Ride Comfort Analysis of In-Wheel Motor Electric Vehicles with PID and Fuzzy Logic Controlled Semi-Active Suspension System

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Abstract

The global warming has significant effects on the life cycle and needs to drop the effects urgently. The main reason of the problem is air pollution within the transportation. Especially capital and crowded cities change the policy with the fossil fuel usage regulations in central locations of cities. As an alternative solution, the hybrid engined vehicles and fully electric vehicles released and used respectively. Another new concept which is IWM (In-Wheel Motor) technology released earlier but still wait to become more popular and efficient. Basically, the system works as the wheel has the all driver system inside the rim as wheel hub, motor, and braking system. The significantly advantages of IWM on the vehicles starts with the torque which gives to the driver a control simultaneously rpm on the wheels with efficient acceleration of the car. The braking system in the wheels are available to work on regeneration of the energy with in-wheel motors. The most important advantage of the in-wheel motors is that the control of individually wheel speed with control unit of a car. Individual control gives the car high ability on the cornering and assist to steering. However, in the main stability system as unsprung mass increasing affect the ride comfort.

The improvements on the ride quality can be done by suspension system changes or adapting the controllers on the system. In this study, the effect of the mass change showed by passive quarter car suspension model. The mathematical modelling and visual simulations have been developed within MATLAB/Simulink. The comparison of two different road profile applied to the different semi-active suspension systems to show the effects onto the car body displacement and acceleration. There are two type of controllers designed and ruled into the systems and their results showed different graphs. The best effective damping has been chosen by comparisons between Bouc-Wen modeled, PID controlled and Fuzzy Logic controlled systems.

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CHAPTER 1

Introduction

Suspension system control and effects on the vehicle dynamics with ride quality have been the research subjects within the applications of different vehicle types in automotive engineering. This thesis concerns the modelling and simulating passive and semi-active suspension systems improving effects on the ride comfort regarding to applications on In-Wheel Motor (IWM) driven electric vehicles. In this chapter, the research main problem and idea identified and mentioned about the aims and objectives followed by through the project. The following research structure introduced to summarize of thesis.

1.1 Problem Definition

The general composition starts with the reasons of new trends of automotive sector follow the route of electric energy. Considering the several research of the world and the main elements on world's requirements, global institutions suggest that every country and manufacturer need to be devoted rules and new arrangements. Especially countries and their most crowded cities have a big role on this situation, but they reflect their respect by new compulsory regulations. On the other hand, by change the powertrain system of a car also requires of cities need a

compatible infrastructure about charging or maintenance within a comparison of older generation engines.

Idea of the electricity affects all systems individually inside the vehicles. Such as new powertrain systems bring new ideas and technologies to invent. Inside of the systems to move the vehicle, new concepts have consequences in the main system such as electrification created new battery types and powertrain systems. The biggest question is which one should be the future for optimum concept vehicles. In-wheel motors are not a new concept but still wait for temporizes applications. For IWM topology, the wheel has the all driver system inside the rim as wheel hub, motor, and braking system. The significantly advantages of IWM on the vehicles starts with the torque, in-wheel motors give the driver control simultaneously rpm on the wheels with acceleration of the car. The braking system in the wheels are available to work on regeneration of the energy with in-wheel motors. The most important advantage of the in-wheel motors is that the control of individually wheel speed with control unit of a car. Individual control gives the car high ability on the cornering and assist to steering.

Interests and questions defined around the vehicle dynamics to answer especially side effects from IWM system. Because of that adding a mass on unsprung mass of the vehicle, changes the ratio between sprung and unsprung mass so that occurs vibration and handling problems while driving. One of the main effects is the ride comfort by change of the mass. This problem is undesirable result on comfort side for passengers. Another criterion is how to solve this situation with minimum trade off on the other side of the system control. Suspension models created to absorb this vibration from road excitations. Different types of suspension techniques already designed and used in vehicles by their valuable uses on different type of cars. By technologic developments, systems evolve to adaptive and more intelligent systems. System controllers shows the way where the manufacturers need to focus and work on developments.

The gap between the IWM technology and controllers have been detected to show potentially valuable topic to focus for this thesis project.

1.2 Research Aims & Objectives

The main aim of this project is to understand the effects of IWM mass changing with respect to ratio change between unsprung and sprung mass by comparing two different controller and their improvement on ride comfort. This will be achieved through PID controllers and Fuzzy Logic controller systems by using control system modelling software such as MATLAB/Simulink in most cost-effective strategy through the combination of both technology and science. Furthermore, gathering data's and applications areas of the project future needs to investigate.

The performance of this strategy will be investigated and evaluated through both simulation and experimental studies. This will be accomplished through the pursuit the following objectives:

1. To investigate the data sets as a car body displacement from both passive and semi-active suspension systems, respectively.
2. The application of the mathematical models on different systems by Simulink.
3. The identification of the controller effects on car body displacement difference in different road conditions through an experimental procedure.
4. The development and evaluation of a changed and tuned controller on semi-active suspension systems.
5. To conclude the thesis results with gathering two different controllers' effects about the ride comfort related with in-wheel motor mass addition to give different aspect on novelty.

1.3 Thesis Structure

This thesis organised into nine following chapters and structure is giving about all project in this section.

Chapter 2 has literature review of generally electric vehicles history and importance of IWM technology on the vehicles. The description of the human body comfort meaning categorisations and ride comfort effect criteria. Giving information about suspension systems and technology about vibration attenuation by passive and semi active suspension system. Finally, a brief review of controlling these systems which have been configurated on passive and semi active systems.

Chapter 3 presents mostly about methodology in connection with mathematical models of suspension systems. Also start with road excitation and how to generate different road profiles. By focusing semi active suspension systems, MR fluid based Bouc-Wen represented and designed under semi active suspension systems. Lastly, controllers' input and output values given in first time.

Chapter 4 describes the mathematical models and other comparative experimental data's of the systems translation into the computational tests which are Simulink based connected and discrete models. Combining within this chapter that requires and includes values of car data, suspension system and controller inputs.

Chapter 5 investigates all approaches about designing a system of controller individually and results of the system sensitivity of damping force and unsprung mass with sprung mass ratio effects on sprung mass acceleration to show the ride comfort effect on passengers.

Finally, the results will be shared under conclusion part as a summary and future works about the project with conclusion part presented in next and final section.

CHAPTER 2

The Connection of the In-Wheel Motors & Suspension System in Theoretical Order

2.1 Introduction

The purpose of this chapter is to combine the subjects of electric car technologies, suspension systems and controller types. The basic definition of dynamics by physics is that to study of things in motion. Naturally, the vehicle dynamic is the study of the vehicles in motion. In another term, the movement side of the aerodynamics which has many mathematics and physics involved within. However, is basically a field of modelling where tried to use simulations to predict what the car going to do or to augment be the information that is getting from the sensors.

Generally, vehicle dynamics relates with longitudinal and lateral load transfers while accelerating or decelerating. While vehicle dynamic shows effect of the vehicle, in the meantime shows characteristics on the driver with ride comfort aspect. Ride quality brings lots of factors to check such as suspension systems, major contributing systems and limiting factors

to get the specific ride. Ride quality can identify the vertical acceleration of the passenger seats and effects on the passenger or driver.

The most important system to reduce this acceleration is that appropriate suspension systems within a right road condition. In another fact that importance of the design of suspension systems to keep road holding or having a good performance while cornering. Every system in vehicles are having a compromise such as every design needs a trade off on the other side of the whole system.

In this chapter, literature review of the electric vehicles technology and following effects of In-wheel motors and suspension systems to connect the other chapters about knowledge of the background information in an order. Different suspension system configuration and importance of the Magnetorheological Damper systems advantages will be identified by controlling ideas of the complex systems with respect to suspension control applications.

2.2 Electric Vehicles & Areas of Applications

Many advancements of science and technology are getting the lives more comfortable such as driving around the cars. However, because of these and other human activities, temperatures on the Earth are rising and the ozone layer that has protected us is being destroyed. Basically, global warming is the rise of the average temperatures on Earth. Due to the increased use of fossil fuels for our cars which has greenhouse gases are being emitted into the atmosphere. These greenhouse gases are causing average temperatures all around the world to rise. In this situation gave the governments to think about to change regulations about central cities about electrification of the vehicles.

The idea that electric vehicles are new is thoroughly misguided. Electric cars are not exactly brand-new technology which were some of the very first cars and for a while they seemed like the way forward. In 1898 the one of the electric cars was fastest car in the world by reaching

sixty kilometres per hour. The developments went on throughout the nineteenth century, but the first golden age was between 1880 and 1920s. In that period the electric vehicle was competing fiercely with steam engine powered car and with the internal combustion engined powered car. Electric vehicles start to lose their dominant position from about 1920s onwards and a lot of that is to do with the changes in manufacturing that come with invention of a new factory lines which meant that these vehicles could be produced at scale at relatively low cost. Lately, the electric vehicles being on people's mind a small group of designers, engineers and innovators who try to push the boundaries of understanding the vehicle. That is increasingly likely that with continued growth of our cities owning individual cars is becoming increasingly problematic which has not space to park so electrification, automation and sharing of the reinforce one another. Many people see that is a combination from having the electric vehicle is an important part of the future of the mobility at the same time more sustainable. The analysis of the electric vehicle technologies covered by Cho, Wylam and Crecelius (2000).[1]

Eventually the petroleum powered internal combustion engine took over because that was cheaper to make easier to power could go away faster. Except, the fact that known as petrol and diesel has a big downside burning produces air pollution. Because of the fact that some car manufacturers have now started moving in another direction which all the way back around electric vehicles or EVs. New generation models are more high-tech than their electric predecessors which is fast, comfortable and can go for a higher distance before needing recharge and most importantly, they do not create as much as air pollution as petrol- and diesel-powered cars. The effects of the electric vehicles on the air pollution reviewed by Freitag, Klopzig and Schleicher (2013).[2]

Normally known as the electric vehicle types that hybrids, plug-in hybrids, battery electric vehicles, In-wheel motors driven electric vehicles and many others. Vehicles can be classified based on drivetrain and fuel type, such as conventional internal combustion engine vehicle, the

alternative fuel internal combustion engine vehicle and the electric vehicle. The internal combustion engine is commonly referred by a short name, ICE. The conventional internal combustion engines include the gasoline and diesel vehicles. The alternative fuel internal combustion engine vehicle refers to vehicles that run on a fuel other than a gasoline or diesel like autogas, natural gas, biofuel, or hydrogen. In all forms of ICE vehicles that drive-train is mechanical. In contrast, electric vehicles use an electric drivetrain for the propulsion. While battery electric vehicles have an electrified drivetrain, they can be classified based on their energy sources, their propulsion devices and how their propulsion devices hybridized.

In general, the hybrid electric vehicle sources the energy solely from gasoline or diesel, while that uses both the electric motor in combination with the battery and the combustion engine for propulsion. The plug-in hybrid electric vehicle is similar to the hybrid electric vehicle, in that uses both an engine and electric motor for propulsion. The difference is that the battery of a plug-in hybrid electric vehicle can be charged by electricity via charging port. In contrast, the battery electric vehicle does not have an engine and is purely powered by electricity instead of fossil fuels. Internal combustion engine car typically uses a spark ignited engine rather than the compression ignited systems used in diesel vehicles. The engine uses a complex mechanical transmission system to transfer power to the wheels. Similar to the gasoline vehicles, hybrid electric vehicles are powered by an internal combustion engine as well. However, in addition, an electric motor can propel the vehicle by using energy stored in the batteries. The battery is in turn charged by drawing energy from the engine by using electric motor as an electric generator. To operate the motor and generator mode, a clever power electronic motor drive is used. Plug-in hybrid electric vehicles are similar to hybrid electric vehicles in that they have both an engine and motor for propulsion. The main difference occurs in the fact that plug-in hybrid electric vehicle batteries are larger and can be externally charged using the onboard charger. This is beside the fact that the battery can be charged using the internal combustion

engine while driving. This application enables the plug-in hybrid vehicles to use the electric motor during larger periods of time when driving.

The disadvantage of the hybrid electric vehicle and plug-in hybrid electric vehicle is that continue to use fossil fuels and has a tailpipe emission. To overcome that problem, battery electric vehicles or all electric vehicles have an only electric motor and not having internal combustion engine. The vehicle uses a large traction battery pack to power the electric motor and the battery must be charged from a power outlet where it is parked.

2.3 Importance of In-Wheel Motor Driven Electric Vehicles

In order to make the operation more reliable, more efficient, and less noisy, the recent trend has been to use In-wheel brushless motors. The brushes in conventional DC motors wear out over time and may cause sparking thus the brushed dc motor should never be used for operations that demand long life and reliability.

In-wheel Motors (IWM) are the next generation drive technology that places motors in automobile wheels. This technology improves automobile safety, environmental impact and driving comfort. The idea of the motor miniaturization research is taking place but motors with sufficient drive performance have been too large and commercialization has yet to be achieved. New technologies achieve driving performance targets while reducing motor size. There are different types of motor configurations with different number of motors inside the system. Both configurations rotate the motors for high gear operations with integrated hub unit. Transmission mechanism makes the possible to propulsion for small motors to provide a large amount of drive torque and sufficient maximum speed. Low gear provides faster acceleration than high gear which after start in low gear, the motor switches to high gear and accelerates until that reaches maximum speed. Using of this motor improves operating efficiency to increase driving

range. Wheel hub motors can be used independent of vehicle body structure which can be used with evolving different driving types.

The rotor of a DC motor is a permanent magnet which has the stator with coil arrangement around and by applying DC power, the coil energize and become an electromagnet. The operation of the motor is based on the simple force interaction between permanent magnet and electromagnet. Stator electromagnets excited by windings and coils which is an important difference compared to the traditional DC motors since the latter can have both stator and rotor composed of electromagnets to increase the magnetic fields and therefore have a higher mechanical power density by unit of weight of the motor. The torque of the brushless motor is due to the magnetic interaction imposed by the electromagnets on the permanent magnets. There is a precise sequence of excitation of the magnets imposes to the permanent magnets in angular movement which is always in the same direction and that is as constant as possible under the same excitation. Obviously, the sequence is cyclical, and the rotor continues the rotation until powered with repeating the sequence from time to time. To be more specific, the sequence of excitation of the electromagnets inside the stator is such that the magnets of the rotor are attracted to the electromagnets without reaching them as the excitation is always and only of those coils not yet reached. When electricity flows into coil, the opposite poles of the rotor and stator are attracted to each other. This process repeated continuously inside the engine and ensuring a constant rotation of the rotor.

IWM systems are getting more popular in different automobile company models to improve road control and keep the dangerous situations at minimum level. In a Wheel which is Rolling perfectly, the velocity of the wheel at the contact point should always be zero. This will make sure that there will not be any slippage between the stationary road and the wheel at the contact point. This condition is possible because the wheel has two kinds of motion. The wheel moves along in the direction of the car and rotates along the axis. That situation makes possible to car

easily cornering. Traction control system can easily work within a same system and helps to prevent hazardous possible conditions. Keeping the system simply with less transmission unit also become the car lighter and less problematic on the road about power propulsion. Torque control gives a highly sensitive capability of breaking and rolling to keep car on the line and better cornering. The advantages of in-wheel motors researched by Le Solliec, Chasse and Van-Frank (2013).[3]

Every useful ability of the IWM system connect the power unit of the system and wheels to same sensitivity and determination. Technology is having a good demand on the applications for better driving and acceleration to have intense experience of the driving. On the other hand, adding that kind of mass inside of the wheels brings negative results in order to ride comfort or handling. Changing the ratio between sprung mass and unsprung mass makes difficult to control about safety and comfort. Every control unit has side effects on another system on the driving to have a better drive. In different road conditions, IWM needs to be able to control to give best results for economy and safety. For different road conditions, effects are examined by Wang, Wang and Jin (2011).[4]

2.4 Vehicle Dynamic Effects of IWMs on Electric Vehicles

Noise, vibration, and harshness, NVH is often used to collectively express these three phenomena that the driver experiences while driving. These phenomena are not only unpleasant to the driver and passengers but also make them worried something might be wrong with their car. Problems involving NVH are often unwelcome to technicians who think they are difficult and time consuming to repair. That is not necessarily true about that knowledge with principles of vibration, understanding of the generating mechanisms to the vibration and noise in vehicles and preventing of these factors. Ride comfort that because the electrical propulsion viewed by Van Schalkwyk and Kamper (2006).[5]

2.4.1 Ride Comfort Effect Criteria

The nature of vibration which just means the rapid oscillation of an elastic solid or fluid. The number of periodic movements or cycles per second is called the frequency. Frequency is expressed by the unit's Hertz. These systems each consisting of a weight and spring are called as vibrating systems. Frequency of vibration varies depending on the strength of the springs and the heaviness of the weight. The frequency at which a particular system oscillates or vibrates is called the natural frequency of that system. When a system is vibrating at its natural frequency and a vibration of the same frequency is added to the amplitude of the vibrations becomes larger. This phenomenon is called as resonance. The source of a vibration is called a vibrating force. A vehicle has a number of components that can be vibrating forces. When a car is parked in the same place for many days or weeks there will be a flat spot at the bottom of the tire. This flat spot will cause the wheel to vibrate each time the tire turns. This can in turn cause the body of the vehicle to shake. An unbalanced propeller shaft also causes vibration each time it turns. This can cause droning or humming noise called booming as well as vibration when the car is running at a high speed.

The engine also is a major source of vibrating force. The torque fluctuations due to combustion in the engine create a vibrating force. This may also cause booming. The engine vibration causes the exhaust pipe to vibrate. The vibration of the exhaust pipe is transmitted to the body if the exhaust pipe support did not fit correctly. The body begins to vibrate and causing the air to vibration. Deep vibration is heard in the form of sound by the driver. In this case the engine vibration is the vibrating force and the exhaust pipe form of a resonance system. Exhaust pipe support forms a vibration transmission system and the body is the vibrating element. The vibrating element causes the air to vibrate and the vibration of the air transmitted to the driver

ear as the noise. According out the various elements of a problem is very important for trouble shooting and should be always analysed problems.

Vibration and noise can be prevented as generally speaking if elimination occurs of one of the elements in the mechanism a vibration. Eliminating of vibrating force, the resonance system, the vibration transmission system for the vibrating element that can minimize vibration. A variety of designs are incorporated into an automobile to prevent or minimize vibration but can also reduce some of the designs that are aimed at attenuating the vibrating forces. The vibration of the engine due to the reciprocating movement of the pistons for example is prevented by the use of balanced weights on the crankshaft. The propeller shaft, the tires and other components that turn at high speed must also be well balanced. A wheel balancer is used to balance the wheels when new tires are installed. All of these measures are aimed at attenuating the vibrating forces. A second way vibration can be prevented by eliminating resonance. A weight is sometimes attached to the accelerator pedal to change its natural frequency in order to prevent resonance. This type of weight that is one that is attached directly to a vehicle component is called a mass damper. When a mass attached to a component indirectly via a rubber pad or cushion that is called a dynamic damper. The third way to prevent resonance is by modifying the transmission system. For example, rubber or other vibration suppressing material is inserted between the engine and the body to prevent vibration from being transmitted to the body. Rubber rings are also used between exhaust pipe and the body for the same purpose. The fourth way is that concerns the vibrating element such as the floor is covered with asphalt sheeting or resin sheets are inserted between steel panels to suppress vibration. These panels are called sandwiched damping panels. The most important thing in troubleshooting is to forget all preconceptions about vibration and listen to analyse customers complains accurately and objectively. Confirm the problem in some detail more importantly should be find out the

vehicle speed and engine speed at which the problem occurs as well as other relevant factors and identify the characteristics of the vibration and noise that accurately as possible.

A vibration frequency analyser is used to measure the frequency of a vibration. Vibration frequency analyser has a pickup probe which is attached to the vibrating part in question. The frequency of the vibration is indicating on the analyser and can read the measurement by moving the cursor on the screen. There are other methods that you can use to estimate the parameters of a vibration. All the need is a hands and intuitive knowledge about the most commonly occurring frequencies.

Sources just basically excitation that put in a system which leads to vibrating and the typical sources of noise in an automotive application.

- Engine (Mechanical, combustion, intake)
- Transmission (Gears, motors)
- Driveline
- Wind Noise
- Road Noise

For example, looking to the engine in a case and start with actual combustion. When the combustion happens, there is a flame that leads to some noise at a pressure wave act against the cylinder above and looking at the slider crank mechanism that having the pistons are oscillating up and down periodically. The crankshaft is again performing a complex movement which is leading to some vibrations. Another important reason of the road vibration is that wheel balancing to cancel out uncomfortable vibration that can be felt when an unbalanced wheel is travelling at speed, but balance is not the only cause of wheel and tire induced vibration. A vehicle may have perfectly four balanced wheels and still experience vibration.

2.4.2 Human Body Comfort

Body vibration by definition is where individuals are standing, sitting, or lying on surfaces that are vibrating. Generally, it would cover you standing in a subway car and cars rattling its way along what individuals are exposed to in that mode. Typically, what happens is that you have individuals driving what are affectionately known as vehicles. When measuring the body vibration is that putting rubber pad on the top of the seat an inside there is a tri-axial accelerometer and can measure the exposure up and down which is the z-axis for an act which is the x-axis and side to side which is the y-axis. That is an objective measure to describe the operation operators' motion. That is a vector quantity which has magnitude or the intensity of kinematic along with the direction of the motion. When characterize the vibration exposure, one is frequency which is how often the gap operator is oscillates the exposure of the vibration to the operator and unit Hertz which is oscillations per second and the magnitude of the acceleration is how much of the vibration exposure are they exposed. Primarily interested in low frequency vibration anywhere from around one to around twenty Hertz. If interested with hand-arm vibration, these tools oscillate at a much higher rate and there are higher frequencies concerned about. The challenge that happens is when the frequency content of the vibration energy matches the natural resonant frequency of the structures receiving the vibration.

