Active Vibration Control of an Automotive Suspension System using PID Controller

M.Tech. Thesis

By

Gaikwad Akshay Jagannath

Department of Mechanical Engineering

Indian Institute of Technology Indore

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Gaikwad Akshay Jagannath

Department of Mechanical Engineering

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Active Vibration Control of an Automotive Suspension System using PID Controller** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period from August 2020 to June 2022 under the supervision of **Prof. Anand Parey**, Professor, Department of Mechanical Engineering, Indian Institute of Technology, Indore

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Gaikwad

30/05/2022

Gaikwad Akshay Jagannath

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

Prof. Anand Parey

24th May 2022

Gaikwad Akshay Jagannath has successfully given his/her M.Tech. Oral Examination held on **24th May 2022**

Girish

01/06/22

Signature(s) of Supervisor(s) of M.Tech. thesis

Date: **24th May 2022**

Convener, DPGC

Date: **24th May 2022**

K. Eswara Prasad

Signature of PSPC Member

Dr. Eswara Prasad Korimilli

Date: **24th May 2022**

Signature of PSPC Member

Dr. Ashish Rajak

Date: **24th May 2022**

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Gaikwad Akshay Jagannath

Abstract

The suspension system is an important and the integral part of an automotive system. The purpose of suspension system is not just limited to supporting the weight of the vehicle body but also to improve the safety, ride quality and comfort by minimizing the effect of vibrations that gets transferred through it by the uneven road surface. When the vehicle is operating in a rough terrain the suspension system must not create large oscillations to prevent the vibrations to get transferred to the car body and it does then it must be eliminated as quickly as possible. Apart from safety and comfort, the vehicle handling is a major responsibility, without suspension system it would be difficult for the operator to control the vehicle since all the vibrations and shock gets transmitted to cabin without any damping. Hence the automotive suspension system has gained a lot of research interest in couple decades and it is still an area of interest in automotive industry due to the recent advancement in the industry and in the field of modelling and simulation.

Recent automotive suspension employs the passive type components that uses spring and damper with fixed design parameters only. Due to this limitation, it creates a conflict between two important aspects of good suspension system that is ride comfort and ride handling. Hence there exists a need to develop a system that can eliminate this constraint of passive suspension system. which is an open loop system.

The main objective this thesis work is to develop a closed loop feedback mechanism by implementing a controller-based suspension system. A computer-based modelling and simulation software is utilized to build and implement a PID controller in a passive suspension system to improve its overall performance.

A quarter car suspension model will be built in a MATLAB Simulink toolbox and a road hump as standard road disturbance will be used to simulate the model.

The simulation results will determine the performance parameters of the system such as sprung mass and unsprung mass displacement and acceleration, overshoot and settling time etc. With this results a conclusion can be established between the passive and PID controlled system which offers the better overall performance it terms of ride comfort, road holding and ride handling capabilities.

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NOMENCLATURE

Notations

A	Amplitude of vibration/ Height of road disturbance (m)
C_1	Tire Damping Coefficient (Ns/m)
C_1	Suspension Damping Coefficient (Ns/m)
de(t)/dt	Derivative error
e(t)	Error signal (output signal – input signal)
F	Actuator Force (N)
k_1	Tire Stiffness (N/m)
k_1	Suspension Stiffness (N/m)
Kp	Proportional controller gain
Ki	Integral controller gain
Kd	Derivative controller gain
Kc	Critical Gain
L	Length of the Hump (m)
m_1	Unsprung Mass (kg)
m_2	Sprung Mass (kg)
Pc	Period of Oscillations
T	Time Period (seconds)
t	Time (seconds)
Ti	Reset Time (seconds)
Td	Derivative Time (seconds)

u(t)	Control Signal
x_1	Unsprung mass displacement (m)
x_2	Sprung mass displacement (m)
$\dot{x}_1$	Velocity of upsprung mass (m/s)
$\dot{x}_2$	Velocity of sprung mass (m/s)
$\ddot{x}_1$	Acceleration upsprung mass $\left(\frac{m}{s^2}\right)$
$\ddot{x}_2$	Acceleration of sprung mass $\left(\frac{m}{s^2}\right)$
y	Road Disturbance (m)

Greek Symbols

ω	Angular Velocity (rad/sec)

ACRONYMS

DOF	Degrees of freedom
Hr	Hours
IRC	Indian Road Congress
ISO	International Organization for Standardization
km	Kilometres
LQR	Linear Quadratic Regulator
PID	Proportional, Integral and Derivative

Chapter 1

Introduction

1.1 Preface

The automobile is a combination of a variety of complex systems that interacts with each other during its operation. One such system which is considered as a substantial for the proper functioning of the automobile is a suspension system. In automobile vehicles the frame and body are not directly mounted on the front and rear axle but through some form of spring and shock absorber arrangement. This system of spring and shock absorber is called as suspension system. Key objective of suspension systems is to support the vehicle weight, good ride handling and to prevent the passengers in the vehicle from discomfort, fatigue and other health related issues arises from road disturbances.

Any suspension system includes multiple elements, some of which are flexible such as springs and dampers, while others are fixed such as wheel assemblies, linkages etc. The major elements of suspension system are shown in figure 1.1.

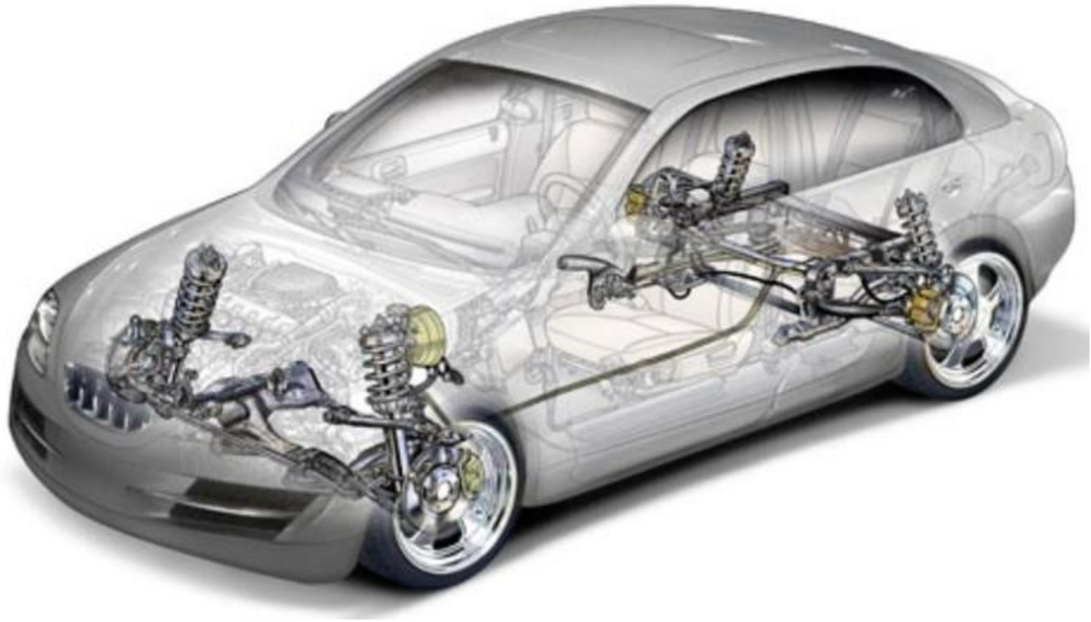


Fig. 1.1: Automotive Suspension System

Springs are the elastic components in the suspension system and have the capability to store the applied energy in the form of loads and deflections. The spring compresses and gets shorten in length to absorb the energy when wheel collides with the road obstruction by forcing it to squeeze. This stored energy by spring is then gets disbursed by extending to its initial shape. The energy freed by the spring is then converted into heat and it is then dissipated by the dampers. Dampers are nothing but the piston cylinder arrangement, filled with hydraulic fluid. It is used to minimize the undesirable bound produced by the springs and to ensure the wheel will always remain in interaction with the ground surface.

Automotive suspension systems are classified as: Passive, Semi Active and Active Suspension. This classification is totally based on its performance in terms of ride control, ride comfort by optimizing the parameters such as sprung mass and unstrung mass acceleration, its displacement, safety of passengers and damage to the suspension system.

1.2 Suspension Systems and its Control

1.2.1 Passive Suspension System

It is simplest form of suspension system widely used in the automotive vehicles. It consists of majorly two components springs and dampers. The energy storing component is a spring and energy dispelling element as damper. Both damping coefficient and spring stiffness coefficient is fixed in this system and hence used to achieve some form of concession between road handling, and ride comfort. Since none of them adds extra energy into the system is called as Passive Suspension system.

1.2.2 Semi Active Suspension System

The term semi active suspension system is coined in early 1970's by Karnopp [1]. It is most common and widely used in vehicles now a days. This system has the ability to accumulate, release and generate energy in the system [2]. It reduces the vibrations transmitted to the vehicle body by adjusting the damping parameters by using the closed loop control techniques [3]-[4]. Adjusting the damper parameters for its optimum values is termed as tuning of damper. The vibrations coming from the uneven road profiles that excites the sprung mass is fed to the controller which controls the damping parameter in such wat that the damping force is comparative to velocity as a time function. In this way semi active damping element functions.

1.2.3 Active Suspension System

The suspension system must sustain the entire vehicle enable the control during the ride handling and efficiently isolate the occupants for road disturbances. From frequency response study shows that for excellent ride comfort lower excitation frequency requires more damping and higher frequencies needs less damping. Hence a suspension system must operate in between these frequency range to obtain the better ride comfort and road holding ability. This system has the ability to manage the system values in demand to achieve the better riding performance. These settings of active suspension system can be changed depending upon the road conditions which cannot be achieved in passive system.

Although active suspension type is superior to the passive one but it adds more complexity to the system. It generally implements more sophisticated electronic devices such sensors, actuators and controllers. Hence the vehicles enabled with active suspension system are more costly and mostly found in luxury and sports vehicles only. This shows that the active suspension type has a large scope in designing low-cost systems and can be used in low as well as medium cost vehicles since it is related to passenger comfort and safety.

1.3 Controller

The active suspension type uses a force actuator to regulate the system parameters in a closed loop control system. The force actuator is a power-driven component that is used in a controller. The controller decides whether to increase or decrease the energy in the system by getting the input signal from the sensor. The sensor provides the information of surface condition to the controller [2].

Recently many control approaches are developed for the active suspensions such as LQR technique [5], adaptive sliding control [6], H infinity control technique [7], sliding mode [8], fuzzy logic [9], proportional derivative [10], nonlinear control [11] etc. Many controller techniques are available but the implementation of the method is depending on the individual performance and the complexity it added to system.

Fig. 1.2: Automotive Active Suspension System

A PID controller is also one such a controller technique that can be used in the automotive suspension system. PID controller is a device utilized in many industrial operations such as temperature and speed control, flow and pressure regulations and other process control variables. PID stands for Proportional, Integral and Derivative which is nothing but the mathematical technique to control the variables in a closed loop feedback instrument to control the variables. It is considered as the most precise and steady controller technique. Its feedback control loop is used to control the actual output as close to the desired output as possible. Hence PID controller can be studied and can be implemented in the active suspensions to control the suspensions parameters for better ride quality.

1.4 Aim of the Study

To develop a PID controller for a passenger vehicle quarter car system shown in figure 1.2 and to review the operation and effect of PID controlled passive suspension system to improvise the system performance by improving the ride comfort, safety and ride handling.

1.5 Objective of the Study

The key objective the thesis work is to conduct a study on effect of PID controller on the suspension system performance. A MATLAB Simulink based quarter car system is built to analyze the system performance for passive suspension and PID implemented suspension system. By implementing the PID controller the passive suspension system can be updated to active suspension type. A standard road hump shape is selected as per the road conditions and used as a road disturbance. The behavior of both the systems is checked by unsprang mass and sprung mass displacement and its acceleration. The same data can be further studied for ride comfort and vehicle road handling.

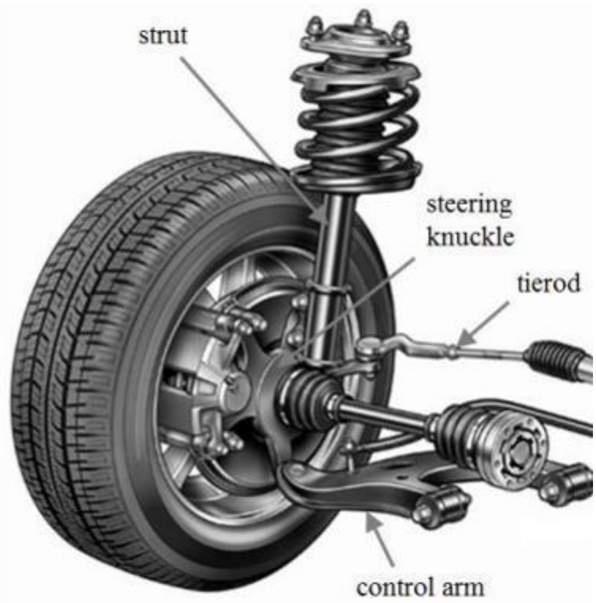


Fig. 1.3: Automotive Quarter Car Suspension System

1.6 Flow of Work

The steps involved in this study will proceed as firstly to study the automotive system layout and its sub functions such as engine, powertrain, suspension systems etc. The suspension system in then identified for a passenger vehicle and the first-generation design which is passive type is consider for fundamental analysis. Since to avoid the complexity a simple quarter car approach is used. From passive suspension system, the suspension systems parameters are studied and later used a standard bassline parameter for developing the PID controller.

The MATLAB Simulink toolbox is utilized to develop the computer simulation model of a quarter car suspension system for both Passive and PID controlled (active) suspension system.

Finally, a comparative analysis is conducted to review the performance of both the systems and the conclusions are made from the simulation results.

1.7 Thesis Outline

The research thesis work is outlined in the chapters as mentioned below. Firstly, the introduction is formulated it sections of preface which gives the overall background the research field, historic developments in the suspension system of an automotive vehicles. This gives the clear understanding of what types of suspension systems are there and what systems are currently used in the vehicles right now. From this information a problem statement is identified and formulated in the form of objective. The computational tools then identified that can be utilized to solve the problem. The outcome of this work is then proposed by properly defining the methodology of this work.

Chapter 2 summarizes the historic progress and the research carried out in the past to address the problems associated with the system. In this unit a well-structured literature study is done and produced in a sequential and logical manner to address the needs in the area of development of suspension systems. The use of controllers in the suspension system to improve its performance is reviewed. The input to system which is nothing but the road disturbance is taken from the standards.

