyre force. Chassis acceleration is related to ride and comfort, and tyre force to road holding and handling.

Comfort is more difficult than quality. Although standards exist, its assessment is a controversial issue, because it is a subjective matter. The suspension system must support the vehicle, provide directional control during handling maneuvers and provide effective isolation of passenger payload from road disturbances. Good ride comfort requires a soft suspension whereas insentivity to applied load requires stiff suspension. Good handling requires a suspension setting somewhere between the two.

Therefore for this whole project, simulation on suspension system will be shown based on some factors to identify the comfortness of passengers in their vehicle.

1.2 Problem Statement

The excitation transferred from wheel to vehicle body (due to road roughness) has cause vehicle body vibrate in many degrees of freedom such as roll, pitch, and bounce (and also combinations of these motions). When the wheel hit the road disturbances such as bump, jounce and potholes, the vibration of the wheel will transmit to the vehicle body, which will lead this to discomfort to the passenger.

The ride comfort sensation by passengers always relates with the vibration acceleration and frequency of vehicle body that occurs during and after the wheel hit the road disturbances. Due to these problems, the suspension system must have the ability to minimize the acceleration and the displacement that sensations by passenger as possible.

1.3 Objective and Scope of Study

1.3.1 Objective

i) To studies concept of semi-active vehicle suspension systems.
ii) To indentify the vibration tolerances relates to ride comfort perceptions.

1.3.2 Scope of Study

Based on project aim, all simulation is being done using MATLAB software using SIMULINK. All research scope are related to suspension system that being use on vehicle. Using two degree of freedom as assumption to start with, equation of motion then generated to achieve objective in this project. After that, all the equation combines to solve the suspension problem from quarter model to half model version. Then, the comparison between passive and semi-active suspension performances will be done.

CHAPTER 2

LITERATURE REVIEW

2.1 History of Active and Semi-active Suspension System

Middle 1950s is date that the first paper related to active suspension is found (Federspiel-Labrosse, 1954). Hedrick and Wormely (1975) were men who carried out review on controlled suspension. Then, in 1983 by Goodall and Korum who surveyed the active suspension Technology. A few years later, Sharp and Crolla (1987) and Aboul Nour (1988) produced comparative review of advantages and drawsback of various types of suspension. Another historical review and also an attempt to present some design criteria was given by Crolla (1995). A first choice in design of fully active suspension is the type of actuation. The actuator can be hydraulic, pneumatic or electromagnetic, or a hybrid solution. Williams (1996) analyzed the merits of an olco-pneumatic actuator; Martin (1999) proposed a hybrid electromagnetic-controlled suspension. An active suspension employing a hydraulic actuator, pressure-controlled rather than flow-controlled, has been proposed by Satoh (1990).

Active suspensions are challenging field for control engineers. All main control techniques developed in the past 30 years have been applied to the problem of controlling vehicle suspension. Majjad, Tan and Bradshaw (1997) addressed the problem of the identification of car suspension parameters. The necessity of trading off among the conflicting requirements of the suspension in term of comfort and road holding led to the use of optimization techniques. In 1976 Thomsaon studies a quater car model and suspension; Chalasani (1987) optimized active ride performance using a full car model. An H_∞ algorithm for active suspensions was proposed by Sammier (2000).

Active suspension systems have been studied also for off-road vehicles (Crolla, 1987). Stayner (1988) proposed an active suspension for agricultural vehicles. Active device have been investigated also for rail application as reported by Goodal (1981).

Semi-active suspensions were firstly introduced in the 1970s (Crosby and Karnopp, 1973, 1974) as an alternative to the costly, highly complicated and power-demanding active systems. Similar work was performed by Rakheja and Sankar (1985) and Alanoly and Sankar (1987) in term of active and semi-active isolators. A comparative study with passive system was carried out by Margolis (1982) and by Ahmadian and Marjoram (1989). The most attractive feature of that work was the control strategies were based only upon the measurement of the relative displacement and velocity. A review can be found in Crolla (1995).

A control scheme known as skyhook damping, based on the measurement of the absolute vertical velocity of the body of the car was proposed in 1970s by Karnopp and still employed in a number of variations (Alleyne, 1993), Yi and Song (1999) proposed an adaptive version of the skyhook control. Some authors (Chang and Wu, 1997), in order to improve comfort, designed a suspension based on a biological, neuromuscular-like control system. Recently Liu (2005) studied four different semi-active control strategies based on the skyhook and balance control strategies.

The reduction of the dynamic tyre force is a challenging field. Cole (1994) did extensive work on it, both theoretical and experimental. Groundhook control logic was also investigated by Valasek (1998) to reduce dynamic tyre forces.

2.2 History of Fuzzy Logic

Fuzzy logic was first presented to the consideration of the academic society by Zadeh (1965) and became popular rapidly. Rao & Prahlad (1997) suggested fuzzy logic based control for vehicle active suspension.

Bourmistrova et al. (2005) applied evolutionary algorithms to the optimization of the control system parameters of quarter car model. The multi objective fitness function which is a weighted sum of car body rate-of-change of acceleration and suspension travel is minimized.

Sharkawy (2005) described fuzzy and adaptive fuzzy control (AFC) schemes for the automobile active suspension system (ASS). The design objective was to provide smooth vertical motion so as to achieve the road holding and riding comfort over a wide range of road profiles. Roumy et. al. (2004) developed LQR and $H\infty$ controller for quarter car model. The structure's modal parameters are extracted from frequency response data, and are used to obtain a state-space realization. The performance of controller design techniques such as LQR and $H\infty$ is assessed through simulation.

2.3 Functions of a Vehicle Suspension

A vehicle suspension system is a complicated system as it has to fulfill a large number of partly contradictory requirements. Ride comfort, safety, handling, body leveling and noise comfort are among the most important requirements that has to fulfill. Ride comfort can be determined by the acceleration of the vehicle body. Acceleration forces are experienced by the passengers as a disturbance and set demands on the load and the vehicle. The suspension system has the task to isolate these disturbances from the vehicle body which caused by the uneven road profile. The lower the acceleration, the better the rides comfort.

The safety of the vehicle during traveling is determined by the wheels ability to transfer the longitudinal and lateral forces onto the road. The vehicle suspension system is required to keep the wheels as close the road surface as possible. Wheel vibration must be dampened and the dangerous lifting the wheels must be avoided. If the dynamic forces occurring between the wheels and the road surface are small, the braking, driving and lateral forces can be transferred to the road in an optimal manner. The necessity of dampening the tyre system is the reason for the known conflict of aims between comfortable and safety tuning.

Another function of the suspension system is the isolation of the vehicle body from high frequency road disturbances. The passengers in the car note these disturbances acoustically and thus the noise comfort is reduced. When there is a change in loading, the suspension system has to keep the vehicle level as constant as possible, so that the complete suspension travel is available for the wheel movements. A lower suspension travel means that lower suspension working space and this is a good suspension design. In order to fulfill all these contradict requirements certain marginal conditions have to be considered.

2.4 Types of Suspension System

They are 3 types of suspension system which is:\

i) passive suspension
ii) semi-active suspension
iii) active suspension

2.4.1 Passive Suspension System

Passive suspension system is the conventional suspension system. However it is still to be found on majority of production car. It consists two elements namely dampers and springs. The function of the dampers in this passive suspension is to dissipate the energy and the springs is to store the energy. If a load exerted to the spring, it will compress until the force produced by the compression is equal to the load force. Dampers will absorb this oscillation so that it would only bounce for a short period of time. Figure 2.1 shows passive suspension system.

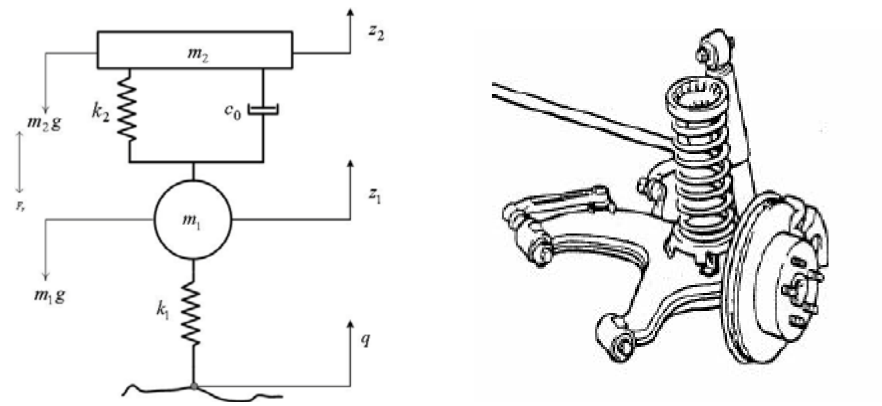


Figure 2.1: Passive suspension system

2.4.2 Semi-active suspension system

Semi-active suspension system is one of the various system that being use on vehicle. It consists of spring and controllable damper that support the suspension. The element in the semi-active suspension system is same with passive suspension system and it uses the same application of the active suspension system where external energy is needed in the system. The difference is the damping coefficient can be controlled. The fully active suspension is modified so that the actuator is only capable of dissipating power rather than supplying it as well. The actuator then becomes a continuously variable damper which is theoretically capable of tracking force demand signal independently of instantaneous velocity across it. This suspension system exhibits high performance while having low system cost, light system weight and low energy consumption. Figure 2.2 shows a schematic diagram of a quarter car semi-active suspension control system.

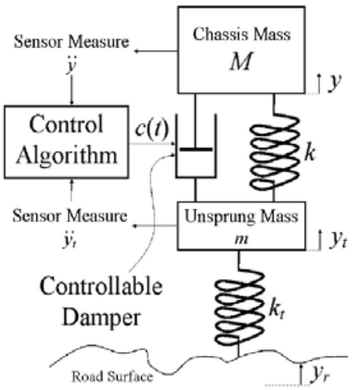


Figure 2.2: Semi-Active Suspension

2.5 Magneto Rheological Dampers

Magneto-rheological (MR) fluids are suspensions of micron-sized, magnetizable particles in an oil based fluid. In the absence of magnetic fields, these fluids exhibit Newtonian behavior. Magnetorheological fluids are materials that exhibit a change in rheological properties (elasticity, plasticity, or viscosity) with the application of a magnetic field. The MR effects are often greatest when the applied magnetic field is normal to the flow of the MR fluid.

There are three main types of MR dampers which is:

i) mono tube
ii) twin tube
iii) double-ended MR damper

Example of each types of MR damper is shown below.

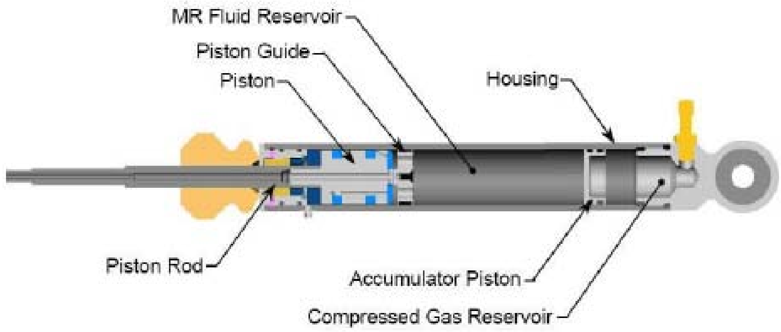


Figure 2.3: Mono tube MR damper

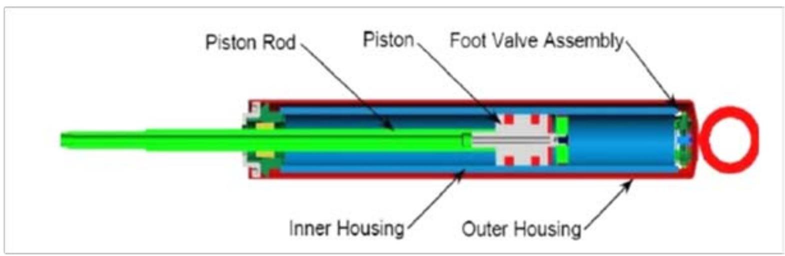


Figure 2.4: Twin tube MR damper

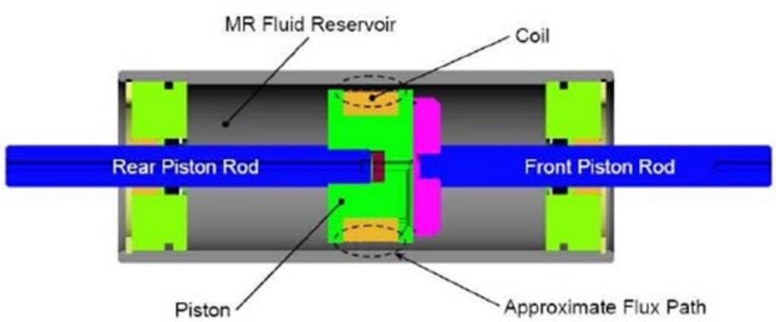


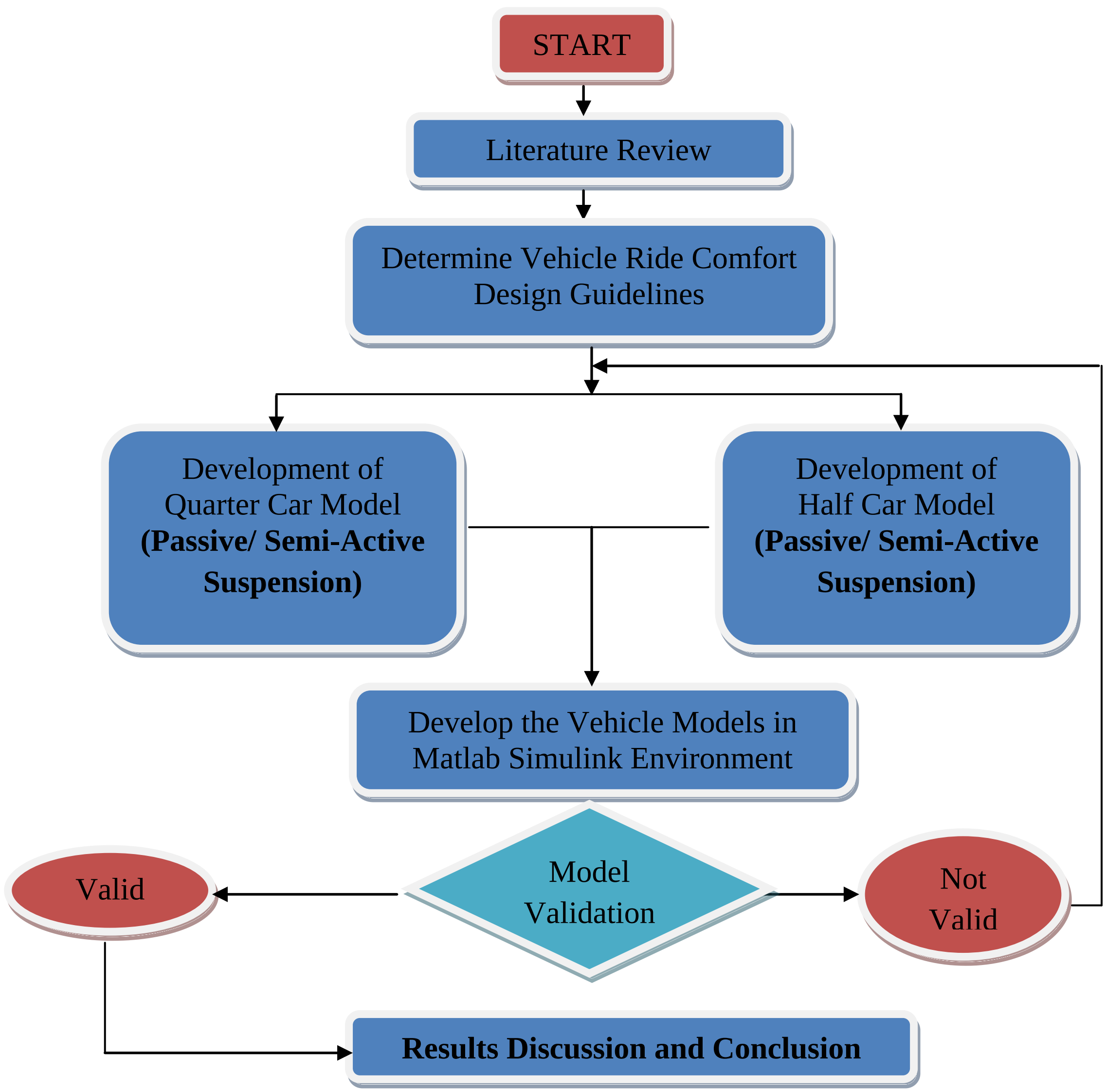
Figure 2.5: double ended MR damper

CHAPTER 3

METHODOLOGY

3.1 Project Planning

Flow chart shows the basic project planning for the project



3.2 Milestone

Table 3.1 and Table 3.2 show the milestone for the project.

