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Comparative Analysis of Passive, PID And Fuzzy_PID Controller For Quarter Car Model

A thesis submitted in Partial Fulfillment of the Requirement for the Degree of Master of Science in Control and Instrumentation Engineering

By

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Abstract

This paper presents a comparative analysis of passive, PID, and fuzzy PID control strategies for a quarter-car suspension system utilizing a fuzzy PID controller to enhance ride comfort and stability by effectively managing displacement and velocity. The quarter-car model serves as a simplified representation of vehicle dynamics, where the primary objective is to minimize the vertical displacement of the vehicle body and control the relative velocity between the body and the wheel. Additional PID controllers often struggle with non-linearity and uncertainties present in suspension systems; therefore, it is proposed a fuzzy logic approach to tune the PID parameters dynamically based on real-time system states. The fuzzy-PID controller integrates the benefit of fuzzy logic's ability to handle uncertainty and the robustness of classical PID control.

Simulation results demonstrate that the proposed fuzzy-PID versus passive controller significantly reduces body displacement by 88 % of overshoot and 56 % of settling time with bumpy input road1. Fuzzy-PID versus passive controller significantly reduces velocity response by 24 % of overshoot and 55 % of settling time with bumpy input road1.

Key words: Active Suspension system, fuzzy logic controller, quarter car model, PID controller.

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List of abbreviation

PSS	Passive suspension system
ASS	Active suspension system
SASS	Semi active suspension system
FBD	Free body diagram
HBS	High Bandwidth Systems
LBS	Low Bandwidth Systems
FLC	Fuzzy logic controller
PID	Proportional Integral Derivative
PLCs	Programmable Logic Controllers
LVDT	Linear Variable Differential Transformer
FIS	Fuzzy inference system
MFs	Membership functions
PSS	Passive Suspension System
ASS	Active Suspension System
PSO	Particle Swarm Optimization
LQR	Linear Quadratic Regulator

List of Symbol

m_c	The sprung mass
m_w	The unsprung mass
k_t	The stiffness coefficient of the suspension
D	The damping coefficient of the suspension
Z_c	The vertical stiffness of the tire
Z_r	Road disturbance
F_S	Spring force
F_D	Damper force
F_g	Gravitational force
$\ddot{z}_c$	Vertical sprung mass acceleration
$\ddot{z}_w$	Vertical unsprung mass acceleration
z_c	Vertical sprung mass displacement
z_w	Vertical unsprung mass displacement
$\dot{z}_c$	Vertical sprung mass velocity
$\dot{z}_w$	Vertical unsprung mass velocity
K_P	Proportional gain constant
K_I	Integral gain constant
K_D	Derivative gain constant
K	Controller proportional gain
T_I	Controller integral time
T_D	Controller differential time

Chapter One

Introduction

1.1 Background

Since there has been an intrigued in making strides the general execution of car vehicles in later a long time, suspensions consolidating dynamic components have been created , and the method moves on to assist improvements and advancements. The car suspension on a vehicle regularly has the taking after fundamental errands. 1. To separate a car body from road disturbance in arrange to supply great ride quality, 2. To keep great street holding, 3. So supply great dealing with, 4. To back the vehicle inactive weight.

The conventional suspension framework utilized in traveler vehicles comprises three fundamental components: a stun safeguard, a coil spring, and interfacing components. Here, the stun safeguard performs the obligation of retaining the stuns beginning from the street, and the coil spring performs the errand of putting away the vitality coming to the chassis. The interfacing components give the association between the wheel center and the suspension components and the association between the chassis and the suspension. Customarily, frameworks with steady damping and spring coefficients, known as inactive suspension frameworks, are utilized in vehicles. Suspension frameworks whose damping properties or vertical speeding-up capacity can be balanced by a control component are known as dynamic suspension frameworks. In order to move forward, driving consolation and security, analysts carry out numerous ponders on frameworks known as dynamic suspension frameworks [1].

Car suspension frameworks are classified into three primary sorts, specifically inactive, semi-active, and dynamic suspension frameworks. Within the inactive suspension, a spring and the suspension framework parts are put between the car body and the wheels. It permit the forward remuneration between driving consolation and the suspension stroke deviation. Concurring with the chassis highlights, the suspension stroke is constrained to a few particular values. The ride consolation is decreased when the suspension deviation comes to these specified restricted values.

Within the dynamic suspension framework, a drive actuator controlled by the input controller is put between the car body. A controlled suspension framework grants forward remuneration between the riding consolation and the execution criteria of the suspensions [2].

1.2 Problem Statement

For a vehicle, it is continuously troublesome to preserve at the same time a tall standard of ride consolation and vehicle steadiness beneath all driving conditions. As the detached suspension framework is an open circle control framework, it does not have a remedial activity. The biggest problem with this suspension framework is that it exchange with a parcel of street input or toss the car on unevenness of the street. The inactive suspension framework, which has the biggest sum prepared on the current vehicle, has spring and damper coefficients that are consistent and cannot alter themselves together with the street surface circumstances. So the dynamic suspension system, which can naturally make returning drives to preserve the vehicle consistent, has taken to the stage. As said above, the most important goals of dynamic vehicle suspension frameworks are to make strides in the ride consolation and solidness of the vehicle. Usually by including degrees of opportunity to the detached framework and/or controlling actuator strengths depending on input data of the framework gotten from sensors. The drive actuator may be a mechanical portion that's included inside the system, which is overseen by the controller. This controller calculate whether to include or disseminate vitality from the framework by the assistance of sensors as an input, which is able to allow the information of street profile to the controller. This proposal is proposed that how might to control a dynamic suspension more viably and respond precisely with the alteration of street surface harshness so that the individuals within the vehicle feel comfortable?

1.3 Objectives

1.3.1 General objective

The general objective of this thesis is to carryout comparative analysis of passive, PID and Fuzzy_PID controller for quarter car model.

1.3.2 Specific objective

- To evaluate and compare the performance of passive, PID, and fuzzy_PID controllers based on settling time and overshoot by using MATLAB/Simulink. .
- To assess the robustness of each control strategy against disturbance variations.
- To quantitatively assess the ride comfort and stability provided by each controller over different driving condition.
- To investigate the adaptive capabilities of fuzzy_PID controllers compared to traditional PID controllers in response to road condition and vehicle dynamics.

1.4 Research Methodology

urge the most extreme advantage out of a variable damping framework, different control calculations have been proposed. In this investigate an actuator is associated in parallel with the damper and spring within the suspension framework and the mathematical clarification of a quarter car suspension framework is additionally considered in point by point. In expansion, the framework yield be compared utilizing Fuzzy_ PID controller based on the responses from MATLAB. An dynamic control calculation incorporates controller in arrange to get distant better;a much better;a higher;a stronger;an improved">a distant better consolation and stability. This calculation accounts for the variety in framework parameters and the task of weights to the execution criteria. So to meet the required execution have to be utilize an suitable strategy of control. In this proposition a Fuzzy_ PID controller, is connected. This strategy is appeared within the figure 1.1.

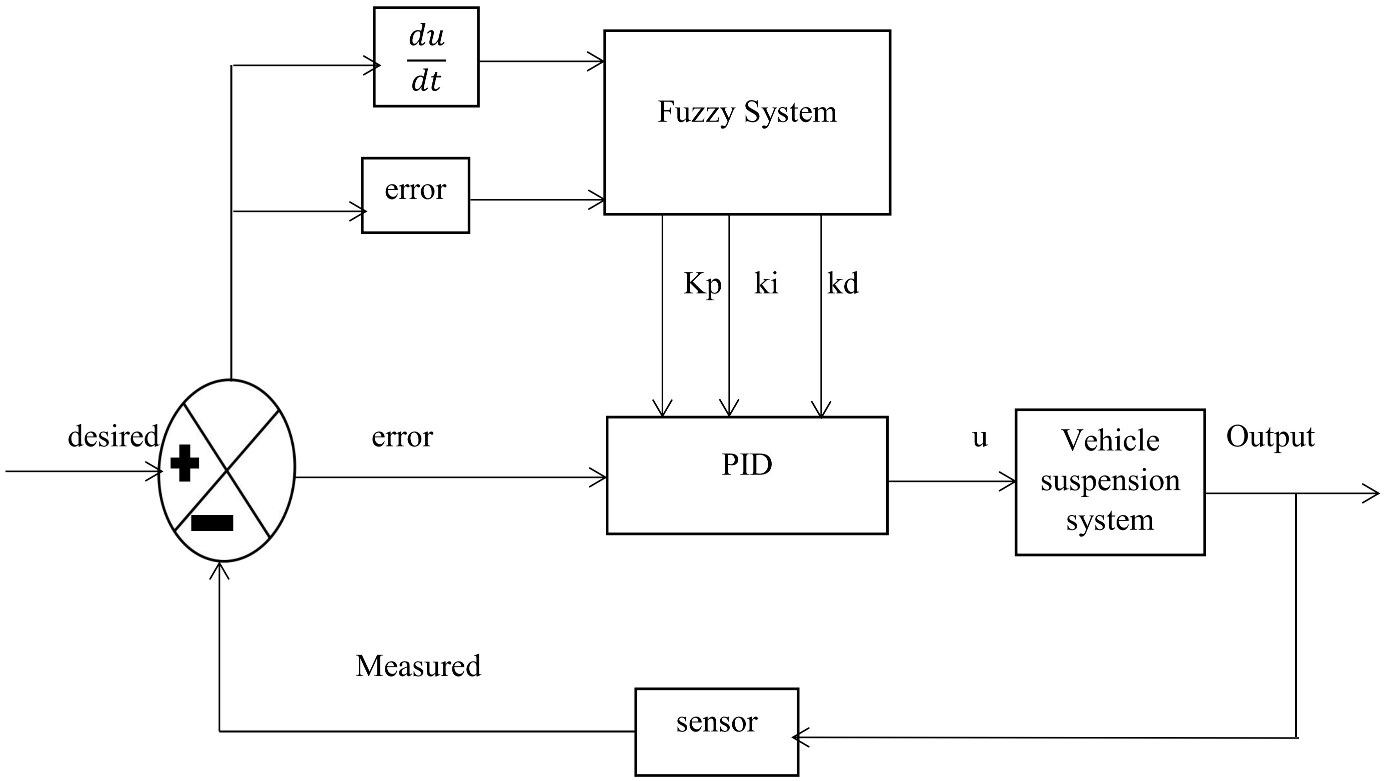


Figure 1.1 The fuzzy PID controller for the quarter car vehicle suspension system.

Where e, Δe are the error and change of error and u is the actuator force. The overall structure of the proposed fuzzy PID controller is shown in Fig 1.1. After develop mathematical model of passive suspension and active suspension systems of quarter car model, next have to select the inputs and output of the FLC. The displacement and velocity are the error and change of error respectively, which are inputs to the fuzzy_PID controller. Furthermore, the input and output parameters should include a membership function and control fuzzy rules. The actuator force is the output from the fuzzy_PID controller, which is given to the quarter car suspension system.

1.5 Scope and Limitations

Scope;

- Improved ride comfort: the Fuzzy PID controller can be designed to optimize ride comfort by adjusting the suspension characteristic in response to varying road condition.

- Enhanced stability: the controller help to maintain vehicle stability by adapting to in load and dynamics, which is crucial for safety.

Limitation;

- Model simplification: the quarter car model is a simplification and may not capture all the complexity of real world vehicle dynamics, such as multi-body interactions or nonlinear behaviors.
- Limited generalization: the fuzzy rules are derived from specific scenarios, which may limit the controllers ablity to generalize across different operating conditions or vehicle types.
- Noise sensitivity: the system may be sensitive to noise in the measurements (e.g road disturbance, sensor inaccuracies), which can affect the performance of the controller.

1.6 Organization of the thesis

Chapter two: In this chapter the background and review papers related to the thesis is explained.

Chapter three: This chapter dictates the mathematical model and fuzzy logic controller and introduces a control technique, which is fuzzy PID controller.

Chapter four: In chapter four simulation of passive, active suspension system be carried out. There is input disturbance that is used to test the system. This confer the results and discussions of this work.

Chapter five: At the end of this thesis conclusion and future works be discussed furthermore. Besides, some recommendations be discussed in this chapter.

Chapter Two

Theoretical Background and Literature Review

Nowadays Suspension framework is one of the foremost imperative components of a vehicle framework, which plays a vital part in solidness execution and the ride consolation characteristics of a vehicle. In a conventional passive suspension framework, there's a trade-off between the clashing necessities of ride consolation and great soundness execution. The reason is that hardened suspension is required to back the weight of the vehicle and to take after the track. On the other hand, delicate suspension is required to disconnect the unsettling influence from the street. Hence there exists a altogether developing intrigued within the plan and control of dynamic suspension frameworks from car engineers and analysts.

2.1 Classification of Suspension Framework

Concurring to the control guideline and work, suspension frameworks can be partitioned into detached suspension,semi-active suspension, and dynamic suspension. These suspension frameworks are exceptionally diverse within the execution viewpoints.

2.1.1 Inactive Suspension System (PSS)

Based on the disentangled quarter-car demonstration, an inactive suspension framework is one in which the coefficients of the components are consistent. Figure 2.1 appears an ordinary structure of a detached suspension framework. Inactive suspension cannot alter its solidness and damping coefficient and has no additional power or actuator. The most components, decided by the architect of the suspension framework, are k, b, and k_t, where k and b speak to the spring and damper coefficients, which are associated between the vehicle body and wheel, whereas k_t represents the tire solidness, and d speaks to the street's unsettling influence.

PSS is the conventional mechanical structure, which contains a basic structure, dependable execution, moo taken a toll, and no extra vitality, and is right now the most broadly utilized on vehicles. Suspension framework parameters are settled and cannot meet the stack, street conditions, speed, and other changes in circumstances. Hence, detached suspension cannot alter firmness and damping, agreeing with the irregular vibration hypothesis. Which means the conventional suspension system does not comprise any controller to influence the spring and the stun safeguard. It can be, as it were, guarantee the particular operating conditions to attain ideal damping impact.It is troublesome to adjust to diverse street profiles and intense utilize. Whereas taking inactive suspension, it is additionally troublesome to procure great ride consolation and holding steadiness at the same time since these two necessities are conflicting sets [3].

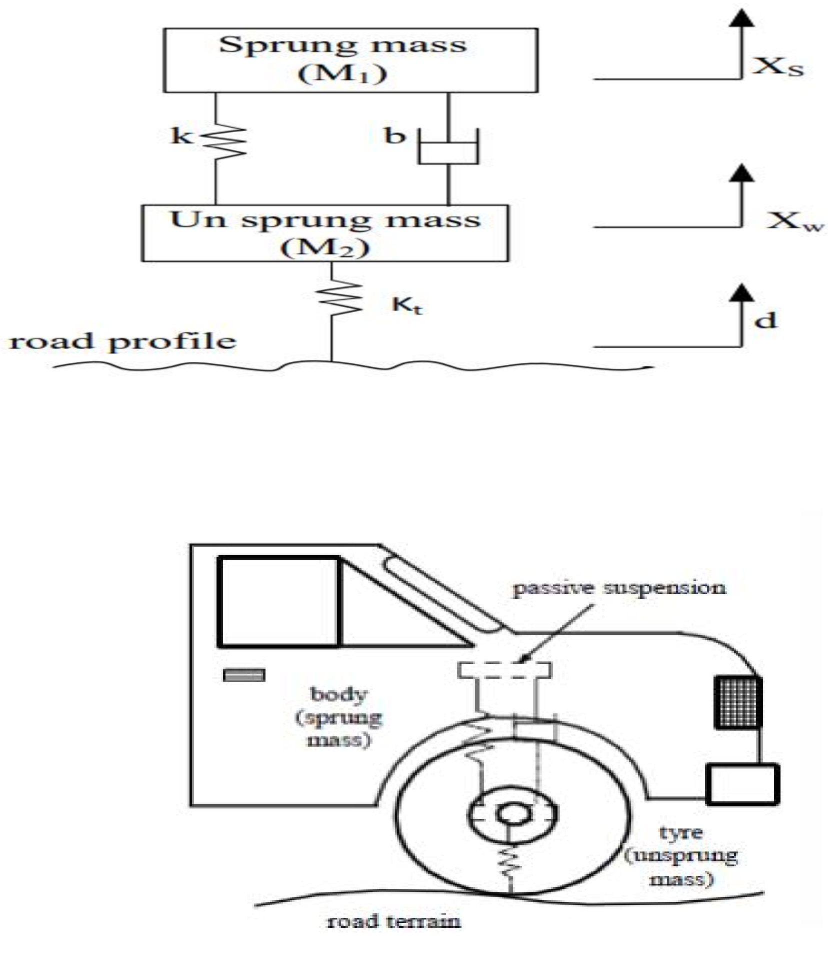


Figure 2.1 Passive quarter car suspension model [4]

A detached suspension framework is able to store vitality from the street's unsettling influence through a spring and to disseminate it by means of a damper. For the most part, conventional suspension comprises springs and dampers and is alluded to as inactive suspension.

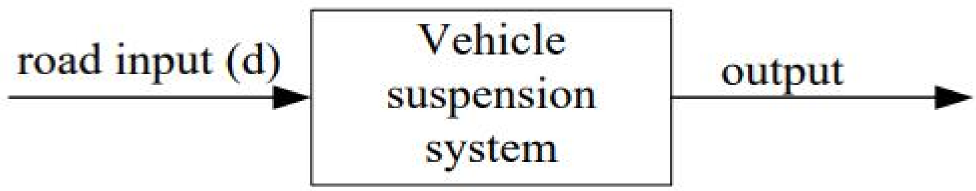


Figure 2.2 Open loop control system of passive suspension system

The passive suspension system is an open-loop control system as shown in Fig. 2.2. It is only designed to achieve certain conditions. There is no energy supplied by the suspension element in the system. The disadvantage of a passive suspension system is that it has fixed characteristics. Figure 2.1 shows traditional passive suspension components and consists of a spring and a damper. The characteristic of passive suspension is fixed and cannot be adjusted by any mechanical part. Therefore, the performance of the passive suspension depends on the road profile.

2.1.2 Semi dynamic Suspension Framework (SASS)

The semi-active suspension framework has the damper with two or more selectable damping rates. This suspension framework is one of the suspensions the versatile component (firmness) and stun safeguard (damping) can alter concurring to the require for control and control.

The dynamic suspension concept was proposed in 1974. A semi-active suspension framework is basically controlled by controlling the stune safeguard damping. The semi-active suspension framework employments the thought of changing the damping rates [5]. At that point in the event that the suspension is remotely controlled by employing a variable damper, it is known as a semi-active. The semi-active suspension framework has no particularly energetic control components. It passes the sensors information to the vehicle controller to calculate the desired control constrain and after that alters the stune safeguard damping to weaken the vibration of the vehicle body.

A semi-active suspension system provides a rapid adjustment in the damping coefficients of the springs. The suspension system lacks life; nonetheless, the damper is replaced with an adjustable damper. The controller determines the damping level according to the control technique and thereafter adjusts the damper to the specified reference input. The most often employed semi-active suspension system is referred to as a skyhook damper. A schematic diagram for semi-active suspension is presented in Figure 2.3. The semi-active suspension system also has its own advantages, such as significantly lower device bulk and cost compared to the active suspension system. This idea fundamentally revolves around the dynamic suspension.