Chapter 3 is focused on developing the methodology and approach to improve suspension system design by incorporating the controller in the passive suspension. The detailed simulation model of passive and PID controlled system in build in MATLAB Simulink tool. The standard road profile with an obstruction of a standard hump is utilized.

Chapter 4 is comprising of the results obtained from the simulation models. The details graphical representation of results produced for analysis purpose and explanations provided for those findings.

Chapter 5 concludes on the results and provides the way forward for this study in the form of recommendations. This section forms a base foundation for future work to be done.

Chapter 2

Literature Review and Problem Formulation

2.1 Introduction

The suspension system is an integral part of the automotive vehicles. The mail goal of this system is to support the vehicle mass over it as well as to isolate the body of vehicles. The suspension system is also designed to diminish the vibrational jerks reaching to the passengers and hence to avoid the discomfort and fatigue to the occupants. It also maintains the wheel and tire in proper place and ensures to preserve the directional steadiness while in operation.

The vehicle suspension system models are categorized into three types based on the study requirement and the area of interest. They are classified as quarter car, half car and full car models [13]. In quarter car model only the part suspension system mounted on a one wheel is consider for study purpose which supports the quarter part of the vehicle. The motion of suspension and wheel is simulated accordingly in vertical direction only. In half car, the half portion of the vehicle is used and either of rear or front wheels and suspension system is used for study of both vertical and angular motions. In full car approach, the entire vehicle structure is utilized and all the motions that can possible as shown in figure. 2.1 are simulated such as lateral, longitudinal, vertical, roll, pitch and yaw motions [14].

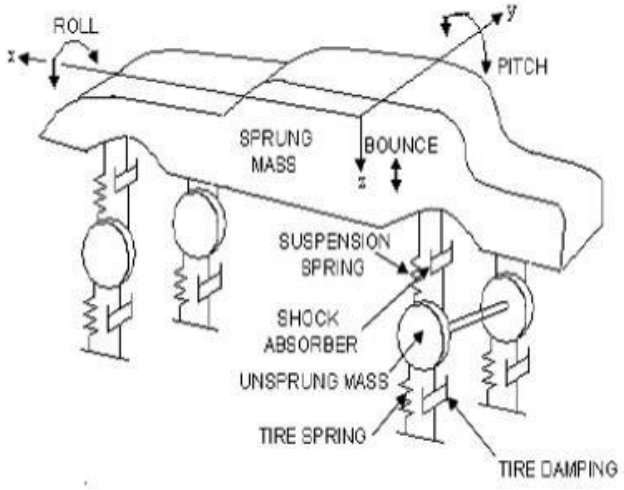


Fig. 2.1: Full Car Model with Motion in 6 DOF and Suspension System

2.2 Literature Review

Mitra et al. [15] has optimized passive suspension system by using the genetic algorithm technique to absorb vibrations as per ISO 2631-1:1997 standards. The genetic algorithm is based on natural genetics and natural selection. Reproduction, cross over and mutation are the three main principle of natural genetics used in genetic algorithm. The suspension system parameter such as spring stiffness, damping constant, tyre stiffness, sprung mass, upsprung mass values are optimized for better ride comfort. Four DOF Simulink model is built to study the system that include seat as well as driver body. After optimization it is found that road holding and driver head acceleration can be improved for comfort.

Bhuyan [16] has used the quarter car passive suspensions system and developed a half car and full car simulation model by extrapolating the quarter car model. The same models are utilized to further study the passive and semi active suspension system using skyhook spring and dampers to optimize the system performance. The state space model is prepared in Simulink and pulse generator to give input to the system. The study shows that adding skyhook system in a full car gives better response and reduced the excess vibrations.

Chavan et al. [17] simulated the passive suspension model to study the non-linearities in the system that can hamper the performance of the system. Quarter car system is built in a MATLAB Simulink software as well as experimental set up carried out and nonlinearities in the spring and damper are studied. The simulated results and experimental data show clear match between the results and the chaotic response present in the nonlinear system.

Hassan [18] used the quarter car model with passive system and evaluated the sprung mass acceleration and displacement for various car speed and damping values. In this study he proposed the that the car speed should not be more the 6.75km/hr for better ride comfort over a circular hump. It shows that car suspension parameters can be tuned in such way that it can offer better performance.

Prasad and Shirahatti [19] studied the effect of hump profile on suspension system with four DOF system. It shows that there exists a safe speed limit for vehicle to pass over the hump. If the speed is higher than that then the passengers will have uncomfortable ride. The safe speed found out to be 25 to 40km/hr with having the tyre force of 4200N and 5000N for front and rear wheel.

Hassan [20] used different type of miniature bumps in order to study the ride quality with a constant car speed. He suggested the different speed values for various bumps for rider comfort. The system is analysed on a novel harmonic hump.

Kanjanavapastit and Thitinaruemit [21] carried out this work to estimate the speed hump profile such that it can avoid the accidents. It proposes method the determine the hump profile using the quarter car model. They implemented the accelerometer to detect the movement of sprung mass and unsprung mass in order to get hump profile in height versus time. The results show the profile can be simulated correctly.

Cho et al. [22] analysed passive suspension system using a quarter car model with and without considering the tire damping for two and three DOF system. They used various tire damping rations with these systems and suggested that ride quality and comfort can be better when tire is having some damping capacity.

Desai and Kale [23] has done a detailed review work on suspension systems of the automotive industry. They have shown cased the suspension system development throughout the years to achieve better performance. Their work also highlights various suspension system types such as quarter car, half car, full car models, suspension system types such as passive, semi active and active suspension system. Semi active suspension uses controlled dampers while active type uses controller technique to achieve the desired properties.

Poynor [24] has proposed an innovative design semi active damper i.e., magnetorheological damper (MR damper). He has carried out a design work on gun recoil of MR dampers and also tested the MR dampers used in automotive applications.

Sánchez [25] developed a robust control method to determine the car mass using quarter car model passing over road disturbance. He developed an algebraic estimating method to find out the car mass. Linear mathematical model used to design sliding mode controller to achieve the passenger comfort.

Agharkakli et al. [26] did a comparative analysis of passive and active type suspension system using quarter car. Linear Quadratic Regulator (LQR) controller is developed for active system. The suspension travel in LQR based active system is found to be half of the passive system. MATLAB tool is used to design the controller and system models.

Almadrahi and Ewad, [27] conducted a study to compare the steadiness of semi active suspension system by designing the controller based on LQR and PID technique. Magnetorheological damper is used with a controller on quarter car model build in MATLAB Simulink environment. The study that both the controller performed well by providing good road handling and comfort. Semi active system with controller able minimize the rise time, settling time, overshoot and strung mass movements.

Jamil et al. [28] conducted a review on semi active system and the implemented the PID control approach in it to further improved it performance. MATLAB Simulink model of quarter car is built with a variable damping and it is managed by PID controller. The controller approach improves the system performance.

Sharkawy et al. [2] used PID based control system for an active suspension model in the Simulink tool and step input is consider as a road disturbance to simulate the suspension system. The study shows that by using PID controller in the system ride comfort and road handling ability of the suspension system can be improved for passive system.

Mouleeswaran [29] developed a PID controlled technique for active suspension system. Quarter car type having two DOF is modelled. Hydraulic dynamics also taken into consideration and the PID parameters are derived for Ziegler Nichols method to fine tune the PID controller. The system has a better and improved performance for passive system.

Mohd. Avesh and Rajeev Srivastava [30] investigated the half car model and use of PID controller in the system to improve performance of system. In this, Simulink model is prepared for half car design and PID added in the system. The PID parameters are tuned manually by looking at each action of the controller such as proportional gain, integral and derivative terms. Proper tuning of PID controller gives better performance by minimizing the sprung mass displacement, overshoot settling time etc.

Patel and Gundaliya [31] have done an extensive study on speed breakers. The speed breakers are also called as traffic calming devices and used to manage and control the traffic. In this study various traffic calming devices are studied to minimize the risk of accidents and crashes. Different speed breakers such as humps, bumps, speed cushions and their advantage and problems associated with them are discussed.

Mohanty et al. [32] reviewd the operational effects of speed breakers in the smart city. The study found that although there are standard available for the speed breakers, but they are not flowed properly. They found that there are numerous variations in the size and shape of speed humps. The study suggested that the traffic calming measures should be built as per standard codes for better utilization.

2.3 Historical Background

2.3.1 Suspension System

In the history of modern automobile, in 1901 which was consider as a beginning of rapid development in the world of automobiles, the first shock absorber was fitted in Mors Machines in Germany which was nothing but the damped suspension system [34]. With this extensive development in the automobiles, the suspension systems design has a lot of problems that needed to be addressed back then such as noise, friction etc.

In 1920, the suspension system equipped with torsion bars developed by Leyland. The most common suspension system back then was independent front suspension was created on Lancia Lambda. The inventor Albert Hotchkiss later developed the rear axle suspension system which called Hotchkiss drive [34].

The automotive suspension system is broadly classified into two ways, one is conventional and other one is advanced. The passive suspension system is a conventional while semi active and actives suspensions are advance in nature [35]. In active suspension system, an externally acting force is generated by the system itself the either to absorb or to release the energy generated when vehicle moving over a rough terrain. This suspension force is generated by the electronically controlled actuators such as pneumatic, hydraulic or magnetorheological [36].

2.3.2 Types of Suspension Systems

The suspension systems are distinguished as Passive, Semi Active and Active suspension systems and are explained as follows.

1. Passive Suspension System: It is a simplest form of suspension systems and it is still used in many automotive vehicles till today and it is an open loop system. It mainly consists of two components springs and dampers. The spring stores the energy while damper dissipates the energy. When the vehicle runs over a road disturbance the spring gets compressed and stores the energy until the external load is equivalent to the spring compression load. Once it is removed, the spring oscillated the attain the original shape. This energy produced the oscillations of spring is then absorb by the dampers to attain stable state within a short period of time.

In passive suspension design, the spring stiffness constant and damping value are fixed and hence it is not suitable for random road profiles since the system parameters cannot give better performance for all the uneven road disturbances. This is the major drawback of this system [32].

A decent suspension system design must deliver a better ride comfort and ride handling which is a very basic expectation from any suspension system. There are two types of disturbances acting on the any vehicles are road and load disturbances. Road disturbances such as on hilly road with has high amplitude and low frequency whereas on a rough terrain where amplitude is small but frequency is high. Load disturbances are nothing but the forces acting on the vehicle while accelerating, braking and cornering. Hence a good suspension system should be soft for road conditions and hard for loads acting on it. A heavily damped system is good for ride handling while lightly damped system gives better ride comfort but it compromises in the ride handling. Hence this suspension system is always a negotiation between the ride quality and ride handling as mentioned in figure 1.5 [29].

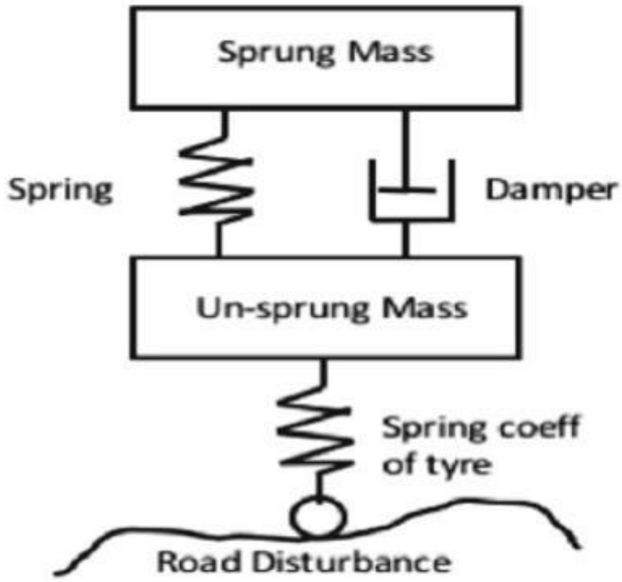


Fig. 2.1: Passive Suspension System

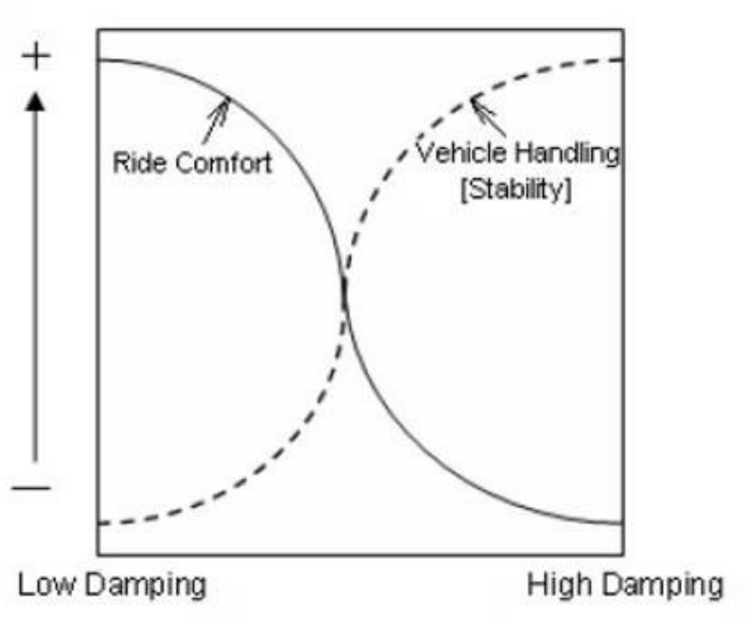


Fig. 2.2: Performance criteria of Passive Suspension System

2. Semi Active Suspension System: This is a better and advance version of passive suspension system. Unlike passive suspension system, in semi active type, the spring stiffness is constant damping coefficient is kept variable and is utilized to control the suspension setting to achieve the improved performance in terms ride quality and comfort.

In this the damper is capable of dissipating the power at a continuously variable rate and can handle random unevenness of the road effectively. It can be remotely operated by electronic devices to soften or harden the suspension system as per the road conditions and hence can be consider as a closed loop control system [29]. This type of suspension system has high performance with low cost, weight and energy consumption [32].

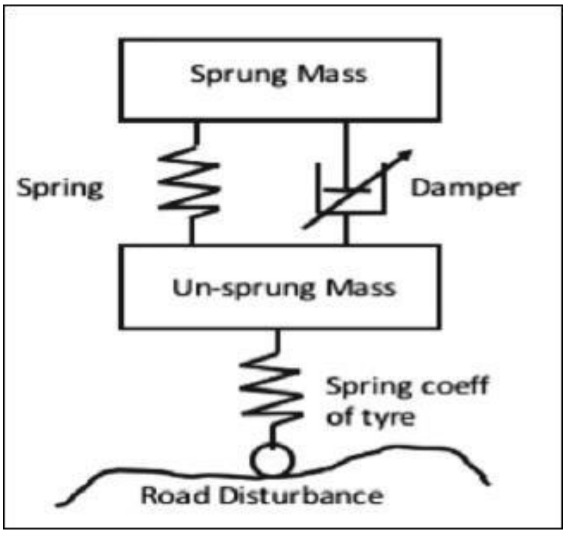


Fig. 2.3: Semi Active Suspension System

Below figure 2.5 shows the electromagnetic (magnetorheological) damper used in automotive suspension systems.