Table 3.1: Milestone project for FYP I (Jan – May 2010)

No.	Detail \ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Selection of Project Topic								Mid Semester Break								
2	Studies on concept Semi Active Suspension																
3	Develop Equation used (Quarter model)																
4	Simulation using SIMULINK on quarter model																
5	Continue on Work Programming (body acc, suspension)																
6	Develop Equation use (Half model)																

- Based on Table 1 the development is focus mainly on understanding the concept of semi active suspension system.
- After finalize desire equation of motion, quarter model of suspension system is being form and simulate them.
- Research & studies of pitch and roll and suspension system then is done to further understanding of the concept

Table 3.2: Milestone project continue for FYP II (July – Nov 2010)

No.	Detail \ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Concept of Fuzzy Logic & MR damper								Mid Semester Break								
2	Develop Equation used (Half model model)																
3	Simulation using SIMULINK on Half model																
4	Continue on Work Programming (body acc, suspension)																
5	Data Analysis																
6	Discussion on graft and data																

- Then, a study on MR damper is done to meet the objective to study the full concept and all part of semi-active suspension system.
- Half model is be developed, and comparison between passive and semi-active suspension system is done.
- Simulation done well, however, some problems occur in simulation. After some change has been made, the simulation is success.
- Discussion on the differences between passive and semi-active suspension then is done to come to the conclusion.

3.3 MATLAB

MATLAB is s software package for high performance numerical computation and visualization. It provides an interactive environment with hundreds of built-in functions for technical computation, graphics, and animation. Also, it provides easy extensibility with its own high-level programming language. The name MATLAB stands for MATrix LABarotary. MATLAB has a number of add-on software modules, calles toolboxes, that perform more specialized computations. Toolboxes deal with applications such as Symbolic computation, Statistics, Financial analysis, Image and Signal Processing, Control System design, Fuzzy logic, Neutral Networks, Wavelets, Simulink, and others.

Since this project is consist of studies and simulations, all data from the derivation of equation of motion from mathematical model of vehicle suspension system will be transferred in MATLAB and analyzed using Simulink to achieve certain desire graft and data.

3.3.1 Simulink

Simulink refers to the repeated execution of a model at successive time steps as simulating the system that the model represents. Simulink is a software package for modeling, simulating, and analyzing dynamic systems.

It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Simulink can be used to explore the behavior of a wide range of real-world dynamic systems, including electrical circuits, shock absorbers, braking systems, and many other electrical, mechanical, and thermodynamic systems.

For modeling, Simulink provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations. With this interface, one can draw the models just as one would with pencil and paper (or as most textbooks depict them). This is a far cry from previous simulation packages that require formulate differential equations and difference equations in a language or program. Simulink includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors.

It is possible to simulate a system manually. However, this is unnecessary as the Simulink engine performs this task automatically on command from the user. Simulating a dynamic system is a two-step process with Simulink. First, a user creates a block diagram, using the Simulink model editor that graphically depicts time-dependent mathematical relationships among the system's inputs, states, and outputs. The user then commands Simulink to simulate the system represented by the model from a specified start time to a specified stop time.

3.4 Simulink Block

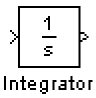
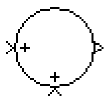
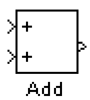
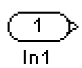
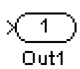
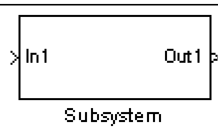
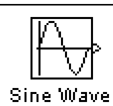
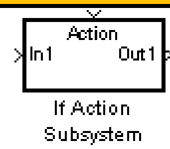
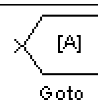
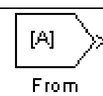
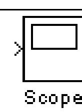
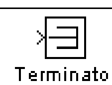
There are several groups of block in Simulink Library, that can be use in order to form a complete simulation programme.

Simulink Library:

i) Commonly Used
ii) Continuous
iii) Discontinuities
iv) Discrete
v) Logic and Bit Operations
vi) Lookup Tables
vii) Math Operations
viii) Model Verification
ix) Model-Wide Utilities
x) Ports & Subsystems
xi) Signal Attributes
xii) Signal Routing
xiii) Sinks
xiv) Sources
xv) User-Defined Functions
xvi) Additional Math & Discrete

The Simulink Editor allows one to change the size, orientation, color, and label location of a block in a block diagram. By default, block names appear below blocks and its default name. Here are some of the blocks that use in this project.

Table 3.3: Block Description

No	Block	Description
1.		The Integrator block outputs the integral of its input at the current time step
2.		The Sum block performs addition or subtraction on its inputs. This block can add or subtract scalar, vector, or matrix inputs. It can also collapse the elements of a signal.
3.		The Gain block multiplies the input by a constant value (gain). The input and the gain can each be a scalar, vector, or matrix.
4.		inport blocks are the links from outside a system into the system.
5.		Outport blocks are the links from a system to a destination outside the system
6.		A Subsystem block represents a subsystem of the system that contains it. The Subsystem block can represent a virtual subsystem or a nonvirtual subsystem.
7.		The Sine Wave block provides a sinusoid
8.		The If Action Subsystem block is a Subsystem block that is preconfigured to serve as a starting point for creating a subsystem whose execution is triggered by an If block.
9.		The Mux block combines its inputs into a single vector output.
10.		The Demux block extracts the components of an input signal and outputs the components as separate signals
11.		The Goto block passes its input to its corresponding From blocks. From and Goto blocks allow you to pass a signal from one block to another without actually connecting them.
12.		The From block accepts a signal from a corresponding Goto block, then passes it as output.
13.		The Scope block displays its input with respect to simulation time.
14.		The Terminator block can be used to cap blocks whose output ports are not connected to other blocks.

CHAPTER 4

MODELING & SIMULATION

4.1 Passive Suspension System

The basic concept of passive suspension system is consisting of spring and damper, sprung mass and unsprung mass.

4.1.1 Quarter Passive Model

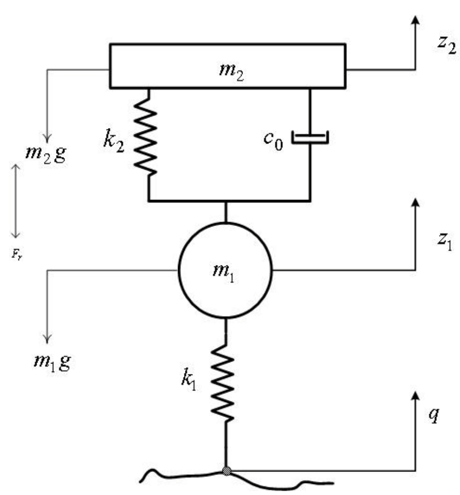


Figure 4.1: Quarter Passive Suspension

(1) $m_1\ddot{z}_1 = k_1(z_1 - q) + k_2(z_2 - z_1) + c_0(\dot{z}_2 - \dot{z}_1) + F_r + m_1 g$

(2) $m_2\ddot{z}_2 = k_2(z_1 - z_2) + c_0(\dot{z}_1 - \dot{z}_2) - F_r + m_2 g$

F_r is a constant friction

4.1.2 Half Passive Model

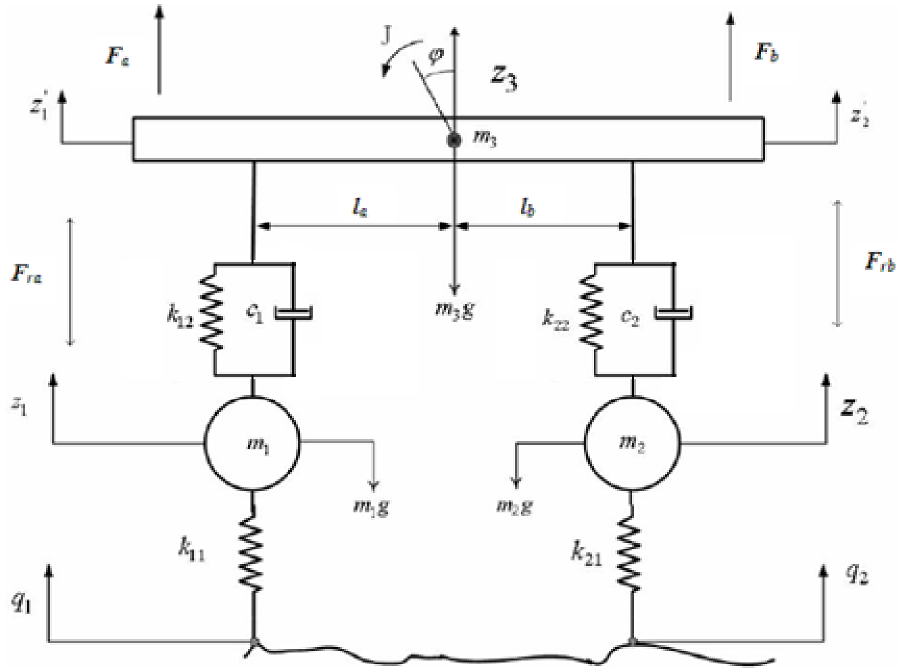


Figure 4.2: Half Passive Suspension (Pitch)

(1) $m_1\ddot{z}_1 = k_{11}(z_1 - q_1) + k_{12}(z'_1 - z_1) + c_1(\dot{z}'_1 - \dot{z}_1) + F_{ra} + m_1 g$

(2) $m_2\ddot{z}_2 = k_{21}(z_2 - q_2) + k_{22}(z'_2 - z_2) + c_2(\dot{z}'_2 - \dot{z}_2) + F_{rb} + m_2 g$

(3) $m_3\ddot{z}_3 = k_{12}(z_1 - z'_1) + k_{22}(z_2 - z'_2) + c_1(\dot{z}_1 - \dot{z}'_1) + c_2(\dot{z}_2 - \dot{z}'_2) - F_{ra} - F_{rb}$

$+m_3 g$

(4) $J\ddot{\varphi} = -[k_{12}(z_1 - z'_1) + c_1(\dot{z}_1 - \dot{z}'_1)]l_a + [k_{22}(z_2 - z'_2) + c_2(\dot{z}_2 - \dot{z}'_2)]l_b$

$-l_a f_{d1} + l_a F_{ra}$

F_{ra} is a constant friction for front half suspension.

F_{rb} is a constant friction for rear half suspension.

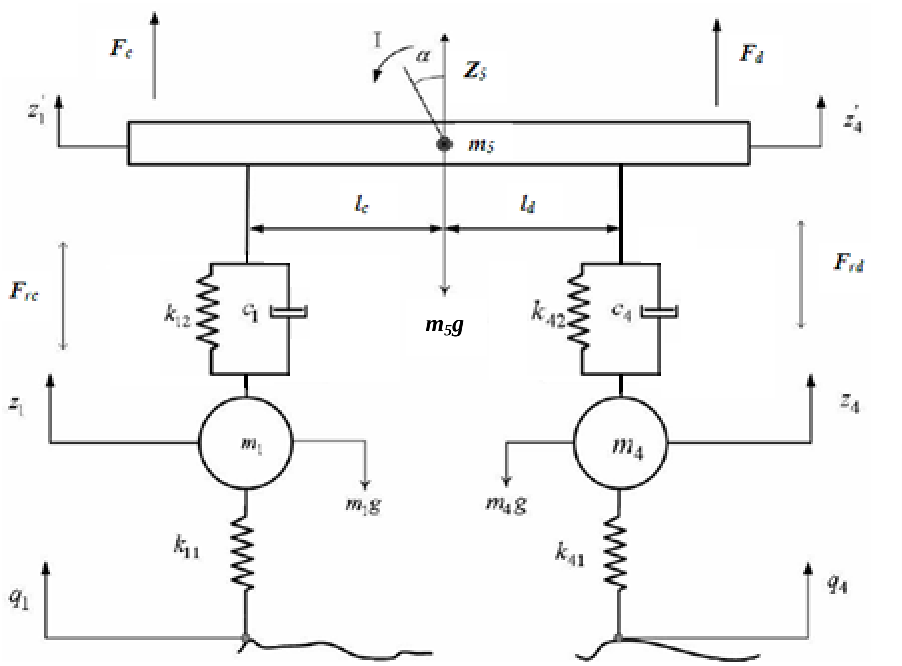


Figure 4.3: Half Passive Suspension (Roll)

(1) $m_1\ddot{z}_1 = k_{11}(z_1 - q_1) + k_{12}(z'_1 - z_1) + c_1\left(\dot{z}'_1 - \dot{z}_1\right) + F_{rc} + m_1 g$

(2) $m_4\ddot{z}_4 = k_{41}(z_4 - q_4) + k_{42}(z'_4 - z_4) + c_4\left(\dot{z}'_4 - \dot{z}_4\right) + F_{rd} + m_4 g$

(3) $m_5\ddot{z}_5 = k_{12}(z_1 - z'_1) + k_{42}(z_2 - z'_2) + c_1(\dot{z}_1 - \dot{z}'_1) + c_4(\dot{z}_4 - \dot{z}'_4) - F_{rc} - F_{rd}$
$+m_5 g$

(4) $I\ddot{\alpha} = -[k_{12}(z_1 - z'_1) + c_1(\dot{z}_1 - \dot{z}'_1)]l_c + [k_{42}(z_4 - z'_4) + c_4(\dot{z}_4 - \dot{z}'_4)]l_d$
$+l_c F_{rc} - l_d F_{rd}$

F_{rc} is a constant friction for left half suspension model.

F_{rd} is a constant friction for right half suspension model.

4.2 Semi-active Suspension System

In the semi-active suspension system, the controllable damper is added to the system. With the added of the controller, it will contribute to the feedback value of the road disturbance.