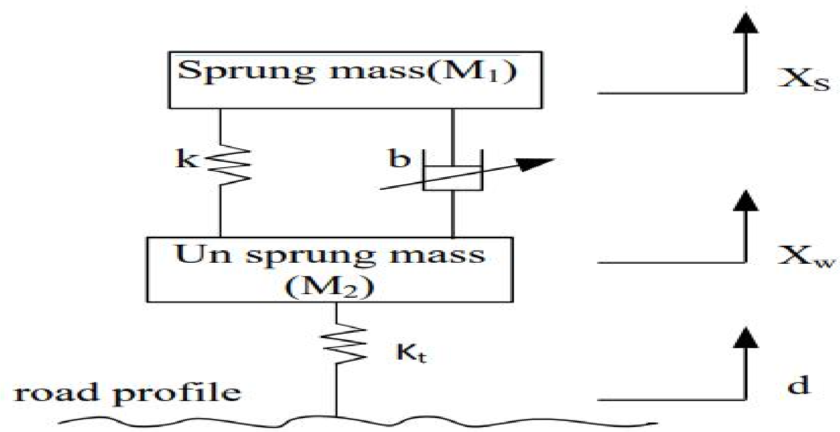
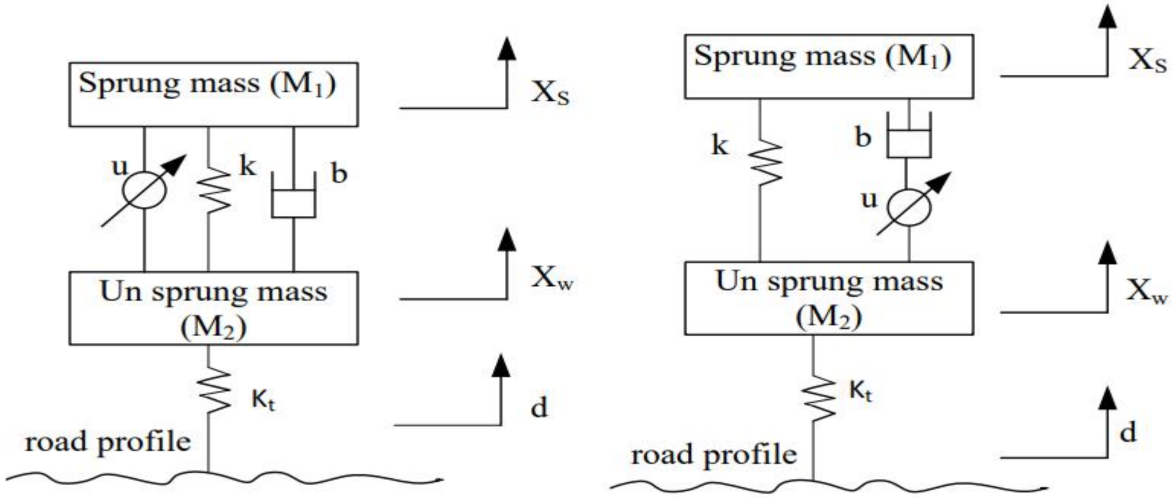


Figure 2.3 Semi active suspension quarter car model [5]

2.1.3 Active suspension system (ASS)

Figure 2.4 shows an active quarter-car suspension system with the basic components. The active quarter-car suspension consists of a suspension spring and damper, unsprung mass, and a tire spring. In addition to the components of PSS, this type of suspension system introduces an actuator in the suspension space that makes the control system closed loop.



a) High band width b) Low band width

Figure 2.4 Active suspension quarter car Suspension [6,7]

As expressed above, semi-active suspension frameworks, with their variable damping characteristics and moo control utilization, offer an impressive change [6, 7]. Critical change can be accomplished by utilizing a dynamic suspension framework, which supplies the next control from an outside source to generate suspension powers to attain the specified execution. The constraint may be the work of a few factors that can be measured or remotely detected by different sensors, so the adaptability can be incredibly expanded.

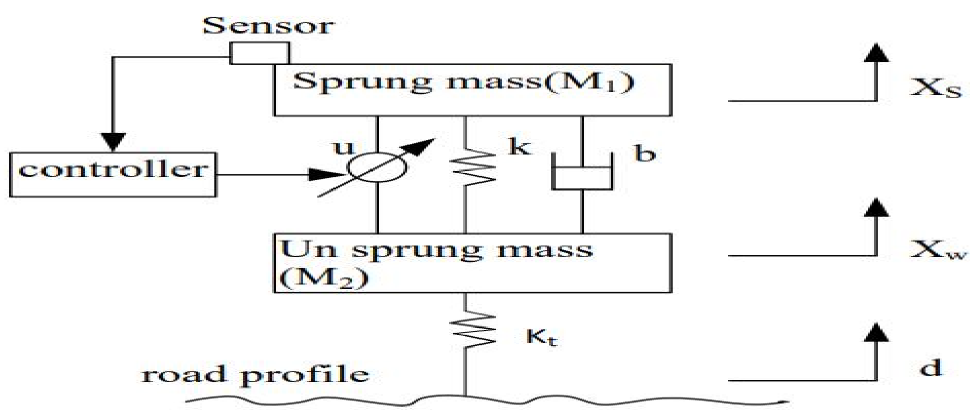


Figure 2.5 Active suspension quarter car control system [8]

A dynamic suspension framework has the capacity to reply to the vertical parameters within the street input. In this proposal, an actuator constraint is added to the suspension framework. So control isn't as it were , put away and scattered but too given to the framework. This constraint has its possess assignment, which is either to include vitality in the framework or disseminate it from the framework. This actuator is controlled by different sorts of controllers, which are decided by the originator.

The dynamic suspension, depending on the street conditions and vehicle stack, controls its own working status. Active suspension has to take effective control procedures to realize the desired performance. Subsequently, the choice of control methodology for suspension features an extraordinary impact on the execution [8]. Selecting the right control methodology will deliver a much better, higher, stronger, and improved compromise between consolation and solidness of the car. Figure 2.5 appears as a straightforward square graph to clarify how the dynamic suspension can accomplish superior execution. In this sort of suspension, the controller can adjust the framework flow by actuating the actuators within the closed circle of the control framework.

2.2 Type of active suspension system

There are two types of active suspension systems. These are high bandwidth system and low bandwidth system.

2.2.1 High bandwidth system(hbs)

This sort of framework is additionally known as a completely dynamic suspension framework. In this framework the body and wheel of the vehicle are associated by an actuator between them. That's in high-bandwidth system components are connected in parallel, because it is appeared in Fig. 2.4(a). This framework controls the suspension over the high recurrence run of the framework. A completely dynamic framework features a noteworthy control utilization and requires actuators with a wide transfer speed that enhance the execution of the vehicle framework. Thus, in this, a completely dynamic suspension framework is connected to get the specified execution.

2.2.2 Low band width system(lbs)

Low bandwidth systems are also known as slow active systems, and low band width frameworks are too known as moderate dynamic frameworks. Fig 2.4 (b) appears this sort of dynamic suspension framework. In this sort of frameworks actuator is joined in arrangement with stun safeguard. This suspension framework controls the suspension over lower transmission capacity and particularly close shake space recurrence. The actuator gets bolted at higher frequencies and the wheel movement is controlled lately.

2.3 Review of related works

A thesis has done by Guido P. A. Koch on Adaptive Control of Mechatronic Vehicle Suspension Systems [9]. The author used a suspension concept called hybrid suspension control system which is simple and easy to validate. But it doesn't give a better performance that means not better ride comfort and stability. So to overcome this it is better to use quarter car model with active suspension system so that can get a better performance than passive system. Therefore, there will be a good performance compared with hybrid suspension control car model.

Abdolva Agharkakli et al. (2012) analyzed that suspension travel in active cases has been found to be reduced to more than half of their value in passive systems by using LQR [10]. They have proposed that, by comparing the performance of the passive and active suspension systems using the LQR control technique, it clearly shows that active suspension can give lower amplitude and faster settling time. But the amplitude of the car body displacement was slightly higher compared with the passive suspension system.

An active quarter car suspension system is presented by Sayel M. Fayyad, however he has taken a 0.08m unit step as disturbance, which is not the real input [11]. Again a quarter car suspension with PID controller has been done by Arti Tiwari et.al [12]. But, they have considered a step input as a disturbance, which is not the real road input. This doesn't work if any random rough input is given to the system as a disturbance. So, take a real input which is bumpy like structure or similar to sinusoidal input.

Swethamarai P S and P. Lakshmi have developed an active quarter car suspension system utilizing a Fuzzy_PID controller to decrease driver body acceleration, achieving successful minimization. However, the settling time and overshoot of the displacement are considerably high, which are 0.38 overshoot and 2.38 sec settling time with LQR indicating a slow rate of stabilization but using Fuzzy_PID controller 0.03434 overshoot and 1 sec . This limitation could be addressed through enhancements to the Fuzzy_PID controller [13].

Abdussalam Ali Ahmed and Omer S. M. Jomah are researchers who have worked on modeling and controlling a quarter car suspension system using a neural network and a linear quadratic regulator, achieving positive results in terms of road handling and stability. However, the LQR approach necessitates a strong grasp of the system dynamics and requires extensive mathematical modeling, while neural networks depend on training data and can be computationally demanding [14]. Therefore, an alternative approach for modeling and controlling the suspension system could involve using a Fuzzy PID controller, as it allows for adjustments through modifications of the rules.

Abut, T.; Salkim, E. focus on controlling and designing a Quarter-Car Active Suspension System that aims to achieve minimal error while enhancing vehicle handling and passenger comfort [15]. They implement linear quadratic regulator (LQR), PSO-based fuzzy logic control (FLC), and PSO-based fuzzy linear quadratic regulator (fuzzy_LQR) methods to manage the suspension system. The linear quadratic regulator requires establishing the optimal control law to minimize the defined performance index and utilizes a state space model. This controller operates on the principle of complete state feedback. Both particle swarm optimization-based fuzzy logic control and fuzzy-LQR are utilized, with LQR fuzzy logic control yielding improved results; however, they are resource-intensive in terms of cost and mathematical modeling, necessitating frequent updates to the suspension model.

Abd El-Nasser S. Ahmed1 , Ahmed S. Ali2 , Nouby M. Ghazaly1 , G. T. Abd el- Jaber1 have done PID controller [16] for active suspension system of quarter car model get relatively better result of the active suspension than the passive but they consider step input 0.1. The result is almost follow the passive which means no more clear output of stability and disturbance handling.

Nguyen Van Trang and Duong Nguyen Hac Lan have completed their research on modeling of a quarter car suspension system utilizing a PID controller, achieving fairly good results in relation to the input. However, because the PID controller is based on the assumption of linear dynamics and operates as a single input single output system, they miss out on the nonlinear characteristics inherent to the nature of suspension systems [17].

Turan Alp Arslan , Faruk Emre Aysal , Ibrahim Celik , Huseyin Bayrakceken , Tugce Nur Ozturk these researchers are done on quarter car suspension system using fuzzy controller and they get almost the same result for the same input/uniform disturbance[18]. so can improve the result by using fuzzy_PID to improve the result.

The research conducted by Tura Alp, Faruk Emre, Aysal, Ibrahim Celic, Huseyin Bayraceken, and Tugce Nur Ozturk on quarter car suspension system using fuzzy controllers has yielded consistent results across various studies. However this consistency may also indicate a limitation in the adaptability and responsiveness of the fuzzy control methods employed. Below is summary of identified gaps and how they can be addressed by implementing a Fuzzy_PID controller.

Each of the three suspension system types covered in section 1.1 possesses distinct advantages and disadvantages. This thesis concentrates on active automotive suspension, mostly for passenger comfort and ride stability. This active suspension system outperforms the previously described two types of suspension systems. The passive suspension functions as an open-loop control system. It lacks a feedback signal to rectify the problem. Conversely, active suspension possesses the capability to enhance ride comfort. This phenomenon occurs through the force actuator being regulated by the controller. The active suspension system is a closed-loop control system. It rectified the fault and produced the result at the desired level. This occurs through a force actuator regulated by the controller. The active suspension system is a closed loop control system . It rectified the fault and produced the output to the specified level.

Quarter car model consists of one wheel and has two degree of freedom. The quarter car model is used when the heave motion needs to be considered. A passive quarter car model is shown in figure 1.1. It has sprung mass and un-sprung mass connected by spring and damper.

Table 2.1 Conclusion and methods used to address the gap.

Identified gap	Proposed improvements with Fuzzy_PID controller
Limited adaptability	The Fuzzy_PID controller combines fuzzy logic adaptability with PID control's precision, allowing for dynamic adjustment based on varying disturbance.
Performance Consistency	Consistence results are beneficial, the lack of differentiation in response to diverse inputs suggests a need for enhanced performance tuning. Fuzzy_PID can adjust parameters in real time to optimize performance.
Response time issues	Fuzzy controllers may introduce delay in response to sudden disturbance.The Fuzzy_PID controller can improve response time by integrating proportional, integral, and derivative actions to react more swiftly to change.
Robustness to varied disturbance	Existing fuzzy controller may struggle under a wide range of real world condition. The Fuzzy_PID's hybrid approach can enhance robustness and maintain stability across different scenarios.
System stability	Oscillations and instability may arise in traditional in fuzzy controller. The Fuzzy_PID controller can improve system stability by effectively managing the control signals based on both fuzzy logic and PID principles.

In general many researchers have done a lot related to suspension system using different control methods with their own strength and weakness as defined above. This thesis work tried to make an improvement on the stability of the quarter car suspension system in terms of settling time and overshoot.

Chapter Three

System Modeling and Controller Design

3.1 Mathematical Modeling of Quarter Car Suspension System

The quarter car model has a simple and easy-to-understand structure. It is frequently used in suspension system design and simulation because it reflects the important features of the full car. The active quarter car model has two main masses, sprung and unsprung, two springs and a damper. This system is activated with the actuator added between the body and the axle. Actuators, which generally consist of elector-hydraulic elements, provide the control of the system by generating forces in both directions. With the system control, the effects of vibrations caused by road disturbances on the vehicle body and passengers are reduced.

3.1.1 Passive Suspension Quarter Car Model

The framework appeared in Fig. 3.1 be a quarter car framework where the sprung mass is m_c, where the unsprung mass is m_w, where the firmness coefficient of the suspension is k_s, where the vertical solidness of the tire is k_t , where the damping coefficient of the suspension is d_s, where the vertical uprooting of sprung mass is z_c, where the vertical uprooting of unsprung mass is z_w , and where the road excitation is z_r. Once more, the distinction between the vertical uprooting of sprung mass and vertical relocation of unsprung mass is the suspension travel. It consider, as it were, mass developments on the vertical pivot, disregarding the rotational development of the vehicle.

The free body diagram (FBD) of the sprung of mass of passive suspension (m_c) is shown in Fig 3.1

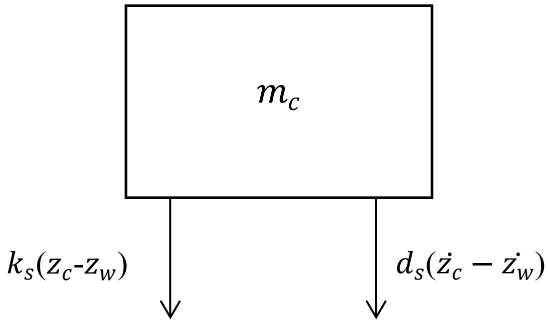


Figure 3.1 Free body diagram of the sprung of mass of passive suspension system

Note that the displacements 'z_c ' and 'z_w' in the system are from the static equilibrium position. Here, the gravity force is neglected, as the spring forces due to the initial compression of the springs balance it.

The free body diagram (FBD) of the unsprung mass (m_w) in Fig 3.2

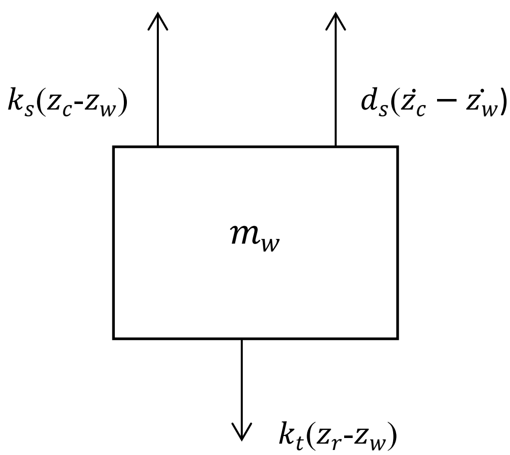


Figure 3.2 Free body diagram of the unsprung mass of passive suspension system

The mathematical model for the quarter car suspension system is derived from Newton's second rule of motion, which asserts that the sum of the forces acting on the body must be equal the product of its mass and acceleration. The mathematical representation for the passive suspension system is:

$F_S + F_d - F_g = ma$ .... (3.1)

Where, F_S is the spring force, F_d is the damper force, and F_g is the gravity force. The dynamic equations of motion for the sprung and unsprung masses of the quarter car model, derived from Newton's law of motion when 'the system is displaced from the static equilibrium position, are presented below [18].

$m_w\ddot{z}_w = k_t\ (z_r - z_w\ ) - k_s\ (z_w - z_c\ ) - d_s\ (\dot{z}_w - \dot{z}_c\ )$ ……………………… …………..….. (3.2)

$m_c\ddot{z}_c = k_s\ (z_w - z_c\ ) + d_s\ (\dot{z}_w - \dot{z}_c\ )$ …………………………...………………………..... (3.3)

The constant parameters of the quarter car suspension system are shown in Table 3.1.

Table 3.1 Parameters of quarter car suspension system [18].

Parameters	Values
m_C(kg)	300
m_w(kg)	50
$k_s(N/m)$	18000
$k_t(N/m)$	190000
$d_S(N-s/m)$	2000

3.1.2 Quarter car active suspension system

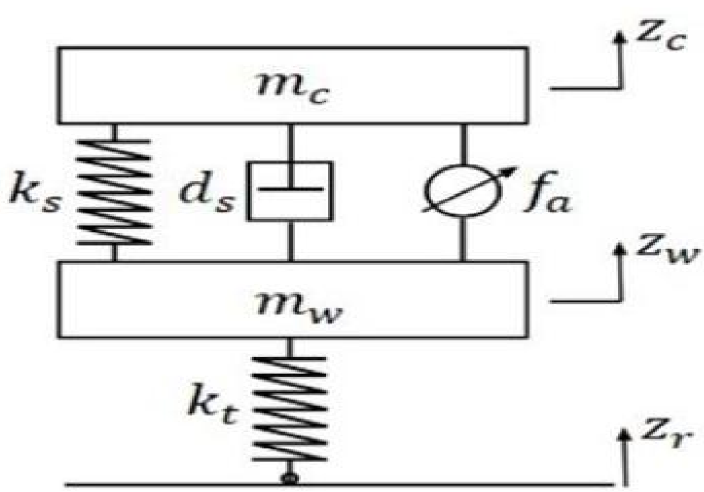


Figure 3.3 Quarter car active suspension model [18].

In addition, the displacement of the spring and unsprung masses are indicated by z_c and z_w, respectively, and the road profile affecting the unsprung mass is indicated by z_r.

The free body diagram of the body of mass (m_c) is shown in Figure 3.4.

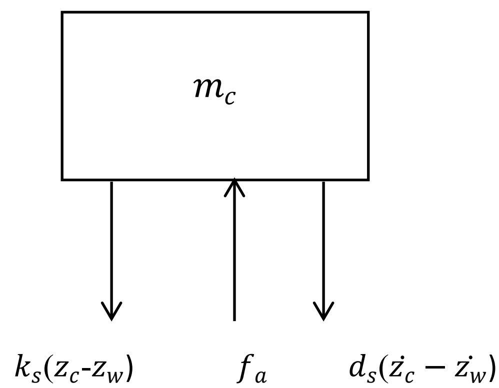


Figure 3.4 Free body diagram of the sprung of mass of active suspension system

The free body diagram of the body of mass (m_w) is shown in Figure 3.5.