3. Active Suspension System: In Active suspension system, the name suggests it is actively managed in order to minimize the vibrations acting on it. Rather than just dissipating the energy out of it, it can add extra energy into the system to control and manage the dynamics of the vehicle by implementing the electronically controlled actuators, sensors and controllers as shown in figure 1.6. The spring and damper are a passive part while controller is an active member of system. If these two parts are connected in parallel then it is called high bandwidth configuration and if those are in series it is called low bandwidth configuration. High bandwidth system is able to handle the higher frequencies and it acts as a passive system when actuator is now working actively [29].

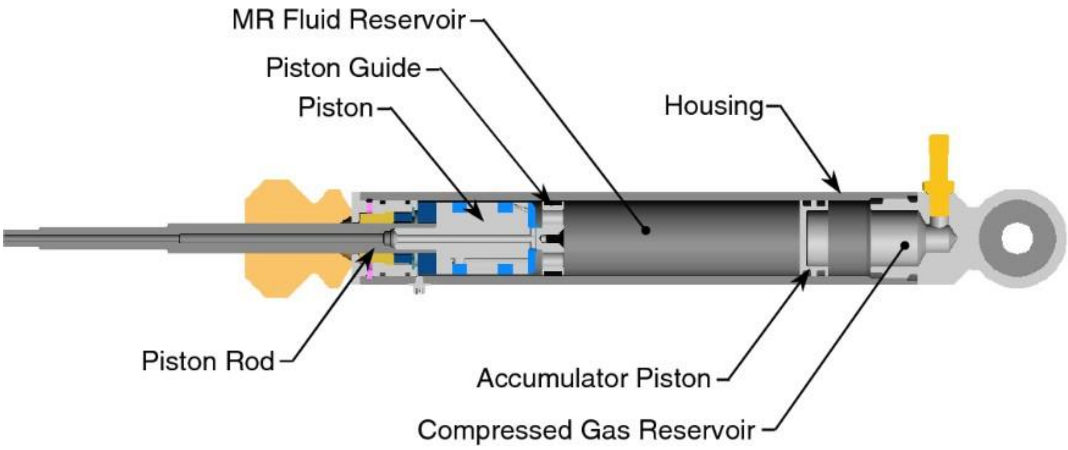


Fig. 2.4: Mono Tube MR Damper

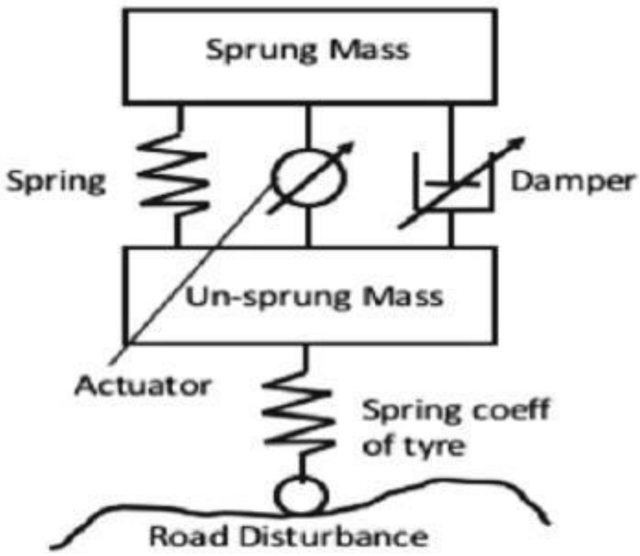


Fig. 2.5: Active Suspension System

The active suspension system contains an extra controlling element that which is an actuator which is controlled by a sensor using the closed loop feedback mechanism. The electronically controlled sensor, actuator and controller provides the necessary suspension force in the system to eliminate the external vibrations. Hence, this system provides the better ride and handling performance. But due to its intricacy, cost and energy necessities, it is mostly used in luxury, sport and high-performance vehicles only [32].

Comparison Parameters	Active	Semi Active	Passive
Spring	Controlled	Uncontrolled	Uncontrolled
Shock Absorber (Damper)	Controlled	Uncontrolled	Uncontrolled
Spring Coefficient (Stiffness)	Varied	Fixed	Fixed
Damping Coefficient	Varied	Varied	Fixed
Cost	High	Moderate	Low
Time of Response	Slow	Fast	-
Performance	High	Moderate	Poor

Table 2.1 Comparison between Active, Semi Active and Passive Type Suspension System

2.3.3 Elements of Suspension System

The main two components of any type are suspension system are springs and dampers.

1. Springs: Springs acts as a resilient component in any suspension system. It absorbs the shock energy via oscillations coming onto it due to the external excitation caused by the road disturbance. This stored energy of oscillation sis then converted into heat and released accordingly. Springs absorbs the shock energy and releases it slowly to provide the better ride comfort and to avoid the jerks. Commonly used springs in the automotive vehicles are as follows:

Leaf Springs: Leaf springs are the critical part of suspension system. It consists of number of layers of steel strips or laminates with gradation their size. The larger leaf is placed on top the layers. They are attached directly onto the frame either at one end or at both ends. They are further classified as longitudinal and transverse leaf springs as per their use.

Coil Spring: It is a spiral shape steel coil used in both front and rear suspensions systems. In most of the vehicles the spring coils are equipped with hydraulic shoch absorbers as shown in figure 1.7. Mostly it is used is light vehicles only.

Air and Gas Springs: This type is springs uses compressed air or gas filled in a cylinder or a bellows. When the tire passes over road obstruction, the air or gas inside the cylinder of bellow gets compressed and eventually expands to attain the stable state by absorbing shock energy [40].

Torsion Bars: It is a solid steel rod as shown in figure 1.7, directly attached the chassis of the vehicle at one and another end is free to move. When the load is applied to it because of some external excitation the rod resists the twisting moment and minimizes the shocks.

Rubber Springs: Rubber material can store more energy as compared other springs with respect its mass. It works on a principle of compression and shear and hence can be directly used as suspension member or can be used with springs to improve the suspension performance [42].

Fig. 2.6: Leaf Spring

Fig. 2.7: Coil Spring

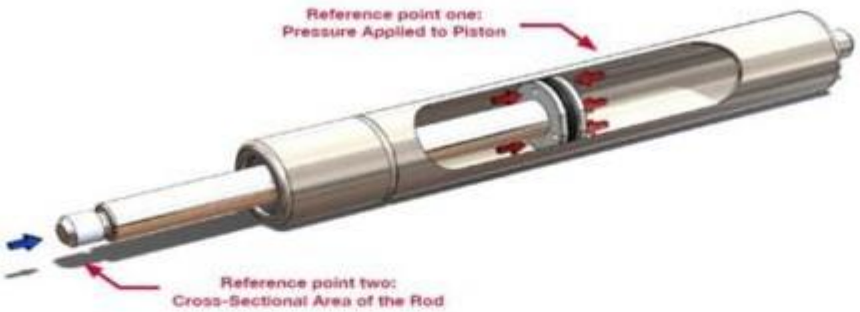


Fig. 2.8: Air / Gas Spring

2. Dampers: Dampers are used to engross the shock vibrations from the bumpy road by slowing down the spring oscillations in a short period of time.

3. Shock Absorbers: Each wheel of a vehicle is equipped with the shock absorber mounted on suspension and chassis. It helps to minimize the spring and wheel oscillations, so that the tyre cannot lose the hold of the ground.

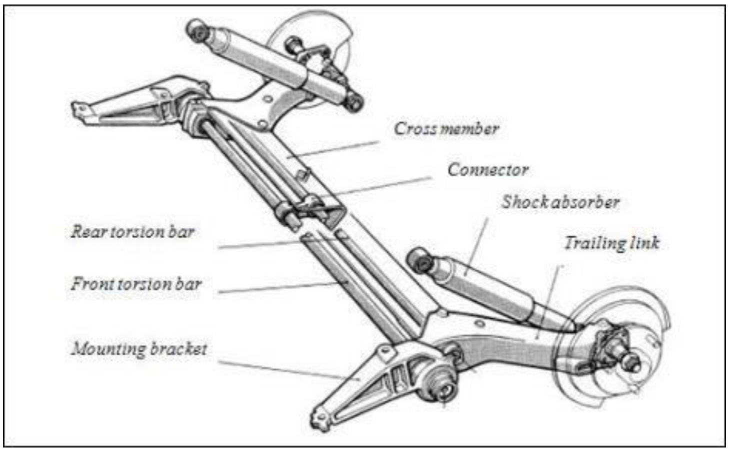


Fig. 2.9: Torsion Rod

Fig. 2.10: Rubber Spring

Fig. 2.11: Shock Absorbers

2.4 Closed Loop Feedback Control Technique

Closed loop feedback system is a technique in which the systems output is checked and monitored. If the system deviated from the desired output value, then an error signal is generated and fed to the controller to make corrections in the input to achieve the targeted output. This permits system to eliminate error and minimize response time. PID controller does the same when added in the system.

The main aim in feedback loop system is to correct the error. To do so, some specific parameters must be cross checked and minimized to attain stable output. Below figure 2.11 shows the response properties.

Rise Time: It is a time taken by system to move from 10 to 90% vale of input signal.

Overshoot: Maximum high value reached when an error signal is generated.

Settling Time: Time taken by output response to reach to 2% band of steady state value.

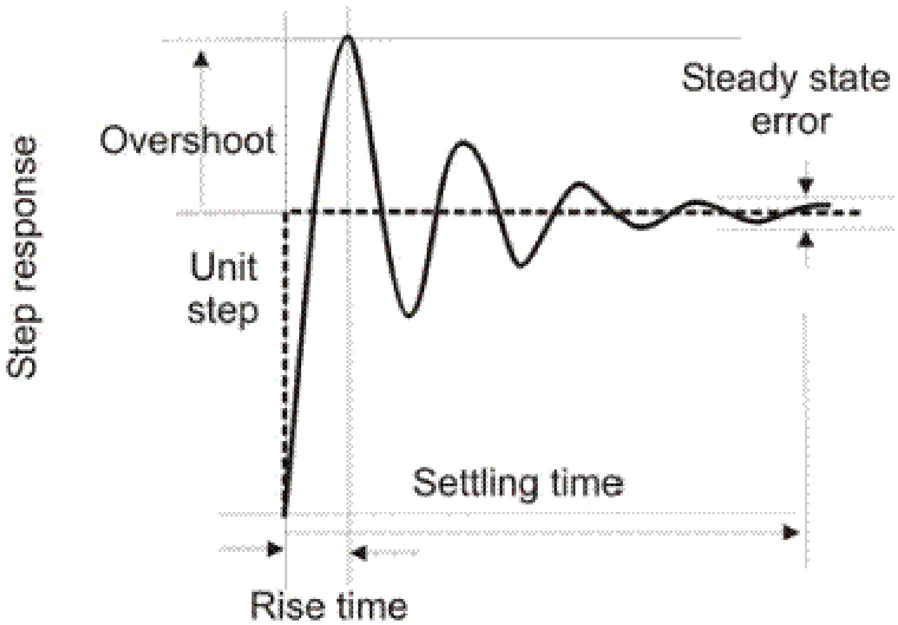


Fig. 2.12: System Response Properties

Steady State Error: The error variation between the actual output value and desired output value.

2.5 History of PID Controller

Elmer Sperry created the primary version of the PID based controller in 1911. The Taylor Instrumental Company (TIC) released an initial pneumatic controller having fully adjustable proportional controller. Up next, control system designers worked on to eradicate the steady state error which is nothing but the error between the calculated value of the process and the anticipated set value. Till the error is non zero, the controller tries to reduce the error by altering the method control inputs seen in proportional controllers by measuring the point of some arbitrary value. The proportional integrator controller was created after rearranging integrated value. The first pneumatic controller with a derivative action was invented by TIC in 1940, which addressed the overshooting value. In 1942, engineers were able to set the correct criteria for PID controller when Ziegler Nichols tuning criteria was developed [45].

2.5.1 PID Controller

The PID control technique is almost used everywhere in the industrial control and process automation. The PID originated from Proportional, Integral and Derivative terms, it is nothing but the action of the controller taken on the output signal in the form of error signal to control the process output as per the desire set point. They are quite robust in nature and also stable in operation. PID controller does very fine work for slow speed rate operations with minor or no instabilities, however the performance degrades on an adverse environment. Unlike other controllers their versatility and simple operation kept then in the relevance in process and automation industry for quite some time [45].

PID controllers are designed to eliminate the error from the output signal with its controller action by continuously monitoring the output signal. Its derivative action is used to reduce the error. Consider a set point to be measured, then error is called as difference between the set point and measured value. (Error) = (Set Point) – (Measured Value), is then adjusted accordingly and forwarded to the systems input in demand to achieve the desired output from the system [29].

The modes of operation of PID controllers are as follows:
1. Proportional (P) Action: This action contributes to the instantaneous error signal obtained for measure output value. It takes the error, multiply it by Kp and later add it to input signal. value. It reduced the rise time and steady state error but increases overshoot. It can control the unstable process parameters with partial performance and non-zero steady state faults. With this action there exist an offset in the system.

2. Integral (I) Action: This action provides the controller output in proportion to the error received. This action collects all the errors, integrate it and then multiplies by Ki. The reduces the steady state error, but increases system oscillations and speed of response. It helps the proportional action to further reduce steady state error. This mode achieves the system inversion to zero frequency. This makes the system to eliminate the offset i.e., steady state error to zero. Controller output = (1/Integral) (Integral of) e(t) d(t).

3. Derivative (D) Action: This is comparative to the rate of variation of measured value or error and it is premeditated by rate of change of measured value with respect to time. This action takes care of change in measurement in rapid way than proportional action. When target value changes, derivative controller sends out a control signal to achieve the set point by taking derivatives of error and multiplying by Kd. Derivative action is imparted to improve the overshoot, rise time and settling time of the system [29].

Since the PID controller is deals with the error signal, it largely depends on the appropriate tuning the of the controller and sensors which is a closed looped feedback control system**.** The working equation of PID controller is expressed as follows:

$$\mathrm{u(t)} = k_p\, e(t) + k_i \int e(t)\, dt + k_d \frac{d}{dt} e(t) \tag{2.1}$$

A PID control system implemented in a vehicle suspension system is as shown in below figure. 2.12.