4.2.1 Quarter Semi-active Model

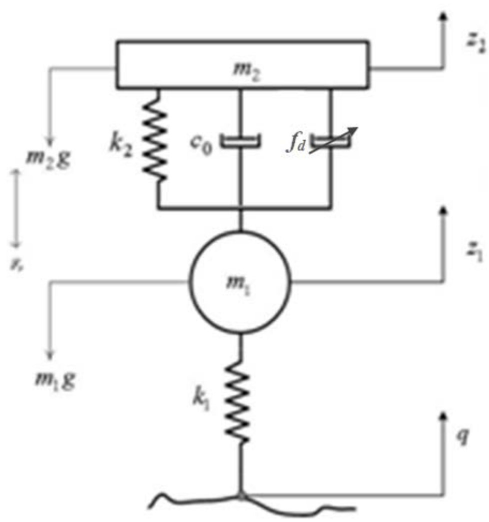


Figure 4.4: Quarter Semi-active Suspension

(2) $m_1\ddot{z}_1 = k_1(z_1 - q) + k_2(z_2 - z_1) + c_0(\dot{z}_2 - \dot{z}_1) + F_r + f_d + m_1 g$
(2) $m_2\ddot{z}_2 = k_2(z_1 - z_2) + c_0(\dot{z}_1 - \dot{z}_2) - F_r - f_d + m_2 g$

F_r is a constant friction

4.2.2 Half Semi-active Model

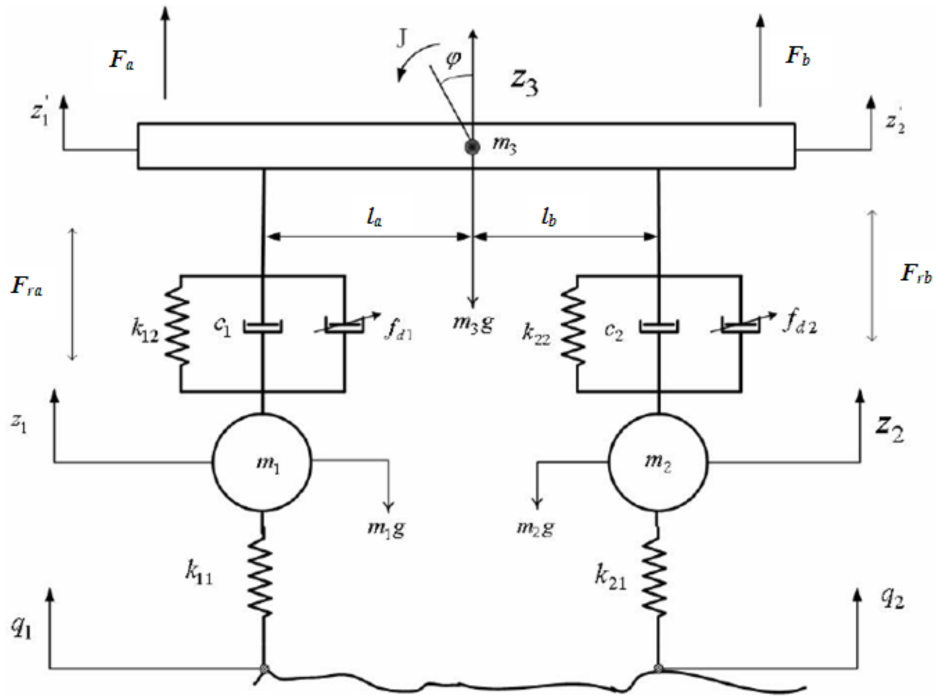


Figure 4.5: Half Semi-active Suspension (Pitch)

(1) $m_1\ddot{z}_1 = k_{11}(z_1 - q_1) + k_{12}(z'_1 - z_1) + c_1\left(\dot{z}'_1 - \dot{z}_1\right) + F_{ra} + f_{d1} + m_1 g$

(2) $m_2\ddot{z}_2 = k_{21}(z_2 - q_2) + k_{22}(z'_2 - z_2) + c_2\left(\dot{z}'_2 - \dot{z}_2\right) + F_{rb} + f_{d2} + m_2 g$

(3) $m_3\ddot{z}_3 = k_{12}(z_1 - z'_1) + k_{22}(z_2 - z'_2) + c_1(\dot{z}_1 - \dot{z}'_1) + c_2(\dot{z}_2 - \dot{z}'_2) - F_{ra} - F_{rb}$
$-f_{d1} - f_{d2} + m_3 g$

(4) $J\ddot{\varphi} = -[k_{12}(z_1 - z'_1) + c_1(\dot{z}_1 - \dot{z}'_1)]l_a + [k_{22}(z_2 - z'_2) + c_2(\dot{z}_2 - \dot{z}'_2)]l_b$

$-l_a f_{d1} + l_a F_{ra} + l_b f_{d2} - l_b F_{rb}$

F_{ra} is a constant friction for front half suspension.

F_{rb} is a constant friction for rear half suspension.

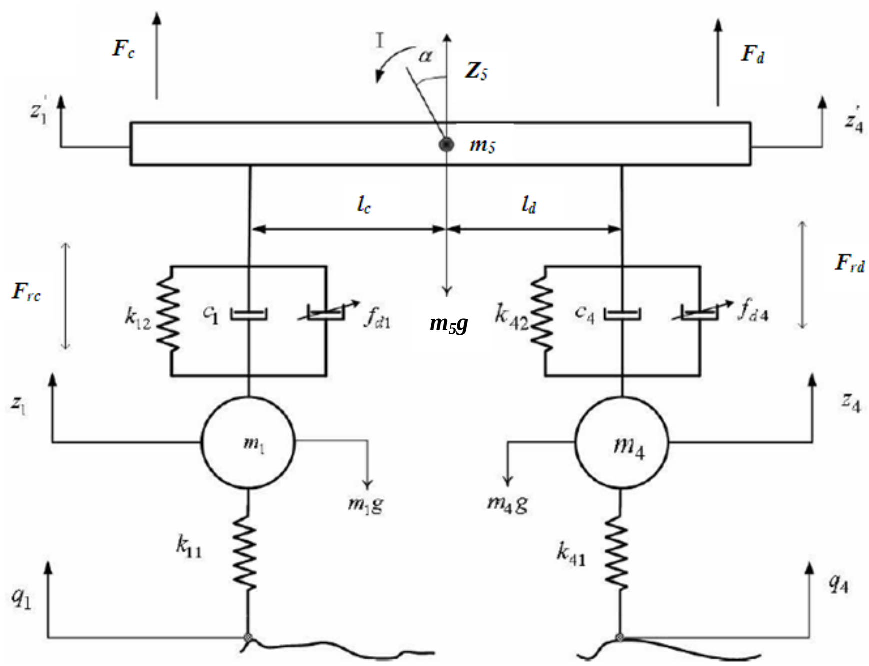


Figure 4.6: Half Semi-active Suspension (Roll)

(1) $m_1\ddot{z}_1 = k_{11}(z_1 - q_1) + k_{12}(z'_1 - z_1) + c_1(\dot{z}'_1 - \dot{z}_1) + F_{rc} + f_{d1} + m_1 g$

(2) $m_4\ddot{z}_4 = k_{41}(z_4 - q_4) + k_{42}(z'_4 - z_4) + c_4(\dot{z}'_4 - \dot{z}_4) + F_{rd} + f_{d4} + m_4 g$

(3) $m_5\ddot{z}_5 = k_{12}(z_1 - z'_1) + k_{42}(z_2 - z'_2) + c_1(\dot{z}_1 - \dot{z}'_1) + c_4(\dot{z}_4 - \dot{z}'_4) - F_{rc} - F_{rd}$
$-f_{d1} - f_{d4} + m_5 g$

(4) $I\ddot{\alpha} = -[k_{12}(z_1 - z'_1) + c_1(\dot{z}_1 - \dot{z}'_1)]l_c + [k_{42}(z_4 - z'_4) + c_4(\dot{z}_4 - \dot{z}'_4)]l_d$
$-l_c f_{d1} + l_c F_{rc} + l_d f_{d2} - l_d F_{rd}$

F_{rc} is a constant friction for left half suspension model.

F_{rd} is a constant friction for right half suspension model.

4.3 Fuzzy Logic

The point of fuzzy logic is to map an input space to an output space, and the primary mechanism for doing this is a list of if-then statements called rules. All rules are evaluated in parallel, and the order of the rules is unimportant. The rules themselves are useful because they refer to variables and the adjectives that describe those variables. Before we can build a system that interprets rules, we have to define all the terms we plan on using and the adjectives that describe them.

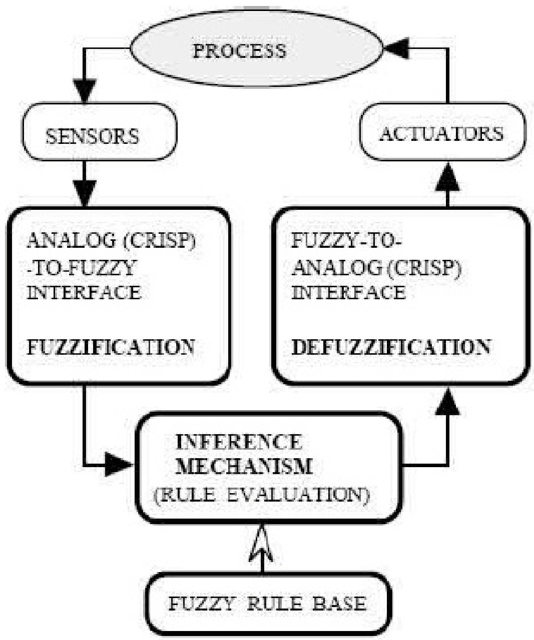


Figure 4.7: Fuzzy Logic process

Steps involved in formulating Simulink model of Semi-active suspension model:

1. Design of Fuzzy Logic Controller
2. Setting this controller in Fuzzy logic controller Simulink block
3. Replacing the constant damping coefficient block in half car passive Simulink model with fuzzy logic controller block, which varies the damping coefficient.

Design of fuzzy Logic controller is achieved by the following steps

1. Selecting the inputs, on the basis of which the controller is to be designed. This is to be taken both for front and rear suspensions. In this work sprung mass velocity and relative velocity are taken as inputs
2. Selecting the output to be controlled (damping coefficient for front and rear suspensions)
3. Setting the ranges for each input and output
4. Formulating the Fuzzy rules using IF-THEN statements.

4.4 Membership Function

In this project, the controller is using a fuzzy logic controller, thus by using following 9-rules, the controller is developed using fis. file.

Table 4.1: Rules in membership function

Relative Velocity / **Body Velocity**	**Negative**	**Zero**	**Positive**
Negative	Large	Medium	Small
Zero	Medium	Medium	Medium
Positive	Small	Medium	Large

4.5 Road profile

The main road profile that being use in this project is by using sinusoidal input convert to step input with difference condition for front and rear. However, basic sinusoidal input and noise input, also being use as road profile in this project.

i) Main Road profile

For front suspension system; using if else (u1= 0.3 to 0.5)

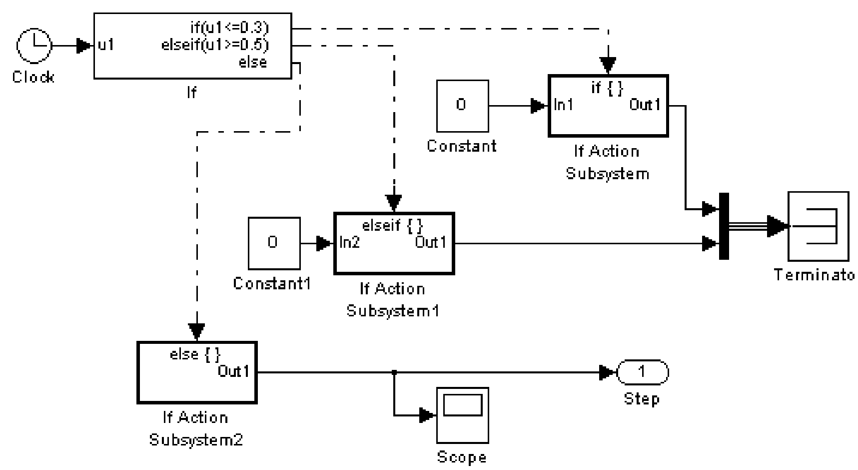


Figure 4.8: Front Road profile input

For rear suspension system; using if else (u1= 1.55 to 1.75)

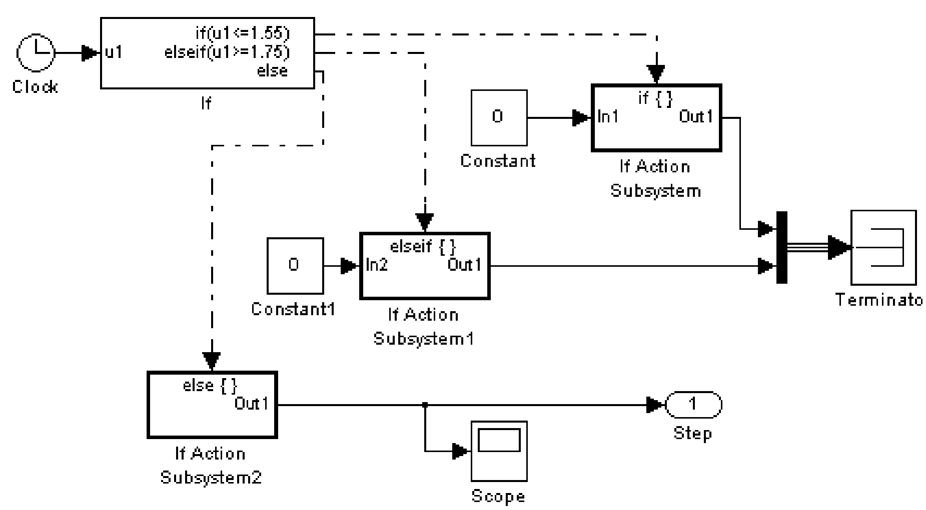


Figure 4.9: Rear Road profile input

ii) Sinusoidal input and noise input

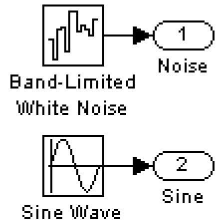


Figure 4.10: Noise and Sine Wave Road profile input

For Noise input all the parameter are using default parameter, while for sine wave, using frequency 3, amplitude 150.