The human ear that is sensitive only to vibrations in the audible range. The audible range is that range of sound frequencies that the human ear can perceive. Below of a frequency of twenty Hertz, the frequencies are known as infrasonic and above a frequency of twenty thousand Hertz the frequencies are known as ultrasonic. But in between these frequencies is the audible range. If any frequency lies in this level, human beings are able to hear that sound.

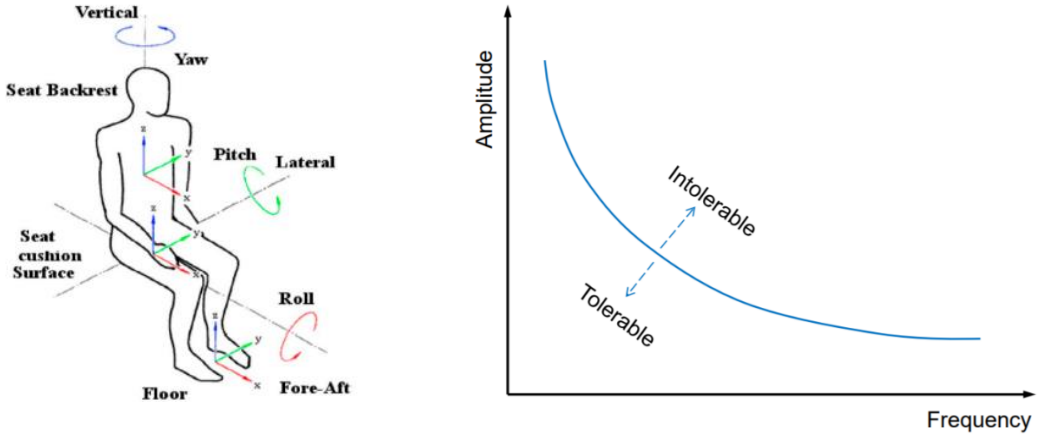


Figure 2.1: Human Body Driving Comfort Range on Different Road Amplitudes

Varies from one individual to another Consists of an assembly of both linear and non-linear elements with resonances varying from 1 to 900Hz Primary ride - vibration of the sprung mass on the suspension Head and neck (1 - 2Hz) Secondary ride - vibration of sprung masses such as the engine on the body. Thorax and abdomen (4 – 8 Hz) 25Hz are usually defined as the upper limit of ride as is approximately the lower frequency threshold for hearing (noise up to 20,000Hz!) 0.6Hz can be used for a practical lower limit.

2.5 Suspension Systems & Technologies

2.5.1 Introduction to Suspension Systems

All vehicles have a suspension system of one form or another. Despite there is a difference of sizes and styles of configurations which they all serve same purpose that is simply to let the tires of a vehicle move independently from the cabin and chassis with the driver. Tires need to move in order to adapt the variations or changes in the road and the goal of the suspension systems is the trying isolate these movements as much as possible. The more sufficient method is that if suspension system can do that more predictable and consistent observed forces has a better result on the ride comfort and better feel for driver. Different vehicles have different expectations on driving over for example, a track car only needs to adapt slide or angle changes in the pavement, or a daily driver has speed bumps to drive over. In all of these cases, the same

fundamental things occur which is meaning that the reaction of the vehicle onto the excitations. When the approach of the suspension systems on vehicles which trying to be proof the tires and wheel sizes are one of the first things needs to be asking to the system design. Usually drivers want enough tire inside wall to absorb small road profiles but do not need to be very big to become unstable. As soon as the tire impacts the object, anything left over will be transferred through to the wheel and the suspension system. When that force arrives to the suspension system, causes to move the system which is given a set amount suspension travel. The travel which the distance from the full extension position of the suspension system to the full compression position. Given a set amount of distance to absorb any amount of force that is applied to the vehicle and how that is controlled with all familiar effects the ride quality on the vehicle. Suspension systems and their different road inputs suggested with a research by Shi, Qian and Li (2006).[6]

The key component of every suspension system is the spring. The job of the spring is that to push up against the weight of the vehicle to supported at a desired ride height. Springs come in different styles which is coil, leaf springs and torsion bars but they all serves the same purpose that simply support the vehicle also push down the tire to keep in contact to the ground when the suspension system unload. The front end of the vehicle reaches the speed bump harmonically goes up and down until settle back original height. In order to control the spring a shock absorber used for suspension systems which is essentially a cylinder that is filled with oil and cycles oil through small openings passed to the valve. That creates resistance in the upward compression stroke as well as the extension rebounding stroke. The advantages of this absorbers that can tune the shock to the high or low force, velocity or movement in both compression and rebound direction. Because of that is given so much control on the movement, the system is able to configurate the performance of the vehicle. Such as, the requirements of as much of the vehicle's movement being controlled by the shock as possible and thus the spring

needs to be as light as possible and strong enough to support the vehicle. For heavier loads on the springs, the design can change with heavier springs which is also have a progressive spring rate. So, instead of compressing same amount under the same load every inch going to be significantly heavier than previous inch. However, the problem with this application that is going to end up with very firm ride which means heavier spring moves less and feels firmer. The advantages of the suspensions systems investigated by Cao, Liu and Li (2007).[7]

There are two different suspension systems configurations in vehicles which are dependent and independent suspension systems. Independent suspension systems as the name implies, the tires are allowed to move independently each other. The advantage of that after tuned properly suspension system, can have a tire impact on an object to isolate and absorb these forces and keep them for transferred through the cabinet chassis or the other tire such as a solid axle applications. Because of that if the vehicle has an independent suspension system that is always going to be giving a best ride quality for any given vehicle. By the design aspect is more complicated than solid axle and dependent suspension systems, the system has a lower and upper controllers, with the CV shaft which has joints both on the differential and at the knuckle to allow that power transferred on the road changes. The system also has joints with steering system because of that linkages moves with tire. Instead of having lots of benefits, there are some disadvantages such as the fact spring and the shock absorbers are mounted on the two lower control arm and usually close to the two a done same ratio. That means twice as much weight as a result of twice as much load. Also, in the design side, geometry, the angle which everything moves has significant effects and a lot of limitations that we can work within the system.

There are different types of the suspension systems for different required applications but should always know that always have some insufficiency on the systems. Impossible to build a vehicle which is nice and smooth on the street and in different road conditions. Certain types

of applications could be combined with different options and setups but needs to be realistic thinking with focusing to choose the most important sides on design and driving quality and handling performance to be best. Another think is that when comes to the tuning the suspensions, that is not always ride quality, also related with ride consistency and predictability. The main goal needs to be able to build a vehicle which is consistent and predictable which knows the limits of system and future effects.

While modelling of the vehicle and suspension systems, car body needs to be modelling as a passive, active and semi-active suspension systems. In the following sections, different models of benefits will be identified individually and in an orderly.

2.5.2 Passive Suspension System

In a vibrating system there are three important elements should be identified. The first one is the mass which relates to the motions of a rigid body and this mass stores the kinetic energy. The second one is the stiffness which corresponds to the deflections of a flexible component and this stiffness component store the potential energy. The third one is the damping which is often illustrated with a dashboard which can absorb vibration energy. Assuming that there is a centrifugal machine mounted on a flexible rubber and attached to the rigid wall in vibrated vertically with save in amplitude on x-axis. The whole body of the machine which is moving up and down can be defined as the mass component. The rubber mounts which can stretch and suppress as the machine is vibrating and defined as stiffness component. The diagram of the model called as mass spring damper model. The machines mounted on a flexible spring on a rigid foam. Vibrating with maximum displacement from the equilibrium position. The amplitude is defined as how far the machine displaces from point zero to next point in a positive and negative directions. Meanwhile, the frequency is defined as how many times the machines goes in one cycle and the more cycles the machine has in one second and the first motion of the

machine which defined as Hertz. The phase described behaviour of the motions and if the body moves in opposite direction that called as move out of phase or has phase different oppositely.

There is another important component which is a damping that is mechanism of absorbing the vibration energy. Some of the vibration energy is easily converted into heat energy or it is change into sound energy. There could be see one of the examples of damper elements in the car which is the dashboard or shock absorbers. It consists of a piston fit into a cylinder where the fluid or the oil inside the cylinder resists the motions of the piston and thus absorbing the motions energy. This type of damping called as viscous damping. When the object moves on a rough surface will have the friction force against the motions of the object which can absorb some of the kinetic energy. And this type of damping is called coulomb damping. Damping also exist in the wall structure when body subjected to the vibration. Vibration energy in that structure is dissipated by the frictions between the internal planes in the material which is called as hysteretic damping. In the vibration analysis, the damping model commonly used is the physical damping model when the force is applied to the physical stepper and the piston displaces on X-axis. The unit of a damping constant is Newton second over meter or kilogram per second. The work done by the damper to dissipate the energy where defines as equivalent translational damping constant of the vibrating system but for the case of rotational motion is called as equivalent rotational damping constant of the vibrating system.

If the system having a spring with a mass attached that spring after stretching the spring, the object will begin to oscillate back and forth, and the oscillations will continue to be cyclical. So that simply means that the amplitude of our oscillation in simple harmonic motion remains constant and that is because the total energy of our system remains constant. A real oscillating system will over time experience a decrease in amplitude as a result of internal friction and air resistance. In other words, simple harmonic motion which is idealized type that neglected the air resistance and frictional forces. But these forces do in fact exist and any real oscillating

system, these forces will decrease the amplitude of the oscillation over time. In that motion some of that kinetic energy and elastic potential energy is transformed thermal energy of the spring and the mass as well as the thermal energy of the molecules surrounding object. Because of that reason the amplitude decreases because of the energy goes into thermal energy. In real situations, any object that is vibrating or oscillating back and forth is experiencing damped harmonic motion. The reason that all application uses simple harmonic motion because that is easier to deal with mathematically and in fact can be used in some instances simple harmonic motion to approximate damped harmonic motion. The damping force is the force that act on the object to impede the oscillations of the object. The damping force creates the damped harmonic motion.

Similarly, the passive suspension system contains a spring and a damper attached at each wheels of the vehicle. The spring is decided with respect to the weight of the car which provides supports to the car and also to absorb and store vibration energy. In designing process, the spring stiffness needs to be calculated, while the shock absorber dissipates vibration energy stored in the spring and converts the input from the road. Required damping needs to be considered at the design state for different variable of vehicle type and required performance for the comfort and road handling. In the realistic illustrations of the system, damper needs to be chosen to give the best applications. In other words, the damper should block the passengers from low frequency vibrational reactions and keeping high frequency road excitations which occurs non controlled springs. The passive suspension model is also used in system control of a vertical motion with pitching and rolling situations. Passive means that the suspension component cannot produce any energy to the system. At the same time by restricting the wheel motion with respect to body of the vehicle by choosing limited displacement and velocity on the ride comfort requirements.

2.5.3 Semi-Active Suspension System

2.5.3.1 Introduction

The reasons that makes the semi-active suspension systems more popular and useful in recent years are due to the economical, requirement and performance aspects. Low cost of the system makes the suspension system more compatible and fail-safe usage makes the system better than the active suspension systems. The properties of semi-active suspension systems have been extensively reviewed by Saravesi (2015).[8]

The concept and name of the semi-active suspension system connected with active suspension system. Active suspension system concept which make use of electromagnetic or hydraulic rams instead of spring and dampers to actively control the wheels position related to the chassis. The semi-active suspension system makes use of an electrically controlled damping along with the springs to adjust the damping. Latest semi-active suspension systems can make changes up to thousand times per second. In order for the semi-active suspension to work properly that requires the data from different control units and sensors like engine control unit, abs control unit and spring travel sensor which the process of these datas on a suspension control unit. For example, dynamic damping control unit that uses the data to provide optimal damping for every different possible riding conditions. Helpful suspension full vehicle control developments occurred by Shahrir (2009).[9]

The working of the semi-active suspension system can be explained through three main steps. The first step is the straight line which in normally standing, the controller unit analyses the data from ECU to determine the wight of acceleration. In that instance, the weight transfer is not rapidly working so the controller opens the electrically actuated damping. When stops the car accelerating and settles into a constant cruising speed, the controller unit decreasing down the compression damping by closing the damping one resulting in a pressure suspension setup

on road surface control unit use the data from the spring travel sensor and reduce the damping accordingly.

Another situation is the cornering that the control unit analyses the data from IMU which is inertial measurement unit sensor to determine the angles increasement and the contact patch. Last but not least that is braking condition. Braking is one of the most important aspect of vehicle performance which is having optimal breaking efficiency.

Semi-active suspension systems can add different systems and sub-devices such as air springs, types of self-levelling solutions and Hydro pneumatic and Hydro gas suspension systems. The controllable damping force can be created by changing the orifice area with a usage of fluid viscosity. Most currently the applicable options are electro-rheological (ER) and magneto-rheological (MR) fluids to the increasement on the control side of the systems. The mechanism of the damping system reviewed by Fischer and Isermann (2004).[10]

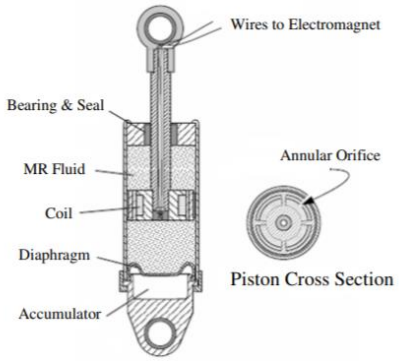


Figure 2.2: Cross Sectional View of MR Damper System

Table 2.1: MR and ER Fluid Mechanical Properties

Property	MR Fluid	ER Fluid
Max. yield Stress	50 to 100 kPa	2 to 5 kPa
Max. field	~250 kA/m	~4 kV/mm
Plastic viscosity,	0.1 to 1.0 Pa.s	0.1 to 1.0 Pa.s
Operable temperature range	-40 to 150 °C	+10 to 90 °C
Stability	unaffected by most impurities	cannot tolerate impurities
Response time	ms	ms
Density	3 to 4 g/cm^3	1 to 2 g/cm^3
Dynamic Viscosity/Yield Stress	5e-11 s/Pa	5e-8 s/Pa
Max. energy density	0.1 J/cm^3	0.001 J/cm^3
Power supply (typical)	2 to 25 V & 1 to 2 A	2000 to 5000 V & 1 to 10 mA

2.5.3.2 Magnetorheological (MR) Dampers

The important example of the semi-active suspension system is that magnetic ride suspensions. Inside of the system, as regular shock absorber but the system has the piston and as the shock absorber compresses, the fluid within moves through the piston rod channels and as that fluid gets restricted through the gaps dampens out the force and tries to just stop the motion. Instead of a regular oil, other small metal particles which can be magnetically attracted because of their metallic properties. On the other hand, inside of the piston which is connected to the shock absorber body through the electromagnet inside of the cylinder. The piston itself illustrate the big coil of copper wires and when the current transmitted through the coil of copper wires which creating the magnetic field. This magnetic field passing through the piston channels where the fluid with the metal and oil is going to be passing through. Without the current, system acts like a regular shock absorber and the fluid can move freely through these piston channels. But when the current activated creates the magnetic field which create the lines off the small magnetic particles inside the suspension. This situation creates thicker structure on fluid so that is going to have much tougher time moving through these layers of electromagnetic particle resist the fluid while passing through the upper side of the suspension because of that magnetic force. This situational change stiffens the suspension system and apply the same principles in different situations such as cornering or braking on the road. The car handling characteristic can easily configurate just by varying how much voltage transferred through via electromagnet.

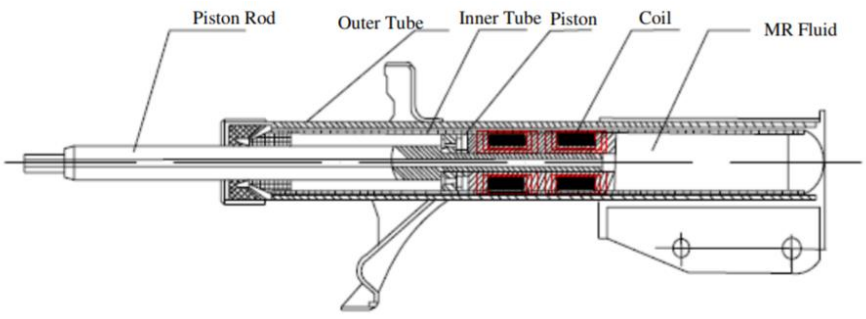


Figure 2.3: MR Damping Application on the Vehicle

The voltage transfer handled by a controller and a lot of cars have different settings that can change how much that statement interferes and changes the driving feel and makes that more comfortable or rigid. There are some advantages of this kind of systems when compared with other types of suspension systems. The advantages of the MR damping system reviewed by Lai and Liao (2002); Yao, Yap, Chen, Li and Yeo (2002).[11][12]

Such as;

- Semi-active means which is fully adjustable damping so that actively control the damping with traditional coil overs has only one setting. Damping control systems detailed by Guglielmino, Sireteanu, Stammers, Ghita and Giuclea (2008).[13]
- This system can activate change the damping ratio in a very quick timing based on different sensor communication setups in variable of vehicles. Most suspensions are not variable and manually controlled damping ratio. System communications exampled in forklift truck application by De Man, Lemerle, Mistrot, Verschueren and Preumont (2005).[14]
- This system gives the independent control of each wheel so rather than having setup of the all wheels doing exact same reaction which does not matter the feedback from the system. This system can change the voltage going to each individual wheel so can give a chance to individually control the suspension. Voltage control system design reviewed by Giua, Melas, Seatzu and Usai (2004).[15]
- The other benefit is that does not consist of the moving parts in system when compared to the traditional coil overs. This keeps the risk level of the wears and fails at low levels.
- The body movement can easily reduce by the semi-active suspension system. The system can keep the car as flat as possible while having a hump on the road or cornering situations.

2.5.4 Active Suspension System

The vehicle suspension system is something that implemented into all vehicles in this time period. Long time ago when the vehicles were just starting to be popular that there was no suspension system and any bumps on the road surface will be a direct effect the passenger comfort. Therefore, suspension systems were adapted to passengers' better comfort and conducive drive. The system responsible for absorption of and gravitation with any impacts of forces from the road. Typically, is made out of a spring and a damper where right below the chassis of the car connected to the wheels.

Many vehicles today are equipped with active suspension which is a computer-controlled system that automatically adjusts the vehicle ride height, ride firmness and steering feel based on changing driving conditions. The suspension computer receives input from several strategically placed sensors including chassis position sensors that monitor changes in body to wheel position, one or more accelerometers which measure the body vertical acceleration rate and a steering wheel sensor that detects rapid changes in steering angles such as those that would occur during a sudden lane change or other avoidance manoeuvre. Based on these incoming signals, the computer adjusts the shock absorber or struts to a firmness setting that is appropriate for the current driving conditions. At the same time that operates a valve and the steering gear that adjust power steering assist to a level suitable for the current conditions. Sensors installed throughout the vehicles assess the situation and transmit the data to an electronic control unit. This control unit analyses the data and adjust the optimum damping level for each level via a proportional valve within just a fraction of a second the electronically controlled system responds to driving style, road condition and the speed individually and based on the situation. The system access has following steps that has hydraulic adjustment and the systems response is gauged via a controller interface. Individual software parameters are varied written back to the control unit. The core of the system is the control unit which constantly

monitors all influences on the driving situation and adjusts each individual controlled damper to the optimum settings. Damping system also communicates with other electronic systems and provides unprecedented additional benefits in terms of safety, Dynamics, and comfort. For instance, the ABS, ESP, and steering systems are linked to each other via a can bus and mutually adjusted. The active suspension system characteristics mentioned by Ram, Venkata and Purushottam (2006).[16]

The active-suspension system where the value of the damping and stiffness of the suspension system can be changed with software control. The difference between passive and active suspensions that passive system has only made up of a spring and a damper with fixed parameters but on active system has an actuator what makes the damping force controllable by using algorithm. Firstly, the system needs to put input as an road profile which is a disturbance of the road. After the error detected and go into where PID controller stands to connect with actuator that actually control the stiffness of the suspension system. The output gives the unity feedback to the input so that can give the data back to the controller. This system called as closed loop system. Dynamically system of the suspensions reviewed by Goncalves (2001).[17]

System is made out three components mainly which are the spring, the damper, and an actuator. Ideally a real model of a car that takes more considerations and clearly involves more components. The idea behind of the system is that the model present the state responds of the difference between displacement of the mass which is the car chassis and stabilizing the car body quickly as possible and does not oscillate at any point because of that affect the comfort of the passenger. This damping control offers just the right solution for increased driving safety and comfort and can be implemented in modern passenger cars of all classes. Electronically controlled suspensions eliminate the conflict between the aims of structurally hard or soft dampers. The dynamically intelligent damper system stabilizes the movements of the body and the wheels in any position.