The desired system parameters can be achieved by fine-tuning the three parameters i.e., Kp, Ki, and Kd. This can be done by using iterative method or by using the Ziegler Nichols tuning criteria. The Kp value provides the stability in the system, Ki eliminated the disturbances in the system and Kd provides damping of shaping the response signal [2].

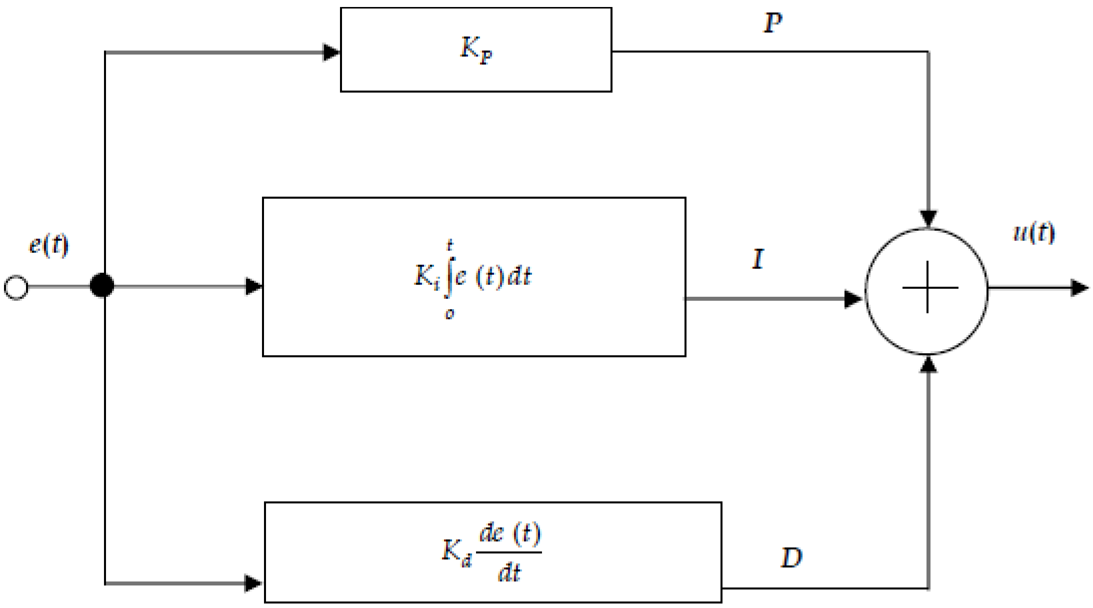


Fig. 2.13: PID Controller

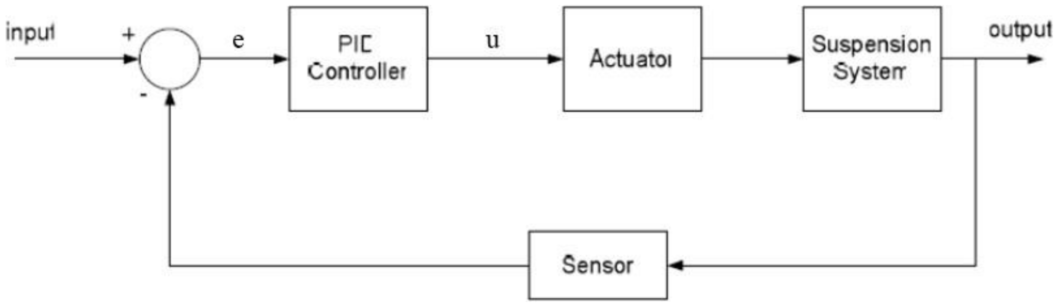


Fig. 2.14: Block diagram of suspension system using the PID Controller

Response	Rise Time	Overshoot	Settling Error	Steady State Error
Kp	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Eliminate
Kd	Small Change	Decrease	Decrease	No Change

Table 2.2: Characteristics of PID Controller

2.5.2 Tuning of PID Controller

The procedure of choosing the optimal parameters of PID gains to optimize the system is called tuning. There are mainly two methods for that iterative method and Ziegler Nichols Method.

In iterative or trial and error method, the proportional term is increase in such way that the system starts to oscillate by keeping integral and derivative terms to zero. This makes the system faster but higher value may create instability. Once proportional gain is decided, then integral gain is supplemented to break the oscillations. Integral term diminishes steady state error but rises overshoot. Hence, this term is attuned to achieve minimum steady state error. Once proportional and integral terms are secure, derivative term is added in the system to diminish the overshoot and for stability.

Ziegler Nichols method, which is quite comparable to trial error method the parameters are calculate from formulas shown in table 2.3. By keeping integral and derivative term to zero, proportional term increased to oscillate the system. Once oscillations start, the period of oscillation and critical gain noted. The PID parameters are the calculated.

Control	P	Ti	Td
P	0.5Kc	-	-
PI	0.45Kc	Pc/1.2	-
PID	060Kc	0.5Pc	Pc/8

Table 2.3: Ziegler Nichols PID Tuning Parameters

2.6 Road Profiles and Road Disturbances

The roads are intended in a precise manner to meet the movement requirements. But in some cases, the speed regulations must be applied in order to slow down the vehicles such as near schools, hospitals, residential areas etc. and also to manage traffic. Hence the roads of different categories are designed and planned accordingly. Certain practical measures are implemented on the roads to improve traffic movement with better safety and convenience.

Hence Traffic calming measure are used to decrease the vehicle speed and volume of vehicles on the road to increase the safely [31].

Speed Breakers

Speed breakers are used to minimize the speed of the vehicles and it helps to maintain the constant of flow of vehicles. It also helps to manage the traffic situations. Since it serves the purpose, the next step is to design the speed breakers so that is can be utilized in an efficient way as per the need. The design parameters such as profile, height, gradient, length and sometime material used in the design. Since they are slightly uplifted for the rod surface, it indicated the drivers to slow down the vehicle in demand to avoid the jerk and sometimes damage to the vehicle. Also, the good thing about the speed breakers are they are easy to install or build with minimum cost [33].

Humps are a type of speed breakers are commonly used in most of the road conditions and used as a traffic calming solution. Humps and Bumps are two different types of speed breakers and they are differentiated according to their design [19]. Speed humps are elevated from the road and spread across some portion of roadway as shown in figure 2.12. They are typically circular, sinusoidal or trapezoidal in shape as shown in figure 2.13 and gentle on the form as compared to bump [18].

As per the standards led by Indian Road Congress [33], the standard design of the speed hump profile should be 0.1m in height, 3m in chord length for the minimum speed of vehicle 20km/hr [32] passing the it as shown in figure 2.15 and must be painted with white zebra stripes on it as shown in figure 2.12.

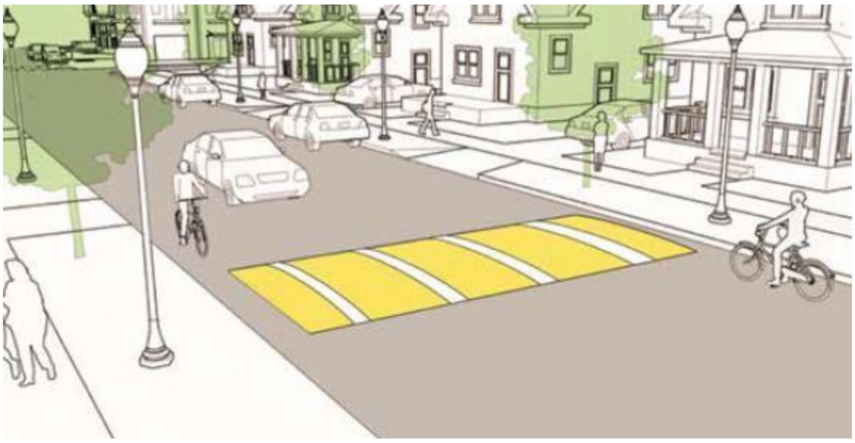


Fig. 2.15: Circular Hump – Shape of a Circular Arc

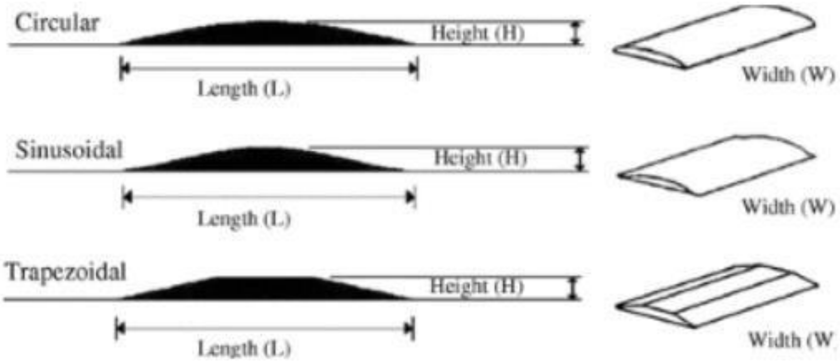


Fig. 2.16: Types of Speed Humps

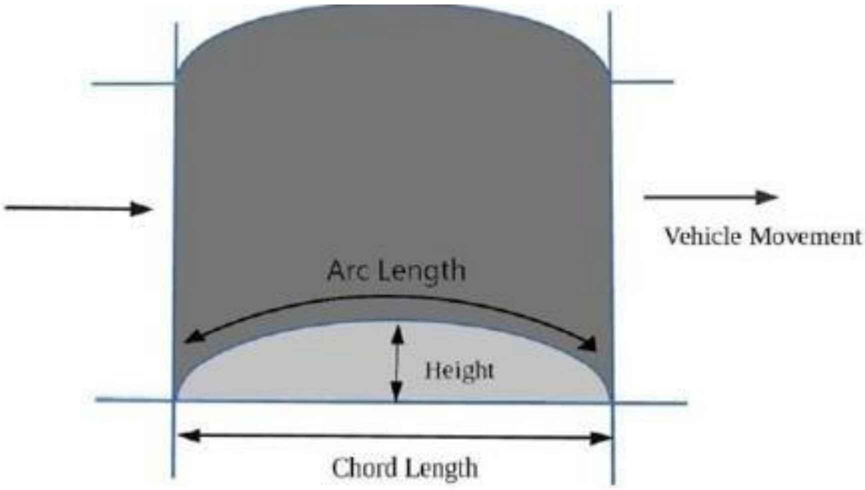


Fig. 2.17: Technical Specification of IRC99 - 2018 Speed Hump

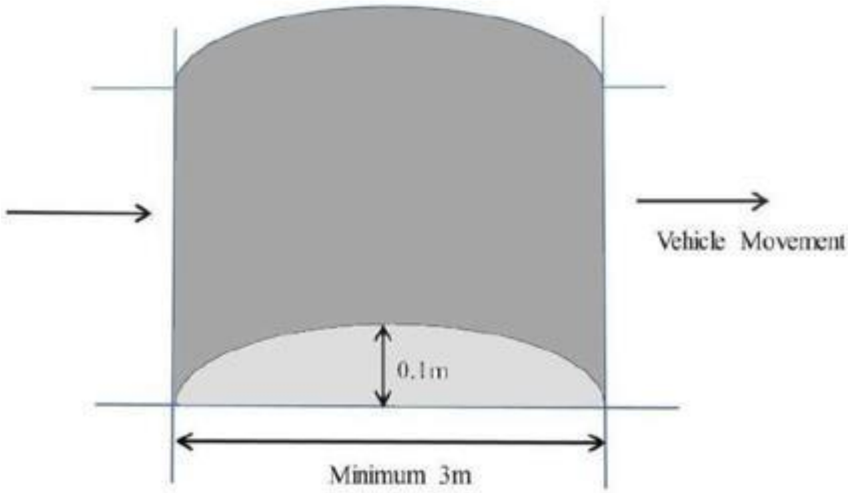


Fig. 2.18: Design Specification of IRC99 - 2018 Speed Hump

2.7 Problem Formulation

The available literature guides through the development of automotive suspension system from the beginning of modern automobile development to the recent research work going on around the world. Since passive suspension system is still common in many vehicles although they are not efficient as other counterpart. They are less complex, easy to install, repair, service and also low in cost and hence widely used.

Passive suspension system is fixed system and its performance parameters cannot be adjusted in real time. Hence there always exists a negotiation between ride quality and ride control in passive suspension system. The semiactive suspension system offers improved performance that passive system by adjusting its damping values during the operation but it is not actively controlled. In active suspension system it is actively manage by electronic devices hence offer best in class experience. They are a complex system itself and hence found only in high performance and luxury cars.

Hence to take this study forward, initially a passive suspension system will be identified with its suspension parameters. The model will be then simplified into a quarter car model to avoid complexity. MATLAB Simulink tool which is most commonly used to perform this study is considered for future work. The performance of passive system will be analysed to select the optimum petametres for spring stiffness and damping coefficient.

The road disturbance which will be used to simulate the system is referred form the standards. A standard hump profile created using sine function will be created. The design specification of the hump and the desired vehicle speed passing over it will be collected from the standard documentation and research papers.

A PID based controller will be then implemented into the passive system to study the performance of it. The required controller parameters will be decided based on iterative methods and by using the in built PID tuner in MATLAB Simulink.

The performance of both the systems with and without controller will be studied and the research work will be then concluded with the results obtained from the simulation models.

Chapter 3

Methodology

3.1 Mathematical Modelling

A quarter car system approach is utilized to study the suspension system response because of its simplicity. Although, it looks simple and less complex but it has a potential to capture many useful and insightful characteristics of the full car configuration. The quarter car type is sufficient enough to verify and validate the suspension system.

Figure 3.1 shows the passive suspension system. Wheel and tire assembly on a quarter portion is consider as unsprung mass while the cabin of the vehicle is supported on a spring and damper is called sprung mass.