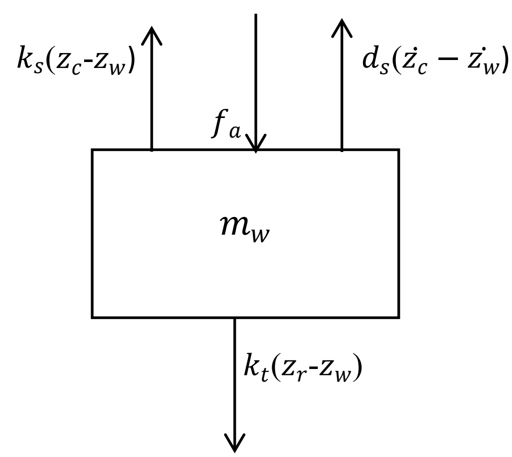


Figure 3.5 Free body diagram of unsprung mass of active suspension system

The linear equations of motion for the sprung and unsprung masses of the active quarter-car suspension system are articulated through Newton's second law as follows [18]:

$m_w\ddot{z}_w = k_t\ (z_r - z_w\ ) - k_s\ (z_w - z_c\ ) - d_s\ (\dot{z}_w - \dot{z}_c\ ) - f_a$ ……………………………………..(3.4)

$m_c\ddot{z}_c = k_s\ (z_w - z_c\ ) + d_s\ (\dot{z}_w - \dot{z}_c\ ) + f_a$ ………………………………………………...…… (3.5)

In order to develop the state space model of the system x_1 , x_2 , x_3 and x_4 parameters are accepted as state variables. Here x_1 represents the displacement of the unsprung mass, x_2 the velocity of the unsprung mass, x_3 the displacement of the sprung mass and x_4 the velocity of the spring mass. Quarter car active suspension model equations of motion are converted into state space model with the help of the following expressions:

$x_1 = z_w$ ……………………………………………………………………………(3.6)

$x_2 = \dot{z}_w = \dot{x}_1$ ……………………………………………………………………(3.7)

$x_3 = z_c$ ……………………………………………………………………………(3.8)

$x_4 = \dot{z}_c = \dot{x}_3$ ……………………………………………………………………(3.9)

$\dot{x}_1 = x_2$ ……………………………………………………………………………(3.10)

$\dot{x}_2 = \frac{1}{m_w}[k_t z_r - (k_t + k_s)x_1 - d_s x_2 + k_s x_3 + d_s x_4 - f_a]$ ……………………………(3.11)

$\dot{x}_3 = x_4$ ……………………………………………………………………………(3.12)

$\dot{x}_4 = \frac{1}{m_c}[k_s x_1 + d_s x_2 - k_s x_3 - d_s x_4 + f_a]$……………………………………………(3.13)

The state space model used to explain the system dynamics is obtained as follows [18]:

$\dot{x} = Ax + Bu$ …………………………………………………………………… (3.14)

$y = C$x ……………………………………………………………………………… (3.15)

$x = [x_1, x_2, x_3, x_4]$T …………………………………………………………… (3.16)

$u = [fa, zr]$ T…………………………………………………………………… ...(3.17)

$$A=\begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{k_t+k_s}{m_w} & -\frac{d_s}{m_w} & \frac{k_s}{m_w} & \frac{d_s}{m_w} \\ 0 & 0 & 0 & 1 \\ \frac{k_s}{m_c} & \frac{d_s}{m_c} & -\frac{k_s}{m_c} & -\frac{d_s}{m_c} \end{bmatrix}$$ …………………………………………………………… (3.18)

$$B=\begin{bmatrix} 0 & 0 \\ -\frac{1}{m_w} & \frac{k_t}{m_w} \\ 0 & 0 \\ \frac{1}{m_c} & 0 \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.19)$$

$$C=[0 \quad 0 \quad 1 \quad 0] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3.20)$$

There are lots of aspects that vibration affects people like acceleration, amplitude (vertical displacement), vertical velocity, frequency and action directions. Among them, the top reasons that vibration causes people uncomfortable are the vertical velocity and displacement. So in this thesis, two evaluation parameters has been chosen: the vehicle body vertical displacement and velocity, which are x_s and $\dot{x}_s$. It compare these with the passive suspension system, the passive, PID controller and fuzzy-PID controller methods by out putting their vehicle body vertical displacement and velocity. The lower in amplitude of x_s and $\dot{x}_s$ means the better performance.

3.2 Controller design

3.2.1 Design requirement

An effective car suspension system is defined by a level of ride comfort and the ability to maintain traction while traversing uneven surfaces. When the vehicle encounters any road irregularities, the body of the car should ideally experience minimal oscillations. The road disturbance (d) in this scenario be modeled by actual input, specifically the bumpy road.

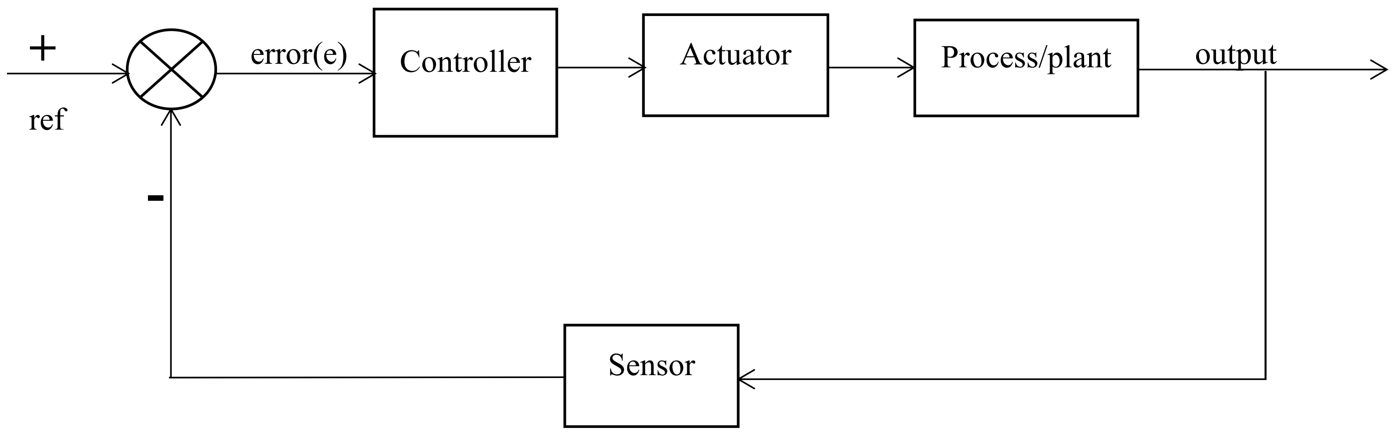


Figure 3.6 Schematic block diagram of the closed-loop feedback controller

The fundamental functions of closed loop feedback controllers involve comparing the actual value with the desired set point value to generate an error signal, which is then fed into the fuzzy PID controller. Based on this error signal, the controller determines which parameters need to be adjusted. The modifications selected by the controller's algorithm are applied to specific adjustable variables, allowing the error signal to be minimized and the measured quantity to reach its target value. Additionally, the current availability of control system components at reduced prices has contributed to the growing use of the feedback principle in various applications. The schematic block diagram of the feedback control system is depicted in Figure 3.6. Clearly, the performance of the entire control system is influenced by the careful selection of each component. For the purposes of designing the controller, the dynamics of the actuator and sensor are typically overlooked, although the saturation limits of the actuator must be considered.

3.2.1.1 Actuator

Sensors and actuators represent the primary components found in every closed-loop control system, which operates on feedback control principles. A standard feedback control system is illustrated in Fig. 3.6, featuring a sensing unit, a controller, and an actuating unit. Actuation systems are the parts of control systems that convert a controller's output into an action. In this context, the actuating unit includes an actuator, which typically serves as a force amplifier or is utilized in situations requiring quicker operations than human response. These actuators can be categorized as pneumatic, electrical, or hydraulic, each coming with its own set of advantages and disadvantages. The type of actuator discussed in this thesis is the hydraulic actuator, which pertains to the methods and mechanisms used to transmit power through fluids

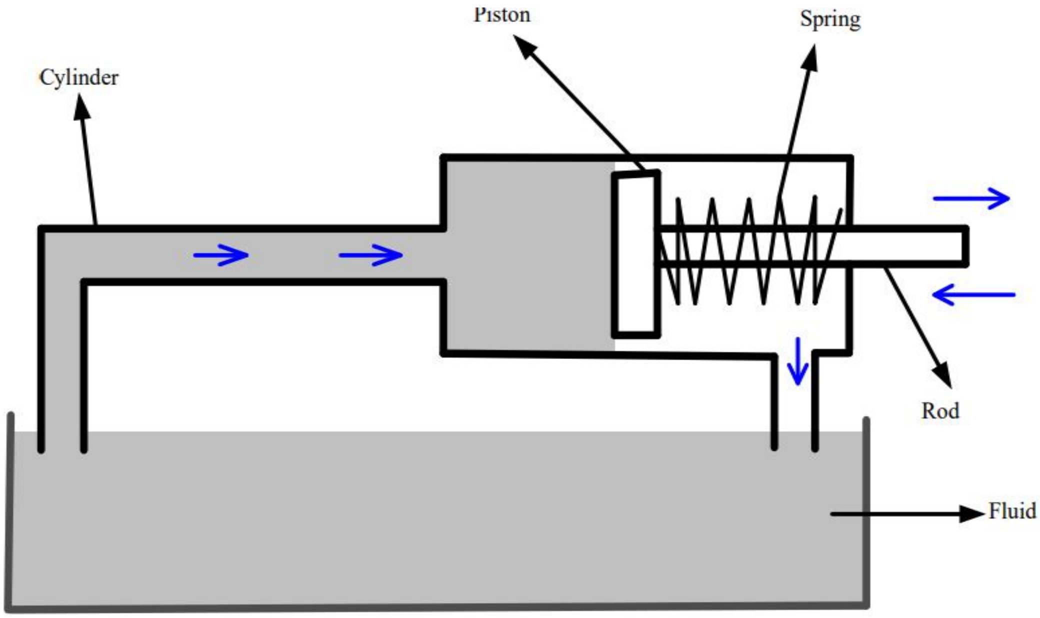


Figure 3.7 Schematic block diagram of hydraulic actuator

Water-powered actuators, as utilized in numerous handle control frameworks, utilize water-powered weight to drive a yield parameter. These are fundamentally utilized where tall speed and huge strengths are required. The liquid utilized in a pressure-driven actuator is profoundly non-compressible so that weight connected can be transmitted momentarily to the part joined to it. A water-powered actuator may be a cylinder-piston course of action in which the cylinder is moved by a pressurized liquid, which is the forward force. The return of the cylinder isn't done powerfully. It is done with the assistance of a spring connected to the bar. The barrel is basic to convert the water-powered vitality that's provided by the pump into valuable work. The biggest advantage of a pressure-driven framework is that the compressibility of water-powered liquids is exceptionally low. Pressure-driven frameworks have better control thickness, i.e., a parcel of control in a little.

3.2.1.2 Sensor

In this thesis, a linear variable differential transformer is employed for measuring displacement. This type of sensor is likely the most durable and dependable option for displacement measurement. The key advantage of the LVDT sensor's design is that there is no electrical contact throughout the position sensing element of the transducer, which ensures that users receive clean data, enjoy infinite resolution, and benefit from a long lifespan.

3.2.1.3 Construction of LVDT

LVDT is a transformer consisting of one primary winding P and two secondary winding S1 & S2 mounted on a cylindrical former, which is hollow in nature and contain core. The two secondary windings have equal number of turns and are identically placed on either side of the primary winding as shown in figure 3.8.

The primary winding is connected to an AC source which produces a flux in the air gap and voltages are induced in secondary windings. A movable soft iron core is placed inside the former and displacement to be measured is connected to this iron core.

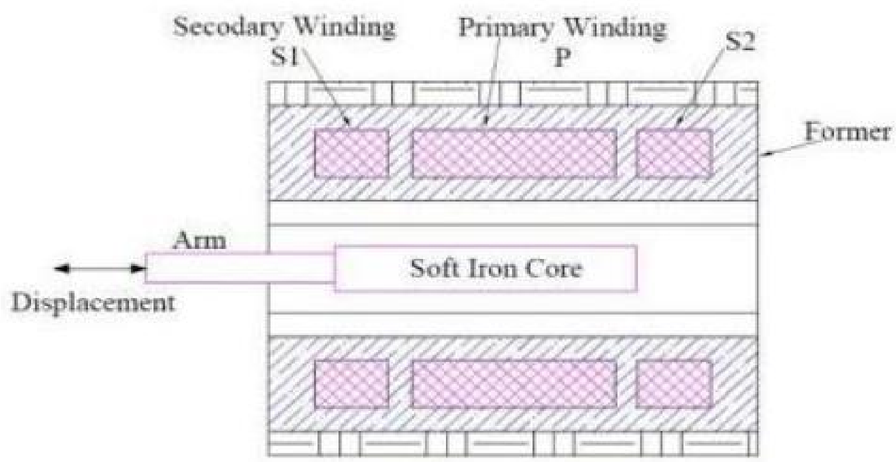
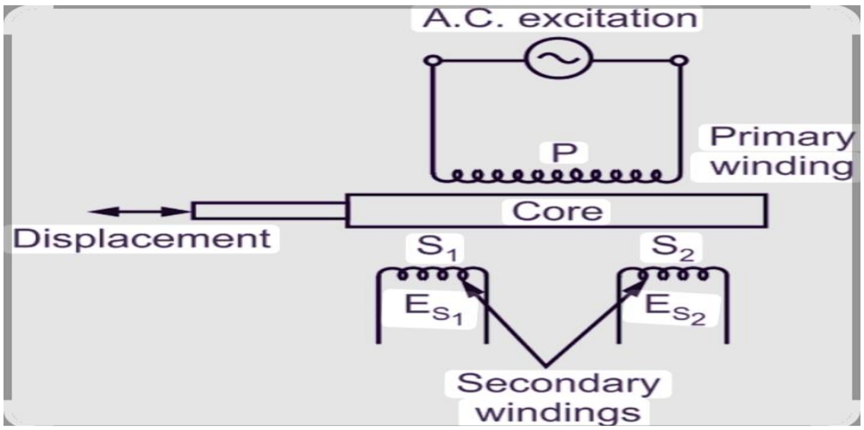


Figure 3.8 Linear variable differential transformer circuit [19]

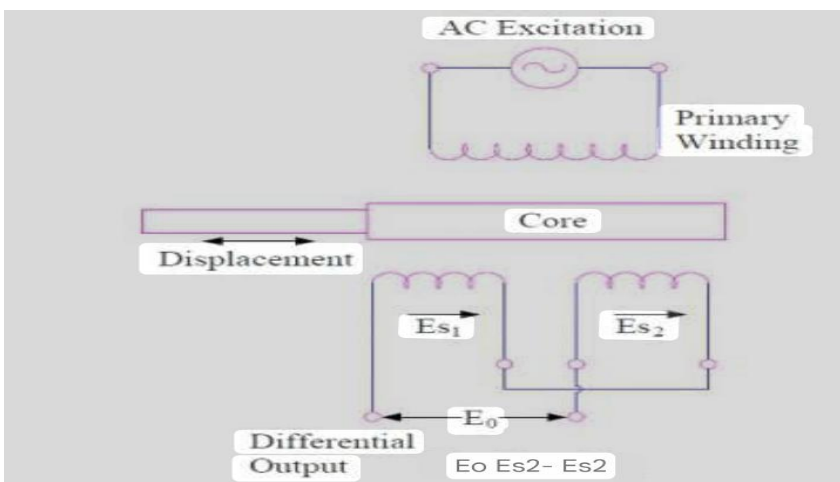
The iron core is generally of high permeability which helps in reducing harmonics and high sensitivity of LVDT. The LVDT is placed inside a stainless steel housing because it provide electrostatic and electromagnetic shielding. Both the secondary windings are connected in such a way that resulted output is the difference of the voltages of two windings.

3.2.1.3.1 Working principle of LVDT

Since the primary winding of linear variable differential transformer is supplied with AC supply, it produces an alternating magnetic flux in the core which in turn link with the secondary windings S1 and S2 to produce emf due to transformer action. The electrical equivalent circuit of LVDT is shown in figure 3.9



(a)



(b)

Figure 3.9 (a) The electrical equivalent circuit of LVDT (b) The electrical equivalent circuit of LVDT for the output voltage [19]

Let us assume that the emf produced in secondary winding s_1 is E_{s_1} and that in s_2 is E_{s_2} . To get a single output voltage from the LVDT, both the secondary winding is connected in series but in phase opposition. Since the secondary winding of linear variable differential transformer are identical and placed symmetrically on either side of core, therefore under normal position the flux linkage of both the secondary winding $s_1 \& s_2$ be same. This means $E_{s_1} = E_{s_2}$ and hence net output voltage E_0 of LVDT is equal to zero. This position of soft iron core is called null position. Thus null position of LVDT is the normal position of movable core where the net output voltage is zero. When an external force is applied, the core can either be moved towards the right or left hand side of the null position.

3.3 Proportional–Integral–Derivative controller

A Proportional–Integral–Derivative(PID) controller is a triad controller with a longstanding history in automatic control, dating back to the early 20th century [20]. Due to its intuitiveness and relative simplicity, it has become a typical controller in industrial environments. A PID controller is a universal feedback mechanism, utilized in industrial control systems. A PID controller seeks to rectify the discrepancy between a measured process variable and a desired set point by computing and subsequently corrective delivering a corrective action that can modify the process to maintain error minimal [21].

PID which is a short form for Proportional – Integral - Derivative, shows the three terms operating on the error signal to produce a control signal. Because of its flexible structure set, parameter tuning, touch-type error robustness, etc. In this chapter, the fundamental concepts of PID controller be introduced. In particular, the meaning of the three actions is explained and the tuning issue is briefly discussed.

The main aim of a control system is to obtain a desired response for any given system. This can be done with a closed-loop control system, where the controller determines the input signal to the process by using the measurement of the output that is the feedback signal. Feedback control is actually needed to keep the process variable close to the desired value despite of disturbances and variations of the process dynamics. Hence, it is better to describe the feedback control loop before look at the PID and fuzzy controllers.

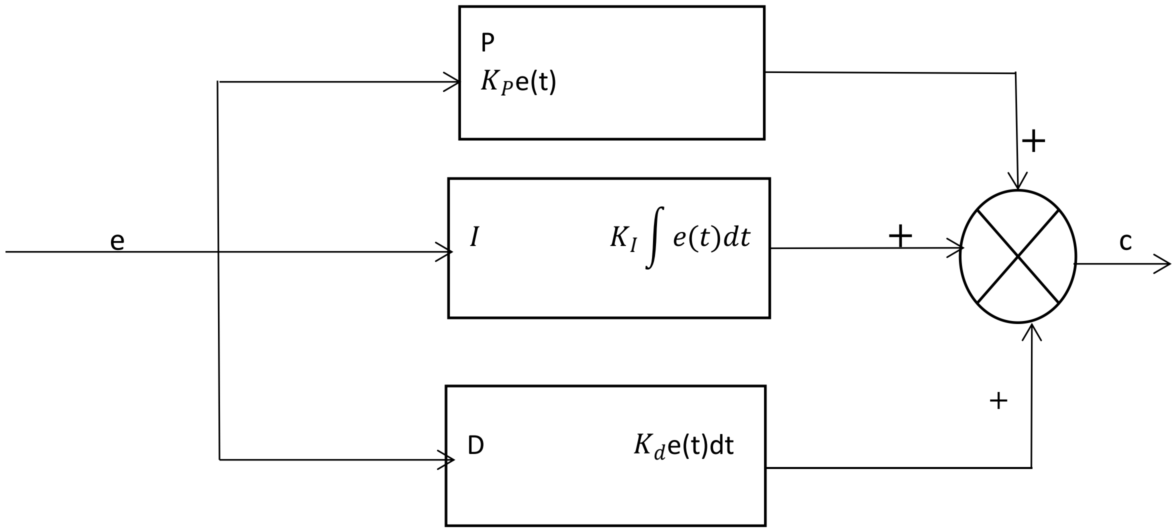


Figure 3.10 Schematic block diagram of PID Controller

Where, p is propertional, I integral and D is derivative. For the disturbance reduction, a PID controller is used in order to decrease the magnitude and settling time of the vertical parameters of car suspension system.