As a result of that active suspension system offers sufficiently wave for the implementation of an individual vehicle philosophy and electronically controlled adjusts the optimum damping force within milliseconds. The vehicle reacts individually to the prevailing situation depending on driving style road conditions and speed. The system increases the level of active driving safety and comfort and also allows dynamic driving. Theory behind the optimum damping and forces mentioned by Mache and Joshi (2007).[18] However automotive controller design for active suspensions designed by Kumar (2008)[19]

2.6 System Control

2.6.1 Introduction to Controllers

Control system is also a system which is the combination or network of components which are combined to get the specific operations, in which the output is controlled by input. There are two types of controlled systems which are open loop and closed loop systems. In an open loop system that can't see any feedback element. Directly, whatever is the input given the system and according to the functionality of the loop system of plant gives the output. There are significant advantages of the system such as being a simple and economical system which the cost to integrate the system is very less. However, the system is easy to construct with being a stable system doesn't provide any other signals or feedbacks. On the other hand, closed loop systems have a feedback as an output of the plant and needed a controller to get system works properly and systematically.

The mathematical environment into the modelling systems called as a plant. Control systems usually occurs plant, controller, and desired value of the general loop system. Controller aims to eliminate the errors which means that the difference between the desired value and feedback of the plant as an output. Different industries refer to these signals by various names which sometimes called something different as plant input and plant output.

2.6.2 PID Controller

Most process control engineers have been exposed to the basic equation in a form of equation which has an output is equal to sum all the proportional, integral, and derivative components. In an industrial controller may have a combination of some or all the components. In the proportional only controller, equation becomes output equals gain times error. First the errors simply the set point minus the process value which where the system desired to be. Then the output is this error times the factor K which is commonly called gain which is a general control method criticized by Dhananjay Rao (2014).[20]

To expand the ideal PID controller and can make it even more robust when trying to control the real system that do not behave like ideal linear models. Focusing to derivative and looking how the device that is sensing the true state of the system and producing a measured state that the controller can use can add noise into the feedback loop. Noise is a random disturbance on a signal and when the system deals with sensors both mechanical and electronic sensors that is unavoidable. The genetic term, noise refers to the summation of different noises created from different sources that stem from things like environment its operating in which is both naturally occurring noise. The specific implementation of the electronics and from manufacturing defects which can exist at very specific frequencies or be spread out across the spectrum. For example, if the noise has equal intensities at different frequencies than called White noise which have probably seen and heard as static in a non-existent radio station. For an ideal PID control, derivatives amplify high frequency signals and can take those tiny barely noticeable wiggles and amplify them to values that can impact the system. For instance, the slope of the signal is the derivative and if look at the point where the signal has the steepest slope to get a visual indication of what value the derivative will return. The steeper line which is higher the derivative shows that how the slope changes for a high frequency signal. The amplitude of the noise has not changed but the increase in frequency generated a steeper slope can reduce the

amplitude of the noise signal and get back to a slope or a derivative that is similar to the low frequency signal. The general idea is that lower the amplitude of high frequency noise so that the derivative is not too large. If the system increases the frequency even more, the slope gets steeper and needs to lower the amplitude to account. When the system leaves really high frequency noise, the derivative path will see that noise even that is really small and amplify it and caused the issues. Looking at the derivative and see that the amplification of high frequencies also make sense mathematically. Any signal can be defined as a summation of an infinite number of sine wave. This is where the Fourier Transform of a signal occurs as a single frequency. If the sine wave taken derivative, will get the new sine wave at the exact same frequency but shifted in phase by 90 degrees and with a new amplitude.

Ideally, implementing a filter of a system brings to remove all of the noise and perfectly pass through all of the signal but this is not something that can be achieved in practice. Luckily for a lot of applications, the noise across the spectrum is relatively low amplitude or low power and the signal which interested in keeping has comparatively large power and low frequency. In this case the low frequency noise does not really impact the derivative much if the amplitude is small and therefore can often remove all of the noise to derivative simply by blocking or attenuating just the high-frequency information by first order low pass filtering.

2.6.3 Tuning Methods of PID Controllers

The system has several methods to tune the loops and use a controller that has an output to connected with the process to give the measured outputs by the sensing elements. First thing that needs to do is recognized that not all PID algorithms are the same. There are three different classes such as standard, parallel and classical. The tuning rules have also different theories as first order or second order closed loop responses or Ziegler Nichols method.

The method used into the whole project is that another powerful way to tune controller which is automatic tuning inside software. Inside the PID block parameters, the option of elect a tuning method and it defaults to a transfer function based tuning method. Respect to requirements of the system, inside the tuner, adjusting the tuned gains by move to sliders work really efficiently. Faster or slower rising time and more aggressive or more robust system needed generally.

2.6.4 Fuzzy Logic Controller (FLC)

The most intelligent creatures that known of Artificial intelligence (AI) is a broad branch of computer science. The goal of AI is to create systems that can function intelligently and independently. The artificial intelligence is nothing but the capability of the machine to imitate intelligent human behaviour. AI is achieved by mimicking a human brain by understanding how thinks, learns and work while trying to solve a problem. The engineering applications of the controller mentioned by Ross (2010).[21] For example, machine which is playing chess or a number plate recognition system which captures the number plate of an over speeding car and processes it to extract the registration number and identify the owner of the car to charged. Deep learning is a subfield of the subfield of artificial intelligence which is a subtopic of the machine learning under artificial intelligence. Actually, all of them is the combination of ideas from several different areas of AI and machine learning like deep learning and reinforcement learning. The importance of the fuzzy logic systems defined by Salem and Ayman (2009).[22]

The artificial intelligence requires a lot of computing power. Recently many advances have been made and complex deep learning models are deployed. Another important thing to show importance of the AI is that having lots of data which is in immeasurable pace. The only need is to find a method or a solution that can help on process and derive useful insight so that can grow business with the help of data.

The Fuzzy Logic is a way of dealing with uncertainties which is something that computers do not do naturally which human do very well. Normally when thinking of logic and thinking about reasoning about things, the way computers tend to deal with things and the way might instantly think of dealing with is true or false which means in Boolean method one or zero. Simple method which there is only one option and no other between. But that is not the way the real world works and human works. With Fuzzy Logic, instead of just going to true or false, the system has a sliding scale between the values what is called as degree of truth. Logic is also closely related with Sets which is a collection of things. Another important relation with membership functions which gives a value for certain things. That system gives to user a way from dealing with uncertainty. The fuzzy system rule optimisation discussed by Kaldas, Caliskan, Henze and Küçükay (2014).[23]

Although the system dealing with uncertainties which calls membership functions that allow to model, the system still have someone imposing the definition of that word onto it and someone still needs to assign the values to the membership. The fuzzy expert systems always need to collect data from many sources with various techniques to consolidate that data and to train the system to be accurate as possible.

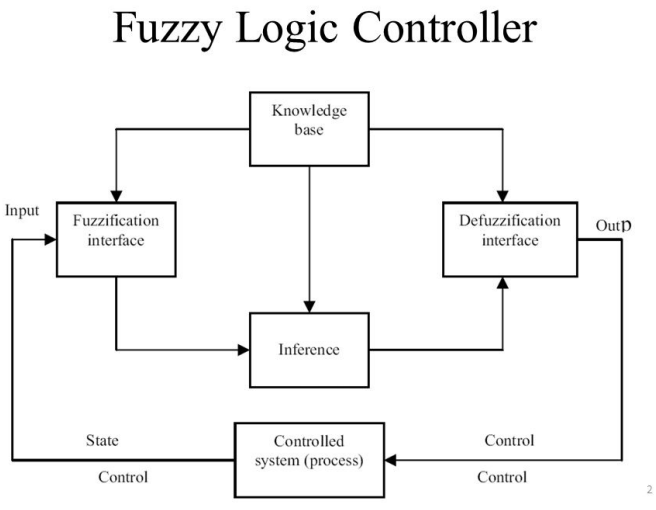


Figure 2.4: Fuzzy Inference System Scheme

Fuzzy Logic systems, the systems which use membership functions and have these fuzzy sets with degrees of truth are very widely used in all sort of the areas. This diagram here use kind of showing the rough outline of fuzzy logic system. The system has an input shapes crisp values which are not yet signed a truth value then they are not in a fuzzy set. Then the system fuzzified them which means looking them on a membership functions and apply some value to the inputs. Then the fuzzy set goes through the inference system which occurs all magic happens means that start from reasons that is why having a rule base at this stage. A rule has the form of an anticipant which actually have a rule basis multiple rules for different membership functions and actions for different outputs. The Inference system runs all of these rules through and combines all different situations. The decided action as an output is in the form of fuzzy sets and then gets defuzzified because computers deal certainties.

Fuzzy Logic allows computers to make decisions and using these unprecise quantities which works more like a human brain. Real world decisions contain high levels of uncertainty which need to be taken into account. Fuzzy logic is used in a number of everyday applications. So fuzzy sets model concepts and objects in real world. Knowledge is represented by fuzzy sets combined using rules and when all of this information is considered, a decision can be made. These decisions are made using fuzzy logic. The applications on semi-active suspension systems of fuzzy logic control systems reviewed by Devdutt (2014).[24] Also, designing of the fuzzy logic controller for mechanical approaches evaluated by Zheng (2010); Titli and Roujieh (1995).[25][26]

CHAPTER 3

Research Methodology & Simulations

3.1 Introduction

In this chapter, started with two different road profile creation and continues with the different suspension systems such as passive, semi-active and active damping systems evaluated to be controlled in a Proportional Integral Derivative (PID) control and Fuzzy Logic control with respect to mathematical and computational modelling. In simulation environment, to represent the vehicle situations, quarter car model performed. Two degrees of freedom models used to implement equations of motions for both three modelling. Scheme designed to see the level of effects of controlling systems and different suspension system improvement of the vehicle body displacement on different road conditions. Road excitations and working principles of the Simulink blocks had given in this chapter. For semi-active suspension system model, MR damping system configurated with Bouc-Wen Model. Modelling diagrams of the systems inner and outer loops identified with general model inputs and outputs. Controlling gains derivation and mathematical functions of the methods and fuzzification steps and rules design investigated by comparing different suspension systems.

3.2 Road Profile Generation

The ride quality is that the level of comfort that someone experiences within a vehicle as travels over a pavement and that has to do with how smoot or rough the pavement and how succeed the suspension characteristics of the vehicle. So, the ride quality is also directly related to the acceleration that people within the vehicle experience. The mathematical approaches designed for different road profiles by Runhua, Ying and Yongxiang (1998).[27] The acceleration is attributable about ride quality to the roughness of the pavement. Roughness has a definition such as anything on a pavement surface that deviates to attended and characteristic affects the Dynamics of the vehicle travelling over which affects ride quality and dynamic load on the pavement. Basically, called as lack of smoothness. Road profile generations has several effects by vehicle dynamics and these phenomena reviewed by Wagner and Liu (2000).[28] The reasons of to show the ride quality importance is that reduces to dynamic loading of the vehicles travelling over the pavement. However, increases the life expectancy with decreasing road user costs because if the users running over the rough roads all the time, car and road needs more services. One of the larger reasons is why ride quality important is that increases the user satisfaction. Roughness is all about potholes in the road or corrugations and imperfections, but international roughness index is also undulations in the pavement that are much longer wavelengths. Especially, random road profile effects written by Tamboli and Joshi (1999).[29]

3.2.1 Sinusoidal Circular Hump

The amplitude of the wave is simply the height between the centre and the peak which is called trough oppositely negative side is crest. The wavelength is the length of the one cycle. The cycle means is that the wave has to go up and then goes back to the middle with has to make the trip down and return back to where started.

The road profile is approximated by the following formula:

$$y = A \sin \frac{2\pi V}{\lambda} t$$

The meaning of the parameters is as follows:

y road excitation

A amplitude

λ wavelength

V vehicle velocity

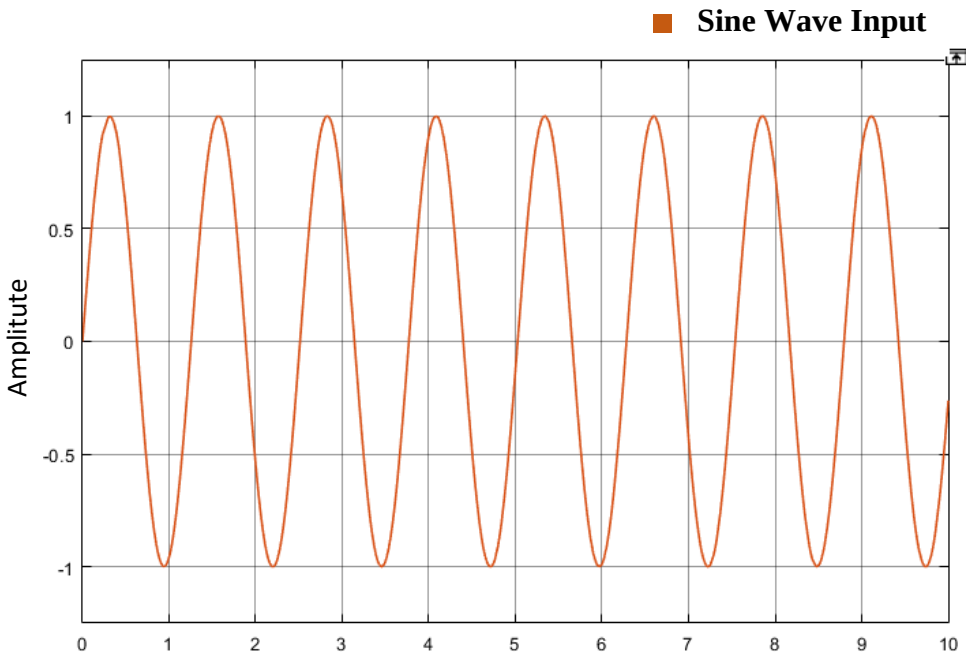


Figure 3.1: Sinusoidal Signal Wave with an Amplitude of 1 and 5 rad/s

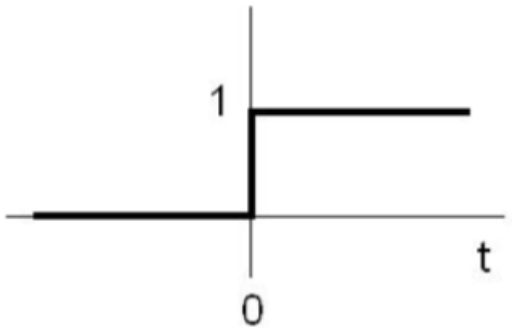
3.2.2 Unit Step Input

Unit step is denoted by u(t) in continuous time and u(n) in discrete time. Step input illustrated as another type of road type such as a bumpy road with an amplitude of one.

A sudden change in a value of the inputs can be generalized a step difference of magnitude, M

The step change created at an arbitrary time denoted as t=0.

$$u(t)=\begin{cases}1 & t\geq 0\\ 0 & t<0\end{cases}$$



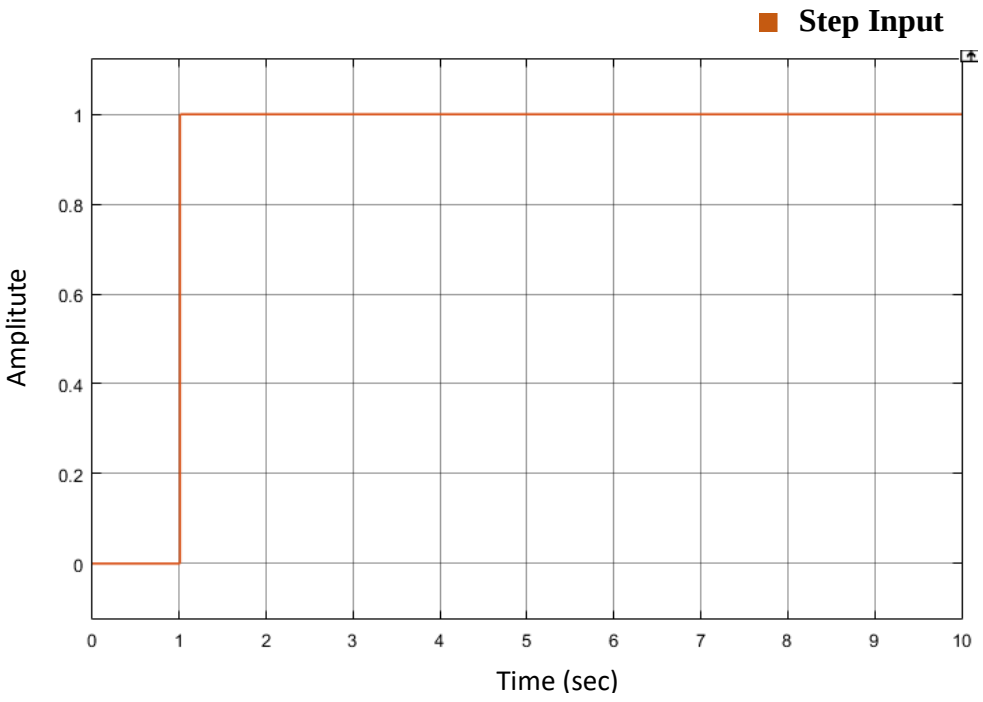


Figure 3.2: Unit Step Input with an Amplitude of 1

3.2.3 Random Road Profile

If the system does not deterministic which means not known about the displacement, velocity, and acceleration. Random vibrations have unknown details but has knowns such as mean, mean square and standard deviation in the variance. To represent a closer real road conditions more advanced techniques needed. Power Spectral Density is the only one method for random vibration model which is a function that shows the strength of the variations as a function of frequency.

The PSD function is formulated as below:

$$q'_{(t)} = -2\pi f_0 q_{(t)} + 2\pi\sqrt{G_0 u_0}\, w_{(t)}$$

$$f_0 = 0.1\text{Hz},\ G_0 = 64,\ u_0 = 20\text{m/s}$$

Where $q(t)$ is the pavement displacement, G_0 is the Road roughness coefficient, u_0 is the vehicle speed, $w(t)$ is the white noise with a mean of zero and f_0 is the lower frequency cut-off.

Table 3.1: Different Road Quality Standards for Random Excitations

DEGREE OF ROUGHNESS EXPRESSED IN TERMS OF Ω

	degree of roughness $\Phi(\Omega_0)(10^{-6}\text{m}^3)$ where $\Omega_0 = 1\text{rad/m}$		
road class	lower limit	geometric mean	upper limit
A (very good)	–	1	2
B (good)	2	4	8
C (average)	8	16	32
D (poor)	32	64	128
E (very poor)	128	256	512

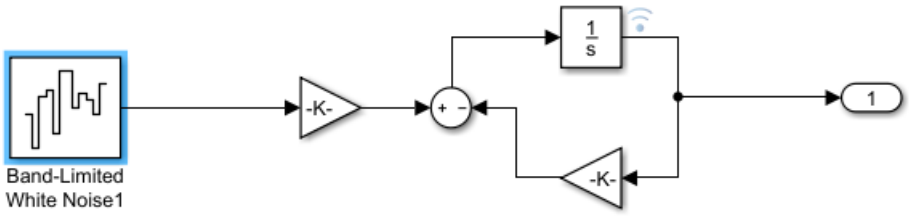


Figure 3.3: Power Spectral Density Method Simulink Scheme

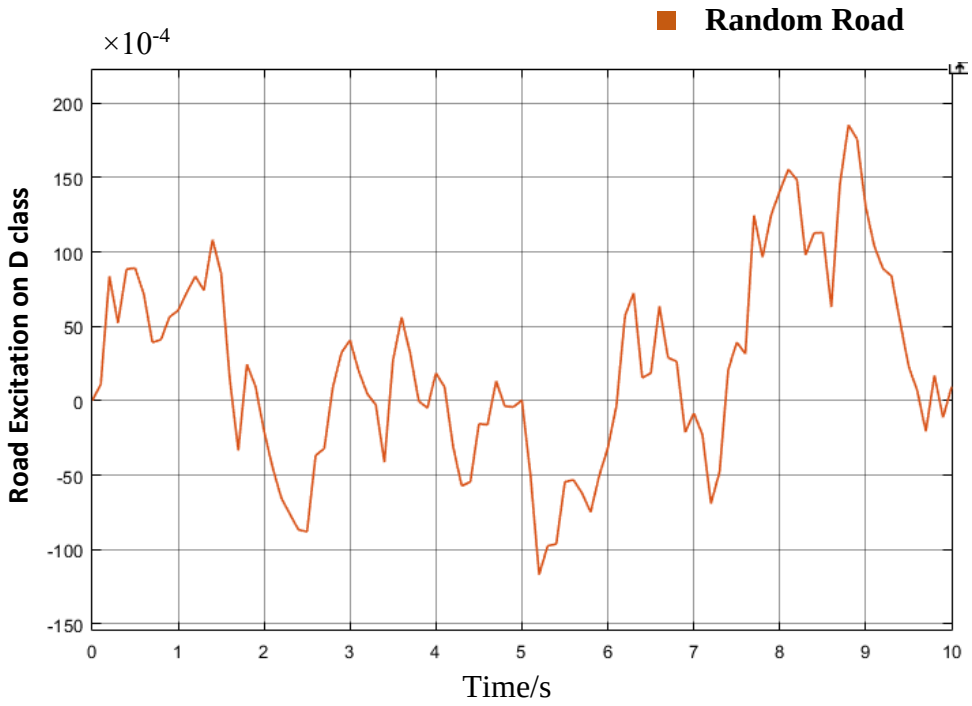


Figure 3.4: Random Road Profile

3.3 Mathematical Modelling of a System

3.3.1 Passive Suspension System Model

3.3.1.1 Introduction

A typical quarter car model as the name itself suggests quarter car model is nothing but one-fourth of actual four wheeled vehicle. The model basically comprised as a portion of vehicle mass, a spring and shock combination representing the suspension and a tire with appropriate stiffness and negligible damping. Because of the advantage of linear system is that can decompose the component parts and solve them independently and then getting the answer at the end to recompose the system.