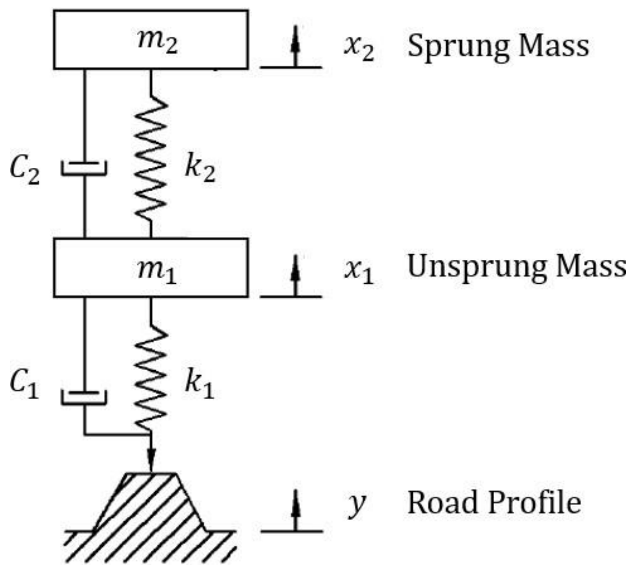


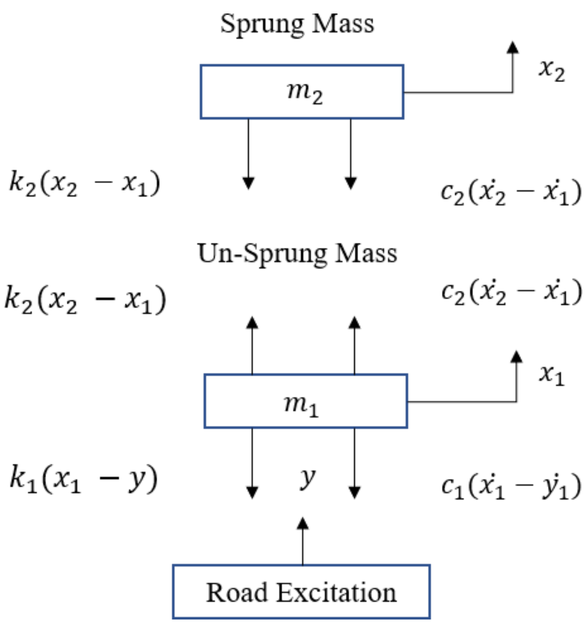
Fig. 3.1: Passive Suspension System of a Quarter Car

The assumptions made to derive the mathematical model of a system are:

1. Two DOF model consider for the analysis is assumed to be linear. The non-linearity associated with the system such a linkage, joints etc are neglected.
2. The tire is having both damping and stiffness properties and tire maintains the contact with road all the time.

3. Suspension spring stiffness and tire stiffness values are linear over the working range.
4. Friction and gravitational forces are assumed to be negligible.

Newton or Euler–Lagrange method is used to derive the dynamic equation of a system [25]. The dynamic motion equation for passive suspension system can be formulated using free body diagram as shown below.



$$m_2\ddot{x}_2 = -c_2(\dot{x}_2 - \dot{x}_1) - k_2(x_2 - x_1) \tag{3.1}$$

$$m_1\ddot{x}_1 = c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) + c_1(\dot{y} - \dot{x}_1) + k_1(y - x_1) \tag{3.2}$$

The passive system can be converted to active system by implementing the actuator in line with the spring and damper. The schematic diagram below shows the placement of actuator in passive suspension system.

The dynamic equation of the above system can be written as follows,

$$m_2\ddot{x}_2 = -c_2(\dot{x}_2 - \dot{x}_1) - k_2(x_2 - x_1) + F \tag{3.3}$$

$$m_1\ddot{x}_1 = c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) + c_1(\dot{y} - \dot{x}_1) + k_1(y - x_1) - F \tag{3.4}$$

The PID controller used in the above system is tuned in such way that it provides the actuating force in the system to minimize the impact of road disturbances on vehicle body so that the jerks cannot reach to passengers.

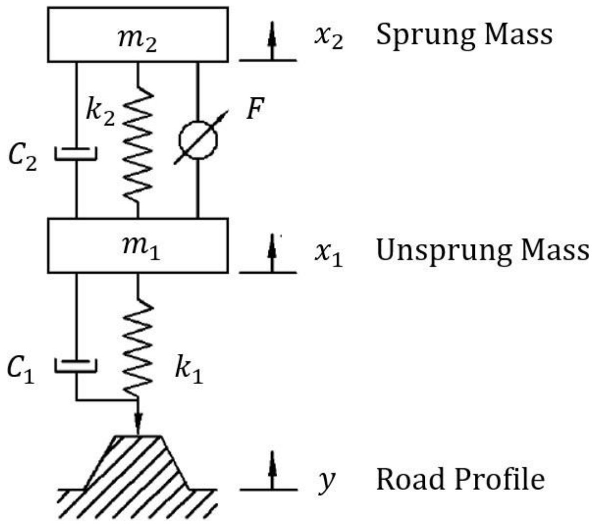


Fig. 3.2: Active Suspension System of a Quarter Car with an Actuator

3.2 System Modelling

3.2.1 Suspension System Parameters

A 2 DOF quarter car type is used for modelling and simulation. The stiffness of tire and also the damping offered by tire is also taken into consideration. Cho et al. [22] conducted a study to check effect of tire damping on suspension system performance. It is observed that tire damping value improves the overall performance of system. Hence a suspension system is selected by taking tire damping into the consideration. The suspension system parameters are given in below table 3.1.

Sr. No.	Parameter	Value	Unit
1	Sprung Mass	275	Kg
2	Unsprung Mass	27	Kg
3	Suspension Spring Stiffness	150000	N/m
4	Tire Stiffness	310000	N/m
5	Suspension Damping Coefficient	1150	Ns/m
6	Tire Damping Coefficient	3100	Ns/m

Table 3.1: Suspension System Parameters

3.2.2 Road Disturbance Model

There are numerous road disturbances can be observed while driving a vehicle that may be continuous or discrete. Continuous disturbances are rough terrain, rough road surface with high undulations. The discrete type may include speed breakers. When vehicle travels over a speed breaker with high velocity then it may act as a road disturbance.

To simulate the road disturbance a hump profile from available standards [33] is selected, which can be represented by a sine wave function. Consider a speed of vehicle as 20km/hr [32] then to replicate a hump as sine function below calculations are performed.

Hump Profile i.e., Half Sinusoidal Wave

Vehicle Speed = 20 km/hr = 5.55 m/s

Length of Hump, L = 3m

Time required by vehicle to pass over hump, T = 0.54 sec

Time Period of Sine Waveform, 2T = 1.08 sec

Road disturbance, $y = A\sin(\omega t)$

$\omega = 2\pi/2T = 5.82$ rad/sec

Hence, hump profile will become, $y = A\sin(\omega t) = 0.1\sin(5.82t)$

The MATLAB based programming code and the simulated profile is shown in figure below.

Editor - Block: Quarter_Car_2DOF_Half_Sin_Hump/MATLAB Function*

MATLAB Function*

```
function y = fcn(u)
%#codegen

if ((u >0) && (u < 0.54))
    y = 0.1*sin(5.82*u);
else
    y = 0;
end
```

Fig. 3.2: MATLAB Code for Hump Profile

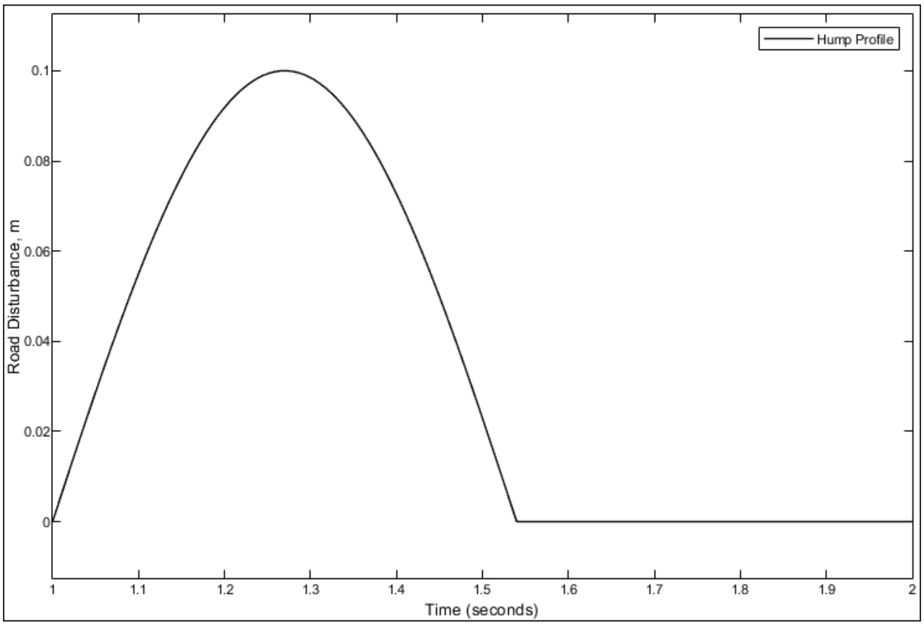


Fig. 3.3: Hump Profile

3.2.3 Modelling of Suspension System in MATLAB Simulink

1. Passive Suspension System

Passive model is based on the system dynamic equation derived from equation 3.1 and 3.2. The Simulink model which is built is an open loop model.

Figure 3.4 shows the schematic diagram of MATLAB Simulink based passive suspension system.

2. Passive Suspension System with PID Controller (Active Suspension System)

When a passive system is equipped with a PID controller it senses the road disturbances and provides additional force input in the system to nullify the disturbing force through actuators. A PID controller with sensors and actuators forms feedback mechanism to deliver the right actuator force in the system. Figure 3.5 shows the PID controlled suspension system.

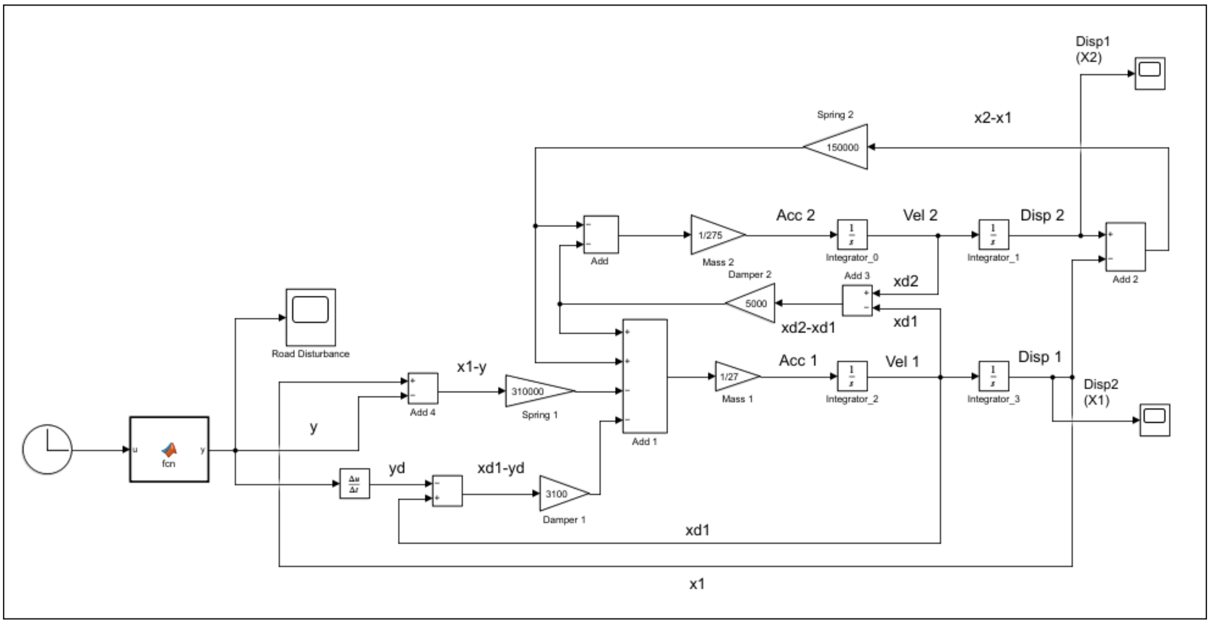


Fig. 3.4: MATLAB Simulink Model Passive Suspension System

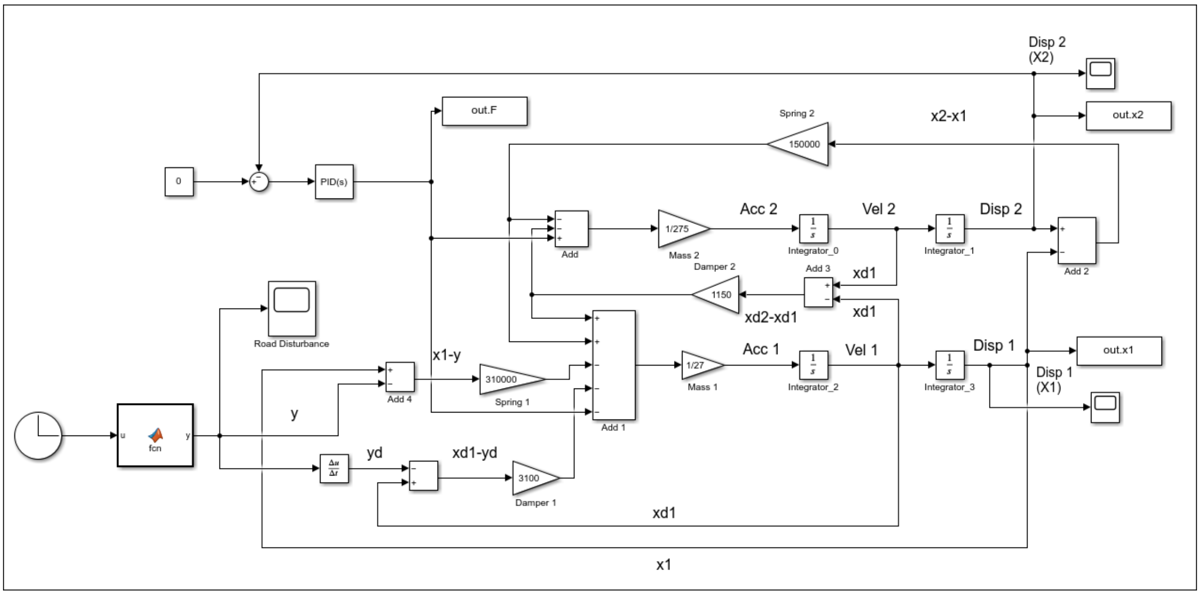


Fig. 3.5: MATLAB Simulink Model with PID Controlled Suspension System

3.2.4 Controller Design and its Parameter Selection

PID is the most commonly used controller in automation industry in the feedback control system and hence it can be utilized in automotive suspension system optimization by active control. The error signal generated by system when passing over a hump is tracked and controlled by controller. This controlled can be achieved by controlling the Kp, Ki and Kd parameters of PID controller. To determine these values an iterative method and PID tuner is used. Table 3.2 shows the controller details and values set in the PID tuner to get the best suitable PID parameters.

Sr No.	Parameter	Comment / Value
1	Toolbox	Simulink PID Tuner
2	Type	PIDF
3	Domain	Time
4	Form	Parallel
5	Response Time (Seconds)	0.07875
6	Transient Behaviour	0.414

Table 3.2: PID Controller Settings

The controller parameter obtained via iterative / trial and error method and utilized in this simulation are given in table 3.3.

