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Comparison of Stabilizing controller and Sliding Mode Controller for Semi-active Suspension Systems

MSc Thesis for the Partial Fulfillment of

Master of Science in Electrical Automation and Control Technology Management

By,

TSEHAYNEH ALEMU ZELEKE (MTR/764/13)

Supervisor,

Dr. Saravanakumar Gurusamy

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By,

TSEHAYNEH ALEMU ZELEKE (MTR/764/13)

Supervisor,

Dr. Saravanakumar Gurusamy

DECLARATION

I hereby declare that the work which is being presented in this thesis entitled "**Comparison of Stabilizing controller and Sliding Mode Controller for Semi-active Suspension Systems**" is the original work of my own, has not been presented for a degree in this or other universities and all sources of materials used for this thesis work have been fully acknowledged.

Name: - Tsehayneh Alemu Zeleke (MTR/764/13)

Signature: ________________________

Place: Addis Ababa

Date of Submission: ________________

This thesis proposal has been submitted for examination with my approval as a TVTI advisor.

Dr. Saravanakumar Gurusamy	____________	______________
Advisor Name	Signature	Date

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Thesis on

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TSEHAYNEH ALEMU ZELEKE (MTR/764/13)

APPROVED BY THESIS ADVISOR COMMITTEE

Name of the Advisor	Signature	Date
Dr. Saravanakumar Gurusamy	--------------------------	-------------------
Name of Examiner Internal	Signature	Date
Dr. Arun pathiran	--------------------------	-------------------
Name of Examiner, Internal	Signature	Date
Mahlet Tsegaye	--------------------------	-------------------
Name of Examiner, External	Signature	Date
Dr. Chala Merga	--------------------------	-------------------
Name of Chairperson	Signature	Date
---	--------------------------	-------------------

ACRONYM

DOF	Degree Of Freedom
MR	Magneto-Rheological
VMC	Vehicle Motion Control
ER	Electro-Rheological
SMC	Sliding Mode Control
MRD	Magneto-Rheological Damper
PID	Proportional Integral Derivative
HTGA	Hybrid Taguchi Genetic Algorithm
MS	Mass Of Sprung
SC	Stabilizing Control

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First of all, I want to share my sincerest gratitude to my advisor, **Dr. Saravanakumar Gurusamy**, has my sincere gratitude for his unwavering support, unending inspiration, and valuable advice throughout the entire process, from the starting research to the finished thesis report. Without the assistance of my advisor, I could not successfully finish my thesis. He has consistently been available and ready to assist me. And thanks for my examiners **Dr. Arun pathiran** and **Mr. Zemenu Tamir** head of electrical/electronics for their advice during proposal.

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ABSTRACT

The suspension system is the largest part that positively affects vehicle performance and ride quality, helping with road handling and serving as a brake device and keeping vehicle inhabitants comfortable and reasonably well isolated from road noise, bumps, and vibrations. The main function of the suspension system is to keep the wheels close to the pavement, while the body of the vehicle is isolated from any road disturbances.

For the comfort of passengers and drivers, sliding mode control approach (SMC) for semi-active suspension is suggested. When compared to passive suspensions, semi-active suspensions have a greater potential for improving important vehicle characteristics like ride comfort, road holding, and vehicle handling. The proposed plan is applying the semi-active suspension system with the comparison between stabilizing control, PID and sliding mode control.

The goal of this thesis is to investigate the various suspension controllers. Generally speaking, the goal of this dissertation is to develop a model for the proposed suspension systems for quarter-car models. To achieve better performance, it is also suggested to simulate the available controllers using MATLAB/Simulink and compare their performances.

Finally, MATLAB software will be used to develop and simulate a controller comparison for a vehicle suspension system.

Keywords: ride comfort; active suspensions; control systems; vehicle handling; SMC.

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CHAPTER 1

INTRODUCTION

1.1 Background

Suspension systems are utilized to create a barrier between the wheels and the vehicle body to allow for relative motion between the two components. The ability to provide good road holding, isolate passengers from road disturbances, and improve passenger comfort are the most common metrics used to evaluate this vehicle. It can be caused by a variety of factors, including road irregularities, aerodynamics forces, tire/wheel assembly non-uniformity, and even braking force. When cornering and swerving, a vehicle's ability to maintain traction on the road is critical. This study focuses on the ability of absorbing road disturbance vibrations. A vehicle's wheels are connected to its suspension system via a series of springs, shock absorbers, and linkages [1].