A car sprung weight is the weight of everything that the suspension supports, on the other hand, unsprung weight is the mass of the suspension and below the system as refers to everything that is not able to be dampened by the suspension.

Generally, the vehicle needs to get a higher ratio of sprung to unsprung weight as this means that the sprung weight can help to push down on the unsprung weight and give the wheels more grip as the car moves. On the flip side the goal is to minimize the amount of unsprung weight as it makes for a car but handles and steers better due to the fact that the lighter unsprung setup can react to small bumps and imperfections in the road more quickly allowing it to maintain grip more constantly therefore improving handling. However, the trade-off to this is that as the unsprung weight reacts more quickly and can transfer more motion to the cabin and ultimately make the ride less comfortable.

Describe of a system starts with a knowledge of degree of freedom and number of equation and how many variables need to know in order to completely describe the system. In this thesis and quarter model simulations, two degree-of-freedom (2DOF) suspension system used.

3.3.1.2 Passive Suspension Model

In this study, a parallel designed spring and dampers used based on the weight of the vehicle to improve the ride comfort on the passengers from low band road surface and frequencies and high frequency road excitations. The passive system model acts as a quarter car model and having 2DOF represented by a linearly configured spring and dampers. The reason of the usage quarter car is that makes to model simple and have a basic equation contain inside for preliminary designs. The parameters of the suspension system chosen from the knowledge of the literature review.

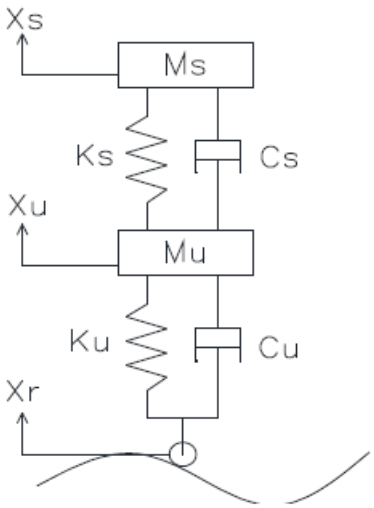


Figure 3.5: Passive Suspension Quarter Car Model

These systems have some disadvantages when compared with active suspension systems such as transmissibility, suspension travel and road-holding characteristic features. The system parameters have given in Table 3.2.

Table 3.2: Parameters used in Simulation

Ms = mass of Sprung(Chassis)	Xu = Displacement of Unsprung mass
Mu = Mass of Unsprung (tire)	Xr = Road Unevenness
Ks = Spring constant of Sprung	Cs = Damper constant at sprung
Ku = Spring constant of Unsprung	Cu = Damper constant at unsprung
Xs = Displacement of sprung mass	

3.3.1.3 Mathematical Modelling of Passive Suspension System

The working through the equations of motion of the quarter car basically summing the spring and damping forces for unsprung mass and getting as an output of the acceleration for the unsprung mass is also spring damping force which is pushing the tire down and the natural spring rate of the tire that is pushing back up. The effective spring rate is effectively on wheel spring rate multiplied by the tire spring divided by spring rates of the sprung masses. The effective spring rate is an invaluable tool which will help us in a multitude of different applications.

$$MsXs'' = Ks(Xu - Xs) + Cs(Xu' - Xs')$$

$$MuXu'' = Ku(Xr – Xu) + Cu(Xr' – Xu') – Ks(Xu –Xs) – Cs(Xu' – Xs')$$

The above mathematical model of equations transferred to the computational system inside of MATLAB Simulink to simulate of motion of equations and analyse the characteristics of passive suspension system by given inputs. The real road conditions converted into signals as sine wave and random signals as an road disturbance. The effects on the ride comfort for mass changes due to the In-wheel motor addition on vehicles investigated on combined control model.

3.3.1.4 Simulink Model of Passive Suspension System

Passive Suspension System modelled demonstrated in Simulink to illustrate body displacement and accelerations by mathematical model. Different road inputs involved the system to get closer real driving situations and to show an effect on the driving comfort. The close loop systems have been used to get outputs and scope to the results on the graphical system.

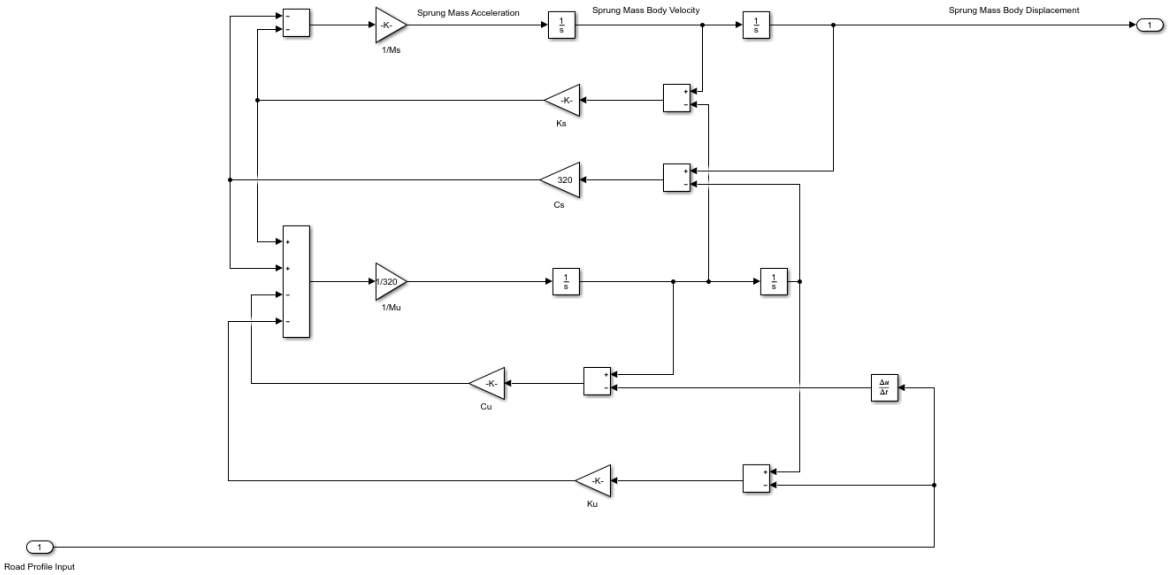


Figure 3.6: Simulink Model of Passive Suspension System

3.3.2 Semi-Active Suspension System Model

3.3.2.1 Introduction

There are several advantages of the semi active suspension systems compared with other suspension systems due to the low energy usage to show the effects on vibration control on the vehicles. The working principle of the semi active suspension systems maintains the being secured system from passive suspension systems and yet contains the advantages of the controlled parameters and functions by active suspension systems. Semi-active suspension systems are very good example of the trade off in the suspension systems such as being simple and low costly system but at the same time having high capabilities on the performance on the vehicle riding comfort systems.

3.3.2.2 Semi-Active Suspension Model

Semi-active suspension system modelled similarly as passive suspension system in Simulink to see the effect of In-wheel motors on driving comfort. As a plant of the suspension system used and controlled by PID controller within the MR Damping system loop. Controller designed to control damping force with respect to voltage to activate MR fluids inside of magnetorheological dampers. The plant act as a real suspension control mechanism and consist of springs and dampers. The semi-active suspension system designed as in figüre xxxxx

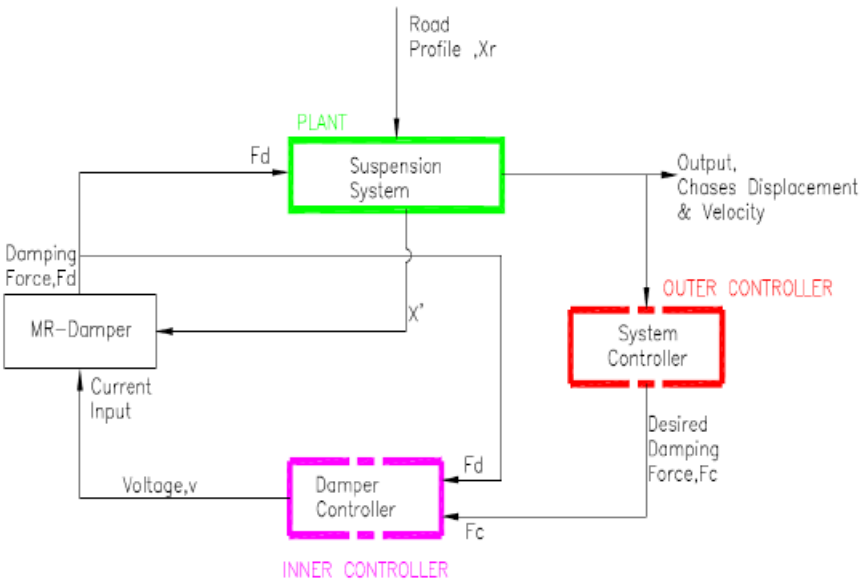


Figure 3.7: Semi-Active Suspension Control Scheme

A theoretical model can be modelled as in figure 3.8 . Since the suspension system involved in 2DOF in every four different suspension system on the vehicle, the system refers to the quarter car model of the semi-active suspension system. The sensors used to control the system signals from the controller and reference inputs.

As mentioned previously, the system of semi-active suspension systems linearly transferred into the Simulink with the linearly and parameters identified in Table 3.3.

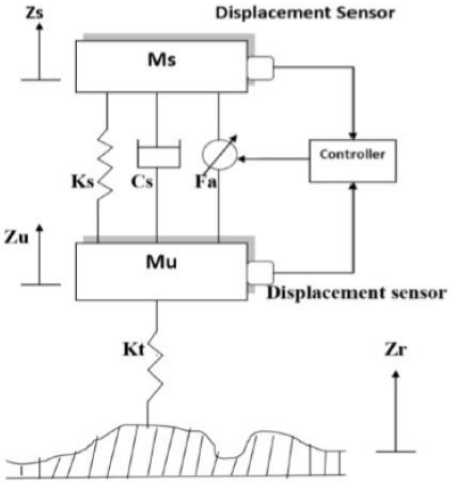


Figure 3.8: Semi-Active Suspension Quarter Car Model

Table 3.3: Parameters used in Semi-Active Suspension Simulation

Parameter	Symbol
Mass of vehicle body	M_s
Mass of the tyre and suspension	M_u
The coefficient of suspension spring	K_s
The coefficient of tyre material	K_t
Damping coefficient of the dampers	C_s

3.3.2.3 Mathematical Modelling of Semi-Active Suspension System

Following motion of equations developed by figure3.8

$$Ms\ddot{z}s + Ks(zs-zu) + Cs(\dot{z}s-\dot{z}u) + U(t)=0$$

$$Mu\ddot{z}u + Ks(zu-zs) + Cs(\dot{z}u-\dot{z}s) + Kt(zu-zr)= U(t)$$

The mathematical modelling of the semi-active suspension system designed by several observations

- 2DOF car body diagram assumed as linear system
- The negligible forces did not include inside of the equations
- Tyre types always considered about damping and stiffness criteria's

3.3.2.4 Magneto Rheological (MR) Damper System

Magneto-rheological (MR) dampers have recently become an object of intensive studies, both due to their interesting physical features, as well as due to their potential applicability to control damping in mechanical systems. The viscosity of the fluid can change with electromagnetically and gives the control system to activate or stop to work of the damper by voltage passage.

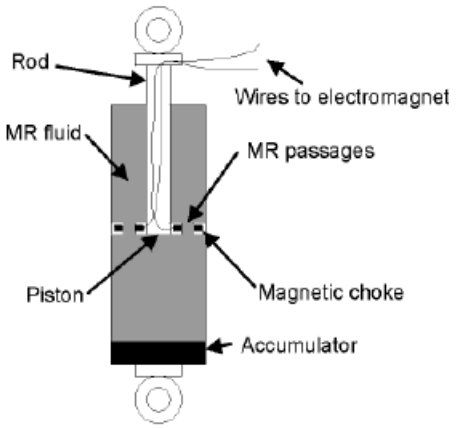


Figure 3.9: MR Damper and Fluid Working Principles

Different mathematical approaches tried to describe the working principles of the system. However, there are some quasi-static models designated but the problem with these models were not enough to show nonlinear force-velocity behaviour. Therefore, nonparametric, and parametric models involved and improved in next research. The most important model of the parametric models called as Bouc-Wen MR damping model.

3.3.2.5 Bouc-Wen Model

In this suspension system Bouc-Wen model used in Simulink simulations. Bouc Wen equation is as follows:

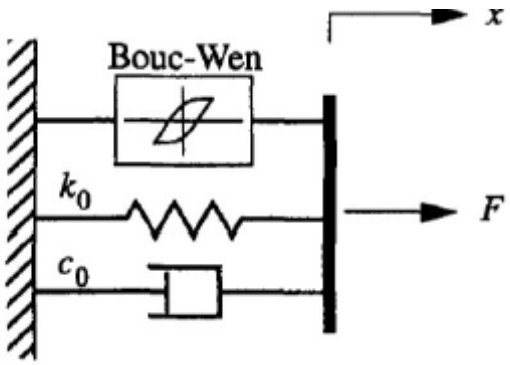


Figure 3.10: Bouc-Wen Hysteresis Model

When the system increase the force on an materials that increase the amount that it extends by but the other thing about elastic material is that the force applied when the materials extending is going to equal the force that applied if the system allows that to react back to its original position. Such as the force increases the extension increases and if the system gradually reduces the force then the extension of the material will decrease. During extension when the first time begin to apply the force, the extension is relatively low but as the force increases the extension increases. So that the hysteresis actually has an effect of damping the vibrations. Damping means the reducing the size of the oscillations. Hysteresis model has been designed and reviewed by Choi, Lee and Park (2001); Wereley, Pang and Kamath (1998).[30][31]

In this model, the system wants to characterize the behaviour of this MR fluid damper, so again needed to reproduce the response of the hysteresis system to the random excitation. The mathematical model of the system can simply describe.

$$F = Co\dot{x} + ko(x - xc) + \alpha z$$

$$\dot{z}=-\gamma|\dot{x}|z|z|n-1 - \beta\dot{x}|z|n +A\dot{x}$$

where,

F=Damping force

x=Initial displacement of the piston

k0=stiffness of fluid

co=damping coefficient of the fluid

By adjusting parameters γ, β, and A of the above equations can control the smoothness of pre-yield and post-yield region of the MR fluid.

z is an evolutionary variable that encompasses the history of the dependence of response. The parameters depend upon the voltage with is given by equation as:

$$\alpha=\alpha a + \alpha bu$$

$$co=coa + cobu$$

where u is the output obtained from the first-order filter and given relation in terms of voltage as:

$$\dot{u}= -\eta(u-v)$$

Table 3.4: Parameters for Hysteresis Loop of MR Damping System

Parameters	Values
γ	1 cm^{-2}
β	-1 cm^{-2}
A	1.5
n	2
K_o	300 N/cm
c_{oa}	4400 N-s/cm
c_{ob}	442 N-s/cm
η	190
α_a	10872 N/cm
α_b	49616 N/cm

3.3.2.6 Simulink Model of MR Damped Bouc-Wen Model

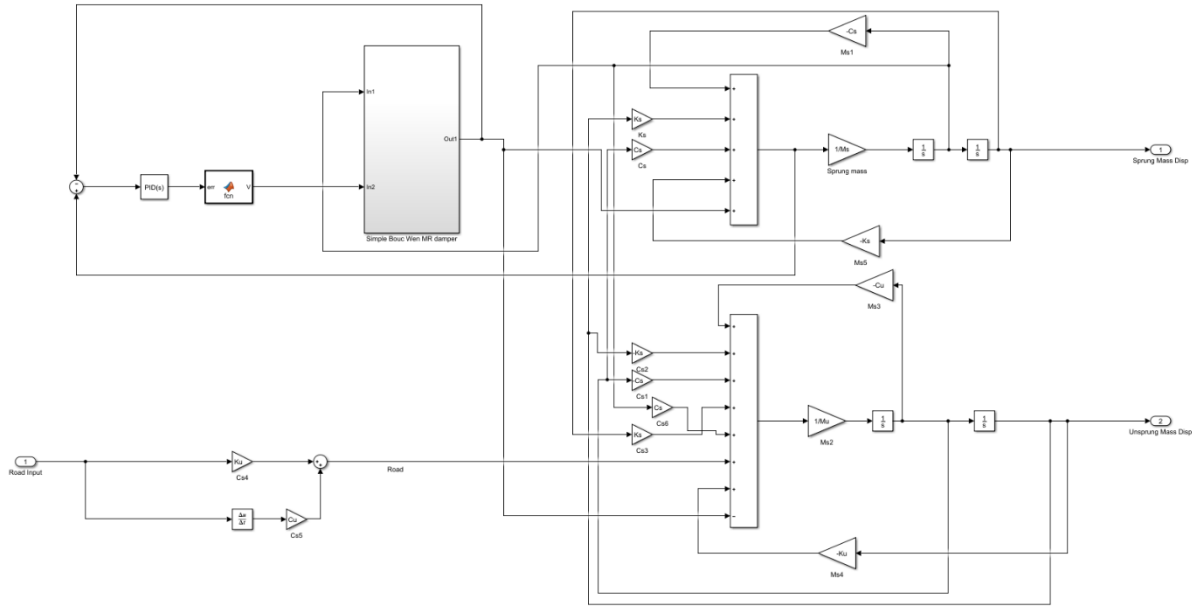


Figure 3.11: Simulink Model of MR Damped Semi-Active Suspension System

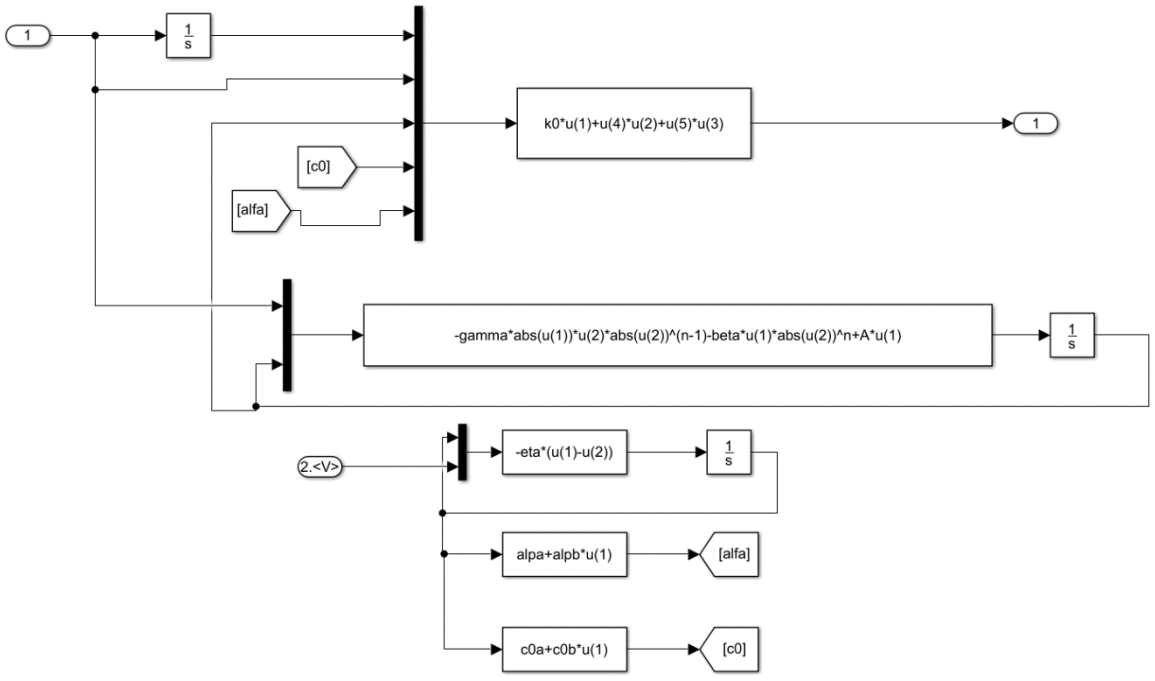


Figure 3.12: Simulink Model of Bouc-Wen

3.3.2.6 PID Controlled Semi-Active Suspension Model

PID Controllers the architecture and using applications have high demand because of that is fairly simple to implement and understand. Primarily, controllers are parameterised by only three values which are namely a proportional, integral, and derivative gains.

Looking at the frequency response of the open loop system and using the knowledge of open loop gain and phase and crossover frequency to predict the close loop system will behave by adding the PID controller and adjusting the location of the two zeros and the gain can shape the open loop to get desired frequency characteristics.