Sr. No.	Parameter	Value
1	Control Technique	Iterative Method and PID Tuner
2	Proportional Gain, Kp	1.495e5
3	Integral Gain, Ki	1.563e6
4	Derivative Gain, Kd	3543

Table 3.3: PID Controller Parameters

Chapter 4

Results and Discussion

4.1 Introduction

MATLAB Simulink is a graphical programming tool used for modelling, simulation and analysing the dynamic systems. The quarter car model built in MATLAB Simulink toolbox is used for modelling and investigation of both passive and PID controlled suspension system. The integrated MATLAB tool is utilized for programming of the system parameters and Simulink used for Model based design.

The simulated results for both the passive and PID controlled suspension system model will be thoroughly discussed in this section. The detailed analysis will be discussed for the responses of the system in direction to conclude on the ride handling and comfort capabilities of the systems when the road disturbance is confirmed as a standard sinusoidal hump. The parameters such as sprung and unsprung mass movement, acceleration of sprung mass etc are which defines the performance of the system will be studied thoroughly.

The objective is to achieve the minimum amplitude value for sprung mass and unsprung mass shift, acceleration, suspension travel and tire deflection.

4.1.1 Passive Suspension System:

The outcomes of passive suspension model are shown in below figures. From figure.4.1, it is clear that the sprung mass of the system has an overshoot of 12% from the stable condition and the acceleration of sprung mass from figure 4.2 is nearly close to 10m/s^2. These numbers are very large and unwanted for ride quality and handling of vehicle. Higher values of overshot is unacceptable for ride quality and life of suspension system. The upsprung mass displacement shown in figure 4.3 is 0.111m which is also not a suitable for ride quality. The system also has a high settling time around 3 seconds, which is undesirable while riding. The suspension travel and the tyre deflection are also on a higher side in passive system.

Hence, to overcome these challenges and to improve the performance of the system, a closed loop feedback system can be implemented to achieve the desired goal.

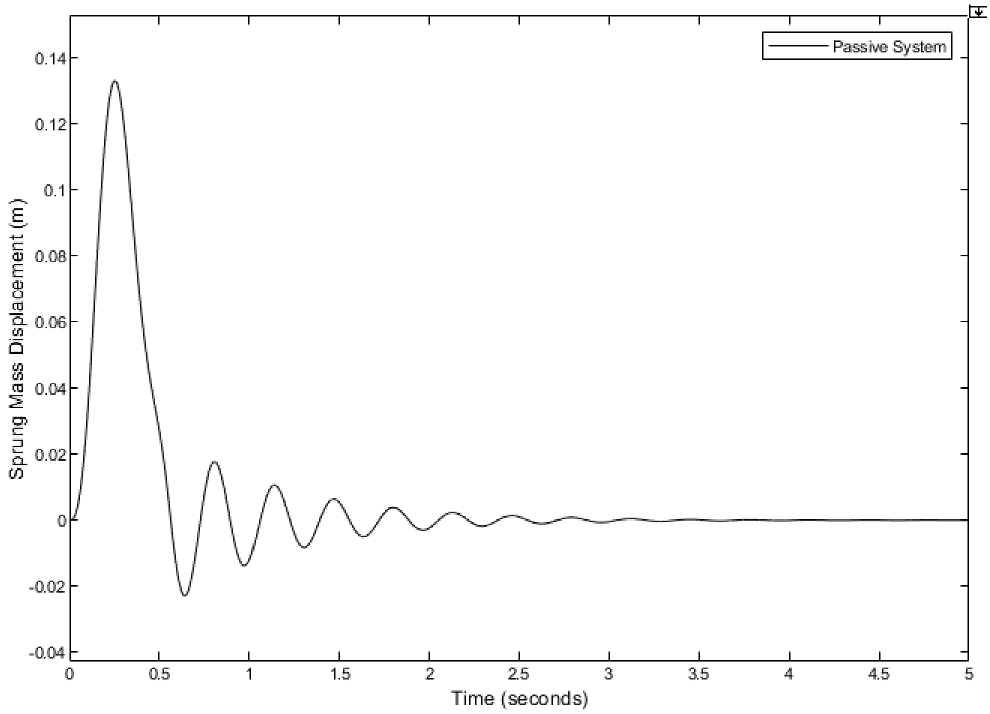


Fig. 4.1: Sprung Mass Displacement of Passive System

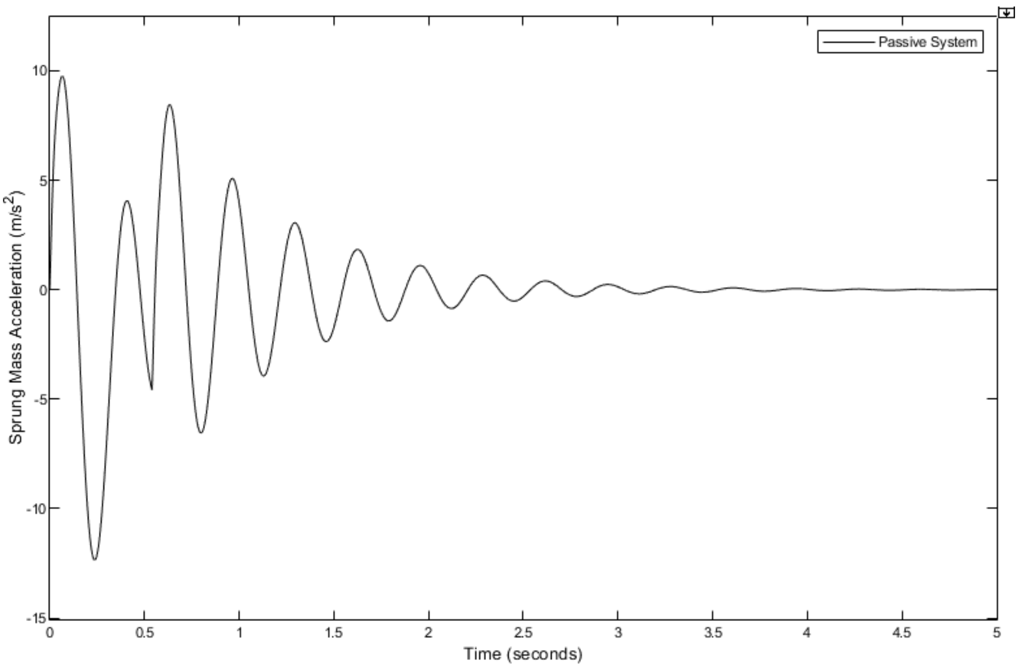


Fig. 4.2: Sprung Mass Acceleration of Passive System

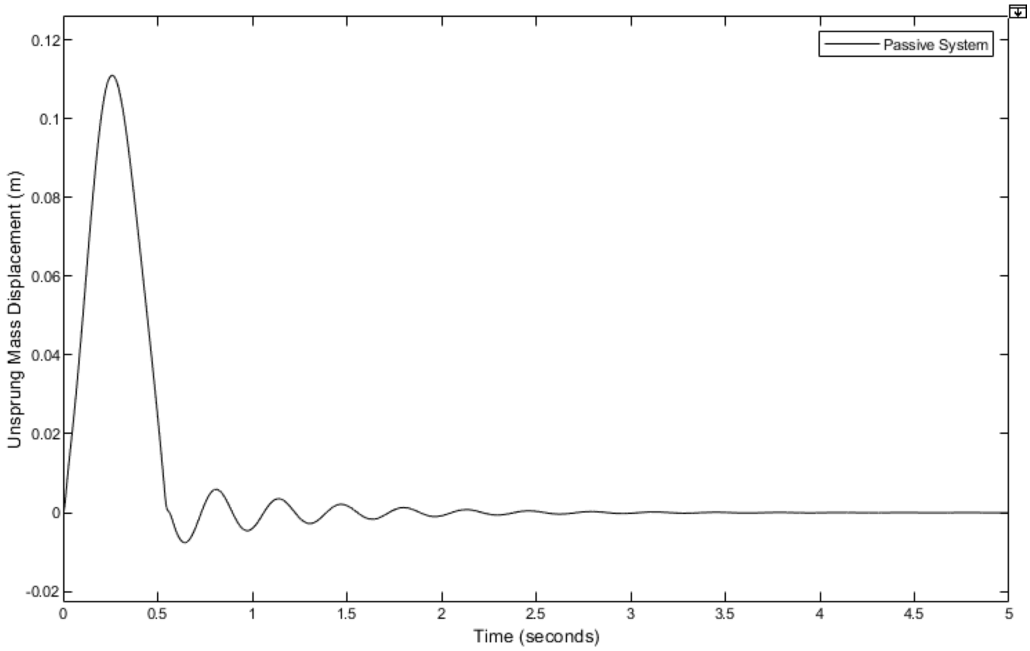


Fig. 4.3: Unsprung Mass Displacement of Passive System

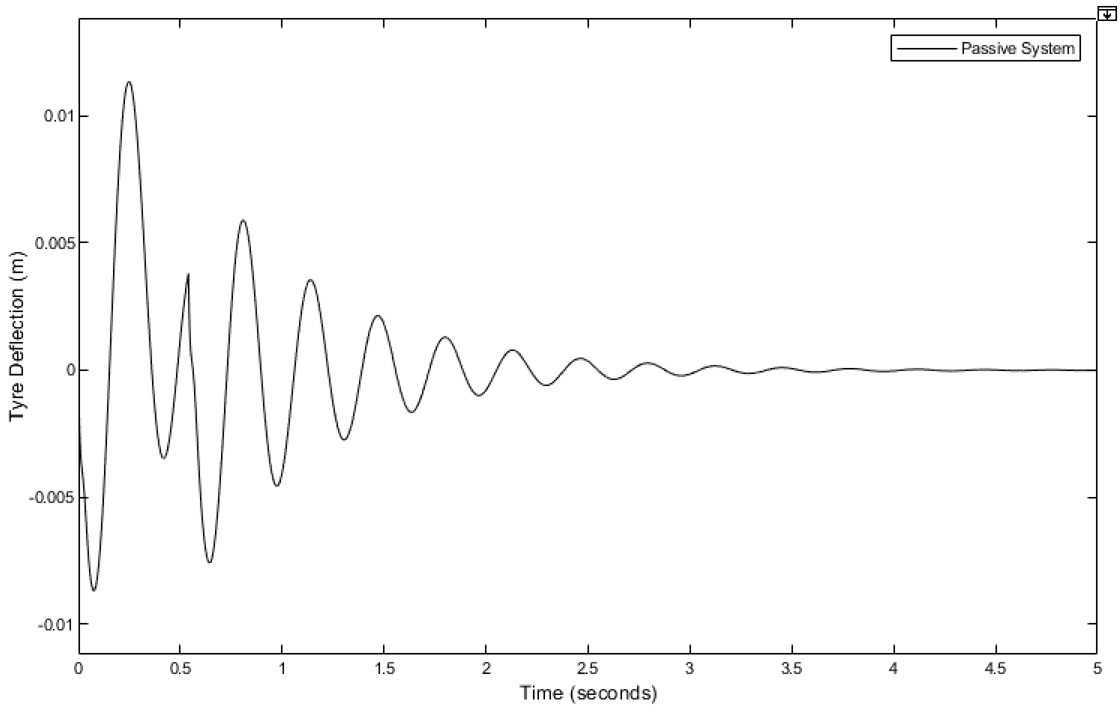


Fig. 4.4: Tyre Deflection of Passive System

4.1.3 Design Parameters Selection for Passive Suspension System:

Although it is evident that the passive system is not the best choice the for-suspension system but designing the optimum stiffness and damping values can serve the purpose sometimes. As in semi active suspension system damping values is kept variable to achieve the desire goal. Similarly, the passive system parameter can be selected in such way that the system is optimized for handling and comfort.

Figure 4.1 shows the passive suspension system with damping of 1150Ns/m. By considering the higher damping value the system response is shown in figure 4.5 for sprung mass displacement i.e., ride comfort with 5000Ns/m and 10000Ns/m damping coefficient.

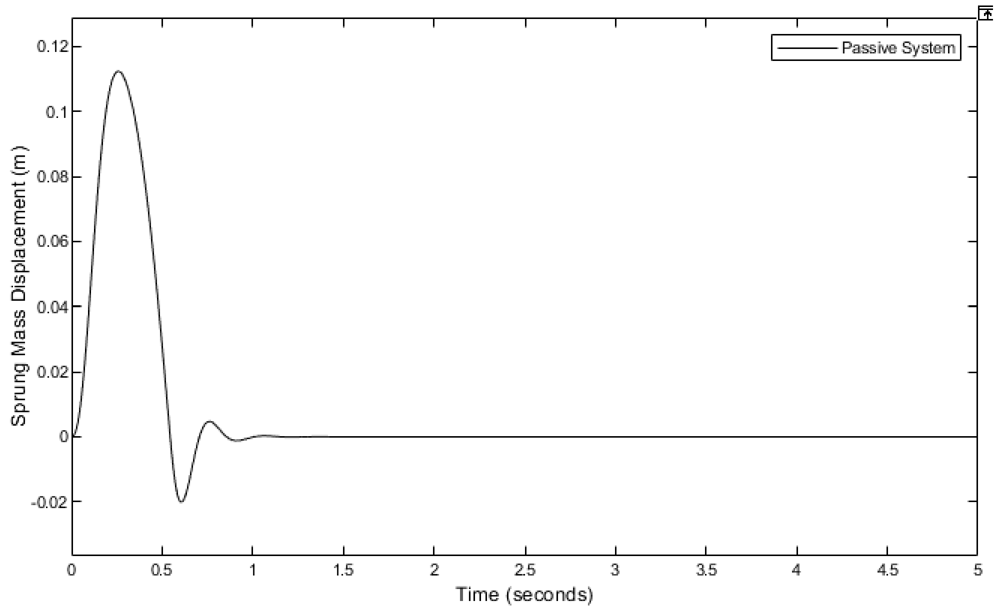


Fig. 4.5: Sprung Mass Displacement of Passive System with 5000Ns/m Damping value

When damping value increases the overshoot and the settling time decrease from 0.1330m and 2.5 sec to 0.1125 and 1.2 sec by keeping the stiffness constant. But the sprung mass acceleration goes on increasing since the system becoming stiffer Hence the ride handling may be increased but the ride comfort has been compromised. Figure 4.5 and 4.6 shows that the settling time and overshoot reduced from the baseline design but the change is not drastic in nature and hence there exist a scope to look for other opportunities the improvise the system performance. This led to the search for controller-based system feedback control to improve the system characteristics.