3.4 Fuzzy Logic Controller

Most real-world processes that necessitate automatic control exhibit non-linear characteristics, this means their parameter values can change as the operating point varies over time or both. In traditional control methods, which are linear, a controller can only be optimized for effective performance at a specific operating point or for a limited duration. If the operating point changes over time, the controller must be re calibrated, this requirement for re-tuning has led to the development of adaptive controllers that can autonomously adjust themselves to align with the current characteristics of the process.

Rapid motion indexing demands high sampling and update rates to maintain stability. Typically, PID control requires less processing time to compute control signals (a key advantage of PID) compared to a similar fuzzy logic controller (FLC). The time needed for processing with fuzzy logic control depends on the number of rules that must be assessed. Large systems with numerous rules would necessitate very powerful and fast processors to operate in real-time and smaller rule base requires less computational power. To alleviate processing time, a static lookup table can be utilized to produce FLC control actions. In certain situations, this approach can significantly decrease processing time compared to executing fuzzy inference.

3.4.1 Configuration of FLC

Fuzzy logic is a technique to train human-like thinking into a control system. So the main purpose of designing fuzzy controller is to represent the human intelligence or human like thinking in the controller to control the process parameters. There are two main fuzzy logic inference systems (fuzzy logic approximators): Mamdani type and Takagi-Sugeno type. The antecedent parts of the rules for both inference systems are the same. These two methods only differ in how they obtain the outputs.

3.4.2 Mamdani fuzzy inference system

E. H. Mamdani proposed the Mamdani architecture for fuzzy logic control in 1974. By determining where the input membership function and the crisp input value cross, it fuzzifies the two inputs. It computes the fuzzy and combines the fuzzified inputs to get the rule strength using the minimal operator. At the rule strength, the output membership function is clipped. Lastly, it calculates the fuzzy "or" for combining the rule outputs using the maximum operator. The method for creating a fuzzy control system is the Mamdani architecture. The bits that follow are fuzzy sets. A human expert can easily understand it, it is easier to create rules for, and it was the first and most widely utilized approach to be offered.

3.4.3 Sugeno Fuzzy Inference System

The Sugeno fuzzy inference system is quite similar to the Mamdani fuzzy inference system. The primary difference is that the output consequence is not computed by clipping an output membership function at the rule strength. In fact, Sugeno FIS there is no output membership function at all. Instead the output is a crisp number computed by multiplying each input by a constant and then adding up the results. Therefore, Takagi-Sugeno fuzzy system, the conclusion of the fuzzy set is not a fuzzy set but a crisp function of the inputs. Takagi-Sugeno model is an alternative architecture introduced by Takagi and Sugeno, which uses a combination of linguistic rules and linear functions to form a fuzzy logic control strategy. The consequent parts are singletons (single spikes) or mathematical functions of them. Moreover, this method needs more effective computation. Also, it is more convenient in mathematical analysis and in system analysis and guarantees continuity of the output surface.

Due to the above advantages mentioned, in this thesis mamdani fuzzy logic inference system is used. The principal components of this Fuzzy logic controller system are:

- Fuzzification block or fuzzifier
- Knowledge base
- Decision making block
- Defuzzification block or defuzzifier

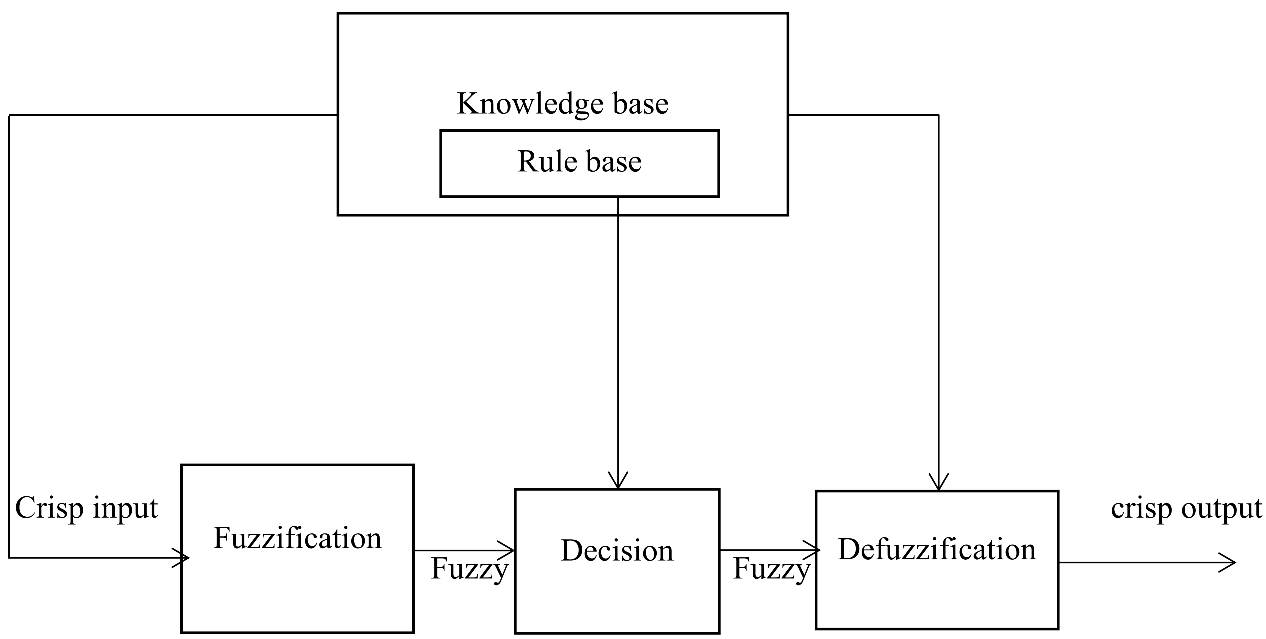


Figure 3.11 Fuzzy logic block diagram [22]

The input given to the FLC block is in numeric form so the first thing to be done is to convert the numerical data/variable into linguistic variable. This task is performed by the fuzzifier. This fuzzification task includes choosing proper MF for the variables so that the crisp inputs can be converted into fuzzy sets. A fuzzy system is characterized by set of linguistic statements based on expert knowledge. The knowledge base consists of the data base and the linguistic control rule base. The rule base is usually in the form of IF-THEN rules, which are easily implemented by fuzzy conditional statements in fuzzy logic. The Rule base defines rules that describe the relationships between the desired result and the data available. The aim of this rule base is to characterize the control goals and policies by using a set of linguistic or If-Then rules. A fuzzy rule is a simple IF-THEN rule with a condition (antecedent) and a conclusion (consequence).

The data base provides the information which is used to define the linguistic fuzzy rules and the fuzzy data manipulation in the fuzzy logic controller. Hence, the main aim of data base is to provide necessary definitions that are needed to define the linguistic fuzzy rules. The decision making block is the most important component of a fuzzy controller because it is the block that decides the output depending upon the given input. The other component of the fuzzy logic controller is the defuzzification, which is the reverse of fuzzification. That is the process of converting a linguistic variable into a crisp variable is known as defuzzification. It is employed because in many practical applications a crisp control action is required.

3.5 Design of fuzzy_PID controller

A fuzzy_PID controller combines the traditional PID control strategy with fuzzy logic to enhance performance, especially in system with nonlinearities.

3.5.1 Theory of Fuzzy PID controller

1. Fundamentals of PID control:

- Proportional (P): the control output corresponds to the present error, which is the difference between the intended setpoint and the observed process variable.
- Integral (I): the control output is related to the cumulative error over time, assisting in the elimination of steady-state error.
- Derivative (D): the control output is connected to the rate of change of the error, which aids in forecasting future errors and stabilizing system response.

2. **Fuzzy logic control:**

- Fuzzy logic offers a method to manage uncertainty and ambiguity by utilizing linguistic variables and rules rather than exact numerical figures.

➢ It uses a collection of "if-then" statements to determine control actions based on fuzzy sets.

3. Integrating fuzzy logic with PID:

➢ In a fuzzy PID controller, fuzzy logic is employed to modify the gains of the PID controller (k_p, k_i, k_d) according to the current state of the system.

➢ The fuzzy rules can be structured to adaptively adjust these gains based on the error and its rate of change (i.e., the derivative of the error).

3.5.2 Block diagram of fuzzy PID controller:

Below is simplified representation of a fuzzy PID controller in block diagram form.

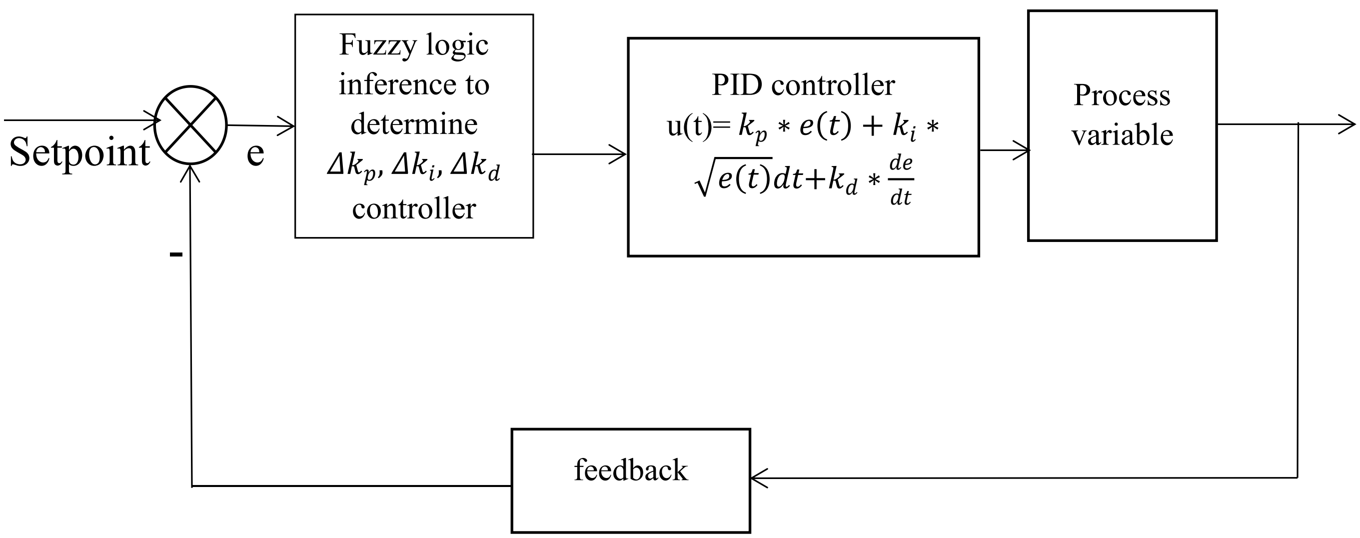


Figure 3.12 Fuzzy_PID controller design

1. Setpoint(SP): the desired value that the system should achieve.
2. Error calculation: the difference between the setpoint and the process variable is calculated to determine the error.
3. Fuzzy logic controller: the error and its change are input into a fuzzy logic system that evaluates predefined rules to adjust the PID parameters(k_p, k_i, k_d).

4. PID controller: the adjusted PID parameters are then used in the standard PID control equation to compute the control output(u(t)).
5. Process: the control output is applied to the process/system being controlled, affecting its behavior.
6. Feedback: the process variable is measured and fed back into the system to continuously adjust and maintain control.

Conclusion of this is the fuzzy PID controller offers a robust solution for controlling complex system where traditional PID tuning may be inadequate due to non-linearity.by incorporating fuzzy logic, it can adaptability tune its parameters based on real time conditions, leading to improved performance.

3.5.3 Linguistic variables, values and membership functions

Optimization:

- **Performance Enhancement:** Optimization techniques, like genetic algorithms or other search algorithms, can fine-tune the rules to achieve desired performance characteristics, such as improved ride comfort or handling.
- **Handling Complexity:** Real-world suspension systems involve complex interactions and nonlinear behaviors that can be challenging to capture with simple rules. Optimization can help find optimal rule combinations even in such cases.
- **Data-Driven Refinement:** Optimization allows for the incorporation of data from simulations or real-world testing to further refine and improve the rule base.

Justification for Combining Expert Knowledge and Optimization:

- **Synergistic Approach:**
- Combining expert knowledge and optimization leverages the strengths of both approaches. Expert knowledge provides a structured framework, while optimization enhances performance and handles complexities.
- **Balancing Interpretability and Accuracy:**

This approach allows for a balance between interpret able rules based on expert knowledge and the potentially high accuracy of data-driven optimization.

- **Iterative Process:**

The rule base can be interactively refined by combining expert knowledge and optimization, allowing for continuous improvement and adaptation to different driving conditions and vehicle types.

In conclusion: A combined approach of expert knowledge and optimization is often the most effective way to justify and develop a rule base for a suspension system, especially when dealing with complex and dynamic driving conditions. This approach balances interpret ability and performance, allowing for a robust and adaptable control strategy.

The linguistic variables are error (e), change of error (Δe) and the actuator (u). All these three linguistic variables have been assigned three linguistic values. The linguistic variables e, Δe and u have linguistic membership values, small, medium and big. Fuzzy logic toolbox from MATLAB is used to design the active suspension system. Why uses triangular function is its simplicity which means it is easy to understand and implement. Computational efficiency and flexibility.

Each input has three Membership Functions (MFs), and the output has three MFs. Therefore, the rule base contains 9 rules. Moreover, it is assumed that input MFs are identical in shape. Each linguistic value is assigned a triangular membership function. The membership functions are shown in Figures 3.13 to 3.14. The triangular membership functions are used for their simplicity as is quite commonly done. Moreover, calculating fuzzified inputs and the areas of these functions is simple and fast when compared to other membership functions. Hence, the membership function is obviously the crucial component of a fuzzy set. It is therefore not surprising that operations with fuzzy sets are defined via their membership functions.

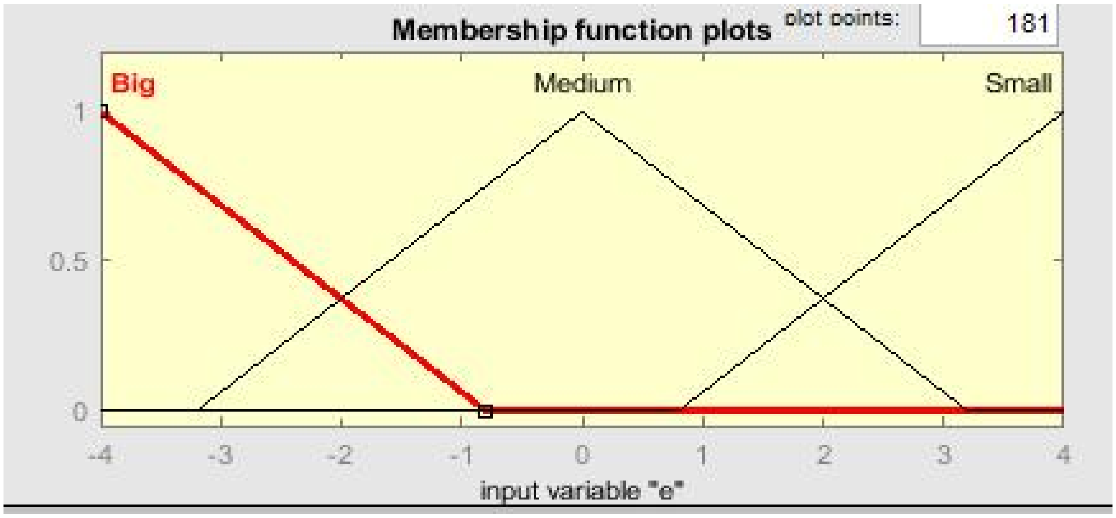


Figure 3.13 Membership function of the body displacement (error)

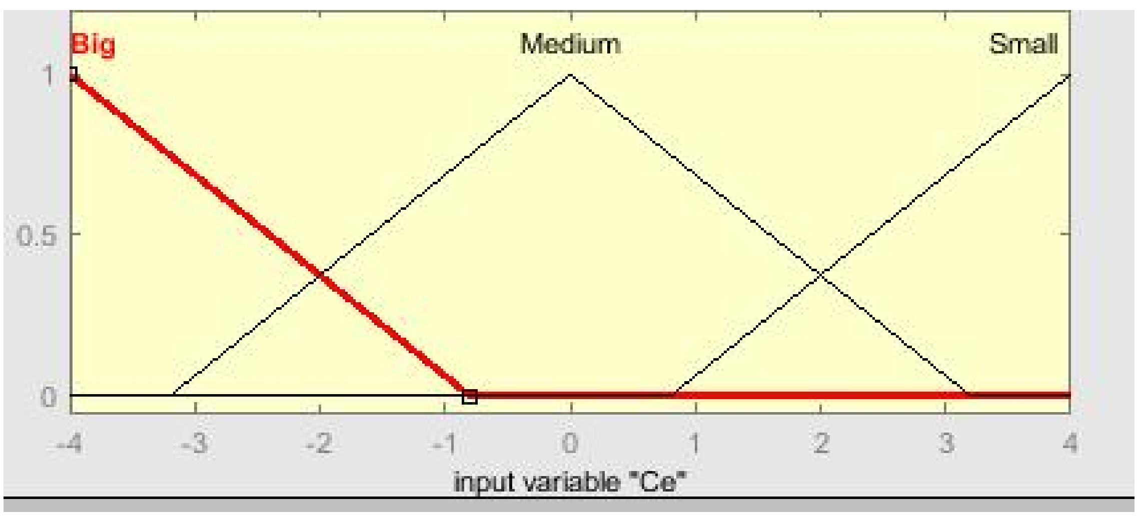


Figure 3.14 Membership function of the body velocity (Δe)