4.6 Suspension Block Simulation

4.6.1 Half Passive Suspension System

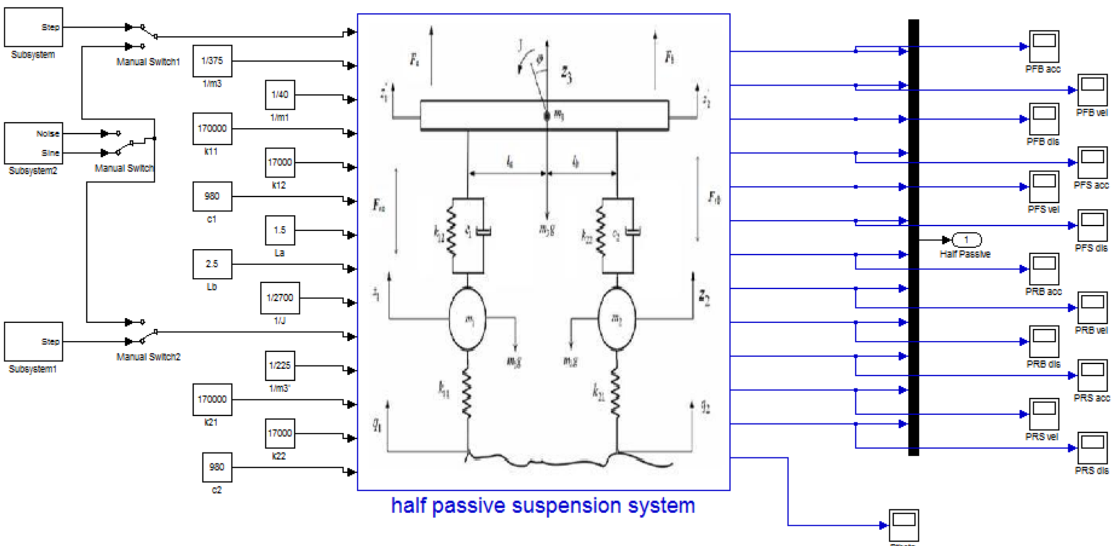


Figure 4.11: half passive suspension system (whole system)

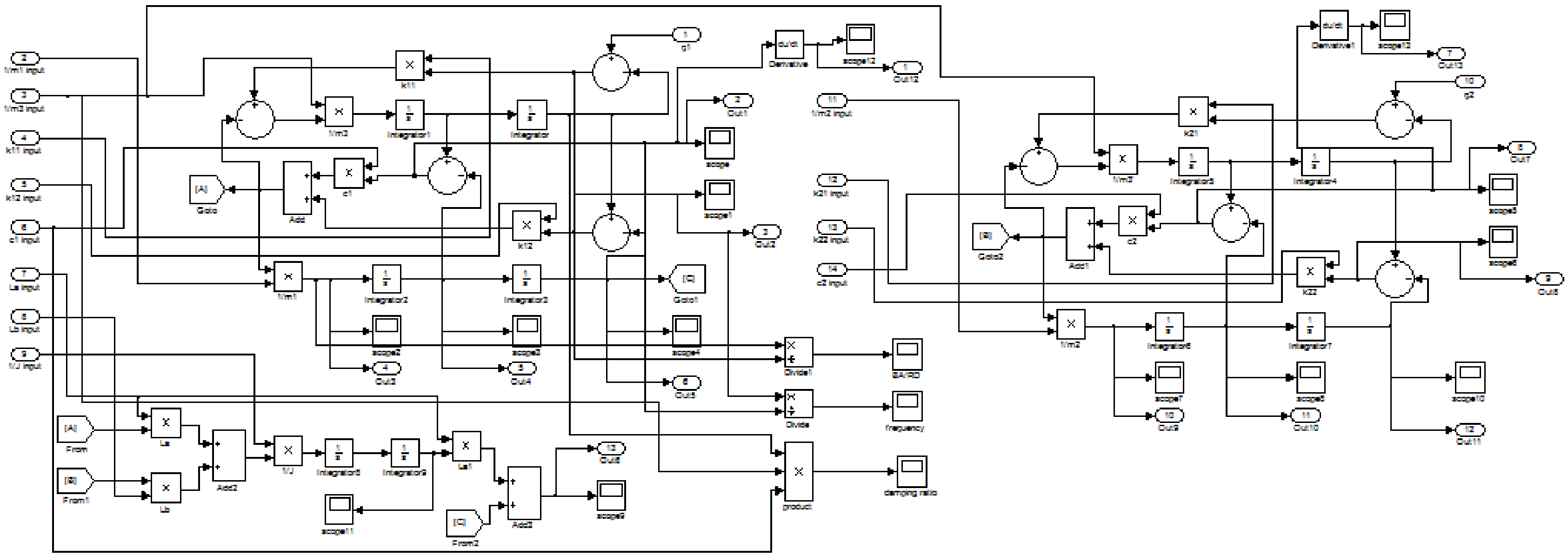


Figure 4.12: half passive suspension system (subsystem)

4.6.1 Half Semi-active suspension system

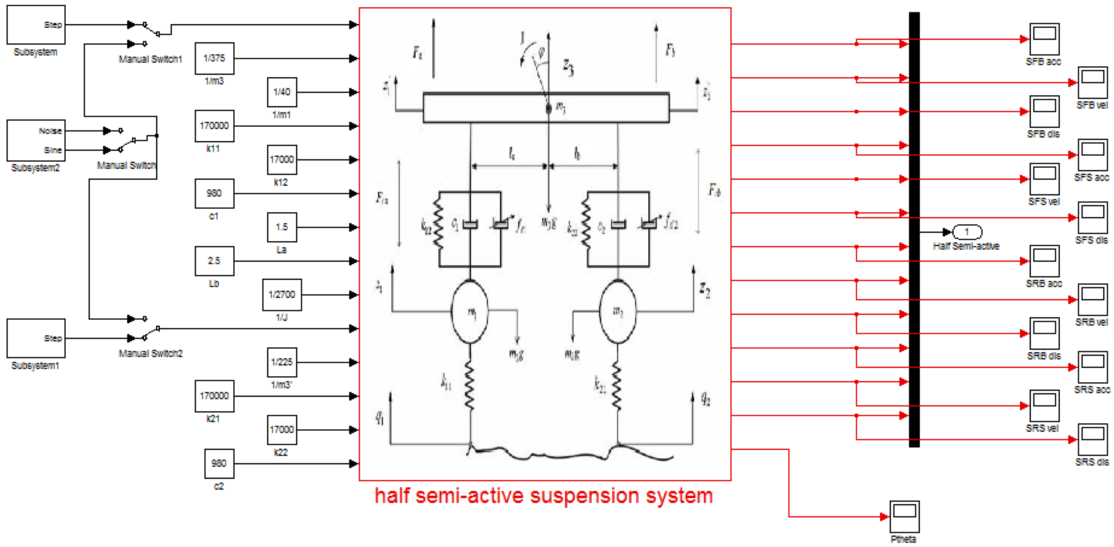


Figure 4.13: half semi-active suspension system (whole system)

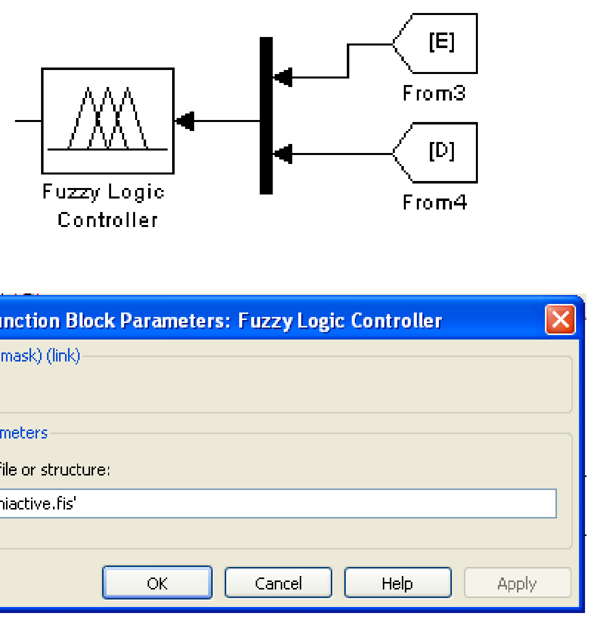


Figure 4.14: Fuzzy Logic controller

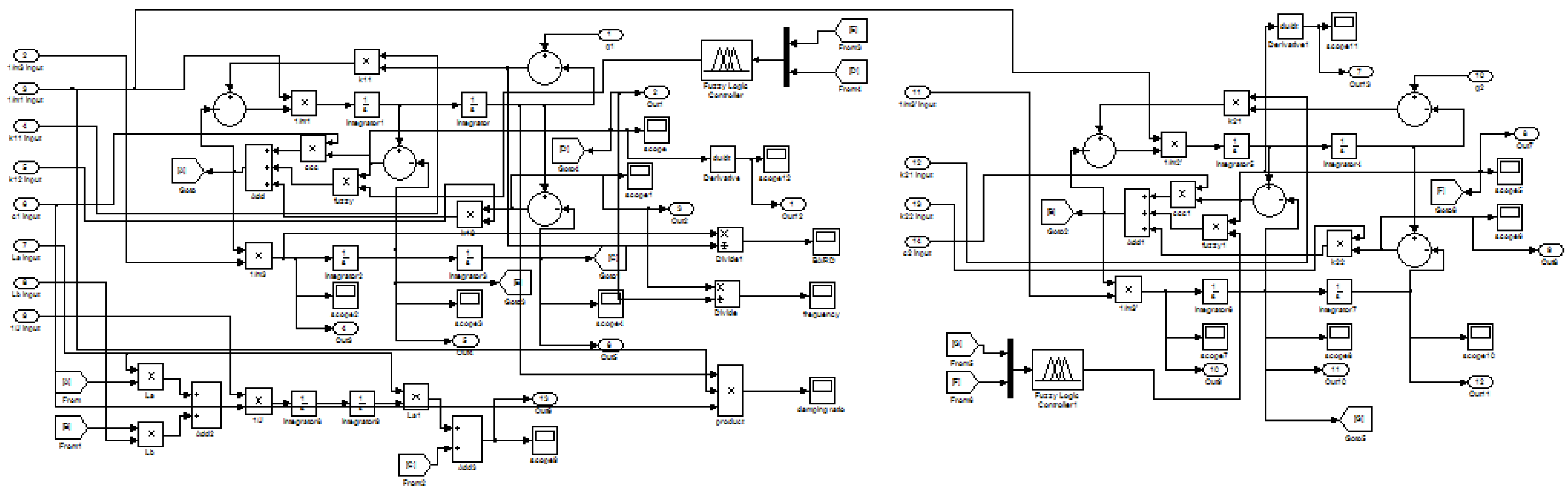


Figure 4.15: half semi-active suspension system (subsystem)

4.7 Passive vs. Semi-active Suspension System

After creating the system for both of them, the data generated with different read disturbance is being analyze to compare the resultant data.

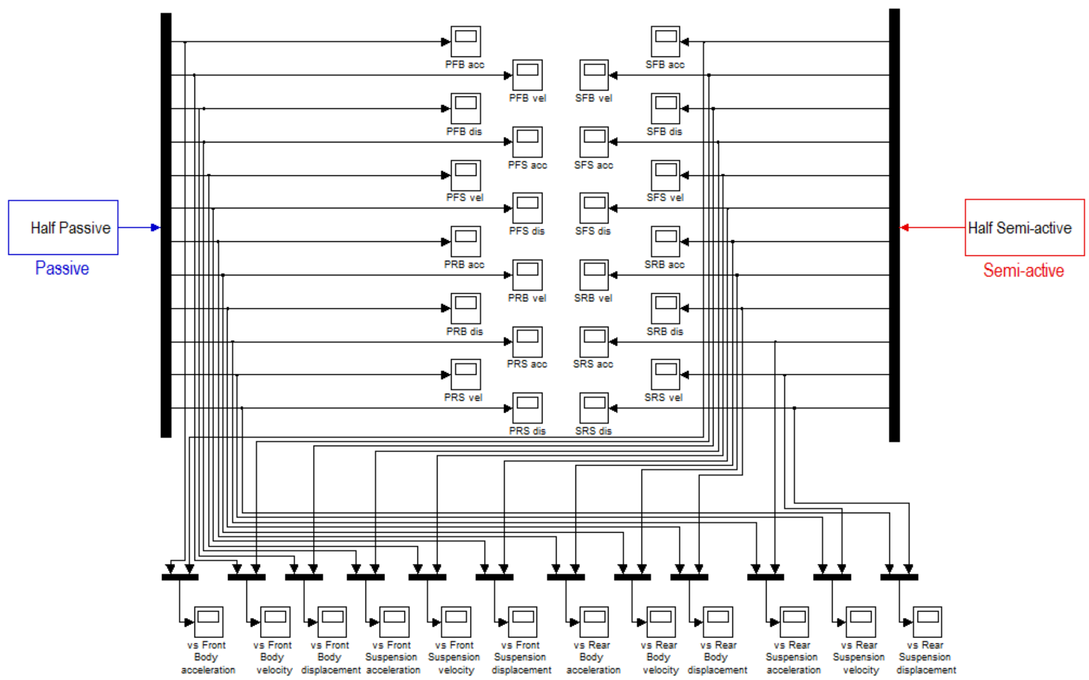


Figure 4.16: passive vs. semi-active suspension system

CHAPTER 5

RESULT & DISCUSSION

5.1 Test Parameters

Table 5.1 shows the parameter used in the simulation.

Table 5.1: Test Parameters Data

Parameters	Symbol	Value	Units
Sprung mass (half of vehicle mass)	m	600	kg
Unsprung mass	m_1 & m_2	40	kg
Sprung mass damping coefficient	c_{b1} & c_{b2}	980	Ns/m
Spring rate	K_{b1} & K_{b1}	17000	N/m
Tire spring rate	K_{w1} & K_{w1}	170000	N/m
Equivalent Front wheel Sprung mass	m_{s1}	375	kg
Equivalent Rear wheel Sprung mass	m_{s2}	225	kg
Length of CG of vehicle from front wheel suspension	L_1	1.5	m
Length of CG of vehicle from rear wheel suspension	L_2	2.5	m
Pitch inertia of vehicle	I_b	2700	kgm^2

5.2 Half Passive Suspension System

Based on step road profile.