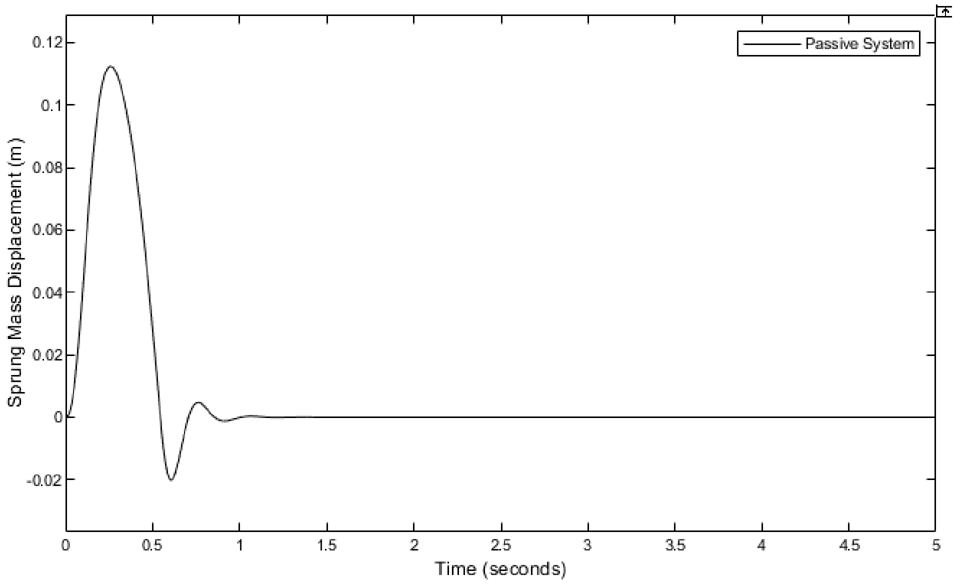


Fig. 4.6: Sprung Mass Displacement of Passive System with 10000Ns/m Damping value

4.1.3 PID Controlled Suspension System:

When a PID controller is implanted in the passive suspension system then it forms a feedback loop with the system and the system performance can be significantly improved. Figure 4.7, 4.8, 4.9 and 4.10 shows the performance of the system for various system parameters.

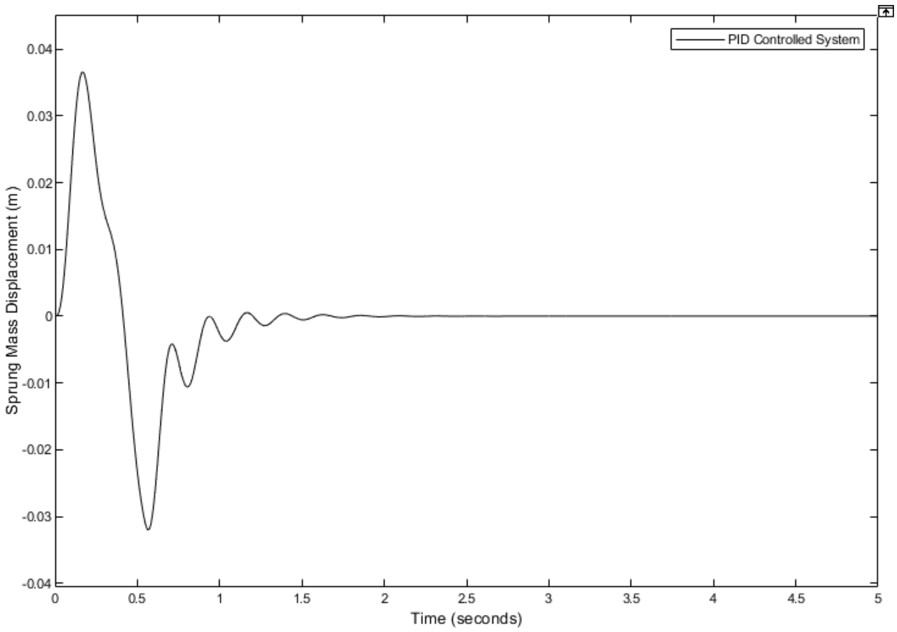


Fig. 4.7: Sprung Mass Displacement of PID Controlled System

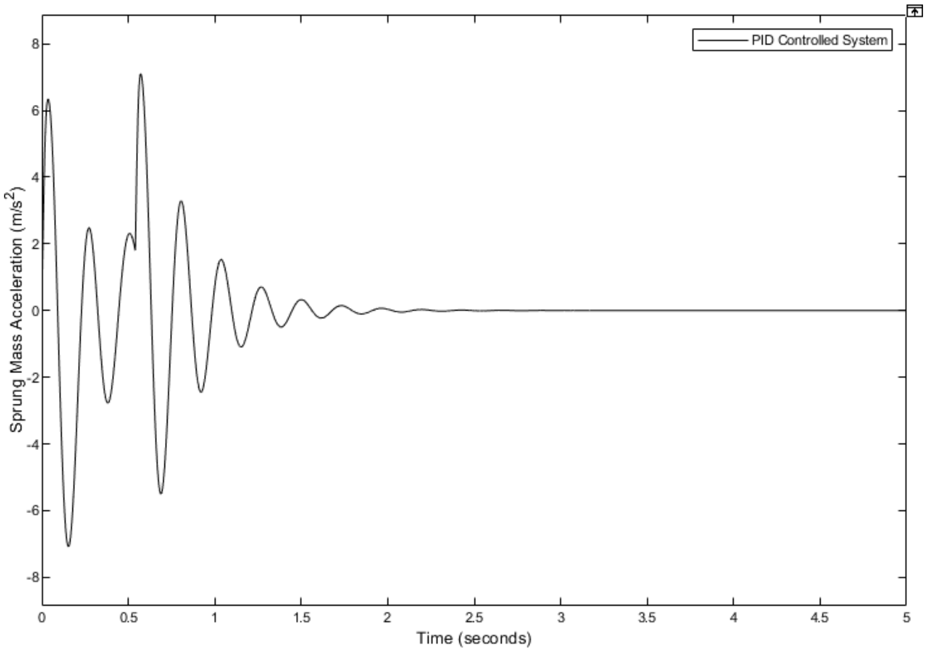


Fig. 4.8: Sprung Mass Acceleration of PID Controlled System

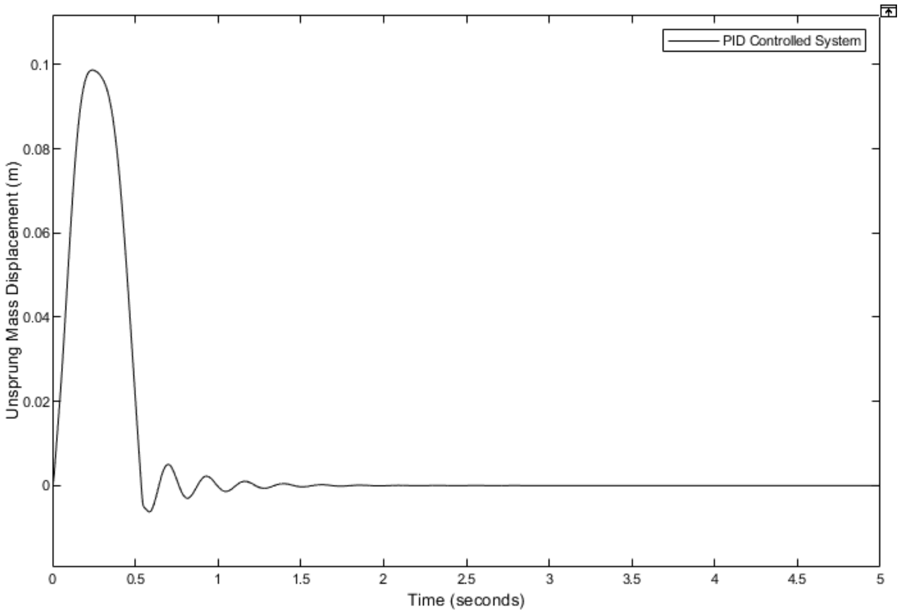


Fig. 4.9: Unsprung Mass Displacement of PID Controlled System

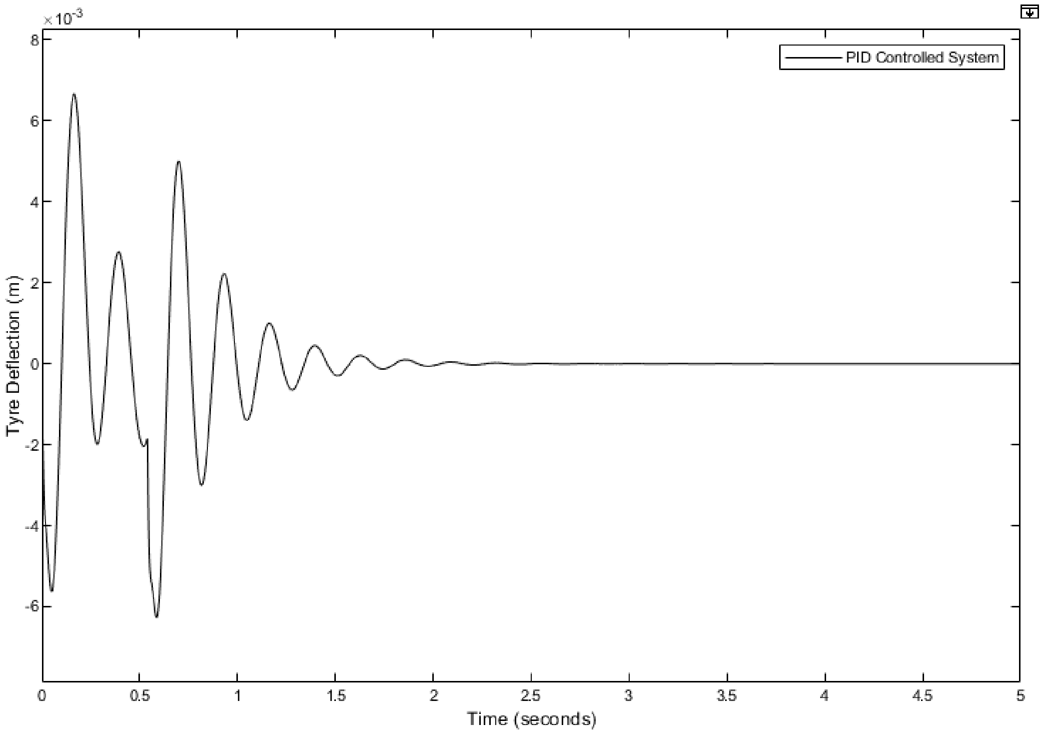


Fig. 4.10: Tyre Deflection of PID Controlled System

From figure 4.1 & 4.7 it is clear that the PID controller improvised the suspension system parameters significantly. The overshoot value dropped drastically and also the settling time reduced by an extent. This show that the road disturbance has very less impact on the vehicle body.

From figure 4.2 and 4.8, sprung mass acceleration declines from 10 to 6 m/s^2, and it indicated that the ride comfort improved from passive model. The jerks to the passenger can be minimize further by improving the controller.

Figure 4.3, 4.4, 4.9 and 4.10, shows that the ride handling can be enhanced by reducing the tyre deflection and unsprung mass displacement.

It is shown that the overshoot value and settling time is minimized in the system controlled by the PID controller compared to passive system. The system values such as sprung mass displacement, sprung mass acceleration have been improved that indicated enhancement in the ride comfort. The unsprung mass displacement, tyre deflection also reduced which proved good ride handling in turn.

Sr No.	Parameter	Passive System	PID Controlled System	% Reduction
1	**Sprung Mass Displacement (m)**	0.1330	0.0365	72.56
2	**Sprung Mass Acceleration (m/s^2)**	10	6	40.00
3	**Unsprung Mass Displacement (m)**	0.1110	0.0987	11.08
4	**Settling Time for Sprung Mass (Sec)**	2.75	1	63.63
5	**Settling Time for Unsprung Mass (Sec)**	2.5	1.2	52.00
6	**Tyre Deflection (m)**	0.0111	0.0060	45.94

Table 4.1: Performance Evaluation of Passive System and PID Controlled System

Table 4.1 shows the reduction in system parameters that be obtained by the PID controller in the system compared to the passive suspension system. It is evident that the controller techniques improve the overall performance of the automotive suspension system.

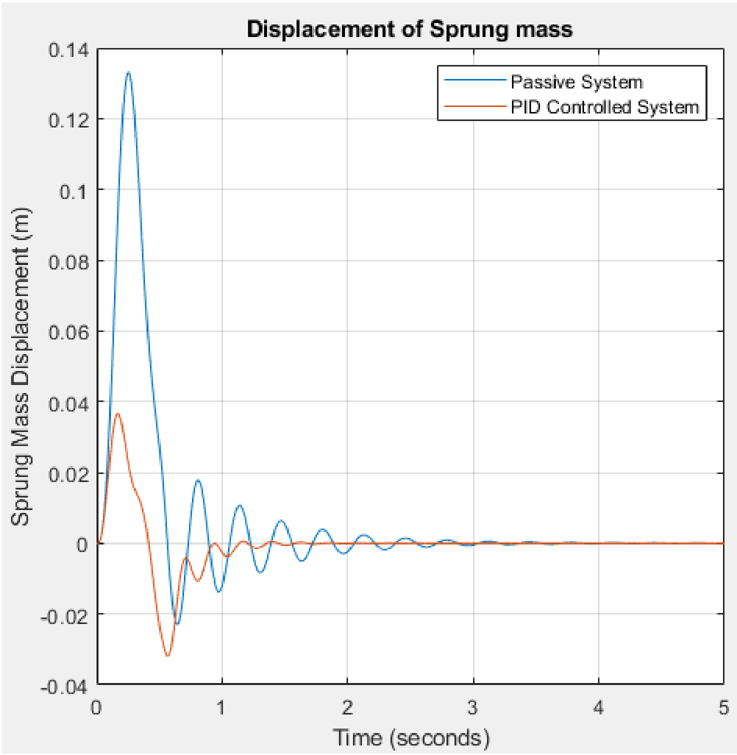


Fig. 4.11: Comparison of Sprung Mass Displacement in Passive and PID Controlled System