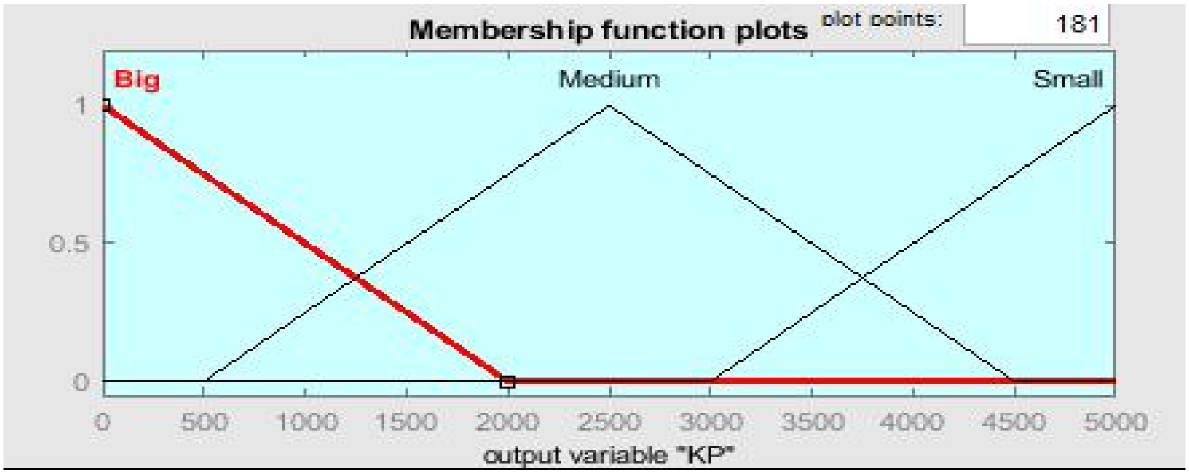


Figure 3.15 Fuzzy proportional action

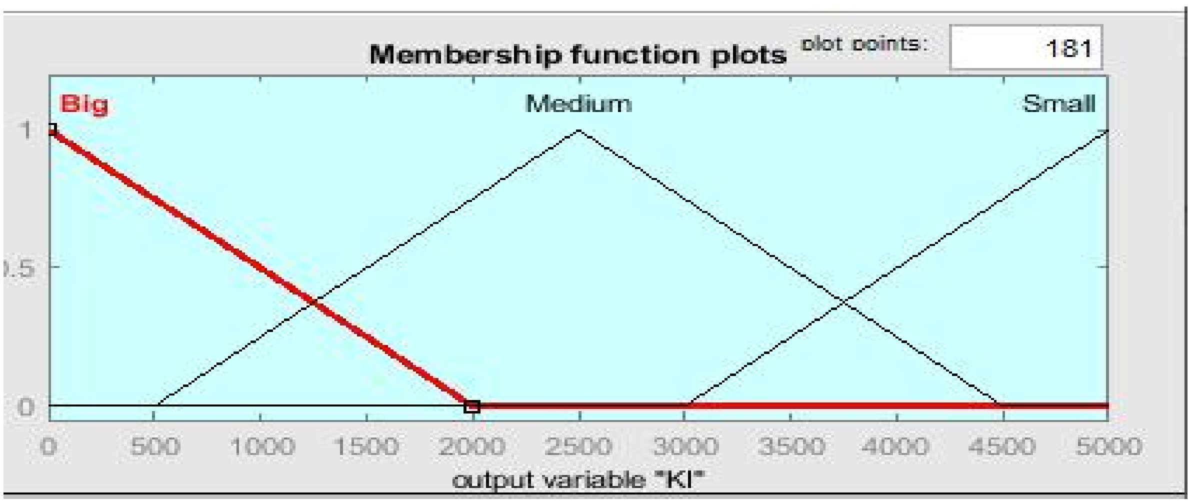


Figure 3.16 Fuzzy integral action

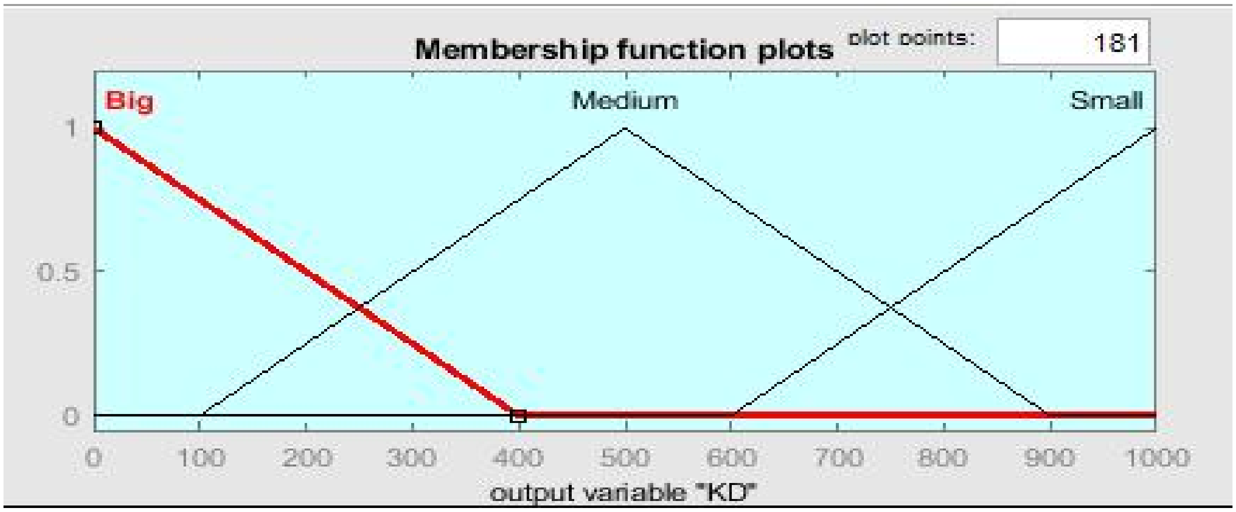


Figure 3.17 Fuzzy derivative action

Figure 3.13 shows two input functions on left named as body displacement and body velocity which are provided as an input to the controller and three output named actuator force on right which is provided by the controller to the actuator in the system.

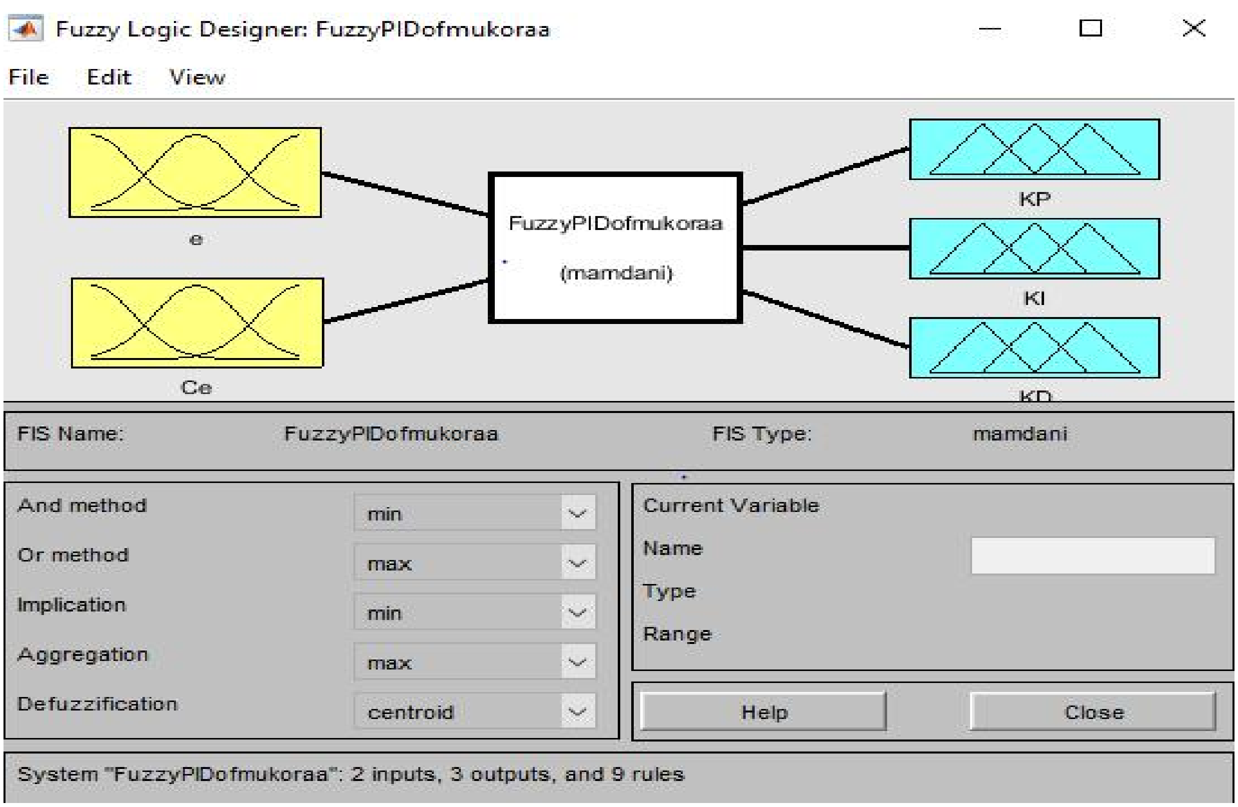


Figure 3.18 Input output parameters

Figure 3.12 shows rule viewer of fuzzy logic controller where 1st column indicates the sprung displacement, the 2nd column indicates the sprung velocity and third column indicates the actuator force.

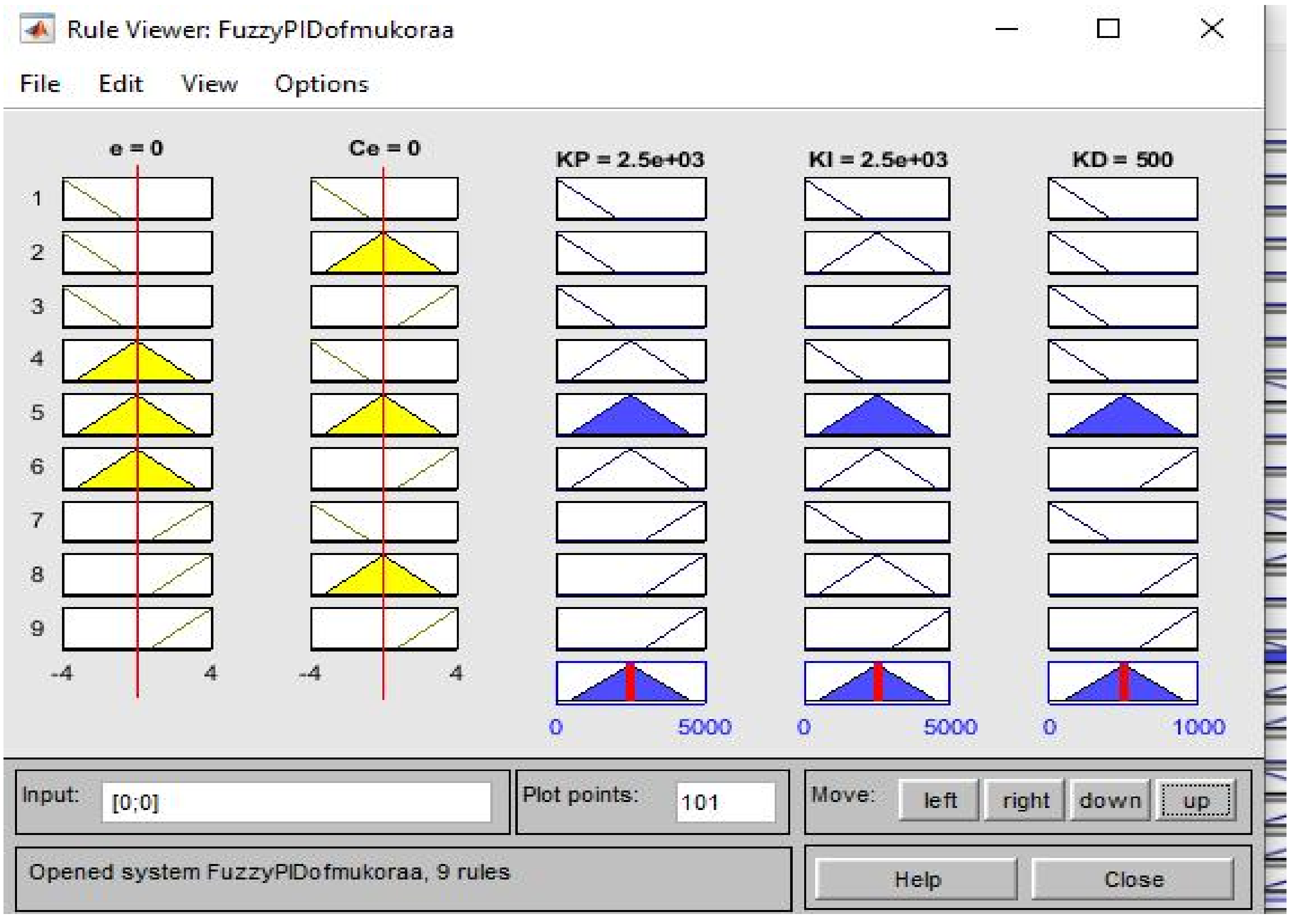


Figure 3.19 Rule viewer

3.5.3 Fuzzy rule base

The fuzzy rule base converts the control strategy into the control rules. The main objective of the FLC design in this work is to get the required ride comfort as well as enhance it. Therefore, the rule base is devised, such that the transmission of forces to the body is minimized. Hence, immediate understanding of the suspension system and logical proofs has been employed.

Table 3.2 Rule base of k_p

Error/error rate →	Big	Medium	Small
Big	Big	Big	Big
Medium	Medium	Medium	Medium
Small	Small	Small	Small

Table 3.3 Rule base of k_i

Error /error rate →	Big	Medium	Small
Big	Big	Medium	Small
Medium	Big	Medium	Medium
Small	Big	Medium	Small

Table 3.4 Rule base of k_d

Error /error rate →	Big	Medium	Small
Big	Big	Big	Big
Medium	Big	Medium	Small
Small	Big	Small	Small

Based on the membership functions that have discussed above, the fuzzy control rules that could be used are the following:

$R^{(1)}$: IF error is big AND change of error is big THEN k_p, k_i and k_d are big.

$R^{(2)}$: IF error is big AND change of error is big THEN k_p and k_d are big, k_i is medium.

$R^{(3)}$: IF error is big AND change of error is big THEN k_p and k_d are big, k_i is small.

$R^{(4)}$: IF error is big AND change of error is big THEN k_p is medium, k_i and k_d are big.

$R^{(5)}$: IF error is big AND change of error is big THEN k_p, k_i and k_d are medium.

$R^{(6)}$: IF error is big AND change of error is big THEN k_p and k_i are medium and k_d is small.

$R^{(7)}$: IF error is big AND change of error is big THEN k_p is small, k_i and k_d are big.

$R^{(8)}$: IF error is big AND change of error is big THEN k_p and k_d are small, k_i is medium

$R^{(9)}$: IF error is big AND change of error is big THEN k_p, k_i and k_d are small.

Chapter Four

Simulation Results and Discussion

In this section, the result of simulation study aimed at evaluating the performance of a fuzzy_PID controller in the context of a quarter car model. The primary objective of this study was to assess the effectiveness the fuzzy_PID controller in enhancing ride comfort and handling stability compared to traditional control methods. The quarter car model serves as simplified yet representative framework for understanding vehicle dynamics, allowing to analyze the controller's response to various road conditions and disturbance.

4.1 Bumpy road input1

The following type of road disturbance is assumed as the input for the system. The road profile input representing is below where 'a' denotes the bump amplitude. The sinusoidal bump with frequency of 8 Hz is represented by the following equation.

$$(t) = \begin{Bmatrix} \frac{a(1-cos8\pi t)}{2} & 0.2 \leq t \leq 1 \\ 0 & otherwise \end{Bmatrix} \ldots\ldots(4.1)$$

Where, road bump height (a) = 0.1.

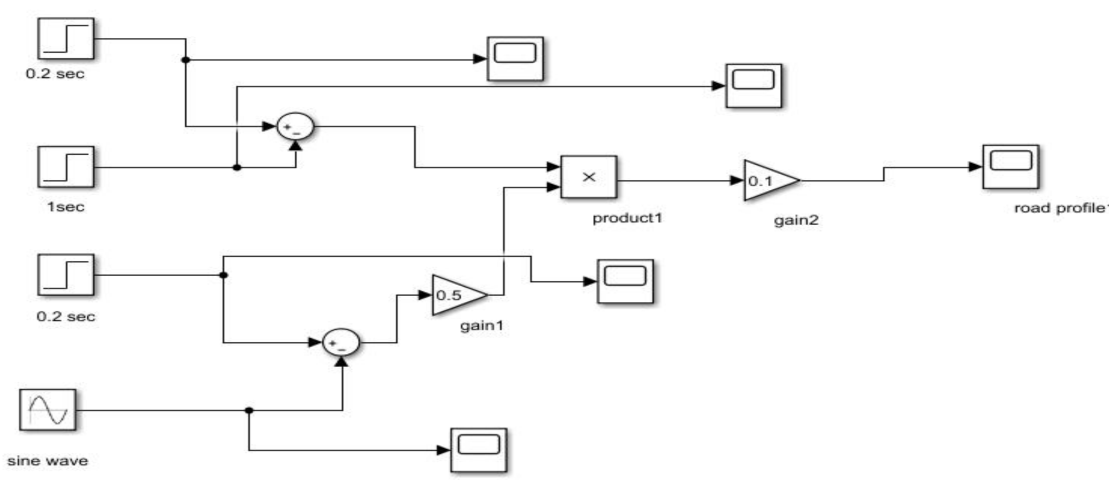


Figure 4.1 Simulink model of road profile 1

As it have mentioned in the section 2.5, for observing the performance of a car, consider a disturbance. So, as it is shown in fig 4.2 a bumpy road profile is taken for simulation of body displacement and velocity.

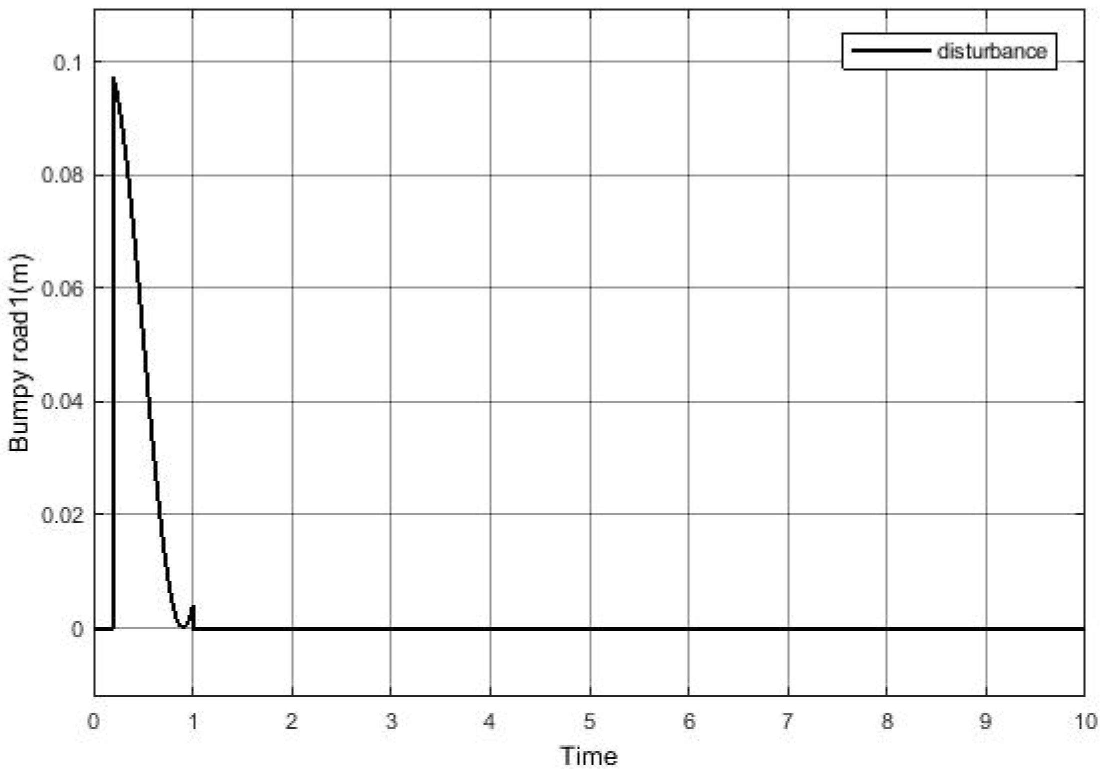


Figure 4.2 Bumpy input road1

4.2 Bumpy input Road2

$$(t) = \begin{cases} \frac{a(1-cos8\pi t)}{2} & 0.2 \le t \le 1 \text{ and } 3.3 \le t \le 4.1 \\ 0 & otherwise \end{cases} \quad \text{.................................}4.2$$

Where, road dip height (a) = 0.1 and 0.07

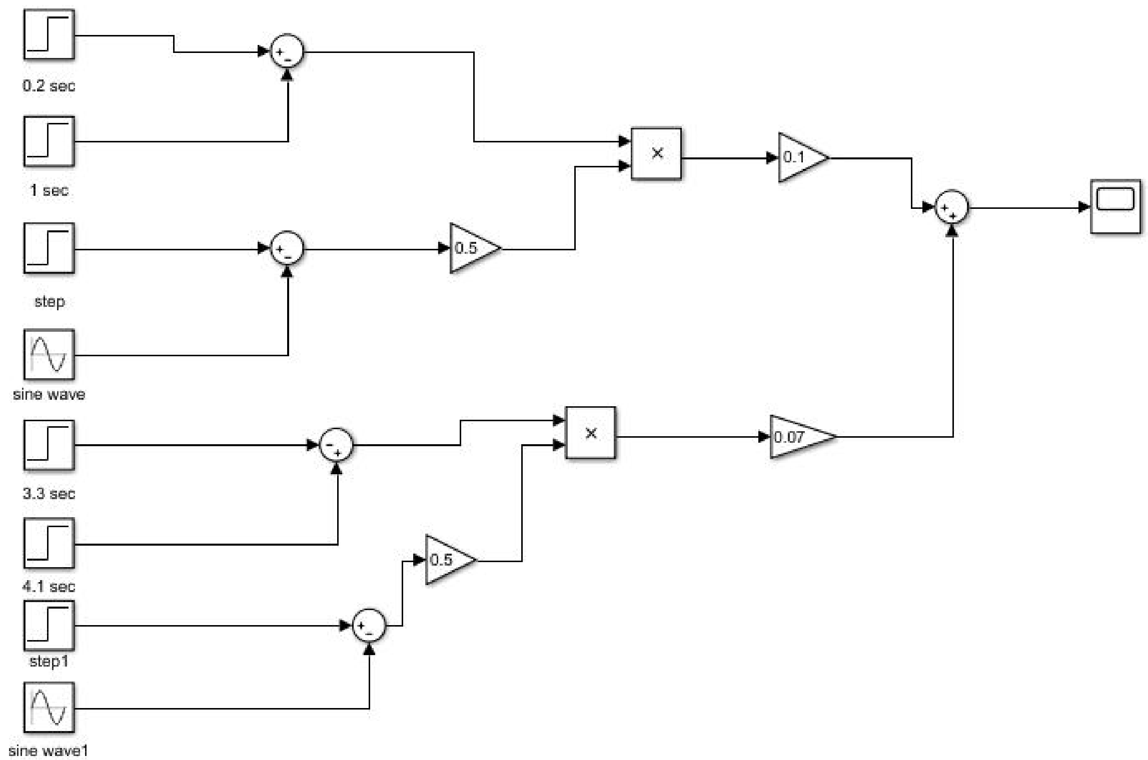


Figure 4.3 Simulink model of road profile2

As it have mentioned in the section 2.5, for observing the performance of a car, consider a disturbance. So, as it is shown in fig 4.4 another a bumpy road profile is taken for simulation of body displacement and velocity.