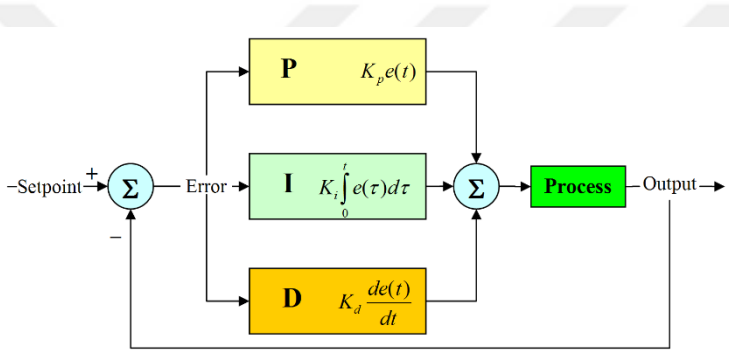


Figure 3.13: Principles of PID Controller Scheme

The main target of the system is that to choose K_p, K_i and K_d appropriately. Ziegler Nichols is the only one of the techniques which allows to do in an iterative online fashion that means can work direct plant without a model. Ziegler Nichols is an iterative, online method to choose the gain values.

$$u(t) = k_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right)$$

Figure 3.14: Ziegler Nichols Formulation in T domain

The steps to define gain values in order to following procedure.

- Starting with K_p equal to small value and set the K_i and K_d as zero.
- Increasing K_p until achieved neutral stability which means per turn the system and oscillates neither decay back to zero nor explode.
- Recording the critical or the ultimate gain $K_U = K_{p\ @\ \text{neutral stability}}$
- Recording the critical or the ultimate period of oscillation
- Find out the K_P , T_i , T_d
- Computing K_i and K_d

Table 3.5: Computation of P, I and D Parameters

Controller	k_p/k_c	T_i/T_c	T_d/T_c	T_p/T_c
P	0.5			1.0
PI	0.4	0.8		1.4
PID	0.6	0.5	0.125	0.85

Control Parameters

Simulation has automatically tuner mechanism to control the specified plant after linearization for better accurate systems.

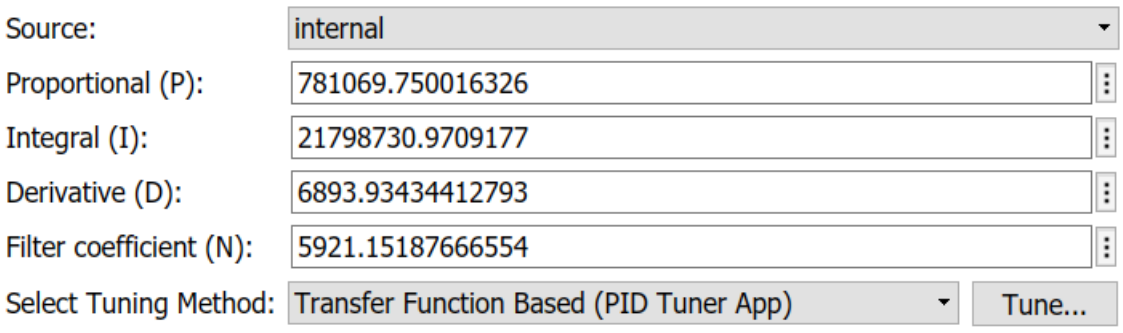


Figure 3.15: PID Control Tuner Parameters

There are different effects of the Ziegler Nichols Tuning method. Such as,

Advantages

- Does not require expert knowledge
- Does not require model/simulation of system
- Often produces good initial values of gains

Disadvantages

- Mathematically not rigorous
- Requires a stable system
- Requires a system that can be driven unstable with increasing proportional gain

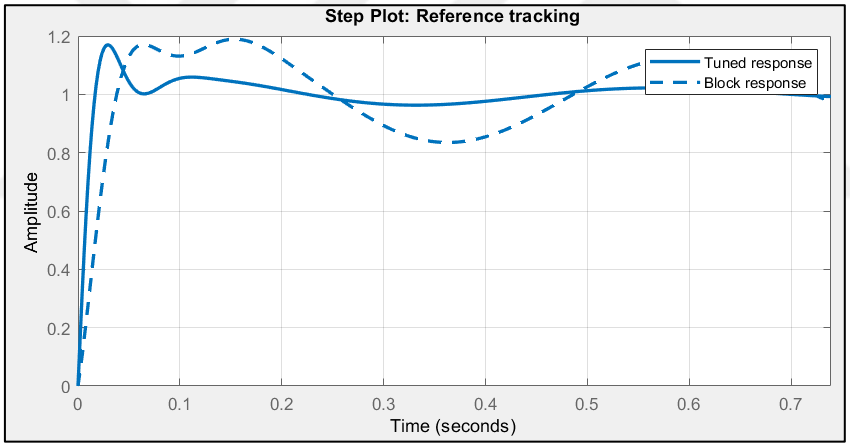


Figure 3.16: Reference Tracking Graph of PID Tuner

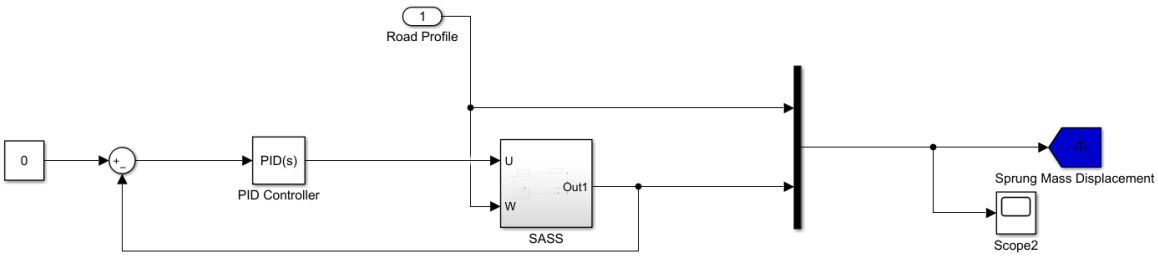


Figure 3.17: Simulink Model of PID Controlled System

3.3.2.7 Fuzzy Logic Controlled Semi-Active Suspension Model

The fuzzy logic control system used with two input which are error and controlled error for the control system of suspension model with an output of the desired damping control force. The fuzzy logic controllers generally occur three main process such as fuzzification, fuzzy inference system and defuzzification. Fuzzification is the process of transforming crisp input values into linguistic values in a system.

There are two steps for fuzzification.

1. Input values are translated into linguistic concepts, which are represented by fuzzy sets.
2. Membership functions are applied to the measurements and the degree of membership is determined.

Defuzzification is another reversing process that converts the fuzzy values into the crisp values. There are three different method for defuzzification which are maximum membership method that choses the element with maximum value. Another method which is used for this project is centroid method. That method finds the centre point of the targeted fuzzy region by calculating the weighted mean of the output fuzzy region Last method is called as weighted average method which is assigns weight to each membership function in the output by respective maximum value.

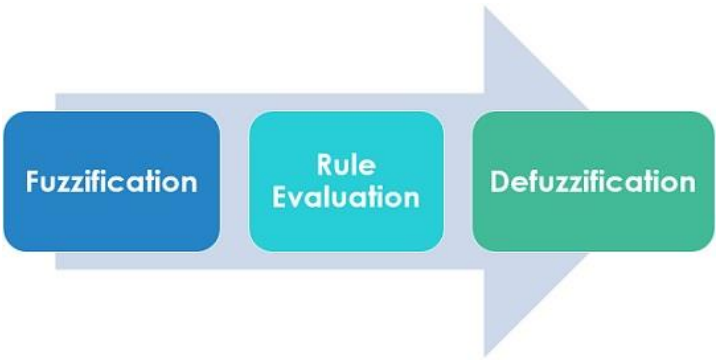


Figure 3.18: Steps of Fuzzy Logic Controller

3.3.2.7.1 Creating Membership Functions and Rule Base System

In the FIS interface, every input and output need to have linguistic divisions to categorize the error and match with the output response. Therefore, linguistic inputs represented as :

- NB: Negative Big
- NM: Negative Medium
- NS: Negative Small
- ZE: Zero
- PS: Positive Small
- PM: Positive Medium
- PB: Positive Big

Table 3.6: Rule Base of the FLC Model

E\CE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

3.3.2.7.2 Rule Base Linguistic Control Table

Thus, the rules of the controller have the general form of:

$$R_i\text{: IF } (e = A_i) \text{ AND } (ce = B_i) \text{ THEN } (output1 = C_i)$$

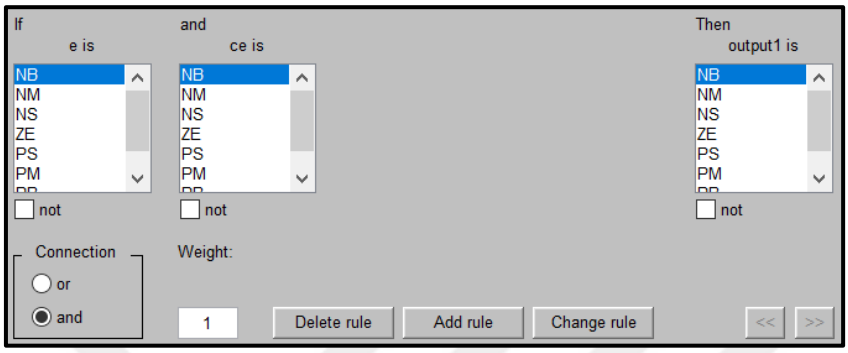


Figure 3.19: If Statements for Rule Base Linguistic Control Tables

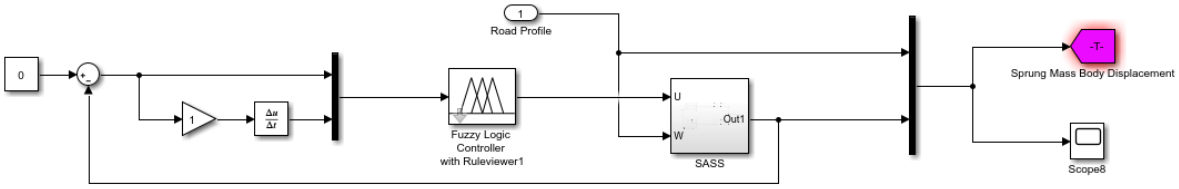


Figure 3.20: Simulink Model of FLC Semi-Active Suspension System

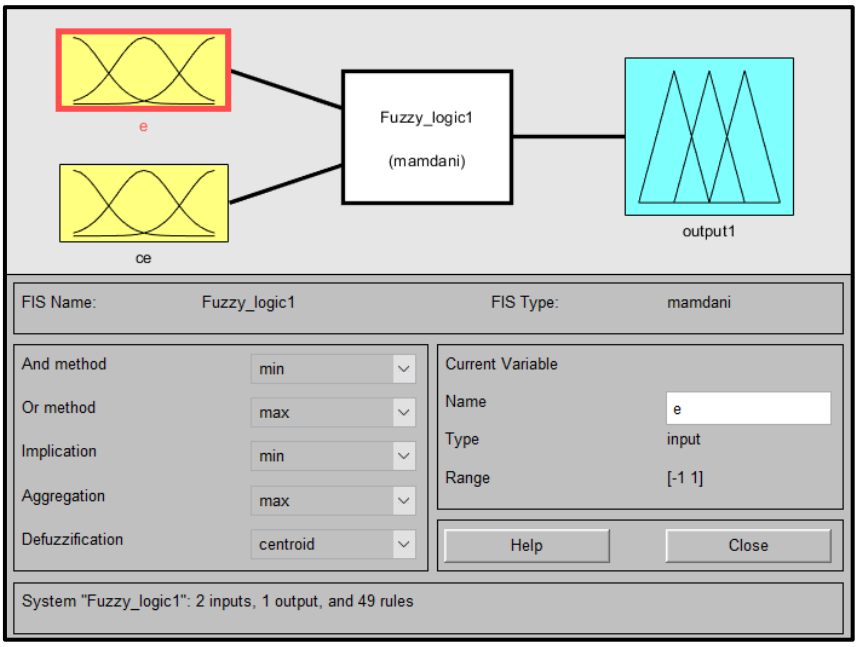


Figure 3.21: Simulink FIS Configurations

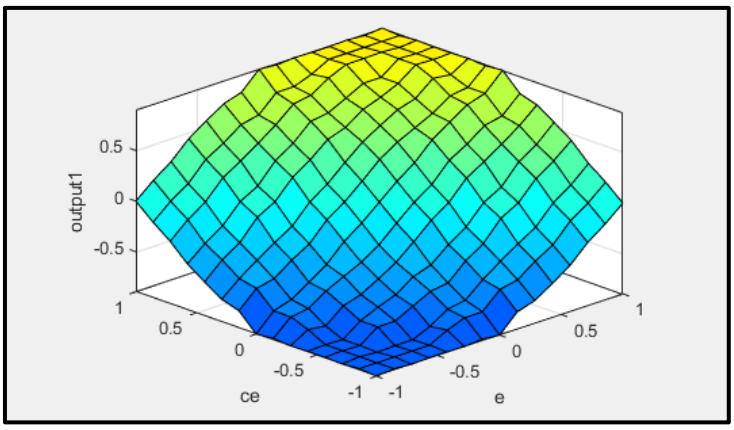


Figure 3.22: Rule Surface View of FIS

Figure 3.23: Error and Controlled Error Division on Membership Function Plots

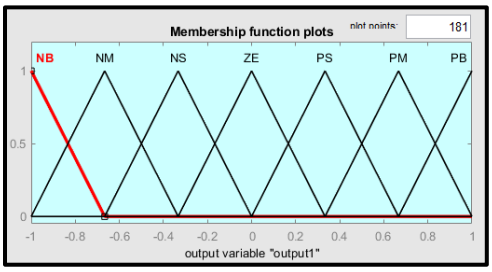


Figure 3.24: Output Division on Membership Function Plots

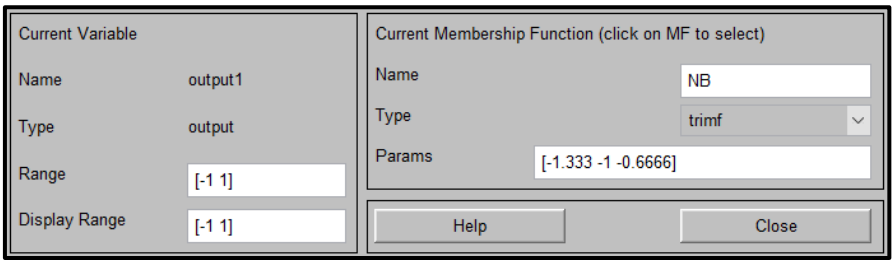


Figure 3.25: Input and Output Limit Values

3.4 Simulation Parameters

In this chapter, the application of the In-wheel motors on vehicles from different companies gathered with the specifications such as main assembly mass addition of the wheels inside the rim. The resultant mass of the motors used averagely in simulation. The car body mass and unsprung mass decided with spring and damping constant in this chapters by giving in a table to provide simulation inputs. Inside of the Simulink for different models, the Simulink block model combined together to simplify the model. The MATLAB workspace matrices created for initial values for simulation. The theory behind the simulation and software working defined by Beucher and Weeks ; Augustaitis, Gican, Sesok and Iljin (2011).[32][33]

3.5 Vehicle Mass Specifications

In the simulation, different aspects of the car model are considered which includes stiffness of the tyre and damping coefficients. The data about the sprung mass and unsprung masses obtained by table 4.1.

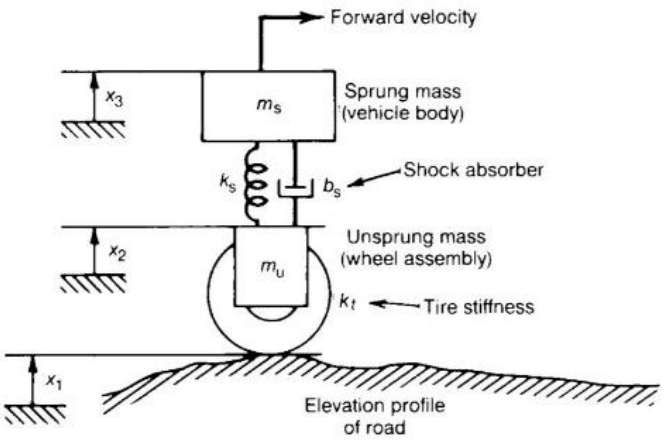


Figure 3.26: Sprung Mass and Unsprung Mass Representation

Table 3.7: General Initial Inputs of System

Parameter	Symbol	Quantities
Mass of vehicle body	Ms	465.5 kg
Mass of the tyre and suspension	Mu	49.8 kg
The coefficient of suspension spring	Ks	5700
The coefficient of tyre material	Kt	135000
Damping coefficient of the dampers	Cs	290/1400

The data of vehicle suspension system parameters taken by different published reference papers such as Table 3.7 gathered by Florin, Manolache-Rusu and Patuleanu (2000)[34]

3.6 In-Wheel Motor Specifications

The general idea of the in-wheel motors that instead of an electric motor which is based inside the vehicle in the middle to help drive the wheels with the transmissions, drive shafts and differentials to get all that torque out to the wheels, generated the motor into the wheels. The motor fits in wheel like a commercial over the road wheel. A wheel motor on each side which mounted to the conventional hub and the bearing system from a production car. The motor occupies inner space behind the wheels then replacing the braking system with a disc brakes to get redundancy. Regenerative braking system usually stays inside the motor and collaborating with redundant mechanical brakes.

The data of the in-wheel motors provided from the data sheets from different producer websites. These two in-wheel motor properties gathered by Protean and Elaphe official websites to use as an input to the system.

Protean Electric Pd18 Datasheet

Table 3.8: Datasheet of the Pd18 In-Wheel Motor

Parameters			
Characteristic		**Pd18**	**Units**
Peak Output Power* Continuous Output Power* Peak Torque Continuous Torque	@400 Vdc	80 60 1250 650	kW kW Nm Nm
Motor Dimensions (diameter, axial depth to rear or stator, excluding cable glands)		433, 125	mm
Motor Mass (including power electronics, excluding bearing, brake and cables)		36	kg
Maximum Speed		1600	rpm
HV DC Supply Voltage Range (for full performance)		200 to 400	Vdc
Coolant Inlet Temperature Range (for full performance)		-20 to +50	°C
Cooling Fluid		50/50 Water/Glycol	
Ambient Temperature Range (for full performance)		-40 to +90	°C
Control Interface (torque demand)		CAN 2.0b	
Ingress Protection Rating		IP6K9K	
Power and Control Electronics		Integrated	
Friction Braking Solution		Integrated	

Table 3.9: Datasheet of the L1500 Datasheets

Elaphe Technology L1500 Datasheets

Added weight	34,8 kg
Peak torque	1500 Nm
Continuous torque	650 Nm
Top speed [at nominal voltage]	1480 rpm
Peak power [at nominal voltage]	110 kW
Continuous power [at nominal voltage]	77 kW (liquid cooling)

The mass of the in-wheel motor used in the simulation to see and changes on the ride comfort effects by comparing the graphs of sprung mass acceleration in different controlled suspension models by averagely 35 kg additionally onto unsprang mass for only one quarter of the vehicle in car model in Simulink.

CHAPTER4

SIMULATION RESULTS & DISCUSSION

4.1 Simulation Results

4.1.1 Step Input System Car Body Displacement Results

MATLAB/Simulink is used a computer added-control system tool for non-physical quarter car which has given input parameters the respond of the system is observed on 10 seconds scale. The simulation results analysed for body displacement. There are two main road inputs simulated with different developed controller. The results are shown in following figures.