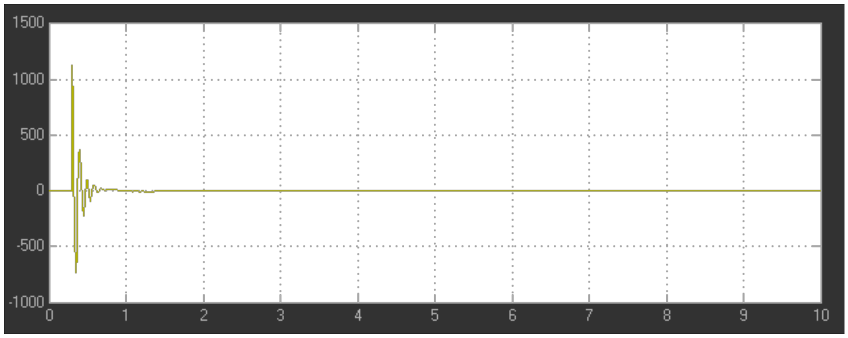


Figure 5.1: passive front body acceleration

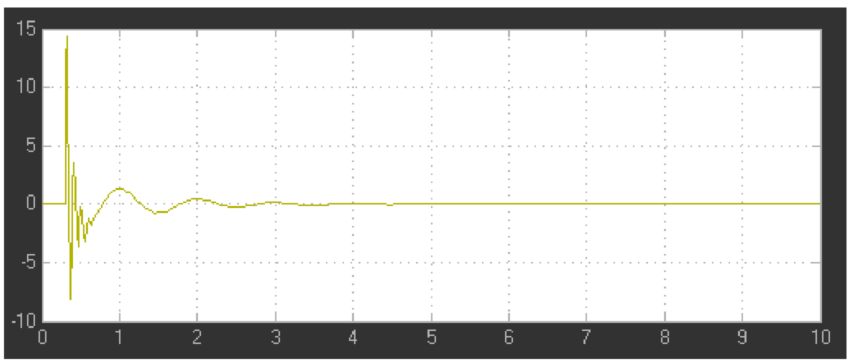


Figure 5.2: passive front body velocity

Figure 5.3: passive front body displacement

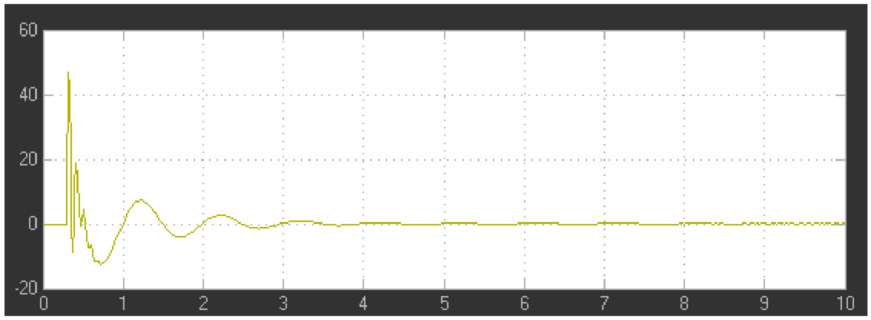


Figure 5.4: passive front suspension acceleration

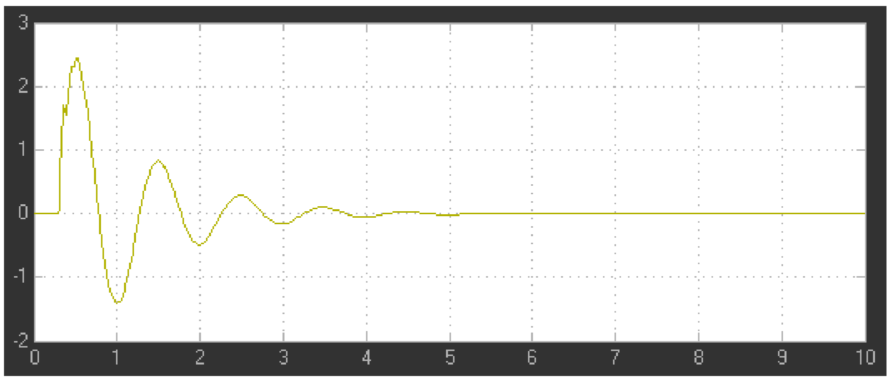


Figure 5.5: passive front suspension velocity

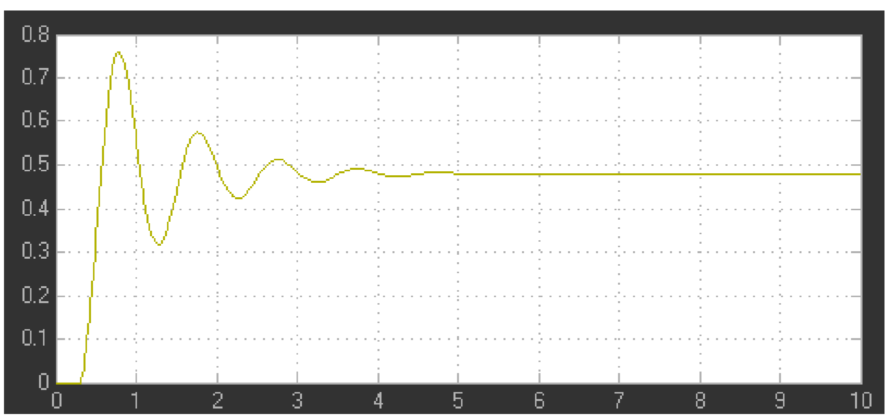


Figure 5.6: passive front suspension displacement

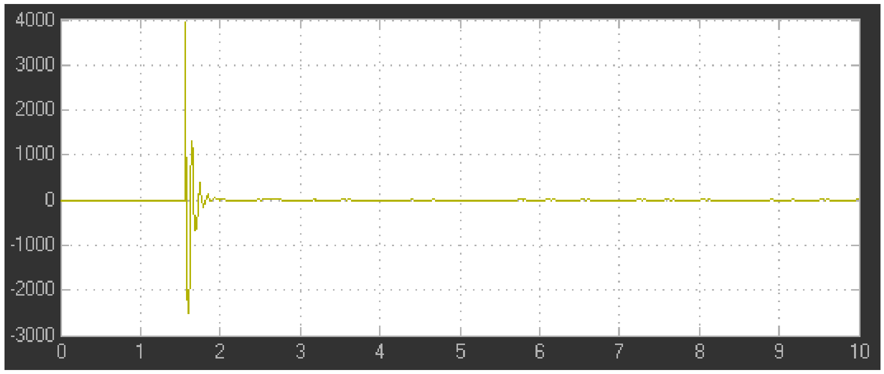


Figure 5.7: passive rear body acceleration

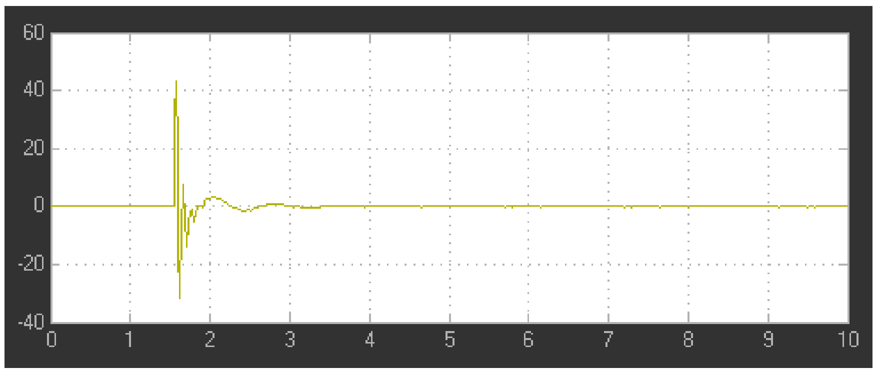


Figure 5.8: passive rear body velocity

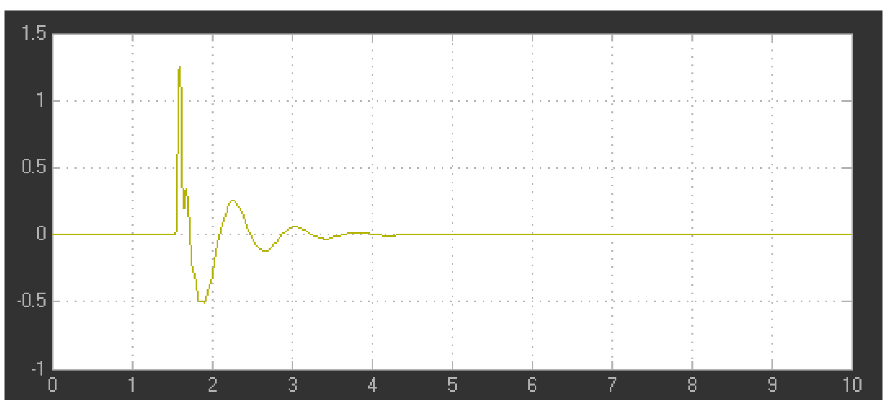


Figure 5.9: passive rear body n displacement

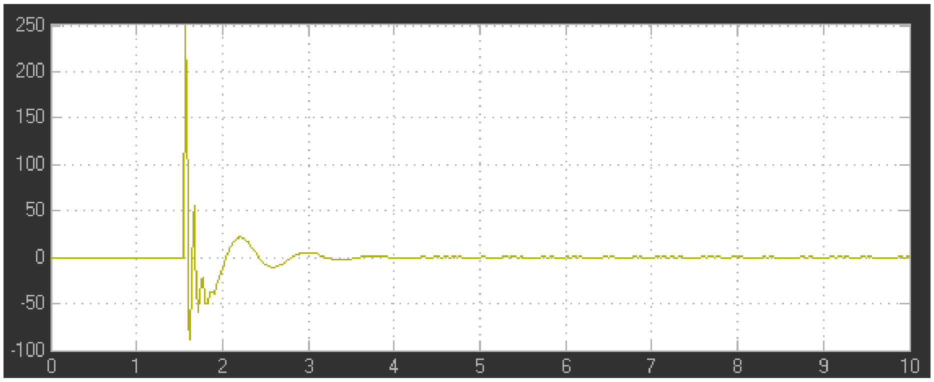


Figure 5.10: passive rear suspension acceleration

Figure 5.11: passive rear suspension velocity

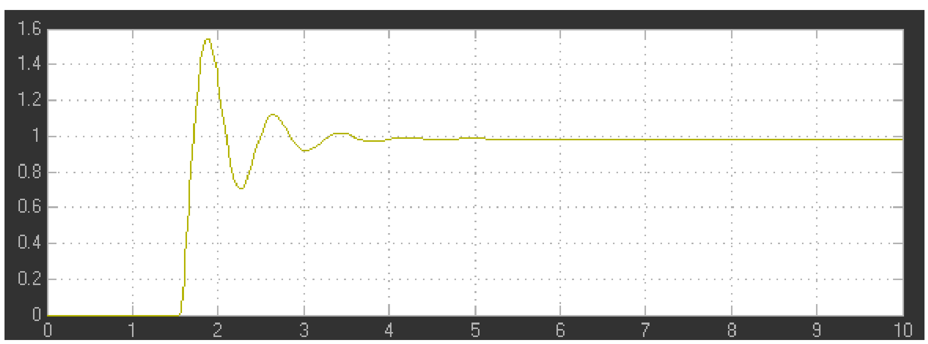


Figure 5.12: passive rear suspension displacement

5.3 Half Semi-active Suspension System

Based on step road profile.