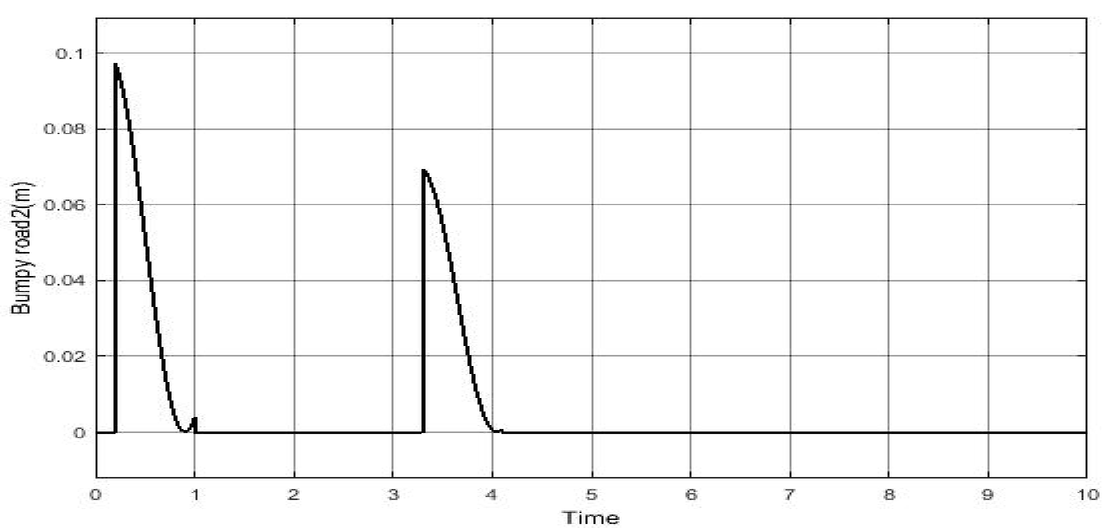


Figure 4.4 Bumpy input road2

4.3 Passive System Simulink Structure and Results

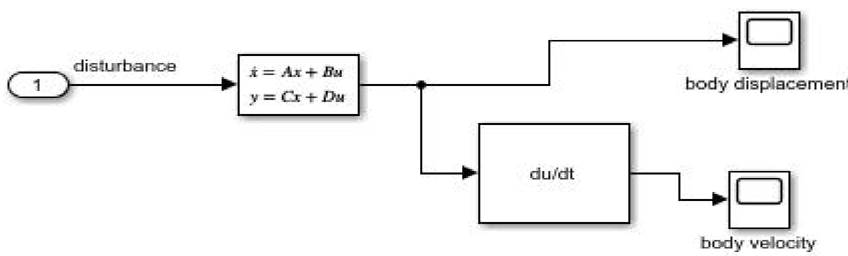


Figure 4.5 Simulink model of passive suspension system

Having the state space model of body displacement and taking the derivative of it gives the vertical body velocity of a car. There is no need of mathematical equation for the body velocity.

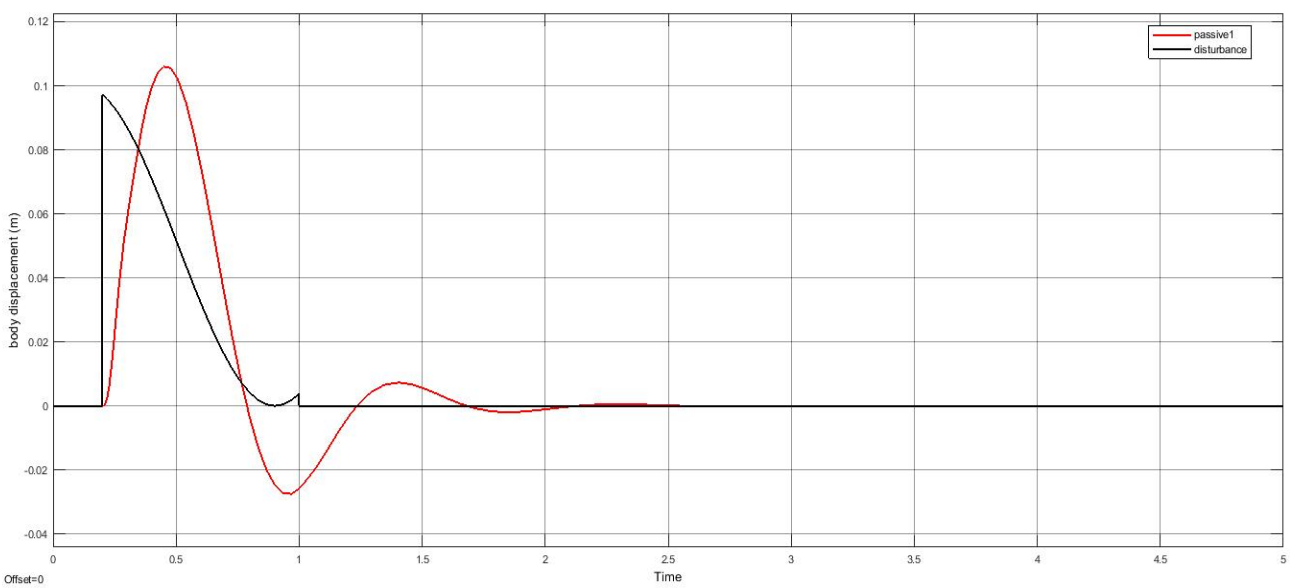


Figure 4.6 Vertical body displacement plot for passive suspension system

While a passive suspension system provides a baseline for vehicle dynamics, a fuzzy_PID controller and a passive suspension system in the context of disturbance for a quarter car model. It needed to consider how each system responds to external disturbances such as road irregularities or sudden changes in load. This exhibits higher overshoot and longer settling time due to its fixed parameters.

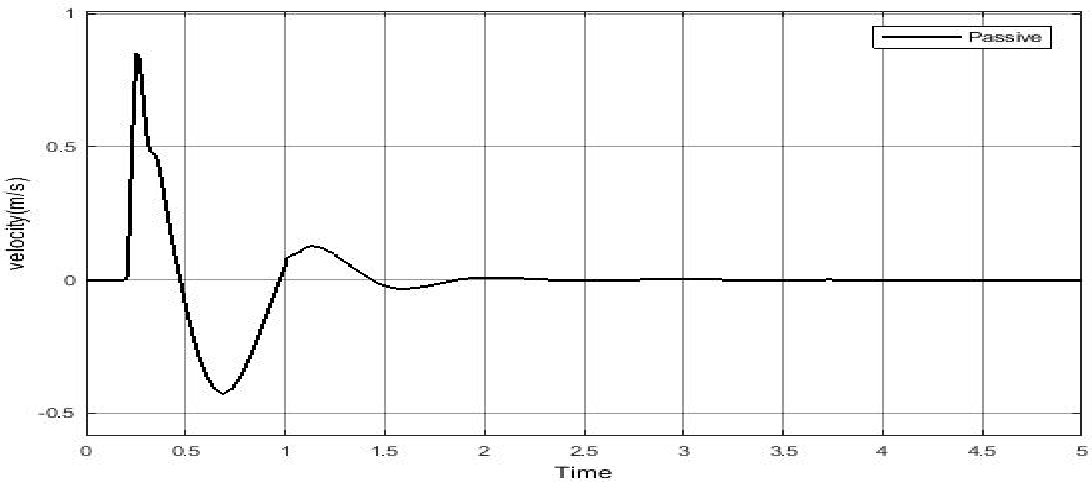


Figure 4.7 Vertical body velocity plot for passive suspension system

From fig 4.7, it can be concluded as the passive suspension system is not excellent in reducing vibrations. The velocity strokes is larger than the bumpy road surface amplitude. Hence, this damage the spring and damper of the suspension system. Therefore, have to find a correct controller that reduces the amplitude of the vertical parameters, which improves the comfort and stability of passengers.

4.4 Comparative Analysis of Passive, PID And Fuzzy_PID Controller Based On Active Suspension System Simulink Structure and Results

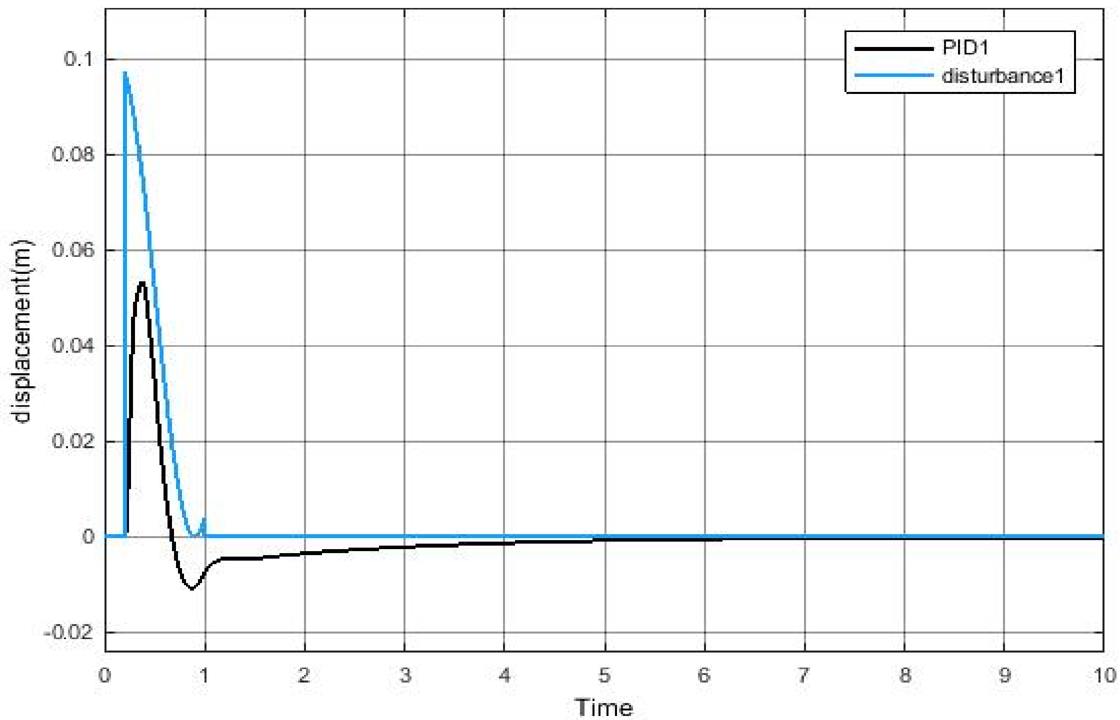


Figure 4.8 Vertical body displacement plot for active suspension system with PID controller

From fig 4.8, it can be concluded as the PID controller is not excellent in reducing vibrations. The body displacement strokes is smaller than the bumpy road surface amplitude. PID controller should show reduced overshoot and shorter settling time compared to passive suspension. So this successful in the above simulation result.

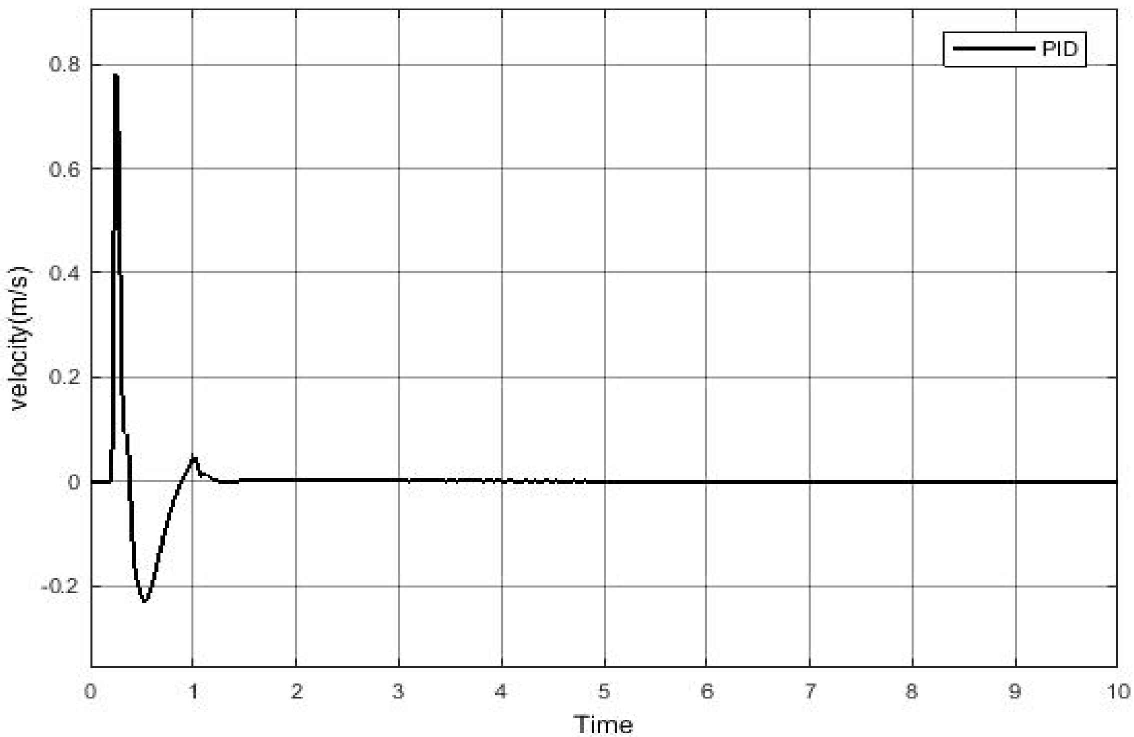


Figure 4.9 Vertical body velocity plot for active suspension system with PID controller

From fig 4.9, it can be concluded as the PID controller is not excellent in reducing vibrations. The velocity strokes is smaller than the bumpy road surface amplitude. PID controller should show reduced overshoot and shorter settling time compared to passive suspension. So this successful in the above simulation result.

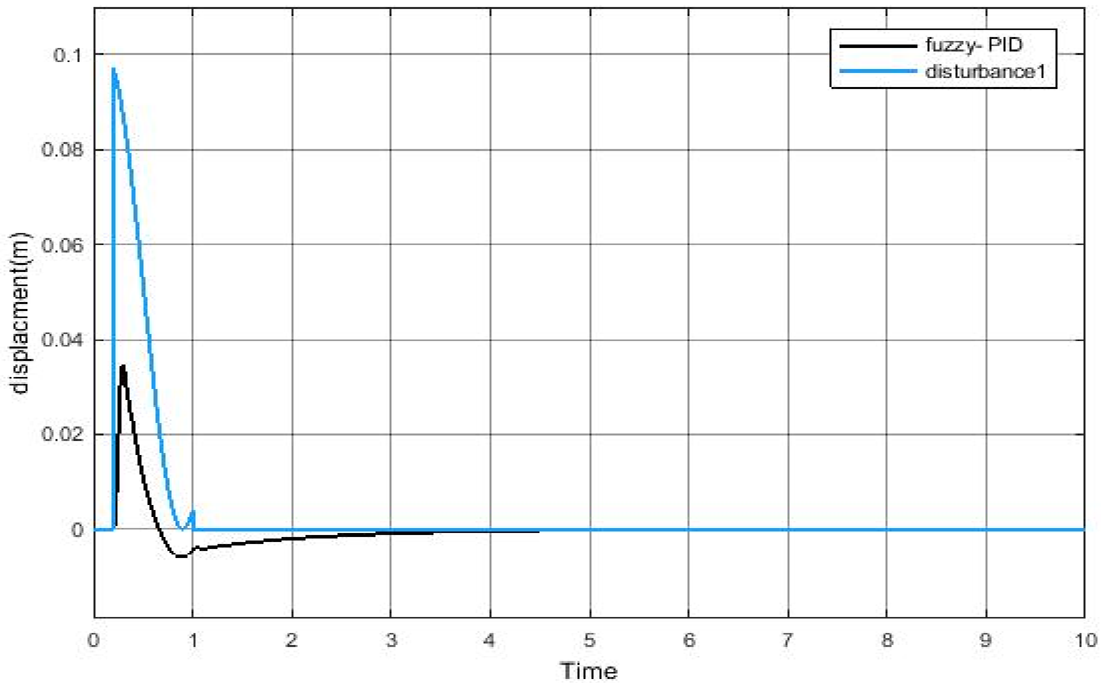


Figure 4.10 Vertical body displacement plot for active suspension system with fuzzy_PID controller

From fig 4.10, it can be concluded as the fuzzy_PID controller is excellent in reducing vibrations. The body displacement strokes is smaller than the bumpy road surface amplitude. Fuzzy_ PID controller should show reduced overshoot and shorter settling time compared to PID and passive suspension. So this successful in the above simulation result.