4.1.1.1 Passive Model without In-Wheel Motor Mass Addition

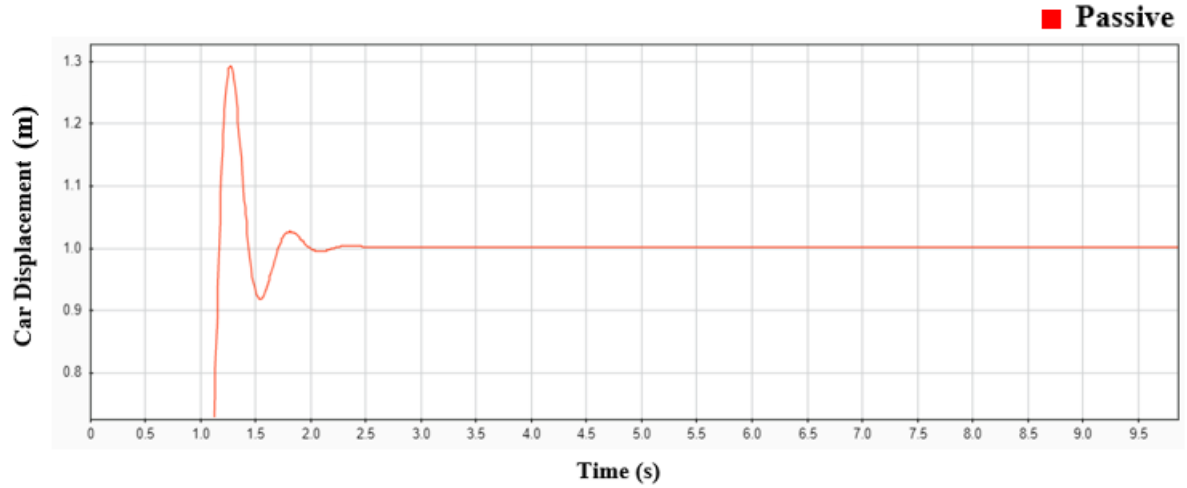


Figure 4.1: Passive Suspension Signal Output Before Adding IWM Mass

4.1.1.2 Passive Model with In-Wheel Motor Mass Addition

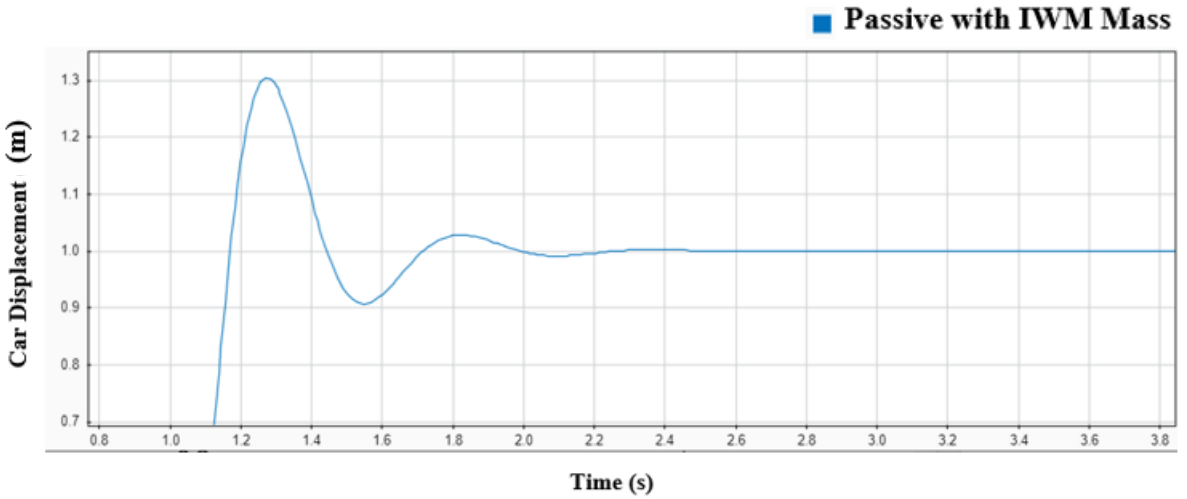


Figure 4.2 : Passive Suspension Signal Output After Adding IWM Mass

4.1.1.3 Effects of the Change of Ratio Between Unsprung mass and Sprung Mass on Ride Quality

The difference between sprung mass and unsprung mass on quarter car model affect the response on passive suspension system as graphed on figure 5.3. The ratio of the changes and the model of full vehicle can reflect how importantly increase the responding time of the damping system.

Table 4.1 : Difference Between the Effect of Change Masses on the Vehicle Suspension

	Passive Suspension Model without IWM Mass	**Passive Suspension Model with IWM Mass**
Car Body Displacement (m)	1.2820	1.3047

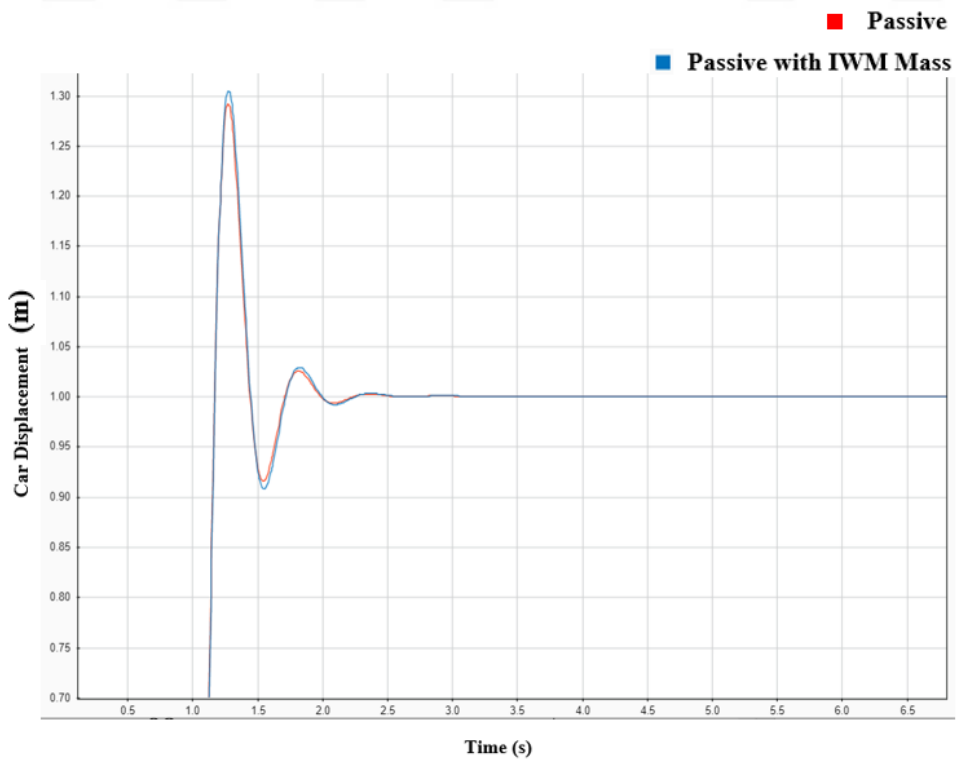


Figure 4.3: The Mass Ratio Effect on Passive Suspension Model

4.1.1.4 Bouc-Wen Model MR Damped Semi-Active Suspension Model

The system which use a MR fluid to control by a voltage changes and having a closed loop PID controller inside. Tyre stiffness and damping included the Bouc-Wen Model to combine hysteric loop of the system. The controlling time starts to linearize the sprung mass around the 6 seconds. Figure 5.4 gives the car body displacement for every time sample. The same model includes the voltage control MATLAB function and PID controller with same input tuner values for gain values such as general semi active models. Linearized plant works regularly inside the PID close loop and show some improvements on the sprung mass displacement. There is a maximum change of 1.2 in the graph which shows the requirements of the shorter time respond controlling system with different semi-active suspension system model.

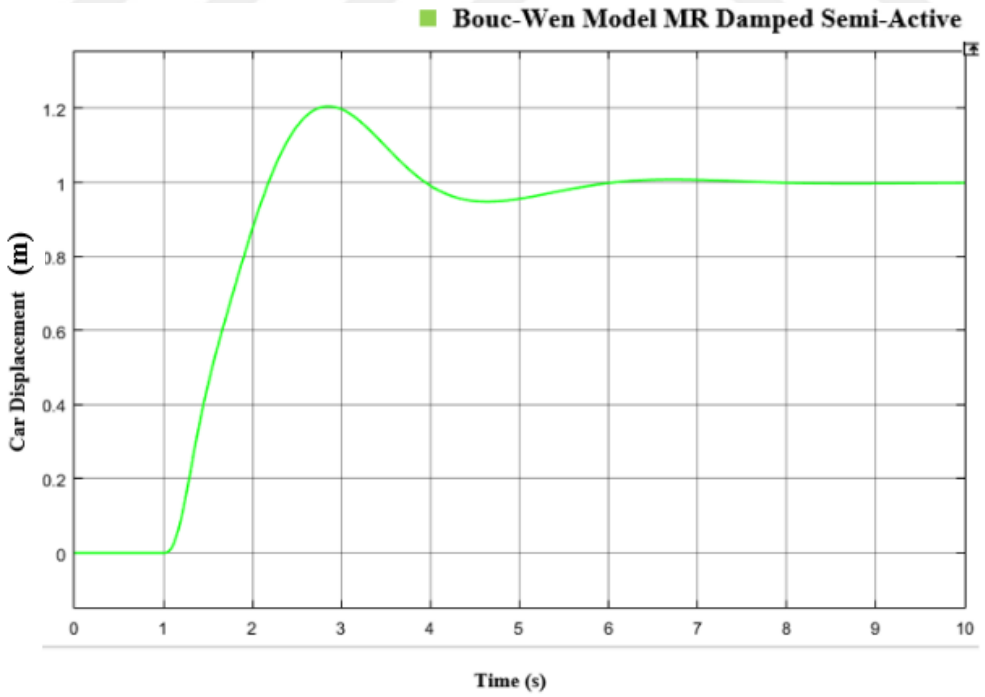


Figure 4.4: Step Input Bouc-Wen Model Sprung Mass Displacement

4.1.1.5 PID Controlled Semi-Active Suspension Model

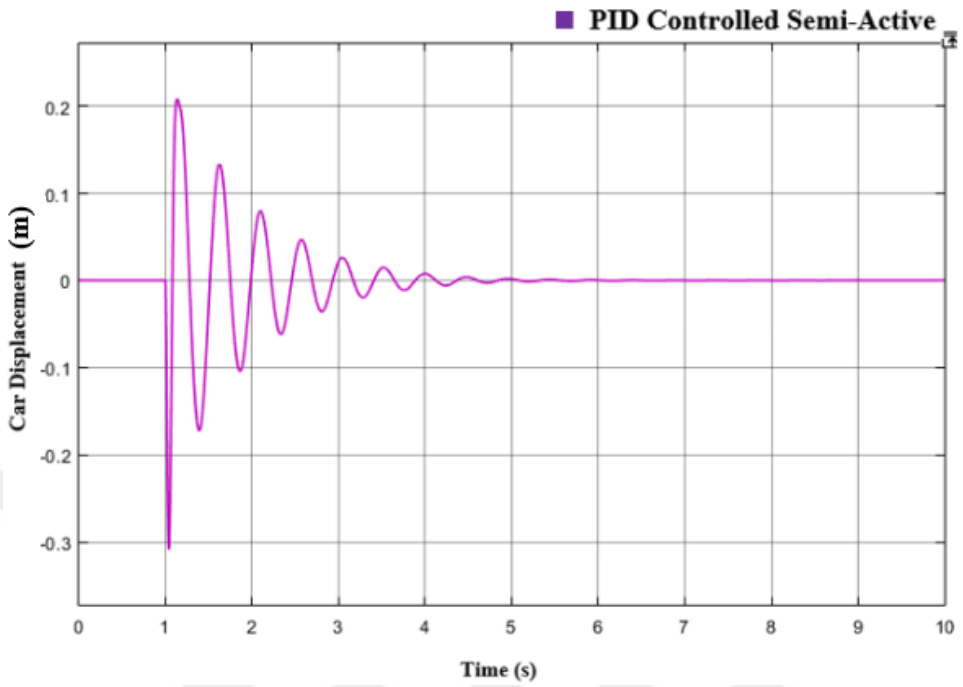


Figure 4.5: Step Input PID Controlled Model Sprung Mass Displacement

4.1.1.6 Fuzzy Logic Controlled Semi-Active Suspension Model

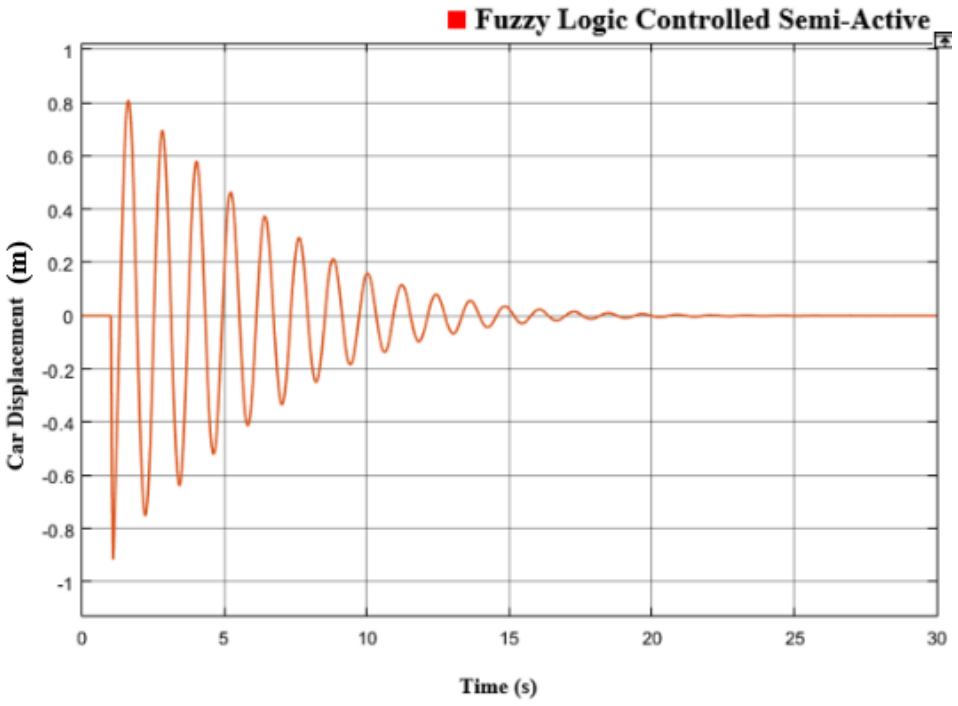


Figure 4.6: Step Input FLC Model Sprung Mass Displacement

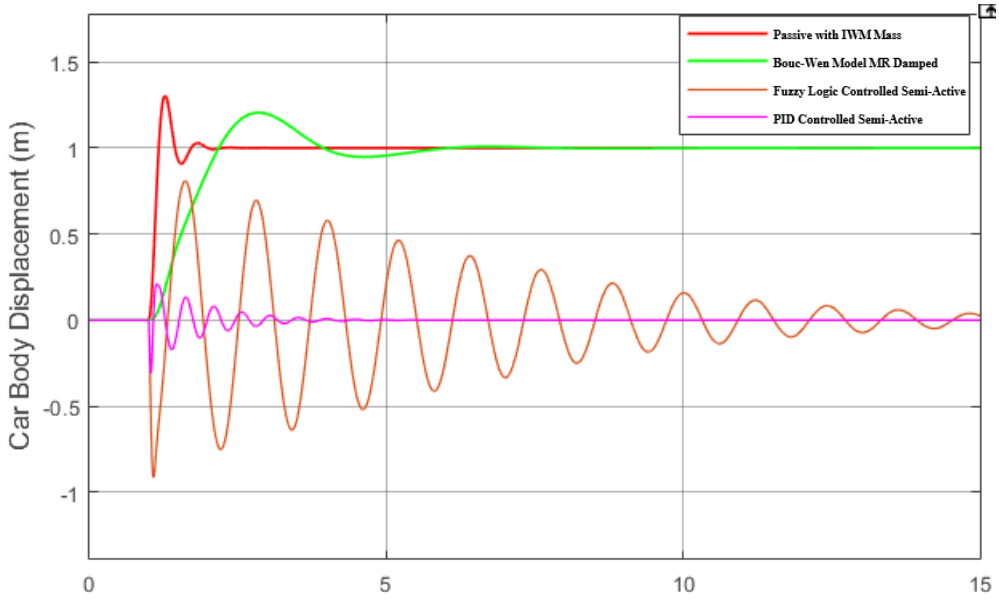


Figure 4.7: Model Responses on Step Input Excitation from Road about Car Body Disp.

Table 4.2: Comparison of Controller Effect on the Car Body Displacement for Step Input

Analysis	System	Controller	Amplitude (m)	Reduction %
Car Body Displacement	Passive Suspension System		1.304	---
	Bouc-Wen MR Damped Semi-Active Suspension System		1.200	8 ↓
	Semi-Active Suspension System	PID	0.208	84 ↓
		FLC	0.809	38 ↓

Step Input road representation applied on general semi-active suspension models with controlled PID and Fuzzy Logic controller. The FLC model has different characteristic than the PID controlled model such as linearization times. The system has late response around 20 seconds with maximum 0.809 m by FLC system which should be acting more accurate and sensitive because of the linguistic rule based system. The PID control with 0.208 m displacement shows considerably rise about the response rate and timing.

4.1.2 Random Road Input System Car Body Displacement Results

Different road profiles can be generated by white noise filtered random road creator block in Simulink. Power Spectral Density method helps to create which road option will enrol as their surface condition and roughness type. Class D type surface conditions applied on closed loop system again to check the effectively controlled systems and their behaviours for random road inputs as a signal output in time response.

Similarly, the same order of the methods on passive and semi-active suspensions and controllers to manage differences between the desired values and body displacement as called as errors. PID Controlled and Fuzzy Logic Controlled systems will be involved comparison as their effects on mass change and ratio between unsprung and sprung mass and ride comfort effect directly. Particularly, controlled system effects expected to have better improvement on ride quality when compared with passive suspension system.