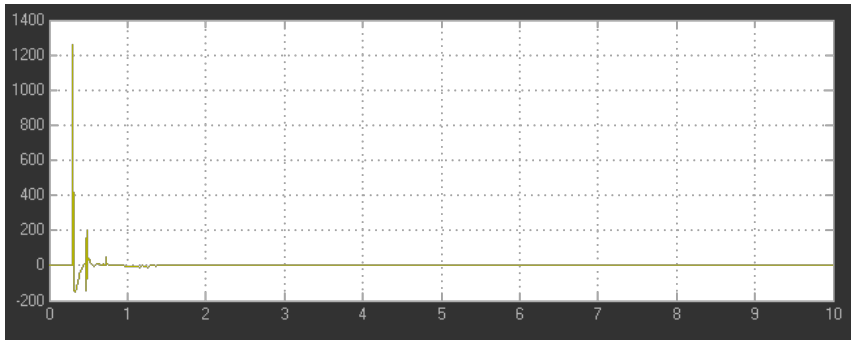


Figure 5.13: semi-active front body acceleration

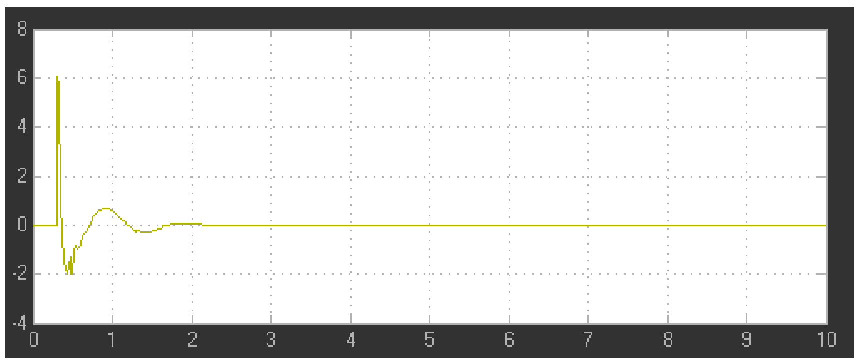


Figure 5.14: semi-active front body velocity

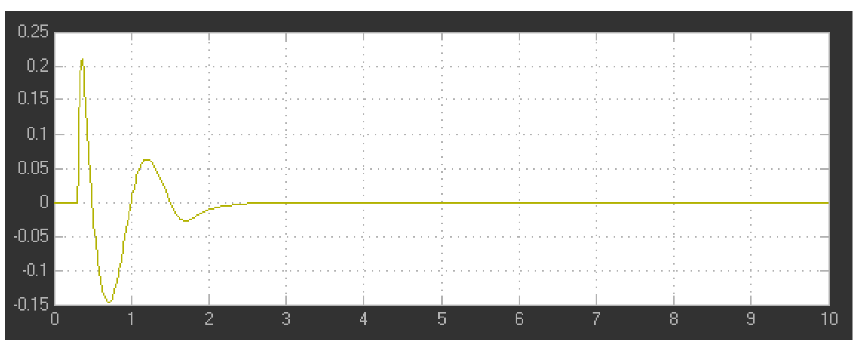


Figure 5.15: semi-active front body displacement

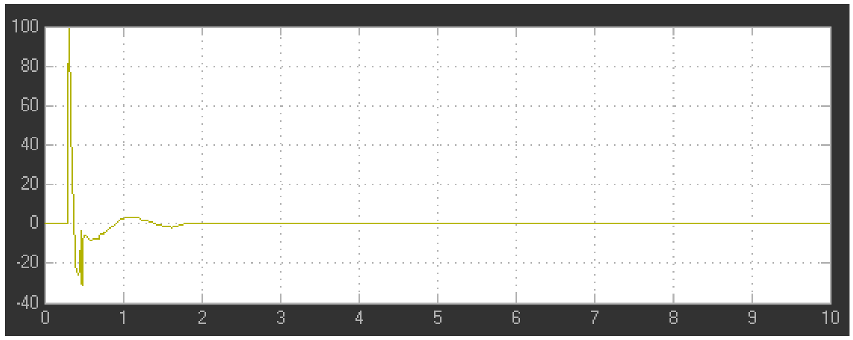


Figure 5.16: semi-active front suspension acceleration

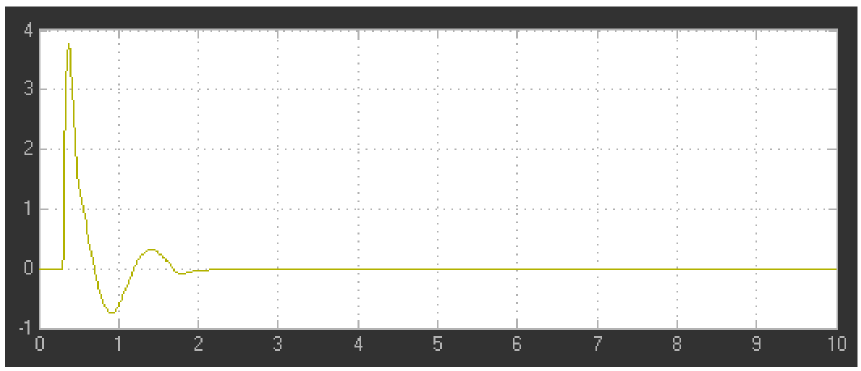


Figure 5.17: semi-active front suspension velocity

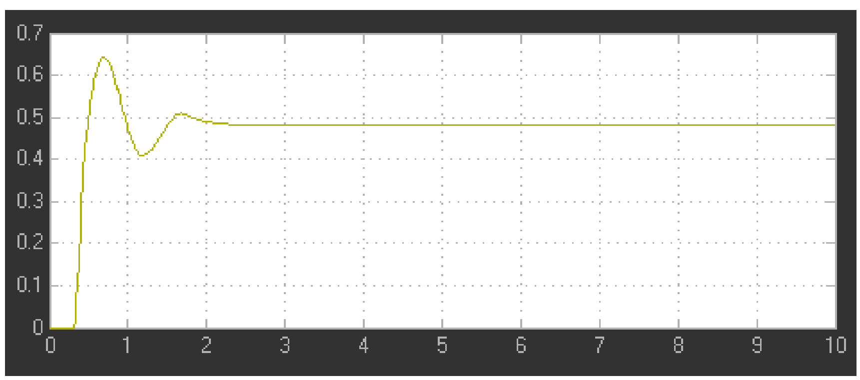


Figure 5.18: semi-active front suspension displacement

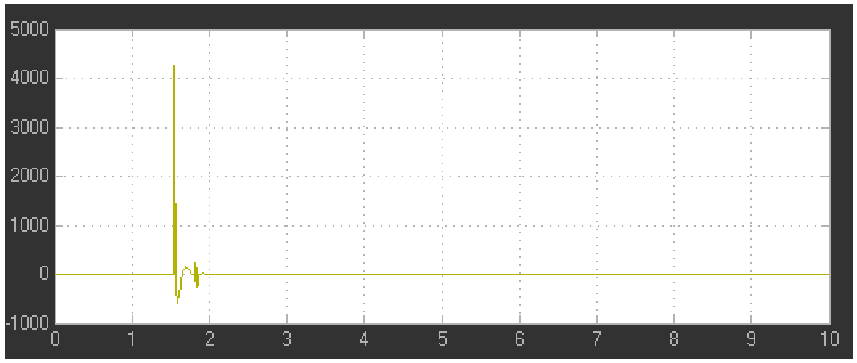


Figure 5.19: semi-active rear body acceleration

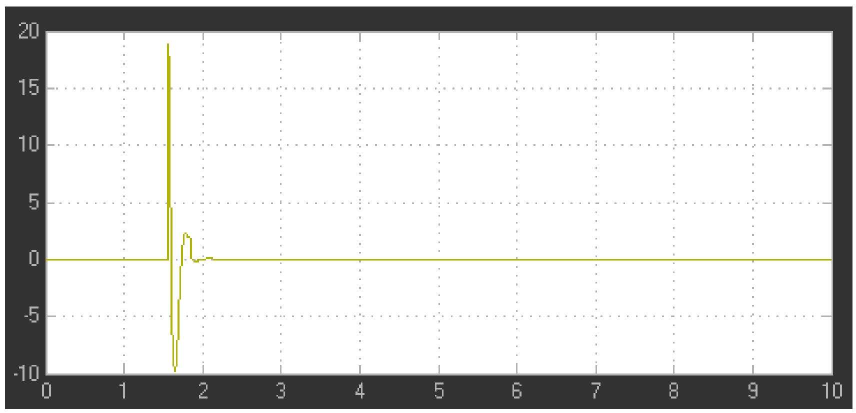


Figure 5.20: semi-active rear body velocity

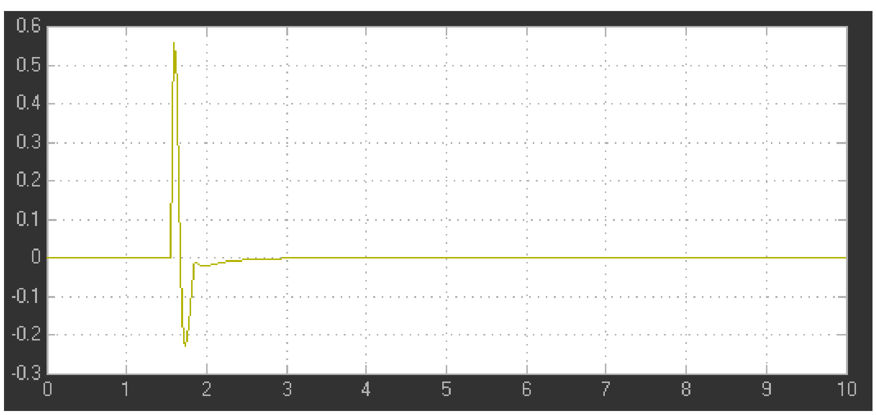


Figure 5.21: semi-active rear body n displacement

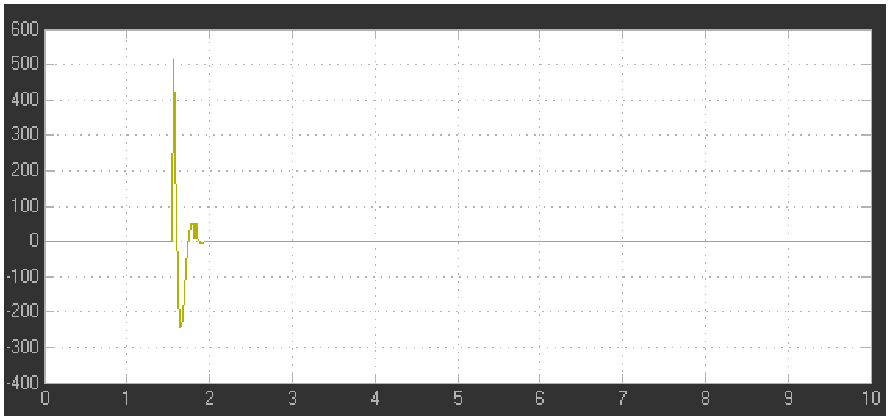


Figure 5.22: semi-active rear suspension acceleration

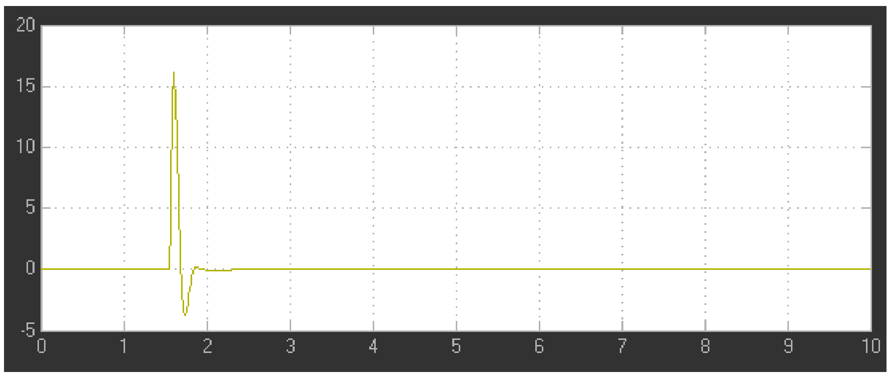


Figure 5.23: semi-active rear suspension velocity

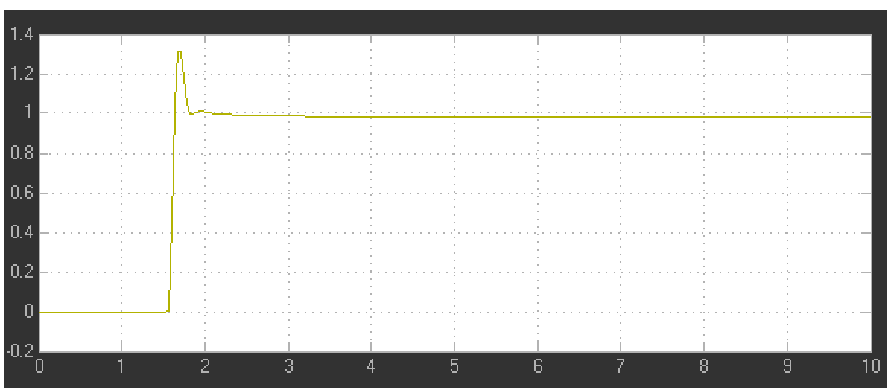


Figure 5.24: semi-active rear suspension displacement

5.4 Passive VS. Semi-active Suspension System

Based on step road profile. Purple graph represent semi-active, while yellow represent passive suspension system.