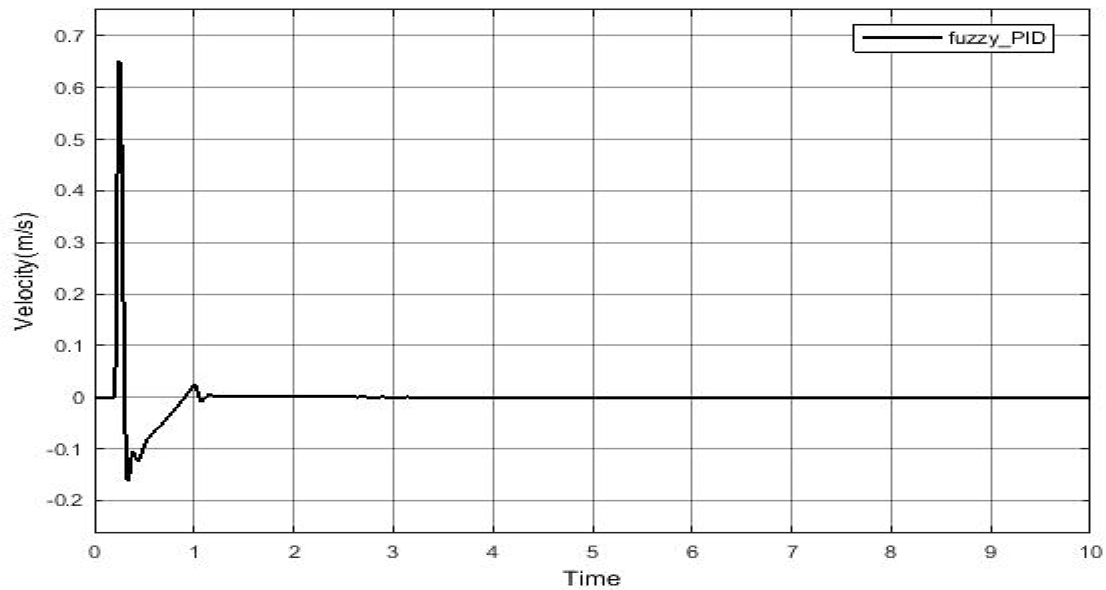


Figure 4.11 Vertical body velocity plot for active suspension system with fuzzy_PID controller

From fig 4.11, it can be concluded as the fuzzy_PID controller is excellent in reducing vibrations. The velocity strokes is smaller than the bumpy road surface amplitude. Fuzzy_ PID controller should show reduced overshoot and shorter settling time compared to PID and passive suspension. So this successful in the above simulation result.

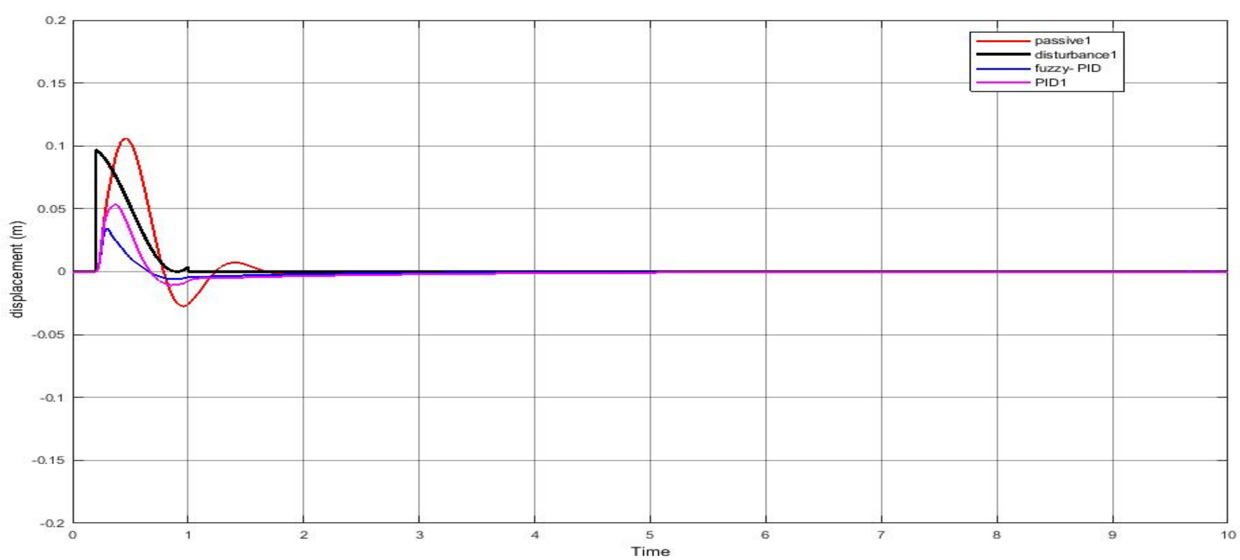


Figure 4.12 Vertical body displacement plot for the suspension system with passive, PID and fuzzy_PID controller

From fig 4.12, it can be concluded as the fuzzy_PID controller is excellent in reducing vibrations. The displacement strokes is smaller than the bumpy road surface amplitude. Fuzzy_ PID controller should show reduced overshoot and shorter settling time compared to PID and passive suspension. So this successful in the above simulation result.

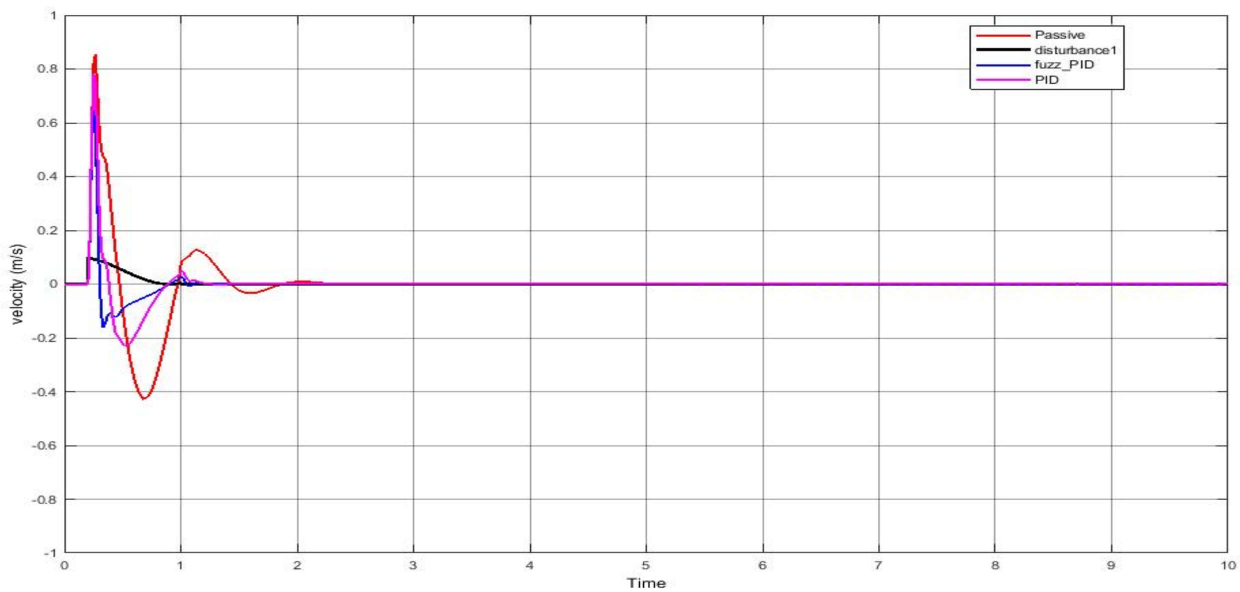


Figure 4.13 Vertical body velocity plot for the suspension system with passive, PID and fuzzy_PID controller

From fig 4.13, it can be concluded as the fuzzy_PID controller is excellent in reducing vibrations. The velocity strokes is smaller than the bumpy road surface amplitude. Fuzzy_ PID controller should show reduced overshoot and shorter settling time compared to PID and passive suspension. So this successful in the above simulation result.

Table 4.1 Comparison of passive suspension system, PID and Fuzzy-PID controller in reduction of overshoot and settling time

Controller	Car body displacement		Car body velocity	
	Overshoot	Settling time	Overshoot	Settling time
Passive	0.1061	2	0.8528	2.2
PID	0.05354	1.7	0.7812	1.3
Fuzzy -PID	0.03467	1	0.6510	1
Reduction(%)				
Passive versus PID	50	15	9	41
Passive versus Fuzzy_PID	68	50	23	55
PID versus Fuzzy_PID	35	42	17	23

In general, from the table above the overshoot and settling time are small using fuzzy_PID controller compared to PID controller and passive suspension. So the ride comfort and stability are improved.

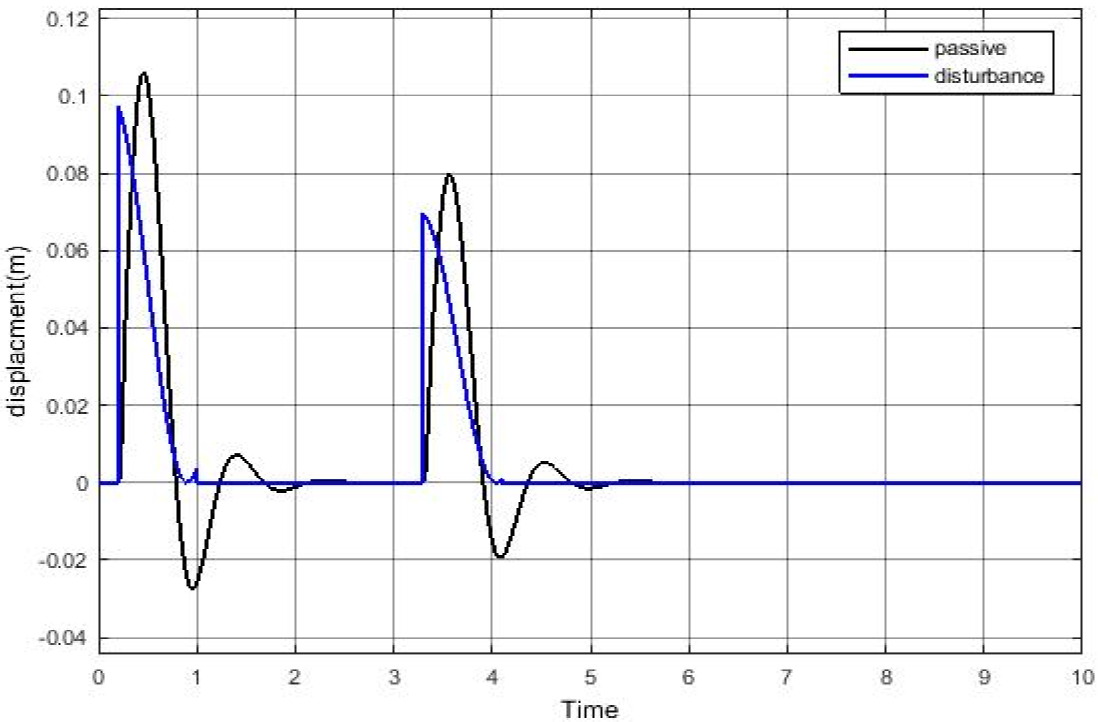


Figure 4.14 Vertical body displacement plot for passive suspension system with bumpy input road2

While a passive suspension system provides a baseline for vehicle dynamics, a fuzzy_PID controller and a passive suspension system in the context of disturbance for a quarter car model. It needed to consider how each system responds to external disturbances such as road irregularities or sudden changes in load. This exhibits higher overshoot and longer settling time due to its fixed parameters in both type of road profile.

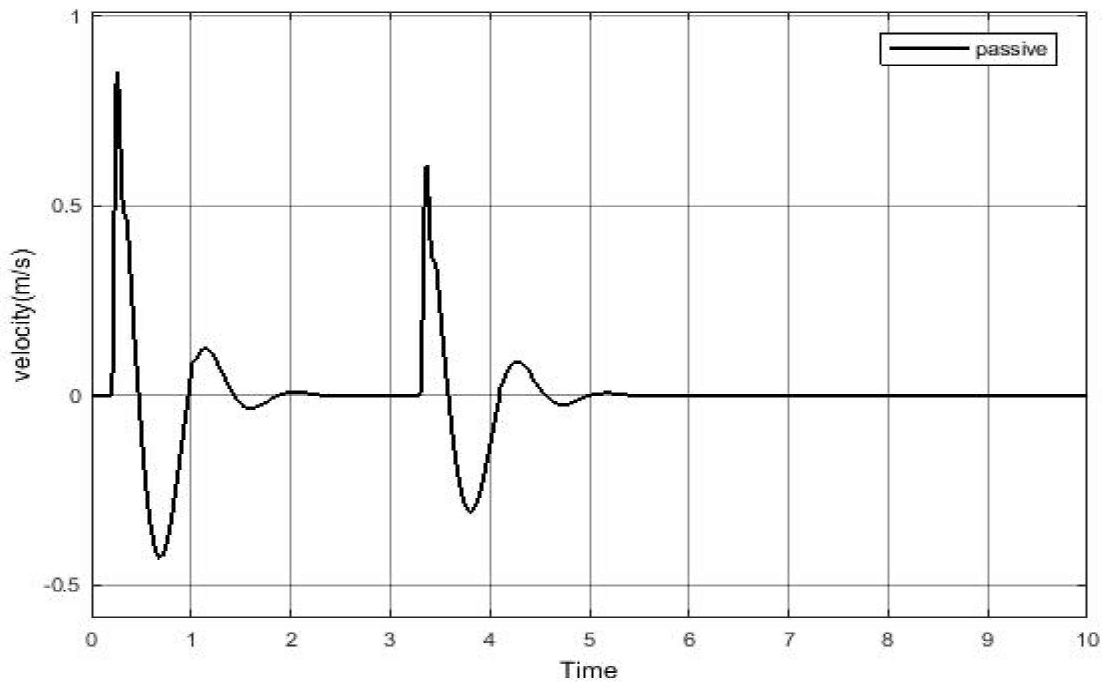


Figure 4.15 Vertical body velocity plot for passive suspension system with bumpy input road2

From fig 4.15, it can be concluded as the passive suspension system is not excellent in reducing vibrations. The velocity strokes is larger than the bumpy road surface amplitude. Hence, this damage the spring and damper of the suspension system. Therefore, have to find a correct controller that reduces the amplitude of the vertical parameters, which improves the comfort and stability of passengers in both type of road profile.

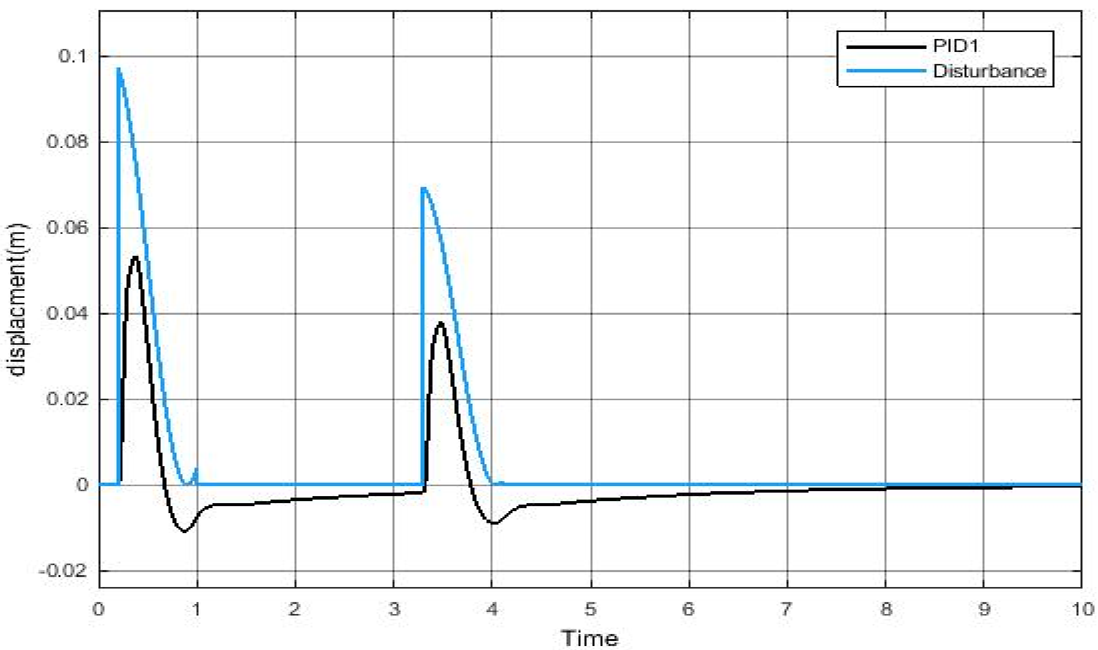


Figure 4.16 Vertical body displacement plot for active suspension system of PID controller with bumpy input road2

From fig 4.16, it can be concluded as the PID controller is not excellent in reducing vibrations. The body displacement strokes is smaller than the bumpy road surface amplitude. PID controller should show reduced overshoot and shorter settling time compared to passive suspension. So this successful in the above simulation result for both type of road profile.

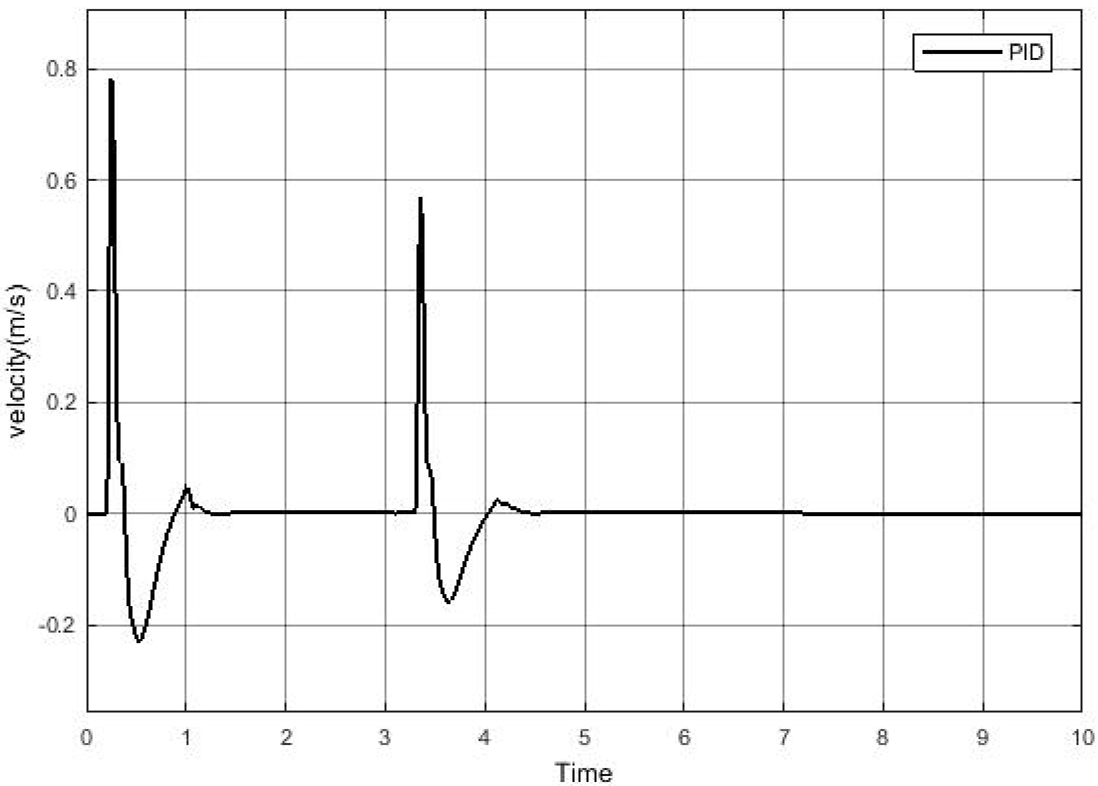


Figure 4.17 Vertical body velocity plot for active suspension system of PID controller with bumpy input road2

From fig 4.17, it can be concluded as the PID controller is not excellent in reducing vibrations. The velocity strokes is smaller than the bumpy road surface amplitude. PID controller should show reduced overshoot and shorter settling time compared to passive suspension. So this successful in the above simulation result for both type road profile.