4.1.2.1 Passive Model with In-Wheel Motor Mass Addition on Random Road Profile

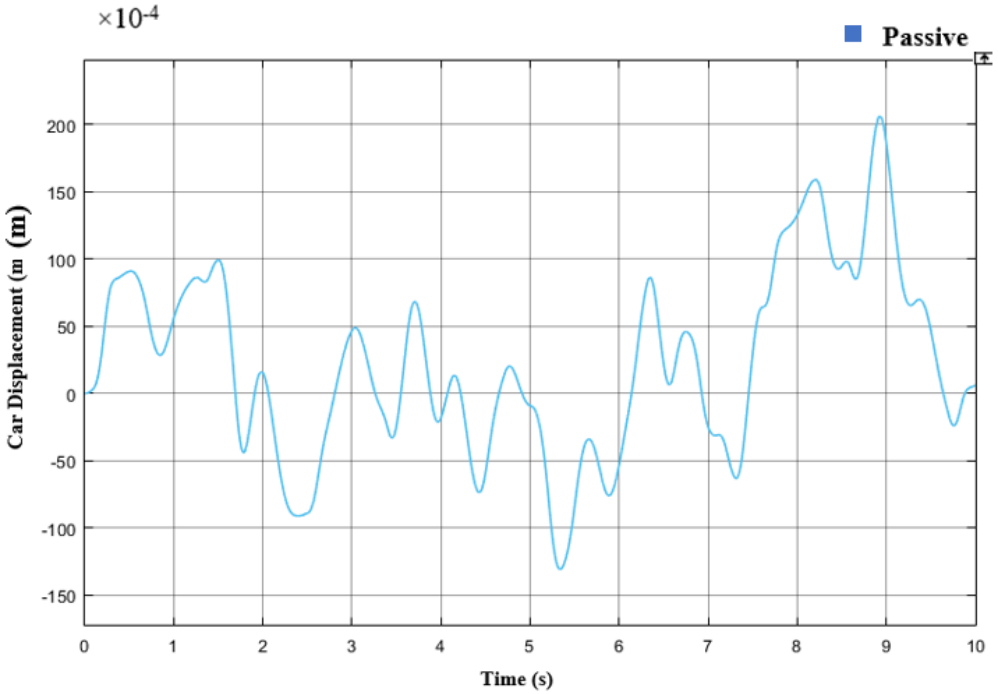


Figure 4.8: Random Road Input Passive Suspension Model

4.1.2.2 Bouc-Wen Model MR Damped Semi-Active Suspension Model

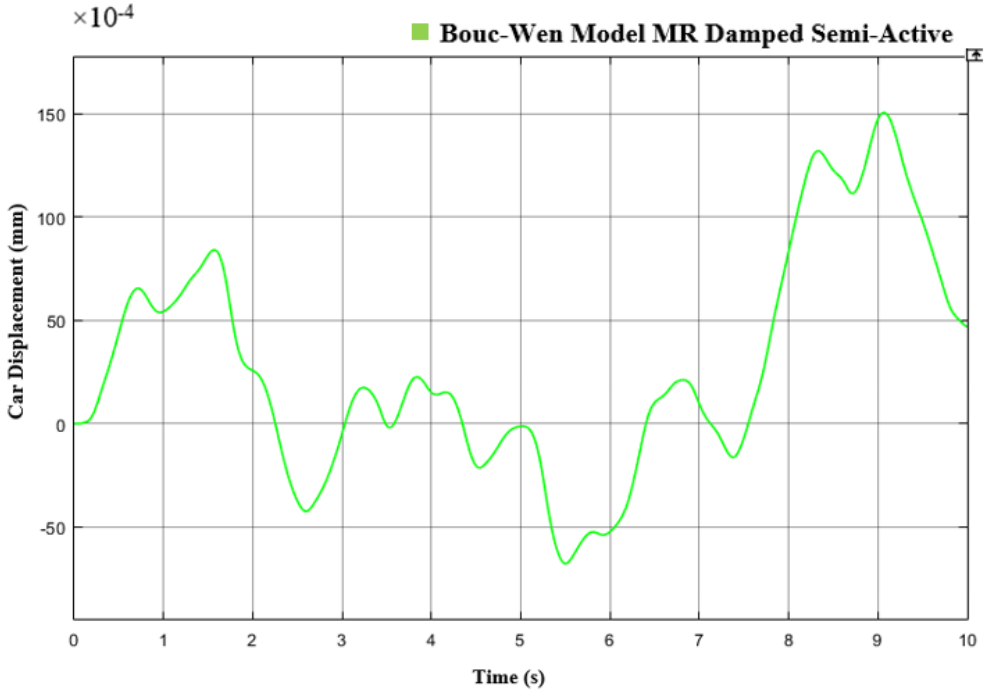


Figure 4.9: Random Road Input Bouc-Wen Model Sprung Mass Displacement

4.1.2.3 PID Controlled Semi-Active Suspension Model

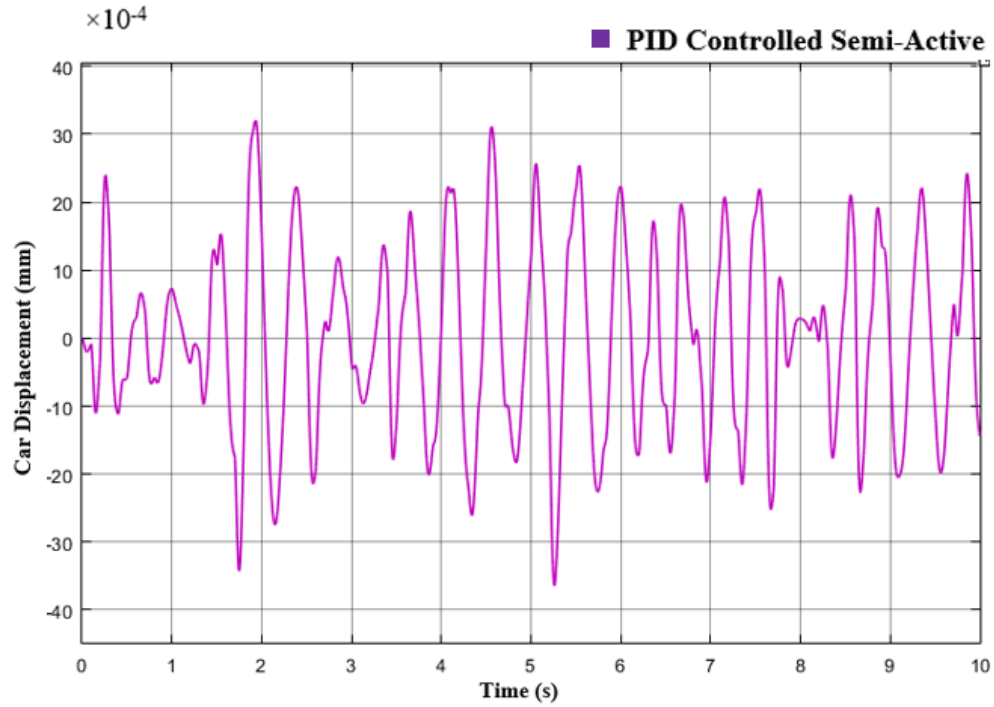


Figure 4.10: Random Road Input PID Controlled Model Sprung Mass Displacement

4.1.2.4 Fuzzy Logic Controlled Semi-Active Suspension Model

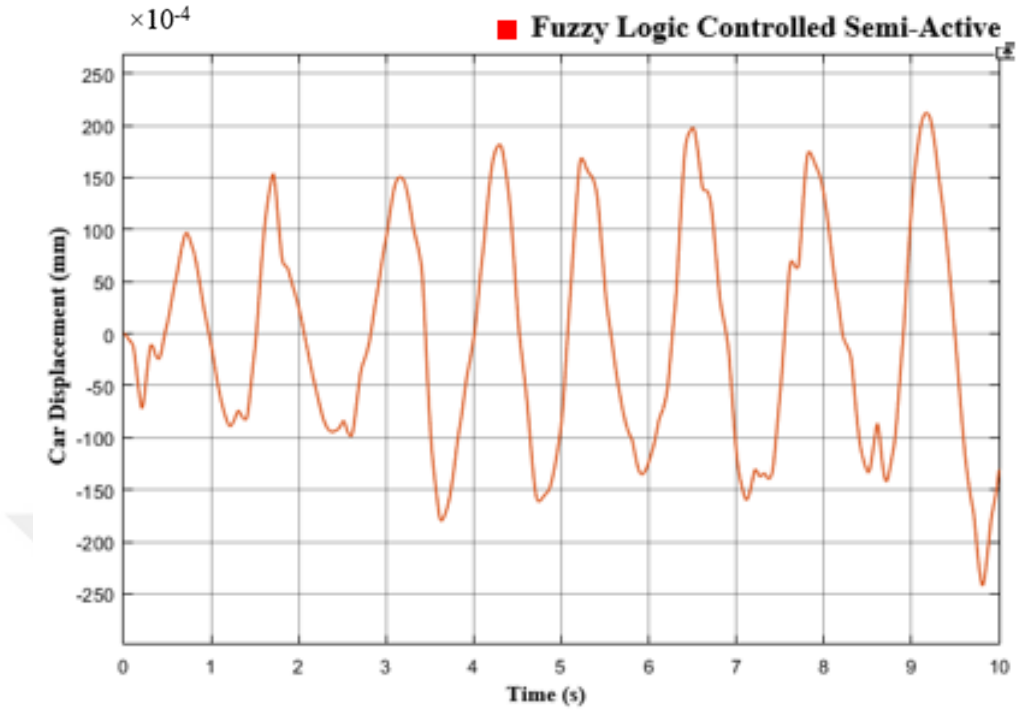


Figure 4.11: Random Road Input Bouc-Wen Model Sprung Mass Displacement

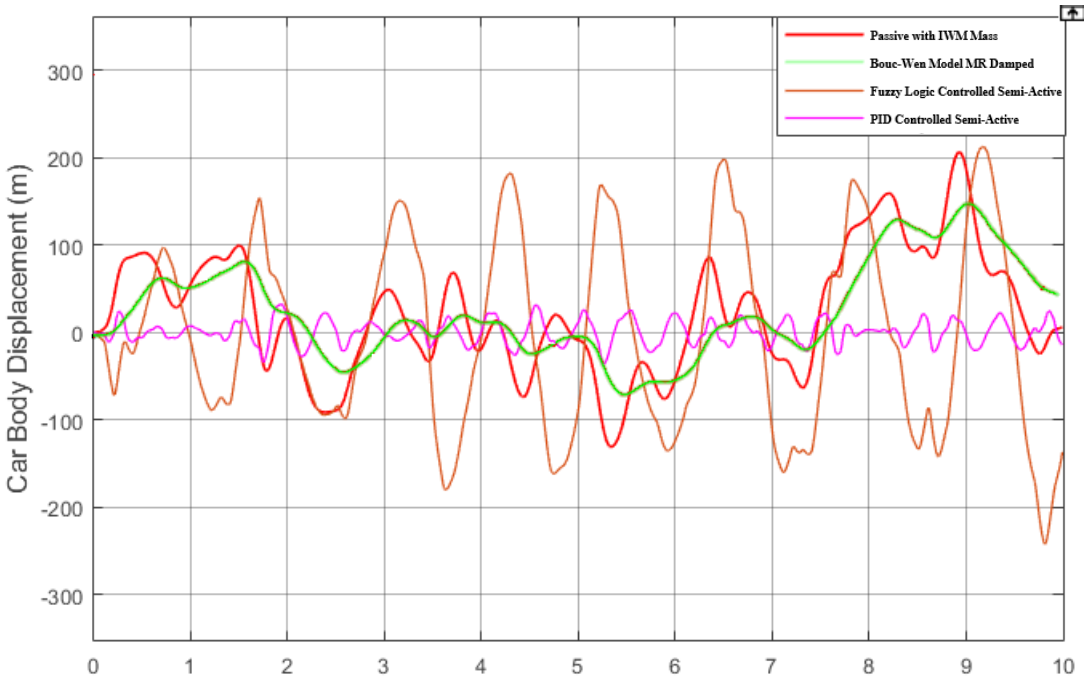


Figure 4.12: Model Responses on Random (Gaussian White Noise) Excitation from Road

Table 4.3: Comparison of Controller Effect on the Car Body Disp. for Random Road Input

Analysis	System	Controller	Amplitude (m)	Reduction %
Car Body Displacement	Passive Suspension System		0.020	---
	Bouc-Wen MR Damped Semi-Active Suspension System		0.015	25 ↓
	Semi-Active Suspension System	PID	0.003	85 ↓
		FLC	0.021	5 ↑

The results show that the passive systems definitely need the control unit about the damping and their behaviours because of having bigger values by road profile generation. The reason of that Fuzzy Logic Controller gives such amount of increasing is the limit of the input of the inference system. Nevertheless, generally controller affects the working limits in both sides but needs to reconfigure for better and accurate results. Conversely, controlling the voltage causes the change effectively the response of the suspension system. Even then the PID controller has effect extremely on the amplitude changes and ride quality. The decreasing of the car body displacement is about 85 percent then the regular . Generally, the results and simulation processes helped by Crolla (1992, 1996)[35][36]

4.1.3 Step Input System Car Body Acceleration Results

4.1.3.1 Passive Model with In-Wheel Motor Mass Addition

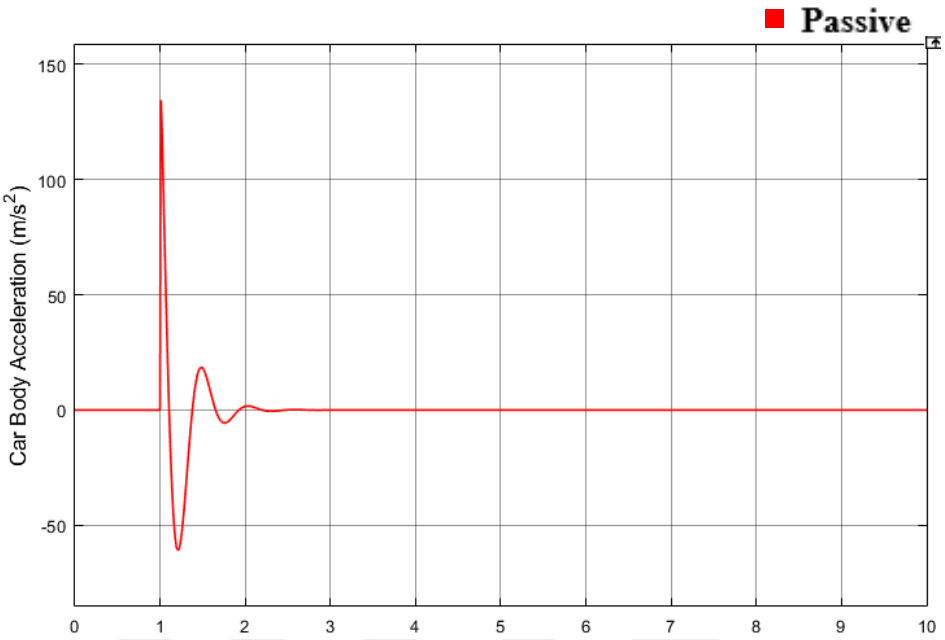


Figure 4.13: Step Input Passive Model Car Body Acceleration

4.1.3.2 Bouc-Wen Model MR Damped Semi-Active Suspension Model

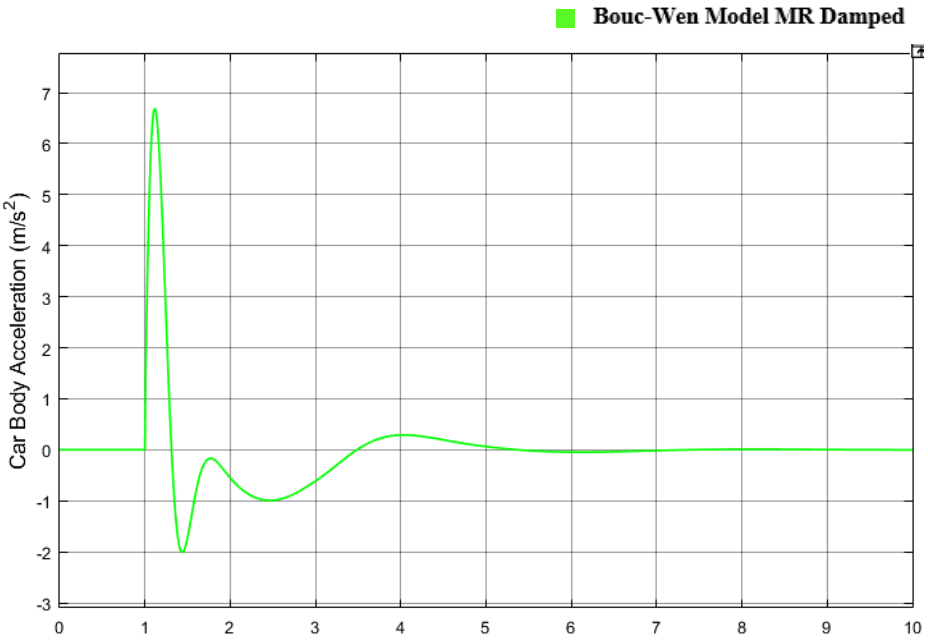


Figure 4.14: Step Input Bouc-Wen Model Car Body Acceleration

4.1.3.3 PID Controlled Semi-Active Suspension Model

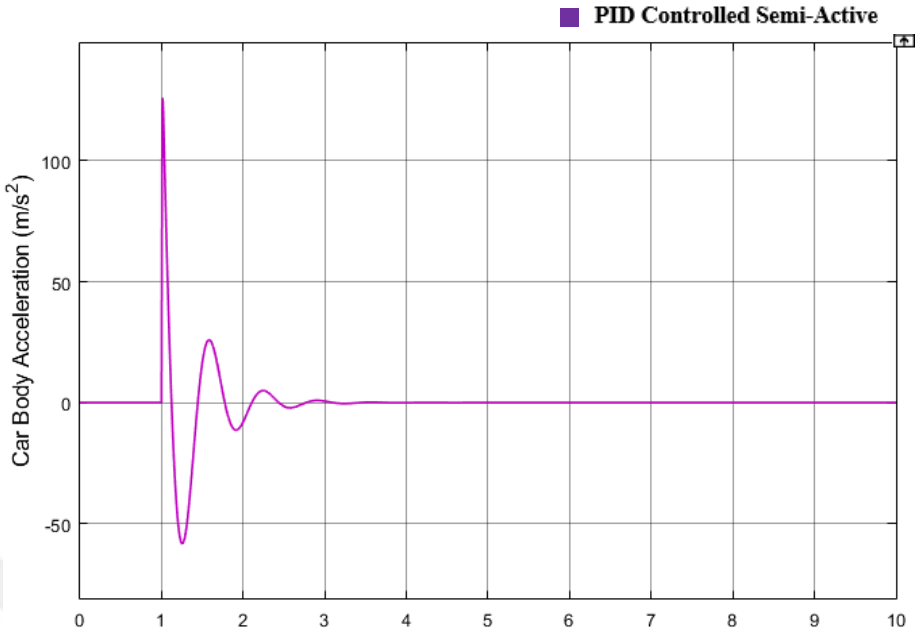


Figure 4.15: Step Input PID Controlled Semi-Active Suspension Car Body Acceleration

4.1.3.4 Fuzzy Logic Controlled Semi-Active Suspension Model

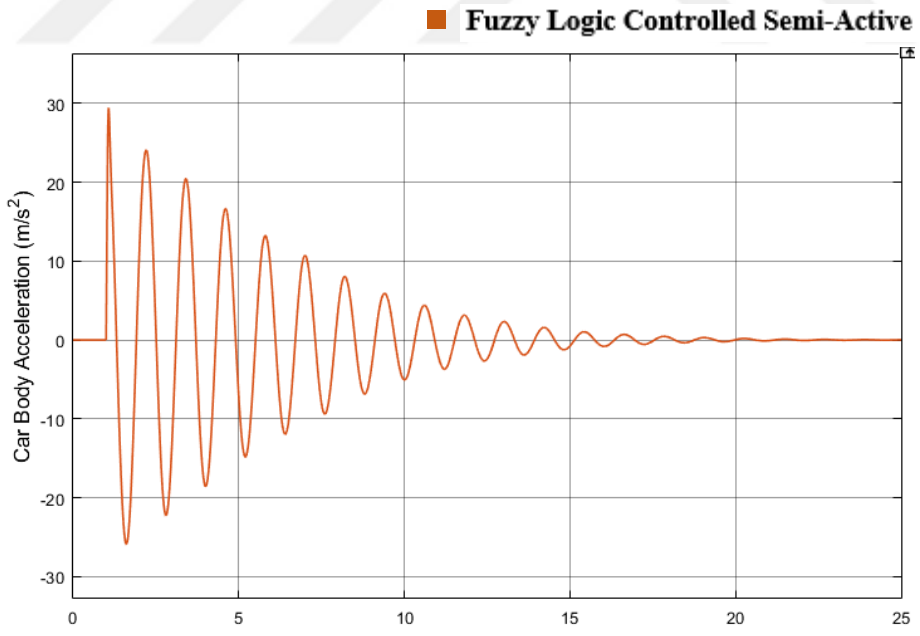


Figure 4.16: Step Input FLC Semi-Active Suspension Car Body Acceleration

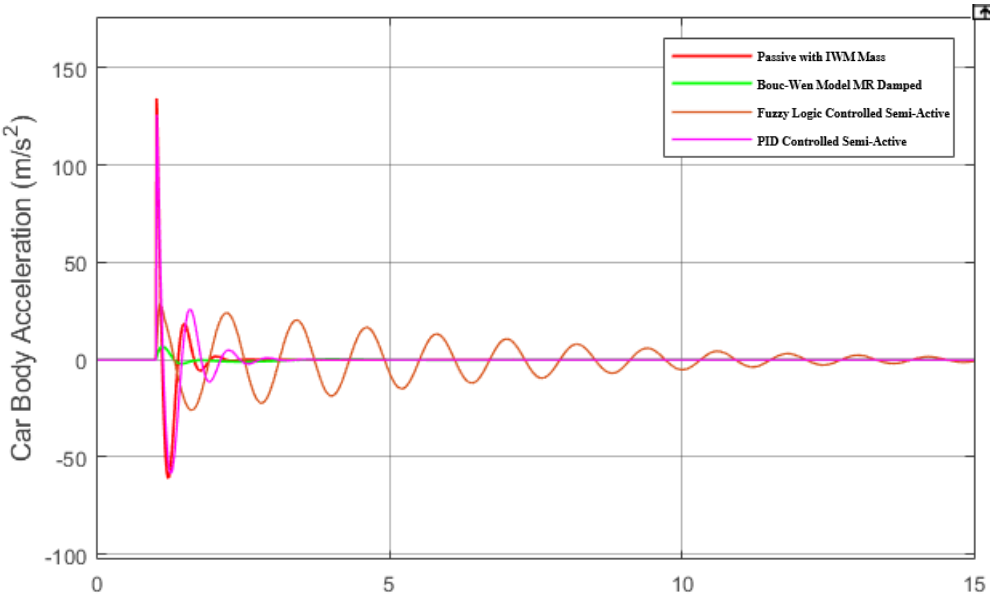


Figure 4.17: Model Responses on Step Input Excitation from Road about Car Body Acc.

Table 4.4: Comparison of Controller Effect on the Car Body Acc. for Step Road Input

Analysis	System	Controller	Amplitude (m/s^2)	Reduction %
Car Body Acceleration	Passive Suspension System		134.5	---
	Bouc-Wen MR Damped Semi-Active Suspension System		6.7	95 ↓
	Semi-Active Suspension System	PID	126	6 ↓
		FLC	29.5	78 ↓