By reducing vibrations caused by deviations in road elevation from a reference level, suspension systems help vehicles maintain their stability and comfort while on the road. Researchers have long been interested in the development of an adaptive strategy to counteract adverse changes in the external environment.

A disadvantage of the Active System is its high power consumption and low weight-to-power ratio. The Semi-Active Suspension Systems, other way use magneto-rheological dampers to control movement and have a low implementation cost. Compared to the active suspension, the control architecture for a semi active suspension system is less complex and does not need to be modified before installation. A magnetic field is used to control the damping properties of magneto-rheological fluids, which are used in the MR Dampers. The disadvantages of semi-active suspension systems include operational restrictions, but their performance is lower than that of active suspension systems. [2].

A damper is a device that absorbs unwanted vibrations. By converting kinetic energy to heat energy, it reduces vibration. When the damper is compressed and extended, the piston, which is made up of orifices, moves through the fluid inside the damper. High pressure is created as the fluid passes through the small orifices, converting the kinetic energy of the moving piston to thermal energy of the fluid. As a result, damping is induced, which reduces vibration in the system. Most cars only have an identical passive damping suspension system ratio throughout the journey. When the car is driven across varied terrains, this commonality is insufficient. Because the damping ratio is only suitable up to a particular range of frequency ratios, a compromise on comfort is made. Semi-active dampers were introduced to address this shortcoming. The most common type of semi-active damper is one that uses magnetorheological fluid. The presence of a magnetic field modifies the rheological properties of magnetorheological (MR) fluid. The fluid is made up of iron nanoparticles and silicon oil, which acts as a carrier fluid.

To keep the iron particles equally dispersed in the carrier fluid, a small amount of grease is added. When this fluid is subjected to a magnetic field, the iron particles realign themselves in the direction of the magnetic flux lines. With the presence of a magnetic field, moving iron particles becomes more difficult. As a result, the MR fluid's yield strength is affected by the presence of a magnetic field. The amount of current sent through the solenoid of the damper can affect damping coefficients when the MR Fluid is utilized in the damper. When an electric current is applied to the MR fluid, the iron particles create magnetic dipoles, increasing the fluid's apparent viscosity. This fluid now has a larger yield strength, and passing it through the orifices of the damper becomes more difficult. The damping force associated with increased flow resistance likewise increases. As a result, the damper's damping coefficients can be changed. When no electric current is given, the MR damper operates similarly to a traditional passive damper.[3]

1.1 Statements of the Problem

Specifications for comfort, road holding, and handling are taken into consideration while choosing the spring and damping coefficients. Since their spring and damping coefficients cannot be adaptively changed in accordance with driving efforts and road conditions, conventional suspensions can achieve a trade-off between ride comfort and road holding. Only when the intended conditions are met can they achieve good ride comfort and road holding. Only in the predetermined conditions can they achieve good riding comfort and road holding. The issue or challenge is to prevent the suspension system issue that happened, which is to isolate certain car components from vibration to increase its stability, robustness, safety of road profile, improvement of its vertical velocity of car body, suspension deflection, acceleration, accuracy of settling time, rise time, overshoot and reliability of suspension system.

The cost, operating speed, safety, minimizing energy consumption, precision, and dependability are the fundamental elements that determine how well a vehicle suspension system performs. To evaluate the system performance and stability, a practical experiment for functional validation and testing of the proposed and developed system is essential. However, the system's size and complexity, which are very expensive due to safety standards, frequently limit the options for experimental testing and optimization.

The control structure is put to compare to other commonly used quick control methods. The proposed control approach's overall good operation and behavior. The existing control approach is needs high energy compared to SMC. The suggested controller can simultaneously enhance riding comfort and vehicle handling while using less energy than existing control approaches. To maximize suspension performance, the SMC controller is an intelligent controller system. This intelligent system's outcomes are compared to those of other well-known suspension control systems, such as most popular and fast.

To increase semi-active suspension to a level of performance that is comparable to full active control by overcoming the restrictions of existing linear control systems. The improved performance might be delivered to provide the same degree of performance that is currently only possible with fully active suspension systems without the requirement for them and the associated cost and power consumption. Develop a SMC control approach for a semi-active suspension that uses the high feasible damper settings than other controller. The reduction of conservatism in the controller design will be taken into consideration to improve performance.