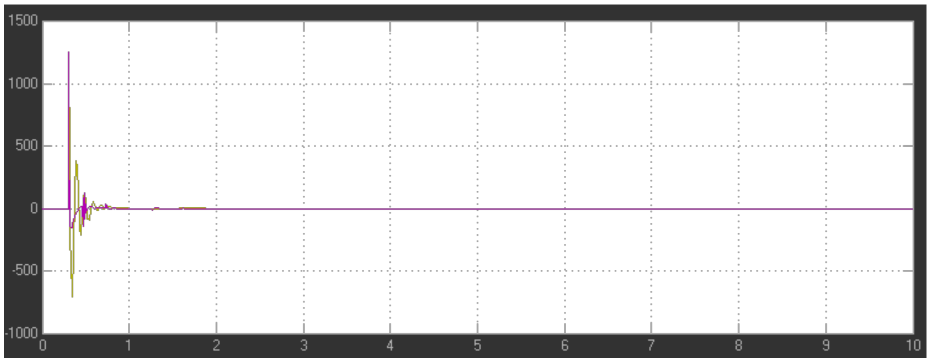


Figure 5.25: front body acceleration

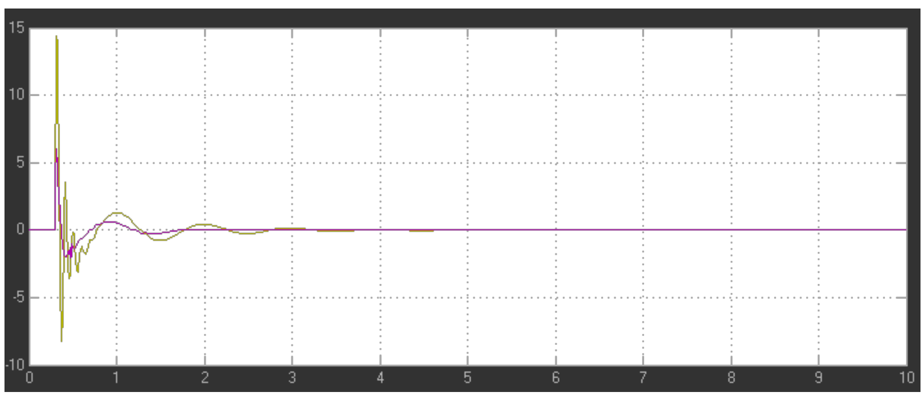


Figure 5.26: front body velocity

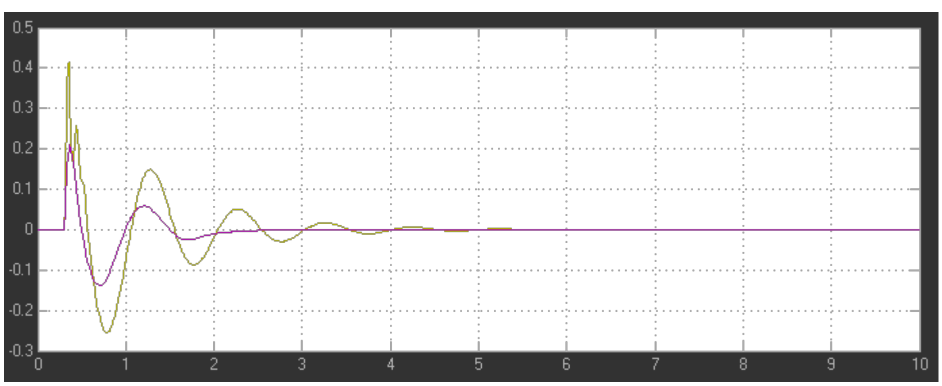


Figure 5.27: front body displacement

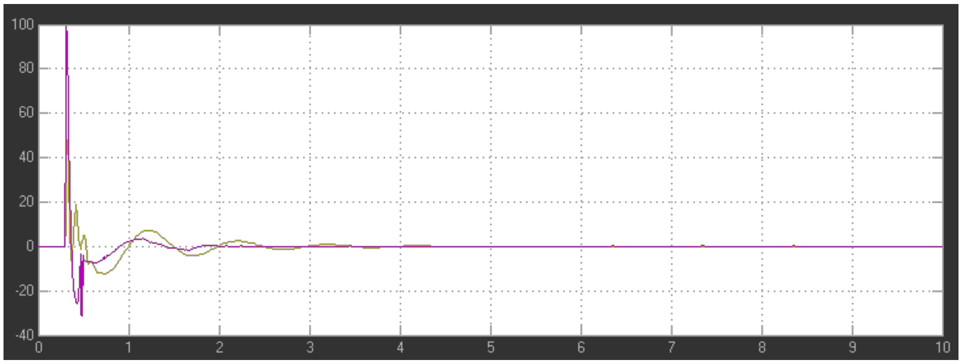


Figure 5.28: front suspension acceleration

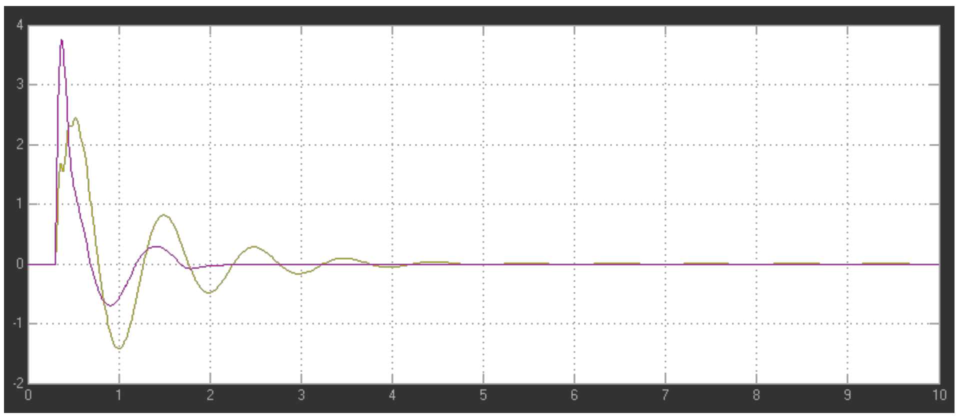


Figure 5.29: front suspension velocity

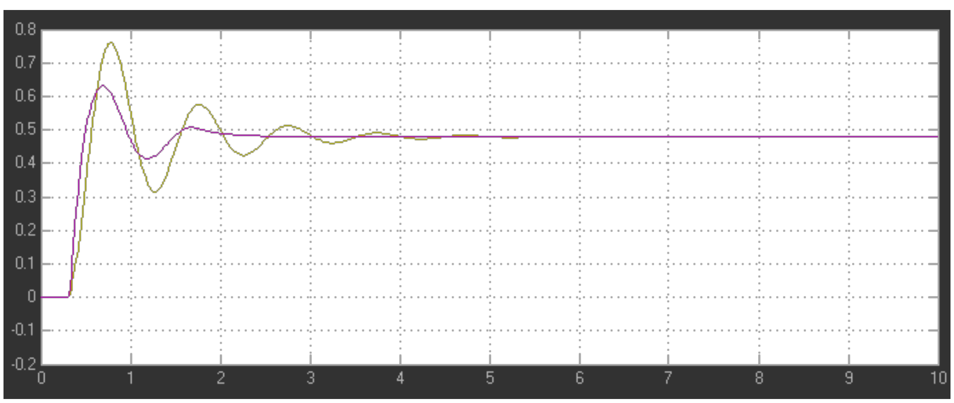


Figure 5.30: front suspension displacement

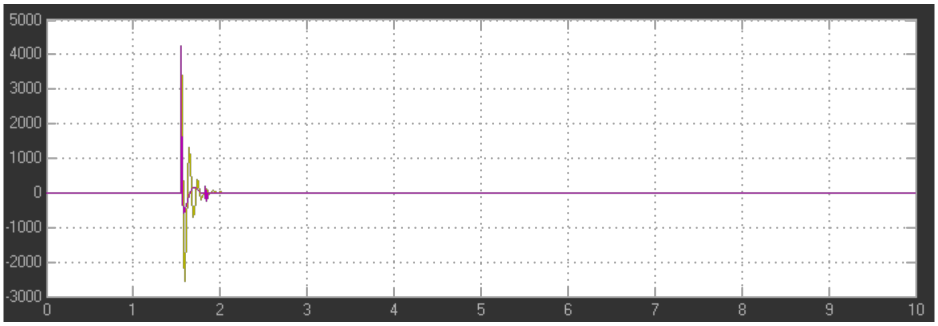


Figure 5.31: rear body acceleration

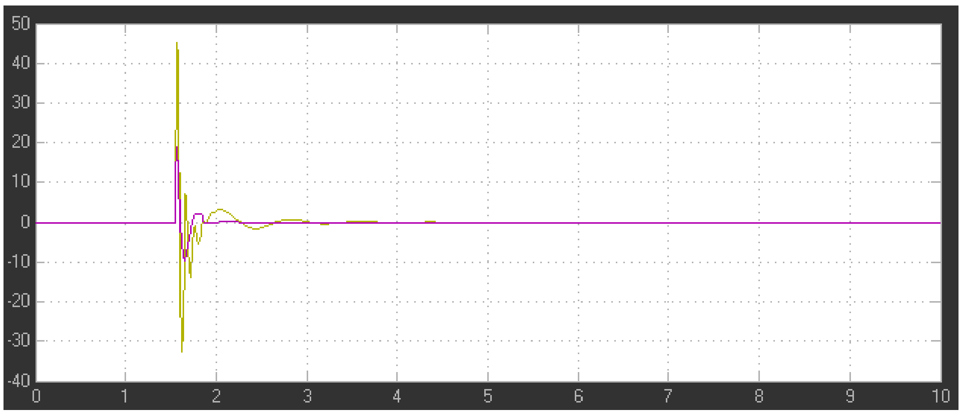


Figure 5.32: rear body velocity

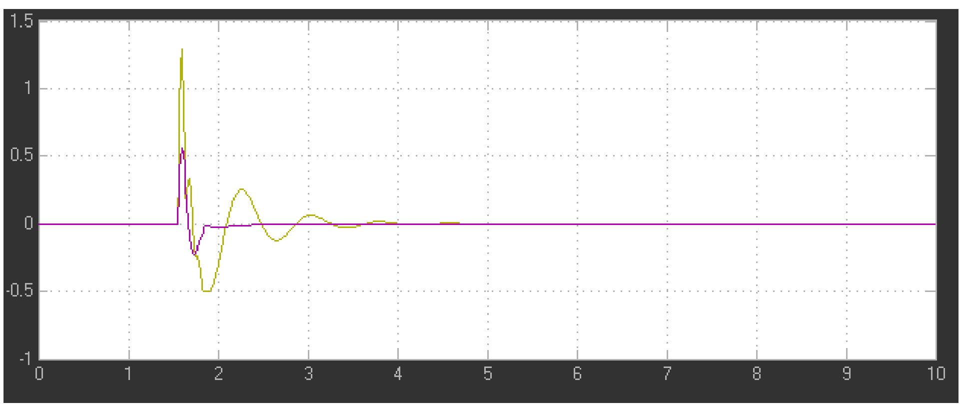


Figure 5.33: rear body n displacement

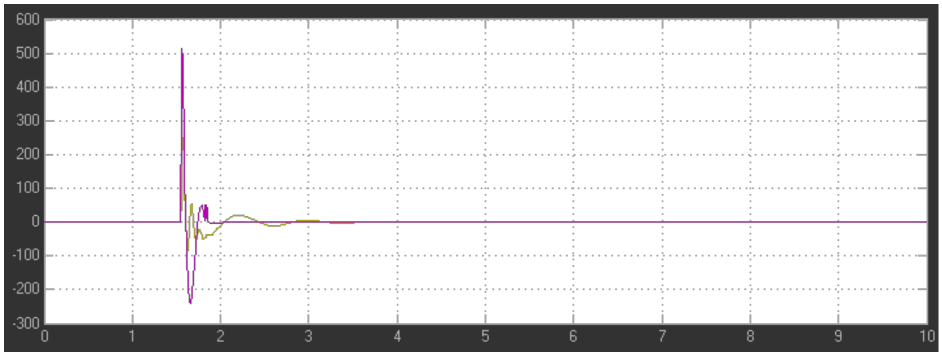


Figure 5.34: rear suspension acceleration

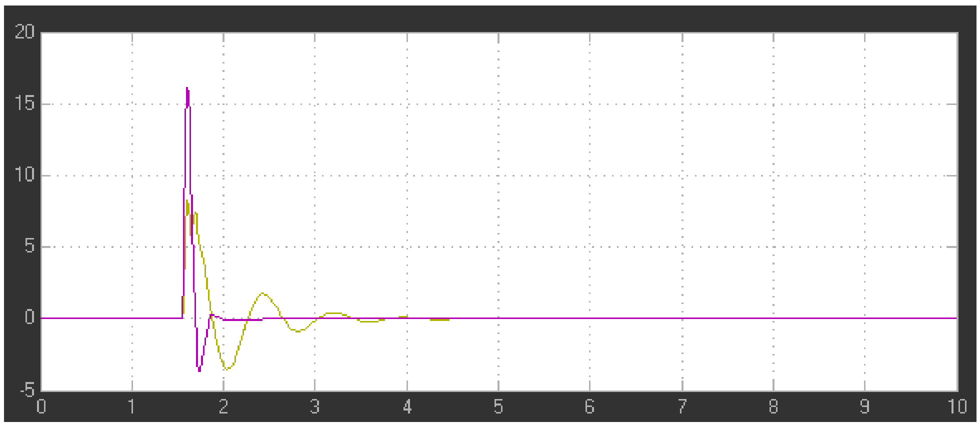


Figure 5.35: rear suspension velocity

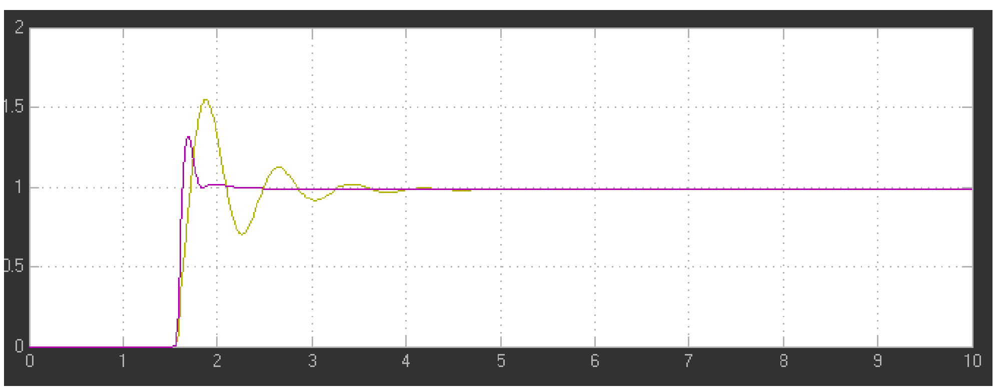


Figure 5.36: rear suspension displacement

Below shows the design guideline how to prove that the system is comfort enough for a vehicle.

Table 5.2: Vehicle Ride Comfort Design Guideline

Characteristic	**Small Car**	**Medium Car**	**Large Car**	**Luxury Car**	**Sports car**
Ride Frequency	1.3 – 1.4 Hz	1.1 – 1.2 Hz	1.1 – 1.2 Hz	≈ 1 Hz	2.0 – 2.5 Hz
Suspension Static Deflection	5 – 6 in	7 – 8 in	7- 8 in	≈ 10 in	4.3 - 7.2 in
Wheel Travel	±4 in	±4 in	±4 in	±4 in	±2 to ±4 in
Damping Ratio	0.2 – 0.4	0.2 – 0.4	0.2 – 0.4	0.2 – 0.4	> 0.4
Dynamic Index	0.9 – 1.0	0.9 – 1.0	0.9 – 1.0	≈ 1.0	≈ 0.8

Source: Thomas D. Gillespie, Fundamental of Vehicle Dynamics, Society of Automotive Engineers, Inc. Warrendale, and William F. Miliken and Doughlas L. Miliken, Race Car Vehicle Dynamics, SOAE, Inc. Warrendale

Based on the table, only Damping Ratio criteria can be determined, where, from the semi-active suspension system that been generated before. Below are the data related to the damping ratio.

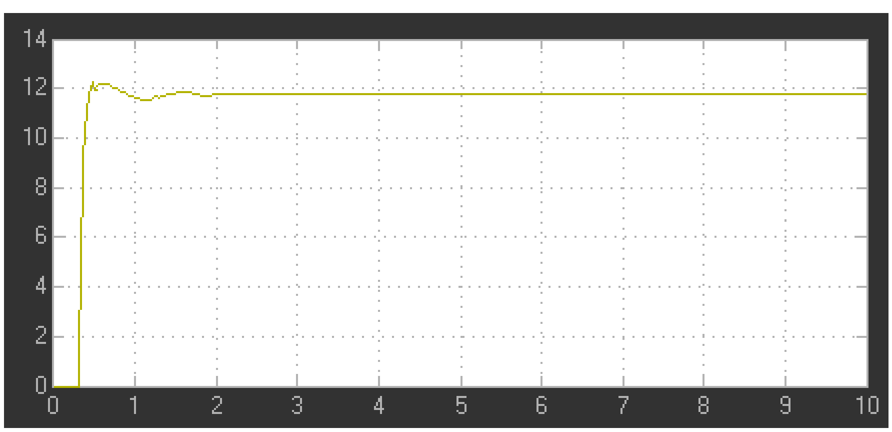


Figure 5.37: Damping ratio (front semi-active suspension)

The steady state condition from the figure is on 11.7459.

(Max) 12.25-11.7459 = 0.4959

(Min) 11.7459-11.5 = 0.2459

The condition for the comfort for a vehicle is between 0.2 – 0.4, therefore, the condition is acceptable as comfort vehicle.

Based on all data on passive and semi-active suspension data using step input; maximum, minimum and settling time, percentage difference between both systems then, being calculated.

For sine wave input and noise input, the graph that being generated can be viewed in the appendices.

Table 5.3: Half Passive VS. Semi-active percentage differences

Parameters	Maximum			Minimum			Max-Min			Settling Time (s)		
	Passive	**Semi-active**	**%**	**Passive**	**Semi-active**	**%**	**Passive**	**Semi-active**	**%**	**Passive**	**Semi-active**	**%**
Front Body acceleration (m/s^2)	1125.93	1255.96	-11.55	-727.71	-154.02	78.83	1853.64	1409.98	**23.93**	1.51	1.41	**6.62**
Front Body velocity (m/s)	14.39	6.02	58.17	-8.07	-2.00	75.22	22.46	8.02	**64.29**	4.57	2.67	**41.58**
Front Body displacement (m)	0.42	0.20	52.38	-0.25	-0.14	44.00	0.67	0.34	**49.25**	5.12	3.36	**34.38**
Front Suspension acceleration (m/s^2)	46.77	98.91	-111.48	-12.46	-31.28	-151.04	59.23	130.19	**-119.80**	5.13	1.95	**61.99**
Front Suspension velocity (m/s)	2.44	3.76	-54.10	-1.42	-0.74	47.89	3.86	4.50	**-16.58**	5.98	2.23	**62.71**
Front Suspension displacement (m)	0.75	0.64	14.67	0.00	0.00	0.00	0.75	0.64	**14.67**	5.15	2.46	**52.23**
Rear Body acceleration (m/s^2)	3931.26	4249.08	-8.08	-2517.99	-593.90	76.41	6449.25	4842.98	**24.91**	3.74	1.99	**46.79**
Rear Body velocity (m/s)	43.37	18.86	56.51	-31.80	-9.81	69.15	75.17	28.67	**61.86**	3.95	1.94	**50.89**
Rear Body displacement (m)	1.25	0.55	56.00	-0.50	-0.22	56.00	1.75	0.77	**56.00**	4.37	3.05	**30.21**
Rear Suspension acceleration (m/s^2)	249.69	515.17	-106.32	-87.78	-244.05	-178.02	337.47	759.22	**-124.97**	4.39	2.14	**51.25**
Rear Suspension velocity (m/s)	8.25	16.13	-95.52	-3.49	-3.71	-6.30	11.74	19.84	**-68.99**	4.93	2.75	**44.22**
Rear Suspension displacement (m)	1.54	1.31	14.94	0.00	0.00	0.00	1.54	1.31	**14.94**	5.17	2.71	**47.58**

CHAPTER 6

CONCLUSION & RECOMMENDATION

6.1 Conclusion

Based on simulation of fuzzy logic controller of semi active suspension system revealed that it improves the ride comfort (23.93% reduction on vehicle body acceleration). Besides, based on settling time taken shown than semi-active suspension system reduce bounce effect 62% as the highest.

Semi-active suspension system has its own advantages against passive and active suspension system. This suspension system exhibits high performance while having low system cost, light system weight and low energy consumption.

6.2 Recommendations

- Further works on simulation for full-model of semi-active suspension system can be done besides working on the experiment model to make clear comparison between the resultant data.