4.1.4 Random Road Input System Car Body Acceleration Results

4.1.4.1 Passive Model with In-Wheel Motor Mass Addition on Random Road Profile

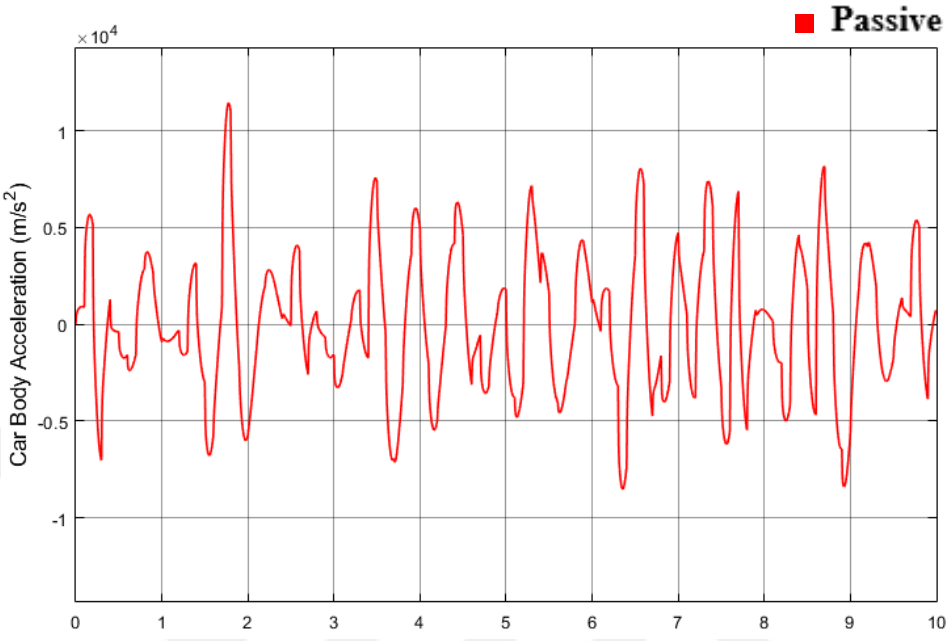


Figure 4.18: Random Road Passive Suspension Model Car Body Acceleration

4.1.4.2 Bouc-Wen Model MR Damped Semi-Active Suspension Model

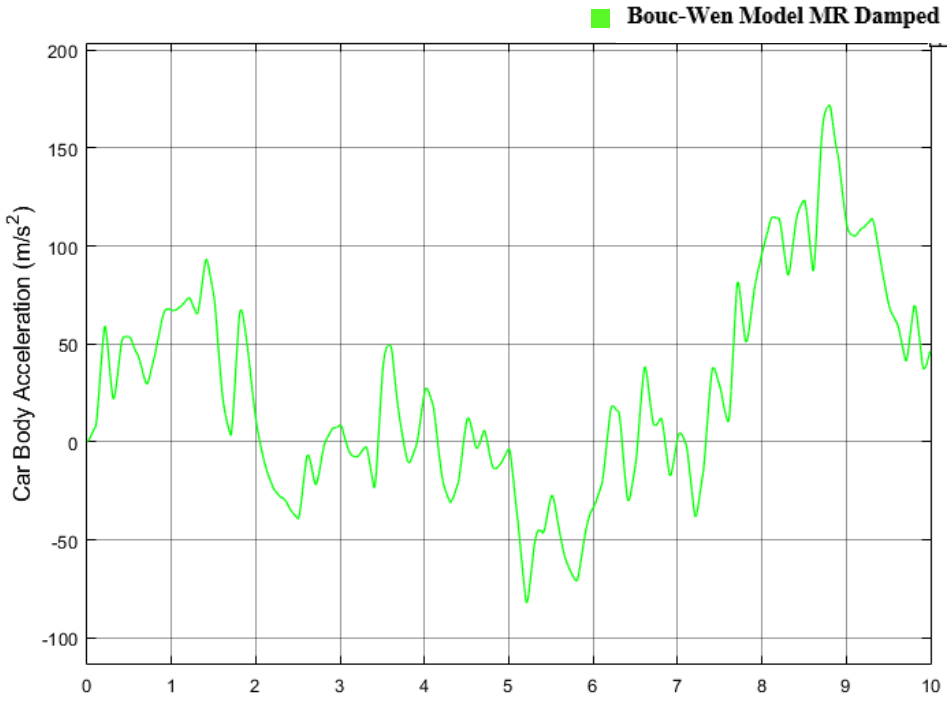


Figure 4.19: Random Road Bouc-Wen Suspension Model Car Body Acceleration

4.1.4.3 PID Controlled Semi-Active Suspension Model

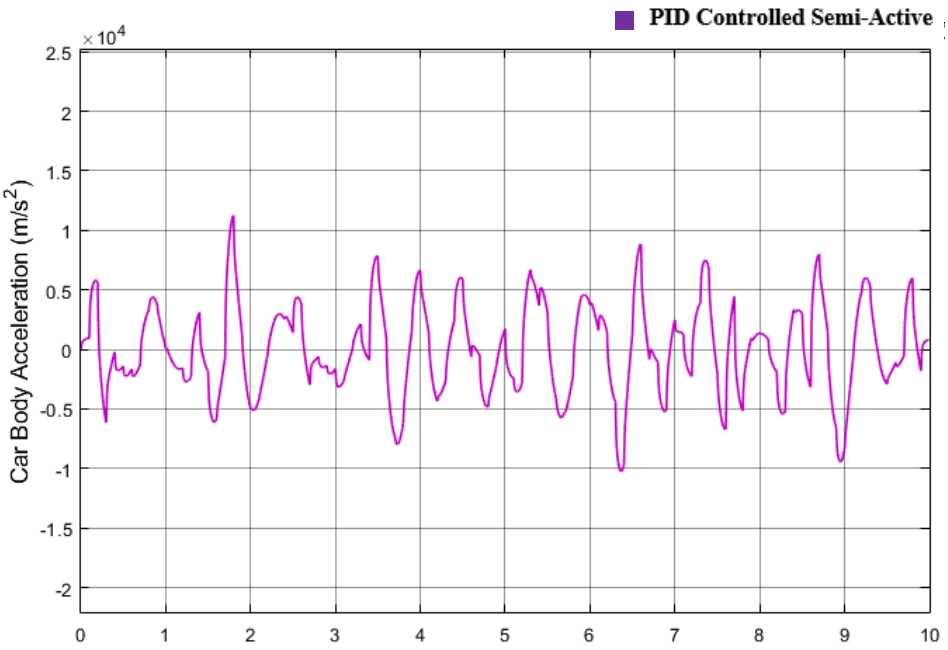


Figure 4.20: Random Road PID controlled Semi-Active Susp. Model Car Body Acceleration

4.1.4.4 Fuzzy Logic Controlled Semi-Active Suspension Model

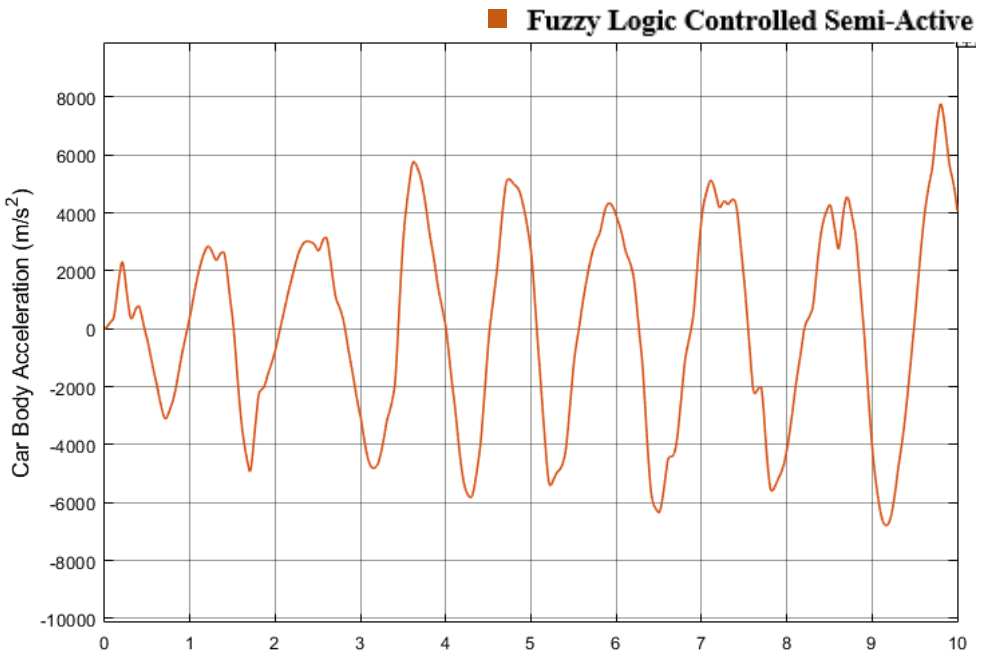


Figure 4.21: Random Road FLC Semi-Active Susp. Model Car Body Acceleration

Table 4.5: Comparison of Controller Effect on the Car Body Acc. for Random Road Input

Analysis	System	Controller	Amplitude (m/s^2) x10^4	Reduction %
Car Body Acceleration	Passive Suspension System		1.145	---
	Bouc-Wen MR Damped Semi-Active Suspension System		0.170	85 ↓
	Semi-Active Suspension System	PID	1.124	2 ↓
		FLC	0.776	32 ↓

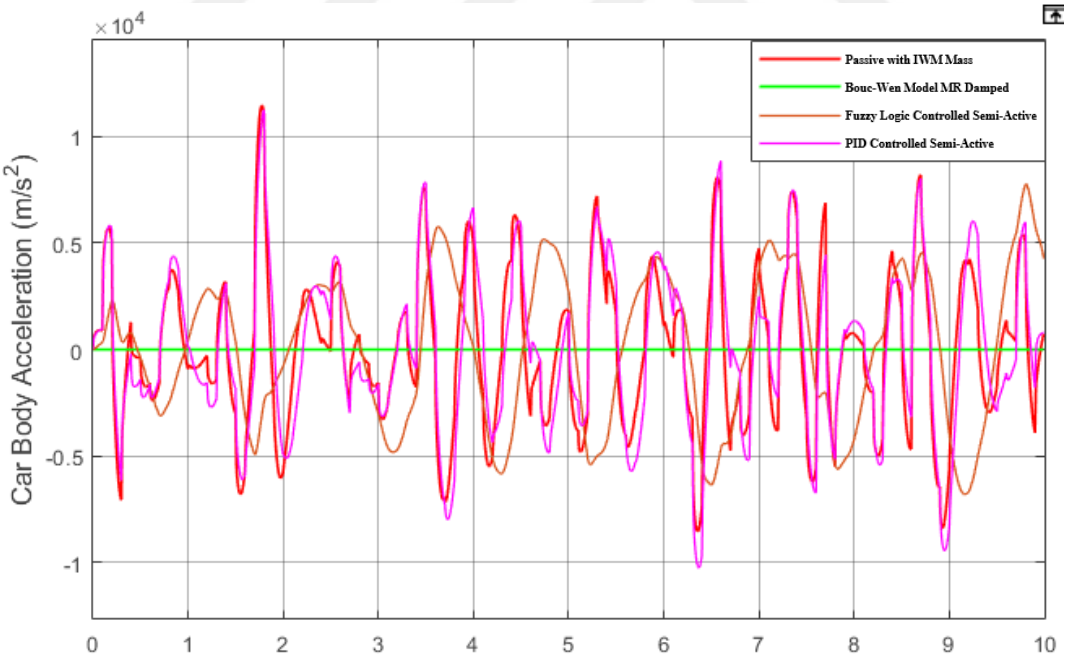


Figure 4.22: Model Responses on Random(Gaussian White Noise) Excitation from Road about Car Body Acceleration

4.2 Discussion

Vehicle dynamic is the most important phenomena that interact with all other systems in the vehicles on driving. Changes on the powertrain systems directly affect the ride quality by changing the load transfer and forces on the driving. In-wheel motor is the futuristic power management systems and focusing of changes on ride comfort always clarify and shows the how important is that being multi connected system and results this discipline.

The project has started as an idea of the next generation cars and dynamically terms on the driving conditions of relationship. Due to the unprecedented circumstances, laboratory test and applications shifted into the virtual simulations by helping of MATLAB/Simulink. The greatest achievement of the software is that every challenges and excitement about to learn new step on the project showed incredible improvement on the progress to use of this simulation programme. The expectations of the system that will be in different road conditions, represent the changes on the ratio between unsprung mass and sprung mass and effects on the ride comfort as a problem. In the following steps, how the different types of control systems can affect suspension system working principles and the rate of the improvement.

There are also different aspects about the advantages of the in-wheel motor powered vehicles such as regenerative braking systems which provides the recycled and stored energy by braking system to extend the driving range. All other side effects need to be considered about safety and ride comfort again.

Passive suspension systems are primitive technologies for new generation suspension systems. Showing the reasons and demonstrations of inadequacies the system to follow the reasons on the needs for a controlling the system by checking the errors on the system. In this section, PID and Fuzzy Logic Controllers used to give a system more abilities on damping control and limitations. The expectations from the controllers to reduce the displacement on the sprung mass to low levels for different road conditions. Because of the fact that fuzzy logic controller work likely more stable and certain. However, different if states within an order of the possibilities solve the system requirements more detailed.

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

In this thesis, mainly focused on different semi-active suspension systems modelling methods to see the effects of in-wheel motor mass addition on the ride quality and comfort. Another focused problem statement which is reaching the best efficient and fastest method to control the suspension system as generally system controlling by helping of MATLAB/Simulink. The system inputs given as different road conditions by getting results as car body displacement on graphical approaches.

From the results the key conclusions include:

1. The changes on the ratio between the sprung and unsprung masses has an effective result on the suspension system performance which are negative about the over looped response of the dampers.
2. The thesis idea and problem definition worked on the system needed appropriate controller and the most suitable suspension model inside of the semi-active suspension. The results had showed that the system definitely controlled by the Simulink controller toolsets.
3. The voltage controlled Bouc-Wen MR damped model has own hysteresis loop as the modelling approach to get better reactions with control damping forces directly by helping of the smart fluids. There are different improvements on the results such as for step input road profile approximately 8 % and random road profile input shows that the results have nearly 25% drops on car body displacement, respectively.
4. The Fuzzy logic controller has also affected to experience a decrease on the semi-active suspension system response. The results show that especially within a step input, the response of the dampers decreasing 38% but oppositely the random road condition has 5% increasing on the maximum values about the displacement loop.

5. The most effective results gathered by PID controller on both step input and random road profiles such as the displacement sharply decreased nearly 85 % for both models.
6. The improvements also gathered on the analysis of car body acceleration by changes in decreasing by approximately 95 % and 85 % on Bouc-Wen Model with step input and random road profile respectively. Oppositely to the car body acceleration system, inside of acceleration solutions shows that the Fuzzy Logic Controller has significant improvements on the suspension system with 78% and 32% respectively.

Finally, the reason of the thesis proved that the passive suspension systems definitely needs to improve themselves with semi-active suspension systems in an application of in-wheeled driven electric vehicles. All of the results, taken by virtual simulations and also need to be working on road testing experience to check the differences on the deviations.

5.2 Recommendation

The technology of In-wheel motors driven vehicles still try to be adapted new designs of the future trends on commercial market. The technology behind the electric vehicles change in every period and this also affects vehicle dynamics directly. This thesis performed on significantly the controllers and semi-active suspension systems. However, there were some limitations about time and facilities because of the system and COVID 19 circumstances. Generally, the abilities on the Simulink as a beginner level student showed improving progress greatly. However, especially time could be used more systematically for Fuzzy Logic Controller testing for different systems to learn more about linguistic control for further development of the project. Because of the fact that proposed answers do not match the actual results because of the number of testing and background knowledge about fuzzy logic controlling. Another important limitation is about experimental facilities and resting the model on vehicles. Because of the pandemic, university facilities did not enable to work on laboratories and only supported by simulation software's on virtual scenarios. Despite the fact that every limitation affected the project, there are also different progress about personal abilities and skills and thinking about the project developments for following tasks.

The following suggestions are made for developing the process in this thesis:

1. Using quarter car model has simple and easy applications on the suspensions systems but does not satisfy more than 2 DOF for the systems. For instance, half car or full car vehicle bodies would be used for next generation of the system to get more accurate results.
2. The system has different applications by helping of the Simulink. Such as to implement the handling and other vehicle dynamic effects to the simulation, the system can combine with the vehicle dynamic toolsets to reach the pitching and rolling.

3. The data which has used in this thesis about the In-wheel motors would be checked by real experiments with the companies which produce the similar systems. The collaboration would make the system more accurate and precise and better source for researchers.
4. In the system of Bouc-Wen model, the damping velocity and forces would demonstrate with the usage of MATLAB scripts.

In addition, system has interesting approaches on the smarter systems such as adaptive suspension control applications. The methods to convert the system smarter is that would be making the system more interesting and connected with the new technologies in today's world.

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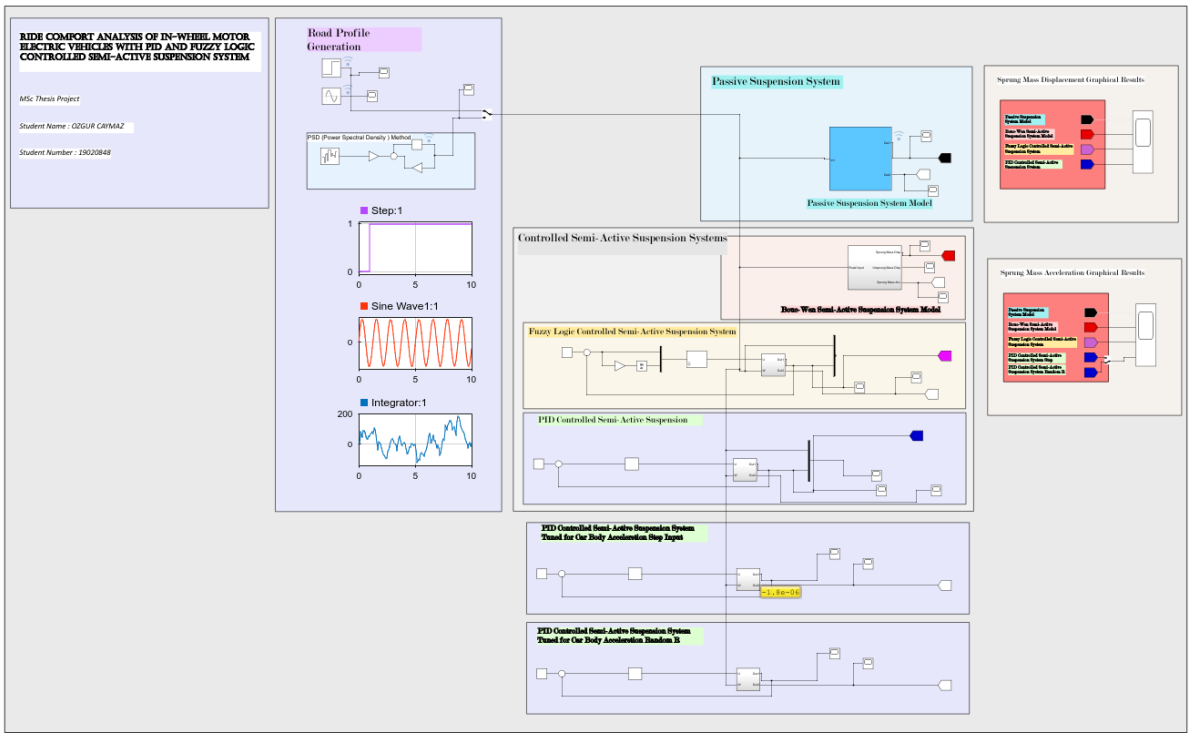
Appendices

Appendix A

MATLAB/Simulink Combined Model Scheme



Appendix B

Bouc Wen Model control loop MATLAB function script.

```
function V = fcn(err)
Vmax=10;
Vmin=1;

if(err>0)
    V=Vmax;

else
    V=Vmin;
end

end
```

Declaration Forms

MSc PROJECT ALLOCATION

Please complete this form and get your supervisor's signature to confirm that the specified project has been allocated to you. Your project must be directly relevant to your course.

This form must be scanned and submitted in the MSc Project Module Blackboard site.

PLEASE PRINT STUDENT NAME CLEARLY USING CAPITAL LETTERS ONLY

Student
Last Name: CAYMAZ
First Name: OZGUR

Course Title: MSc AUTOMOTIVE ENGINEERING

Proposed Project Title: Effects of In-Wheel Motors on Ride Comfort with Comparison of Active & Passive Suspension Systems

Health & Safety Concerns? **Yes /** **No** (please circle). If Yes, please specify:

_____

Ethics Concerns? **Declaration,** **Fast-track. Full applications** (please circle).

Brief indication if NOT **Declaration**

_____

Name of Supervisor: Dr. Abdul Waheed AWAN

Supervisor's Signature: A.W.Awan

Student Signature: OzgurCaymaz

RESEARCH ETHICS

Disclaimer Form

The following declaration should be made in cases where the researcher and the supervisor (where applicable) conclude that it is not necessary to apply for ethical approval for a specific research project.

PART A: TO BE COMPLETED BY RESEARCHER

Name of Researcher:	Ozgur Caymaz
School	Staffordshire University

Student/Course Details (If Applicable)		
Student ID Number:		19020848
Name of Supervisor(s)/Module Tutor:		Dr Abdul Waheed AWAN
PhD/MPhil project: ☐		
Taught Postgraduate Project/Assignment: ☒	Award Title:	MSc Automotive Engineering
Undergraduate Project/Assignment: ☐	Module Title:	ENGG71020-MSC PROJECT

Declaration

I/We confirm that the University's Ethical Review Policy has been consulted and that all ethical issues and implications in relation to the above project have been considered. I/We confirm that ethical approval need not be sought. I/We confirm that:

The research does not involve human or animal participants	☒
The research does not present an indirect risk to non-participants (human or animal).	☒
The research does not raise ethical issues due to the potential social or environmental implications of the study.	☒
The research does not re-use previously collected personal data which is sensitive in nature or enables the identification of individuals.	☒
Has a risk assessment been completed for this project?	☐ Yes ☒ N/A

Signature of Researcher:	OzgurCaymaz	Date:	21.04.2020
Signature(s) of Project Supervisor(s) (If student) OR Signature of Head of Department/ Senior researcher (if staff)	A.W.Awan	Date:	21.04.2020

NB: If the research departs from the protocol which provides the basis for this disclaimer then ethical review may be required and the applicant and supervisor (where applicable) should consider whether or not the disclaimer declaration remains appropriate. If it is no longer appropriate an application for ethical review **MUST** be submitted.

General Risk Assessment

Form

GENERAL RISK ASSESSMENT FORM			**Severity** multiplied by **Likelihood** equals **Risk Rate.** NB: Calculated after taking in to account existing precautions				
School/Service: Staffordshire University		Severity / Likelihood	Insignifi-cant (1)	Minor (2)	Moder-ate (3)	Serious (4)	Fatal / Critical (5)
Task/Activity/Area: Ride comfort simulation – Vehicle Dynamics		Almost Certain (5)	5	10	15	20	25
		Likely (4)	4	8	12	16	20
Assessed By: Ozgur Caymaz	Signature:	Possible (3)	3	6	9	12	15
Supervisor: Dr Abdul Waheed Awan	Signature:	Unlikely (2)	2	4	6	8	10
Date of Assessment: 24.04.2020	Review Date: 24-6-2020	Rare (1)	1	2	3	4	5

	Activity/Process/Machines	Hazard	Persons in Danger	Severity 1-5	Likelihood 1-5	Risk Rate	Measures/Comments	Result
1	Simulation Damage/Crash	PC Component Battery- Graphic Card Problems	No Person in Danger	2	2	4	Should be monitoring by User	A
2	Sitting long time on Chair	Back Problems	User	3	3	9	Should be monitoring by User Taking equal rest gaps	A
3.	Looking the Computer Screen Long time	Eye Straining Problems	User	3	3	9	Should be monitoring by User Checking Regularly Eye Health , Rest intervals	A