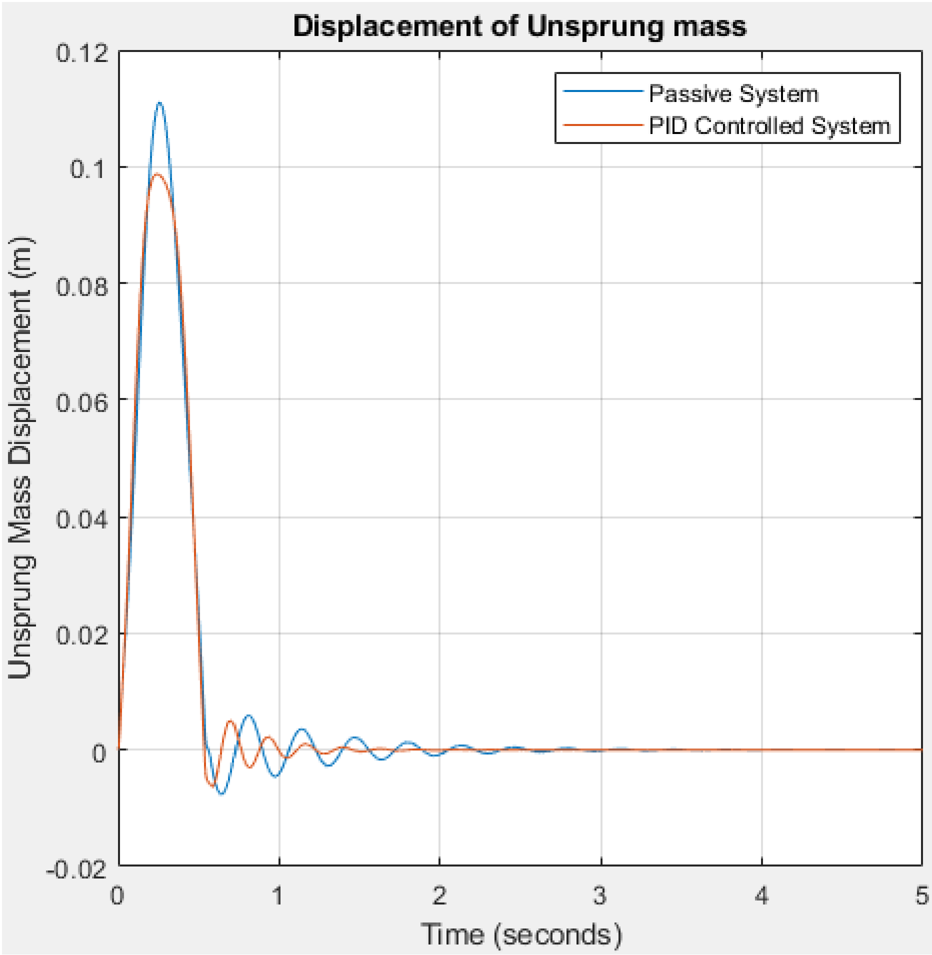


Fig. 4.12: Comparison of Unsprung Mass Displacement in Passive and PID Controlled System

Figure 4.11 and 4.12 clearly shows the improvement in the system when controller is utilized in passive system.

Also, the data showcase in table 4.1 indicated that the suspension system parameters that defines the ride quality, ride comfort, ride handling and road holding capabilities of the controlled suspension system is drastically improved.

Chapter 5

Conclusions and Scope for Future Work

5.1 Conclusion

The main objective of any automotive suspension system is to isolate the passengers from the vibrations and jerks coming for the uneven road surfaces. This work focuses on to provide the techniques to improve the suspension system parameters so as to minimize the impact of road disturbances on the suspension system performance.

In this passive suspension model is studied for the ride handling and ride comfort parameters and subsequently controller technique is implemented on it to improve the suspension parameters further. A Simulink based quarter car portion is used with appropriate design values and the PID controller technique is overlap on it to achieve the goal. A standard speed breaker as road disturbance is utilized to facilitate the actual road scenario. The PID based suspension system model performed very well as related to the passive model. The simulated results show the road holding and ride quality improved drastically when feedback loop is used for the system than passive model.

From the results obtained in the previous chapter, a brief summary of conclusions can be made as follows:

1. The passive system can be optimized for stiffness and damping values but the there exists a negotiation between those values in demand to maintain the ride quality and handling.
2. Improving the damping characteristics improves the overshoot and settling time up to certain extent but the ride quality gets compromised dur to increase in car bode accelerations.
3. Hence, the controller technique shows the better results than the passive system when it comes to comfort and controlling ability.
4. The vehicle overshoot and the settling time can be reduced drastically when PID controller is added in the system. The overshoot and the settling time for the sprung mass decreases by 72.56% and 63.63%.

5. The decrease in the sprung mass displacement by 72.56% and sprung mass acceleration by 40% indicates that the ride comfort is improved for passive system.
6. Also, the reduction in the settling time by 52%, displacement by 11.08% of unsprung mass and tyre deflection by 45.95% show that increase in the ride holding and ride handling ability.

With this analysis data and results, the implementation of PID controller in the automotive suspension system can be a feasible and viable solution to advance the overall performance of the automotive suspension system.

Hence, the aim and objective of this research project led at the beginning of the work have been achieved and fulfilled.

5.2 Scope for Future Work

1. The PID is one type of a control technique, but there exists a lot of control methods that can be utilized in the automotive suspension system. LQR, fuzzy logic etc are the other control methods can be studied.

2. The experimental study also needs to be done in order the verify the results obtained through simulation methods. In that way results and test data can be correlated and validated.

3. The tuning method used in this work is based on the iterative mode and other sophisticated methods can be used to better optimized the system.

4. System non linearities are not consider for the study and that can also be included in the future work.

5. This is the idealized quarter car type considered for the simplicity of the work and more multifaceted models such as half car and full car can be utilized for detailed study which replicated more realistic model.

References

1. Karnopp, D. C., Crospy, M. J. **(1974)**, System for Controlling the Transmission of Energy between Spaced Members U.S. Patent 3,807,678

2. Andel Nasser Sharkwy, Nouby M Ghazaly, Ahmed Saad Ali, Gamal Abdel Jaber **(2015)**, PID Controller of Active Suspension System for a Quarter Car Model, International Journal of Advances in Engineering & Technology.

3. Mehdi Ahmadian, Brian A. Reichert, Xubin Song **(2021)**, Harmonic Analysis of Semiactive Suspensions, International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE), DETC97/VIB-4122, V01AT04A003

4. Ivers D., Miller L. **(1989)**, Experimental Comparison of Passive, Semi-active on/off, and Semiactive Continuous Suspensions, SAE, Truck and Bus Meeting and Exposition, Charlotte, NC.

5. M. S. Yahaya, and M. R. A. Ghani **(2000)**, LQR Controller for Active Car Suspension, Proc. On TENCON, Malaysia.

6. Po Chang Chen, An Chyau Huang **(2015)**, Adaptive sliding control of non-autonomous active suspension systems with time-varying loadings, Journal of Sound and Vibration, Volume 282, Issues 3–5

7. Du H, Zhang N. **(2007)**, H∞ control of active vehicle suspensions with actuator time delay, Journal of Sound and Vibration, 301 (1-2), 236-252

8. Elnaz Akbari, Morteza Farsadi, Intan Z., Mat Darus, Ramin Ghelichi **(2010)**, Observer Design for Active Suspension System Using Sliding Mode Control Proceedings of 2010 IEEE Student Conference on Research and Development, 14 Putrajaya, Malaysia.

9. H., Elbab, Allam, E., Hady, M., and Abouel Seoud, S., **(2009)**, Performance of Active Suspension with Fuzzy Control, SAE Technical Paper 2009-01-1614.

10. H. M. Abdelhafez, Osama Omara **(2017),** Controlling quarter car suspension system by proportional derivative and positive position feedback controllers with time delay, Journal of Vibroengineering, Vol. 19, Issue 7, p. 5374-5387 https://www.jvejournals.com/article/18056

11. Pan Huihui **(2018)**, Nonlinear Control for Vehicle Active Suspension Systems, Ph.D. Dissertation, The Hong Kong Polytechnic University

12. Herman Van der Auweraer, Enrico Risaliti, Tommaso Tamarozzi, Mathieu Sarrazin **(2017)**, Virtual sensing based on design engineering simulation models, Confrence Paper, ResearchGate

13. Abdolvahab Agharkakli, Ghobad Shafiei Sabet, Armin Barouz **(2012)**, Simulation and Analysis of Passive and Active Suspension System Using Quarter Car Model for Different Road Profile, International Journal of Engineering Trends and Technology, 3, 636-644.

14. Yahaya Md Sam, N. M. Suaib J. H. S. Osman **(2006)**, Sliding mode control of a hydraulically actuated active suspension. Jurnal Teknologi, 44, 37-48.

15. A.C. Mitraa, G.J. Desaib, S.R. Patwardhanc, P H Shirked, W. M. H. Kurne, N. Banerjee **(2016)**, Optimization of Passive Vehicle Suspension System By Genetic Algorithm, ICOVP (Science Direct).

16. Atanu Bhuyan **(2013)**, Passive suspension modelling and analysis of a full -car model, International Journal of Advanced Science and Engineering Technology Vol.3, No.2, ResearchGate.

17. S.P. Chavan, H.S. Sawant, J.A. Tamboli **(2019)**, Experimental verification of passive quarter car vehicle dynamic system subjected to harmonic road excitation with nonlinear parameters, Journal of Mechanical and Civil Engineering (IOSR-JMCE).

18. Galal Ali Hassan **(2014)**, Car dynamics using quarter model and passive suspension, Part I: Effect of Suspension Damping and Car Speed, International Journal of Computer Techniques Volume 1 Issue 2.

19. P.S.S. Prasad, Anilkumar Shirahatti **(2006)**, Investigation on effect of hump on a vehicle suspension for the comfortable ride, Conference Paper, ResearchGate.

20. Galal Ali Hassan **(2015)**, Car dynamics using quarter model and passive suspension, Part II: a novel simple harmonic hump. Journal of Mechanical and Civil Engineering, 12(1), 93-100

21. Apichan Kanjanavapastit, Aphirak Thitinaruemit **(2012)**, Estimation of a Speed Hump Profile Using Quarter Car Model, 4th International Science, Social Science, Engineering and Energy Conference (I-SEEC 2012)

22. Cho, M. D., Win, H. H., & Latt, A. K. **(2017)**, Vibrational analysis of passive suspension system for solar vehicle, International Journal of Scientific and Research Publications, 7(12), 2250-3153.

23. Nikhil Desai, Bharatbhushan Kale **(2016)**, A review work on suspension systems models, control strategies for suspension system, Journal of Emerging Technologies and Innovative Research (JETIR), Volume 3, Issue 10.

24. James C. Poynor **(2001)**, Innovative designs for magneto-rheological dampers, Ph.D. Dissertation, Virginia Polytechnic.

25. Ervin Alvarez-Sánchez **(2013),** A quarter-car suspension system: car body mass estimator and sliding mode control, Iberoamerican Conference on Electronics Engineering and Computer Science.

26. Abdolvahab Agharkakli, U.S. Chavan, Phvithran S. **(2012)**, Simulation and analysis of passive and active suspension system using quarter car model for non-uniform road profile, International Journal of Engineering Research and Applications (IJERA), Vol. 2, Issue 5.

27. Shaia Kaid Mosleh Mohammed Almadrahi, Heisum M. Ewad **(2021)**, Enhancing the controller for quarter car semi active suspension system, European Academic Research Vol. VIII, Issue 11.

28. Mohsin Jamil, Salman Zafar, and Syed Omer Gilani **(2018)**, PID Controller Based Semi-Active Suspension System, Institute for Computer Sciences, Social Informatics and Telecommunications Engineering.

29. Senthilkumar Mouleeswaran, Design and Development of PID Controller Base Active Suspension System for Automobiles **(2012)**, PID Controller Design Approaches – Theory, Tuning and Application to Frontier Areas, ResearchGate

30. Mohd. Avesh, Rajeev Srivastava **(2012)**, Modeling Simulation and Control of active suspension system in Matlab Simulink environment, ResearchGate.

31. Mitul Patel, P. J. Gundaliya **(2017)**, A Study on speed breakers, International Journal of Advance Engineering And Research Development, Volume 4, Issue 3, March

32. Malaya Mohanty, Yash Raj, Subhangee Rout, Utkarsh Tiwari, Sagarika Roy, Satya Ranjan Samal **(2021)**, Operational effects of speed breakers: a case study in India, European Transport Issue 81, Paper no. 1

33. Guidelines for Traffic Calming Measures in Urban and Rural Areas, Indian Road Congress (IRC99 – 2018)

34. M. Ravindran, S. Palanisamy, R. Senthil Kumar, M. Soundarrajan, J. Prabakaran **(2018)**, Design and Analysis of Front Suspension for Light Duty Vehicle. International Journal for Scientific Research and Development, 6, 406-409

35. AMIT M. **(2013),** History of Suspension Systems. https://www.scribd.com/document/129980206/History-of-Suspension-Systesm.

36. CAO, J., LIU, H., LI, P. & BROWN, D. J**. (2008**), State of the art in vehicle active suspension adaptive control systems based on intelligent methodologies. IEEE transactions on intelligent transportation systems, 9, 392-405.

37. Chandrakant Kumar Nirala **(2011)**, A Novel Semi Active Suspension System for Automobiles Using Jerk-Driven Damper, M.Tech. Dissertation, Indian Institute of Technology Hyderabad

38. Leaf springs an Overview **(2019)**, Power Plant Instrumentation and Control Handbook (Second Edition), ScienceDirect

39. How car suspension works, By: William Harris & Kristen Hall-Geisler, Jun 28, 2021 https://auto.howstuffworks.com/car-suspension.htm

40. MOON S. (2014), Fabrication of an Active Air Suspension https://www.slideshare.net/suchitmoon/active-air-suspension-system

41. E.A. Azrulhisham, Dzuraidah Abd Wahab, C. H. Che Haron, Nik Abdullah Nik Mohamed **(2008)**, Service Loads Prediction in The Reliability Characterization Of Automotive Rear Axle System, Engineering Postgraduate Conference (EPC), ResearchGate

42. SINGH, A. (**2019)**, Rubber Suspension System https://www.scribd.com/document/363310778/Rubber-Suspension-System

43. Rubber Spring, https://www.gmtrubber.com/products/rubber-springs/

44. Shock Absorbers: https://en.wikipedia.org/wiki/Shock_absorber#/media/File:Mini_Shocks.JPG

45. PID Controllers, https://www.omega.co.uk/prodinfo/pid-controllers.html

46. Differnet types of Humps:

https://theconstructor.org/transportation/road-humps-features-design-criteria

47. Automotive Suspensuion System http://usciencecompendium.blogspot.com/2015/07/car-suspension-system-functions

48. Indrani Mikklineni, Shyam Patel, Chia Hung Tai **(2014)**, Optimizing a PID Controller for Simulated Single-Joint Arm Dynamics.

49. PID Theory Explained, https://www.ni.com/en-in/innovations/white-papers/06/pid-theory-explained.html

50. Pankaj Sharma, Nittin Saluja, Dimple Saini and Parveen Saini **(2013)**, Analysis of Automotive Passive Suspension System with Matlab Program Generation, International Journal of Advancements in Technology, Vol. 4 No. 2