Improvement(%)= $\left|\frac{active - passive}{passive}\right|$ *100%

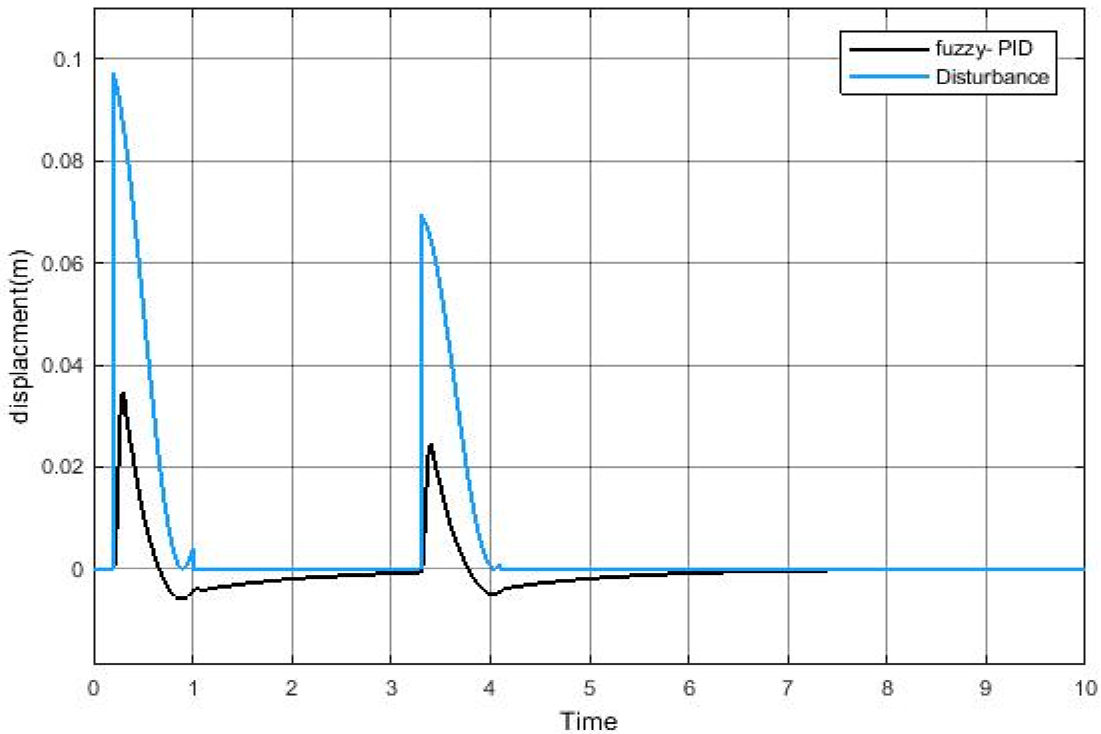


Figure 4.18 Vertical body displacement plot for active suspension system of fuzzy_PID controller with bumpy input road2

From fig 4.18, it can be concluded as the fuzzy_PID controller is excellent in reducing vibrations. The body displacement strokes is smaller than the bumpy road surface amplitude. Fuzzy_ PID controller should show reduced overshoot and shorter settling time compared to PID and passive suspension. So this successful in the above simulation result for both type of road profile.

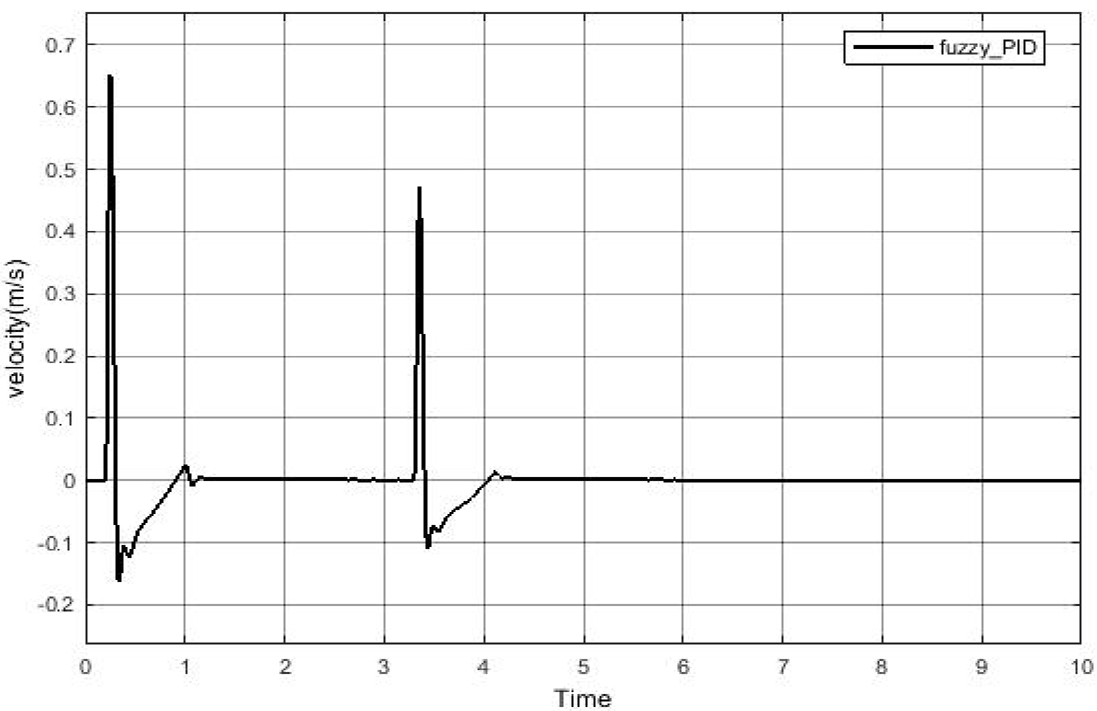


Figure 4.19 Vertical body velocity plot for active suspension system of PID controller with bumpy input road2

From fig 4.19, it can be concluded as the fuzzy_PID controller is excellent in reducing vibrations. The velocity strokes is smaller than the bumpy road surface amplitude. Fuzzy_ PID controller should show reduced overshoot and shorter settling time compared to PID and passive suspension. So this successful in the above simulation result for both type of road profile.

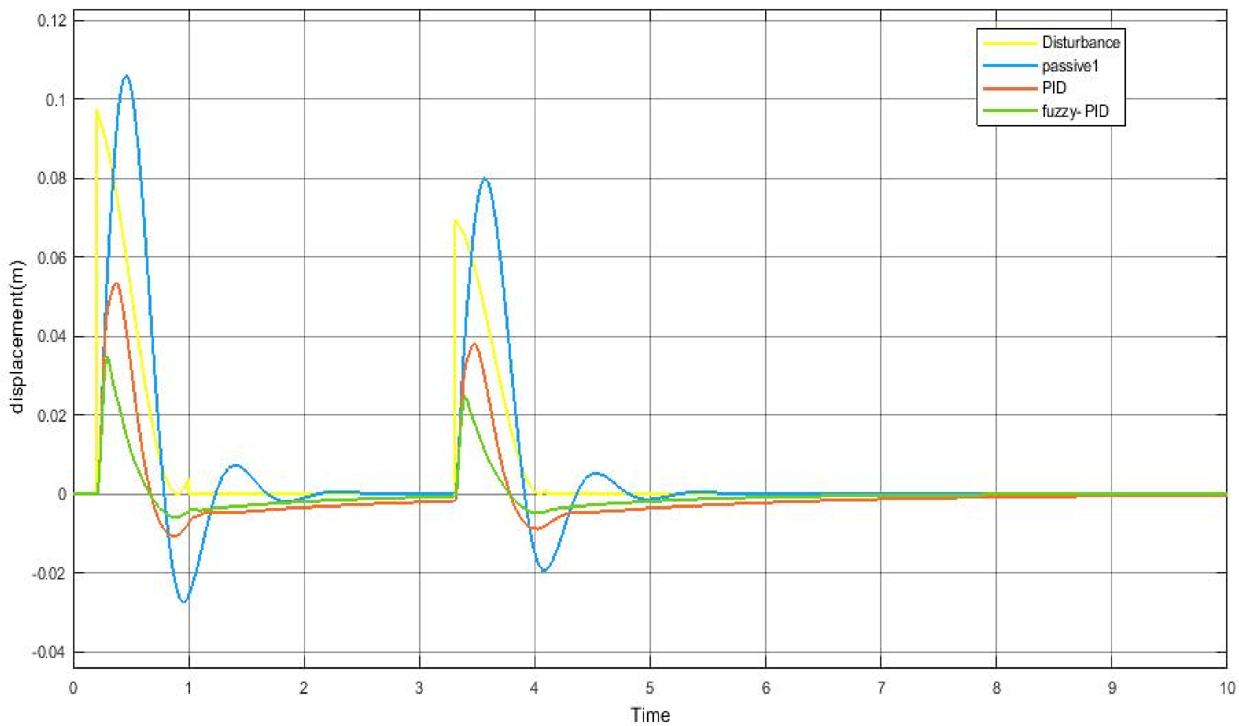


Figure 4.20 Vertical body displacement plot for the suspension system of passive, PID and fuzzy_PID controller with bumpy input road2

From fig 4.20, it can be concluded as the fuzzy_PID controller is excellent in reducing vibrations. The displacement strokes is smaller than the bumpy road surface amplitude. Fuzzy_ PID controller should show reduced overshoot and shorter settling time compared to PID and passive suspension. So this successful in the above simulation result for both type of road disturbance.

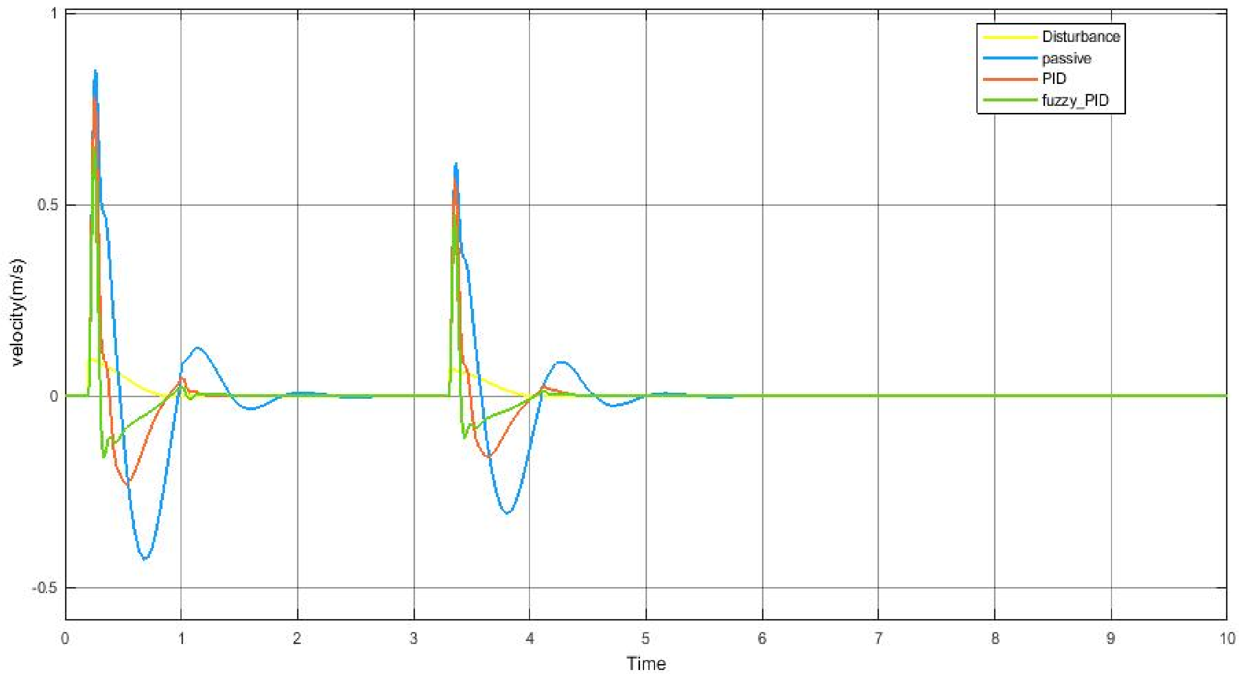


Figure 4.21 Vertical body velocity plot for the suspension system of passive, PID and fuzzy_PID controller with bumpy input road2

From fig 4.21, it can be concluded as the fuzzy_PID controller is excellent in reducing vibrations. The velocity strokes is smaller than the bumpy road surface amplitude. Fuzzy_ PID controller should show reduced overshoot and shorter settling time compared to PID and passive suspension. So this successful in the above simulation result for both type of road profile.

Table 4. 2 Comparison of passive suspension system, PID and Fuzzy-PID controller in reduction of overshoot and settling time

Controller	Car body displacement				Car body velocity			
	0.2≤ t ≤1		3.3≤t≤4.1		0.2≤ t ≤1		3.3≤t≤4.1	
	Overshoot	Settling time	Overshoot	Settling time	Overshoot	Settling time	Overshoot	Settling time
Passive	0.1061	2.2	0.1941	5.3	0.8528	2	0.3071	5.5
PID	0.05354	1.2	0.03799	4.4	0.7812	1.3	0.5688	4.5
Fuzzy -PID	0.03467	1	0.02453	4	0.6510	0.9	0.4732	4.2
Reduction %								
Passive versus PID	50	46	81	17	9	35	85	19
Passive versus Fuzzy_PID	68	56	88	25	24	55	54	24
PID versus Fuzzy_PID	36	17	36	10	17	31	17	7

In general, from the table above the overshoot and settling time are small using fuzzy_PID controller compared to PID controller and passive suspension. So the ride comfort and stability are improved for both type road profile.

Chapter five

Conclusion and Recommendation

5.1 Conclusion

Fuzzy_PID and PID controller versus the passive suspension system. The mathematical model of the quarter car model suspension system is developed to simulate in MATLAB/Simulink environment. The effectiveness and performance of the controller can decide based on the system with Fuzzy_PID controller for the car body displacement ,which reduce the overshoot 88％ and settling time 56％ and car body velocity 24％ overshoot and 55％ settling time with road1 .body displacement 68 ％ overshoot and 50 ％ settling time and improves velocity response 23 ％ overshoot and 55 ％ settling time with road2 profile. Fuzzy_PID versus PID controller the car body displacement overshoot decrease by 36％ and settling time by 42％. This better performance of the vehicle suspension system is verified by two bumpy road inputs. Then the simulation show that in controlled active suspension system have overshoot and settling time is much less than the uncontrolled passive suspension system. This means the suspension system is more stable using Fuzzy_PID controller comparatively than PID and passive system.

5.2 Recommendation

From the observation that Fuzzy_PID controller exhibit very good response towards reducing overshoot and settling time. As an extension for future work efforts can be made to further improve the results Fuzzy_PID controller by employing greater number of membership functions and of different shapes in order to further reduce parameters. Additionally, other control and optimization approaches like artificial neural networks, genetic algorithm and particle swarm optimization can also be adopted for optimal control of these systems.

Reference

[1] T. A. Arslan et al. Quarter Car Active Suspension System Control Using Fuzzy Controller Engineering Perspective 2 (4): 33-39, 2022

[2] Abdussalam Ali Ahmed Mechanical Engineering Department Bani Waleed University Bani Waleed, Libya and abdussalam.a.ahmed@gmail.com Omer.S. M. Jomah Engineering and Information Technology Research Center (E.I.T.R.C) Bani Waleed, Libya immer.jomah@gmail.com 2020

[3] Patil et al. (2013). Performance Evaluation of Active Suspension for Passenger Cars Using MATLAB. In Second National Conference on Recent Developments in Mechanical Engineering, IOSR Journal of Mechanical and Civil Engineering, Sree Chatrapati Shivaji College of Engineering, Pune, India, (pp. 06–14).

[4] Nemat Changizi, Modjtaba Rouhani/ TJMCS Vol .2 No.3 (2011) 559-564

[5] R.A. Williams (June 1994) "Electronically controlled automotive suspensions," Computing & Control Engineering Journal, Jaguar cars Ltd, Coventry, UK, vol. 5, Issue 3, pp. 143-148.

[6] Hac (1985). A.Suspension optimization of a 2-dof vehicle model using a stochastic optimal control technique. Journal of Sound and Vibration, Vol 100, ISSUE 3, Institute of Acoustics, Great Britain, pp 343-357.

[7] D.A. Wilson et.all. (1986). Application of linear optimal control theory to design of active automotive suspensions. Vehicle System Dynamics, International Journal of Vehicle Mechanics and Mobility, Department Of Electrical And Electronics Engineering, Volume 15, Issue 2, 15, 2, university of Leeds, pp 103-118.

[8] Yagiz. N, Hacioglu (2008). Y, "Back stepping control of a vehicle with active suspensions", Control engineering practice, vol.16, Issue 12, Elsevier, British, pp. 1457-1467.

[9] Guido P. A. Koch (2011). Adaptive Control of Mechatronic Vehicle Suspension Systems.

Technische universit ¨at m ¨unchen. pp. 5 – 27.

[10] Abdolvahab Agharkakli et.all (2012). Simulation and Analysis of Passive and Active Suspension System Using Quarter Car Model for Different Road Profile, Department of Mechanical Engineering, Shahrood Branch, - Volume3, Issue5 - ISSN: 2231-5381, Islamic Azad University, Shahrood, Iran, pp 636 – 640.

[11] Sayel M. Fayyad (2012). Constructing Control System for Active Suspension System, Contemporary Engineering Sciences, Vol. 5, Issue 4, Al Balqa Applied University Amman, Jordan

pp.189 – 200.

[12] Arti Tiwari1 et.all (2015). Controlling the Vibration of Bus Suspension System using PID Controller, Volume 5, Department of Electrical Engineering, Integral University. pp. 519.

[13] P.Swethamarai and P.Lakshmi *Dept.EEE Anna University* Chennai, India. sswethamarai@gmail.com . p_lakshmi@annauniv.edu on 29 July 2020.

[14] Abdussalam Ali Ahmed Mechanical Engineering Department Bani Waleed University Bani Waleed, Libya abdussalam.a.ahmed@gmail.com Omer.S. M. Jomah Engineering and Information Technology Research Center (E.I.T.R.C) Bani Waleed, Libya immer.jomah@gmail.com 2020

[15] Abut, T.; Salkim, E. Control of Quarter-Car Active Suspension System Based on Optimized Fuzzy Linear Quadratic Regulator Control Method. *Appl. Sci.* **2023**, *13*, 8802. https://doi.org/10.3390/app13158802

[16] Abd El-Nasser S. Ahmed1 , Ahmed S. Ali2 , Nouby M. Ghazaly1 , G. T. Abd el- Jaber International Journal of Advances in Engineering & Technology, Dec., 2015.

[17] Nguyen Van Trang* , Duong Nguyen Hac Lan Ho Chi Minh City University of Technology and Education Website: https://jte.hcmute.edu.vn/ Email: jte@hcmute.edu.vn 2022.

[18] Turan Alp Arslan1 , Faruk Emre Aysal2* , İbrahim Çelik2 , Hüseyin Bayrakçeken1 , Tuğçe Nur Öztürk2 ngineering Perspective 2 (4): 33-39, 2022.

[19] Yagiz. N, Hacioglu (2008). Y, “Back stepping control of a vehicle with active suspensions”, Control engineering practice, vol.16, Issue 12, Department Of Mechanical Engineering, Facility of Engineering, Istanbul University, Istanbul, Turkey, pp. 1457-1467.

[20] Wong, J.Y. (1988). Theory of Ground Vehicles, Department Of Mechanical and Aerospace Engineering, New York474. pp. 13 – 19.

[21] Michael Akpakpavi (2017) Modeling and Control of a Car Suspension System Using P, PI, PID, GA-PID and Auto Tuned PID Controller in Matlab/Simulink, Journal of Multidisciplinary Engineering Science Studies (JMESS) ISSN: 2458-925X Vol. 3 Issue 3, Accra, Ghana. pp. 1506 – 1511.

[22] Hina Shahid et.all (2016). Design of a Fuzzy Logic Based Controller for Fluid Level Application, vol 4, Issue 3, Electrical Engineering Department, Lahore College for Women University, Lahore, Pakista, pp. 470