REFERENCES

Books

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[2] Analysis of an Automobile Suspension by Dr. Vu Trieu Minh. (UTP) (2008)

[3] Fuzzy Logic Toolbox™ 2 User’s Guide (www.mathworks.com) (2010)

Journal

[4] Multiobjective Optimisation of Active and Semi-Active Suspension Systems with Application of Evolutionary Algorithm By: Bourmistrova, A., Storey, I. , Subic, A

[5] Vehicle Suspension System Modelling, Chen,Yi (2006)

[6] Vehicle ride performance with semi-active suspension system using modified skyhook algorithm and current generator model By: Saiful Anuar Abu Bakar, H. Jamaluddin, R.A. Rahman and P.M. Samin, K. Hudha (2008)

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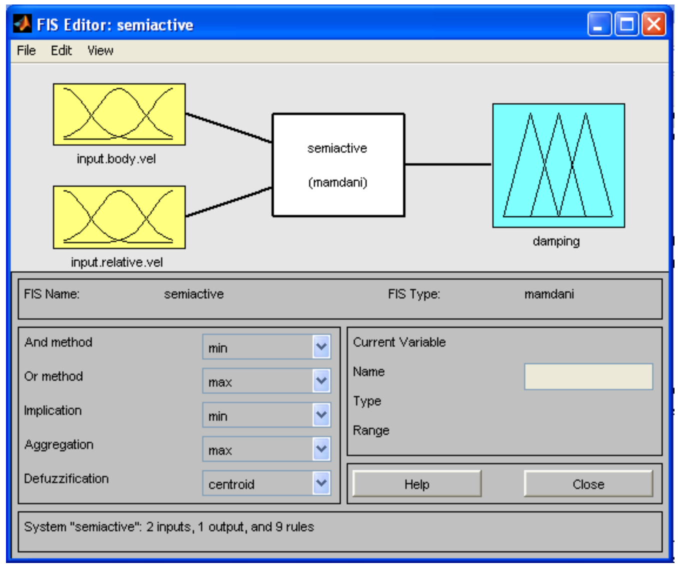
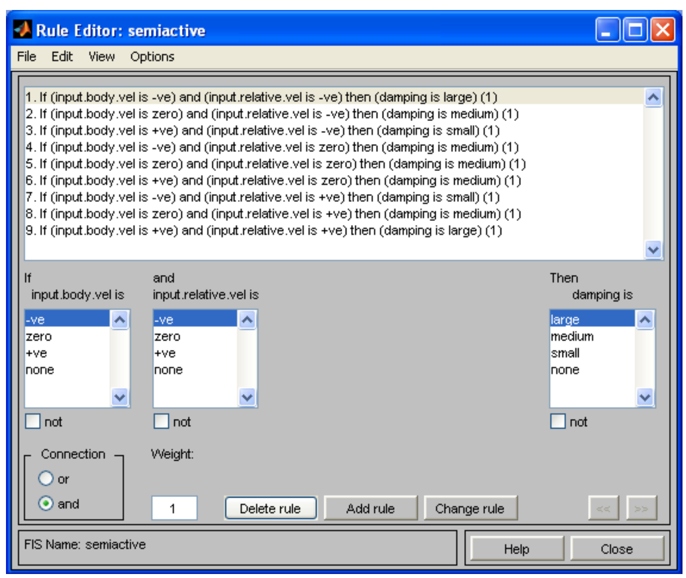
[8] Vehicle suspension analysis using Fuzzy Logic. By: V.Bhanu Chander

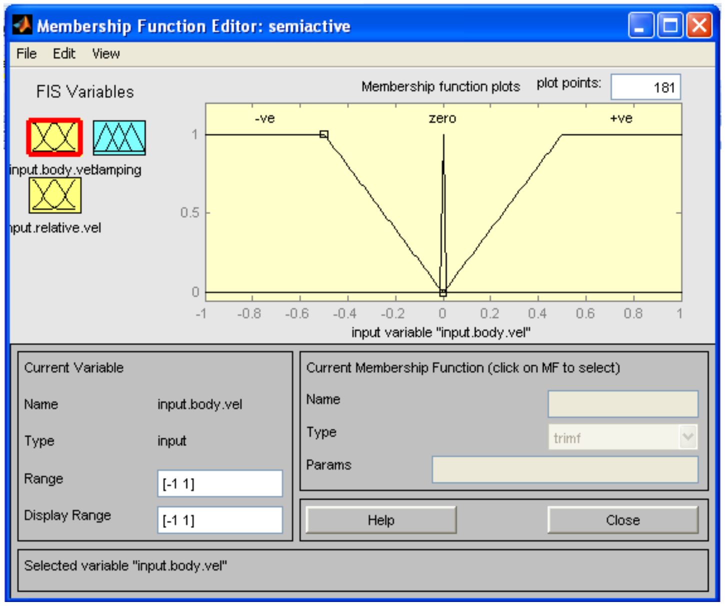
[9] The Improvement Of Ride Comfort Performance In Passenger Road Vehicles Using Active Suspension. By: Mohamed Haryzul Bin Mohamed Ghazali (2010)

APPENDICES

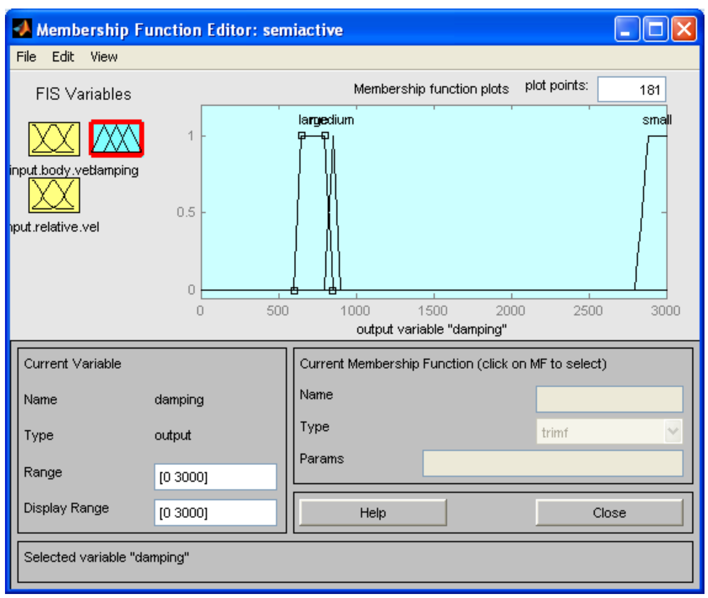
Membership Function





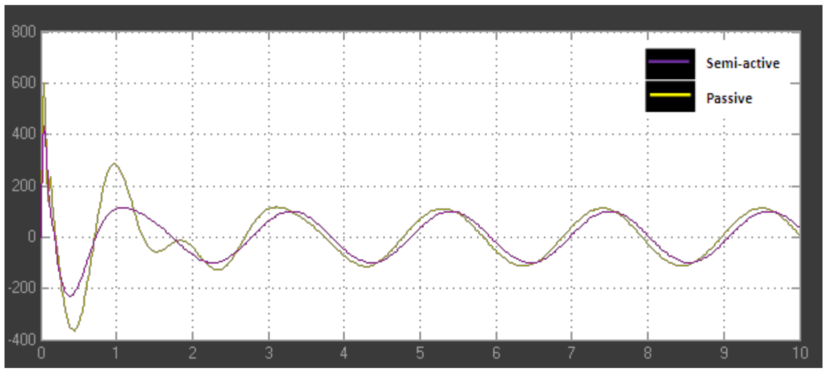


Example of membership function data

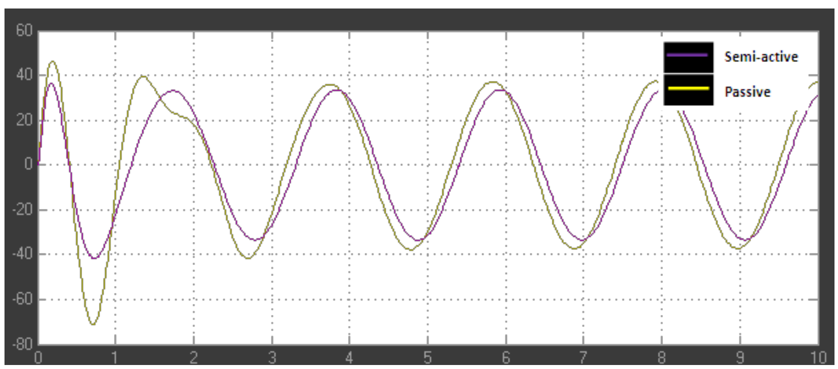


Example of membership function data

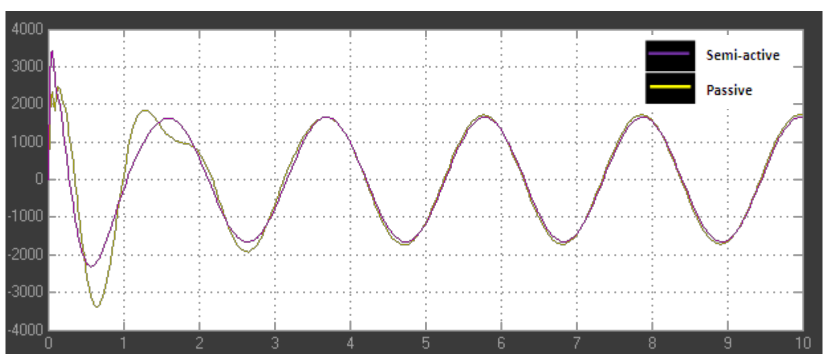
Sin Wave : Output Data



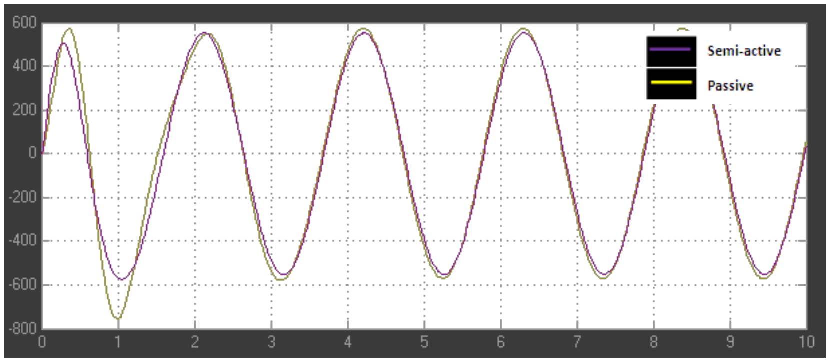
Suspension velocity



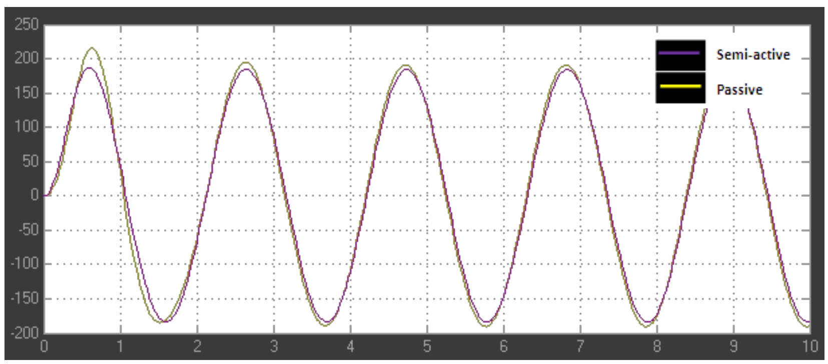
Suspension Displacement



Body Acceleration

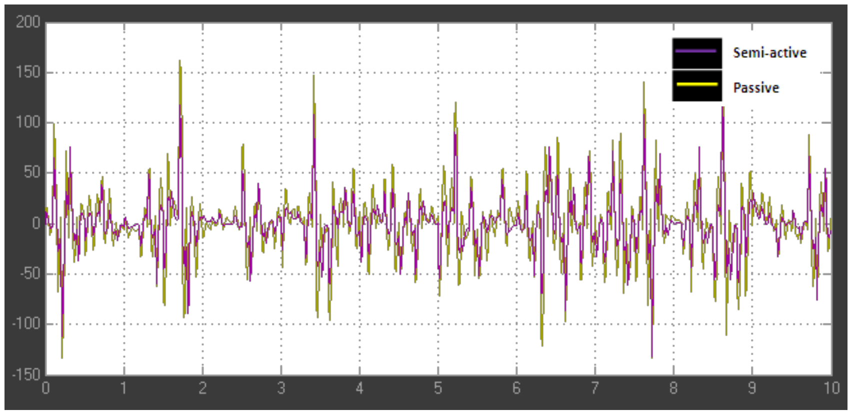


Body Velocity

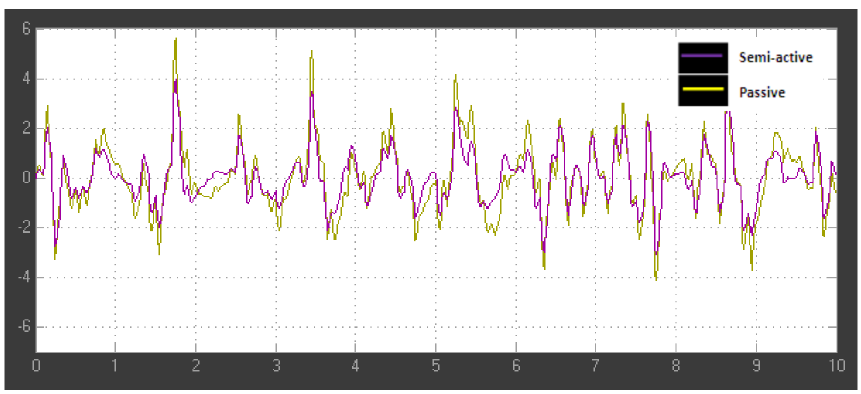


Body Displacement

Noise : Output Data



Suspension Velocity



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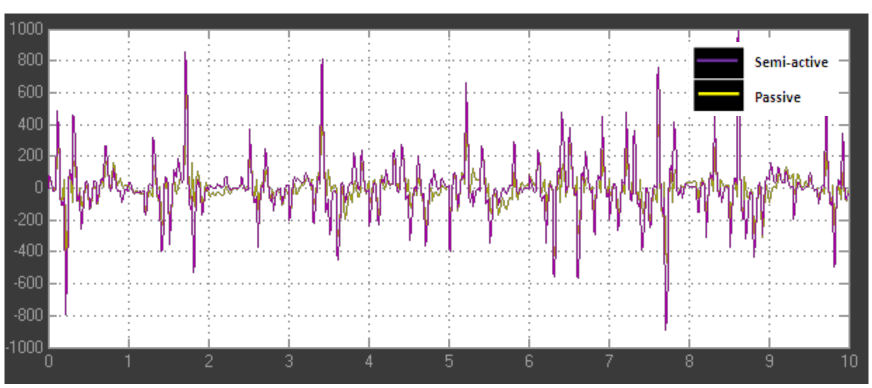

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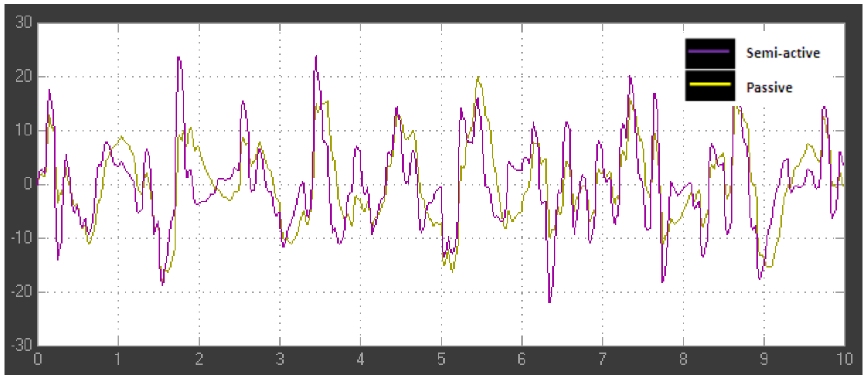

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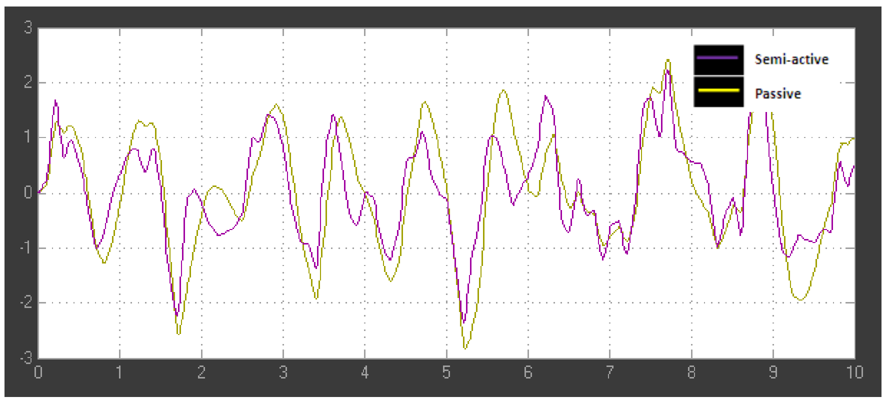

Body Displacement