1.2 Solution of the gap

It will be taken into consideration to reduce conservatism in the controller design in order to improve performance used to reduce chattering. The sliding mode surface and its derivative are used to regulate the sliding mode in the preceding example. To reduce vehicle vibration during driving, stabilizing controller and SMC for semi-active suspension based on spring case is developed for comparing which controller is best performance by ride comfort and passenger safety. The spring case damper in relation to the semi-active suspension system is evaluated. In the presence of parameter uncertainty, the performance of the sliding mode controller is stable and resilient.

1.3 Motivation, purpose, and goals of the research

This study aims to improve semi-active suspension to a level comparable to full active control by overcoming the constraints of conventional linear control systems. With the improved performance, it may be possible to achieve the same level of performance that is presently only possible with fully active suspension systems, but without the astronomical cost and power consumption that go along with them. The greater performance can be used to improve ride quality or to allow vehicles to travel at higher speeds retaining passenger comfort. Another option is to deliver the same riding experience on a track that is less well-maintained or of poorer quality. The following research objectives have been identified in order to achieve this goal:

1.3.1 General objective

To design and simulate semi-active suspension system in vehicles that will enhance their ride comfort and road holding using sliding mode control and stabilizing controller comparison approach.

1.3.2 Specific Objective

- To Work on quarter car vehicle modeling and simulation and control design for Suspension control that is semi-active.
- Using the Verify the damper model development of the suggested control approach and assess the accompanying system performance.
- To Compare SMC performance with SC controller and show the improvement of non-linear SMC scheme.

1.4 Significance of the study

In designing a heavy vehicle suspension, road friendliness (road damage) and vehicle ride comfort must be taken into consideration. Even though there have been some studies on these criteria, the majority of the studies have focused on improving passenger vehicles rather than heavy vehicles and have only used simulations. Semi-active suspension control strategies must be developed to lessen road damage and enhance vehicle ride comfort since passive suspension is used in most vehicles. These vehicles are driven in various terrains and carry cargo.

Improved vehicle ride comfort can reduce the risk of damage to vehicles carrying goods, i.e. machines or other equipment sensitive enough to high vibration. Ride comfort enhanced by incorporating the proposed controller into passenger cars .The development of a non-linear control system for semi-active suspension is described in this thesis. It can be used to achieve performance levels that are currently only possible with full-active suspension without the high costs and energy consumption that come with it.

The proposed is thought to contribute to the current study field in the following ways:

- A new semi-active control approach due to a SMC and The SC controller was created and optimized through simulation to improve semi-active suspension performance.
- In this investigation, the proposed control approach to vehicles and the improvements in ride quality.

1.5 Delimitation/Scope of the thesis

The main focuses using a new method of sliding mode control (SMC), the proposed approach aimed to improve road comfort and handling in a semi-active suspension system. Because the SC is in charge of regulating distortion, lowering it improves handling.

Using a new SC control technique, the proposed methodology explained how to make a semi-active suspension system's handling and comfort on the road better. Because the SC controls distortion, lowering it low handling. The proposed (SMC) system's handling is high when compared to traditional SMC based SC systems and there is a requirement for the development of a control strategy to bring superior handling. Learn about the Semi-active suspension for quarter cars is a feature of Sliding Mode Controller. Compare the suggested Sliding Mode Control with the performance of SC approach and MATLAB/Simulink will be used to demonstrate how a simulation works. We can summarize the above

1. Examine the semi active suspension concept and gain a better understanding of it.

2. Research and contrast, SC and slide mode control, on suspension systems, and semi-active.

3. Write a final report that includes a discussion and conclusion based on the simulations.

4. The investigation will employ the Mat lab Simulink platform.

5. The quarter vehicle semi active suspension model represents two degree of freedom.

1.6 Limitation of the thesis

Semi-active suspension quarter car method is used but not include half and full-vehicle suspension system.

1.7 Methodology

In controlling linear parameter varying controller using semi-active suspension damper the following steps has followed.

1) Select controller
2) Data Collection

3) Design the controller
4) check validation
5) Analytical and simulation behaviors performance requirements
6) Finalized

1.8 Methodology for investigating a vehicle's suspension system

The following approach will be used to fulfill the objectives specified in the above objective. The thesis will begin with a thorough analysis of the literature on suspension system technology, as well as control systems and methodologies related to vehicle suspension system technology. The controller's mathematical modeling is then built, and the dynamic equations are presented.

Methodology of the research

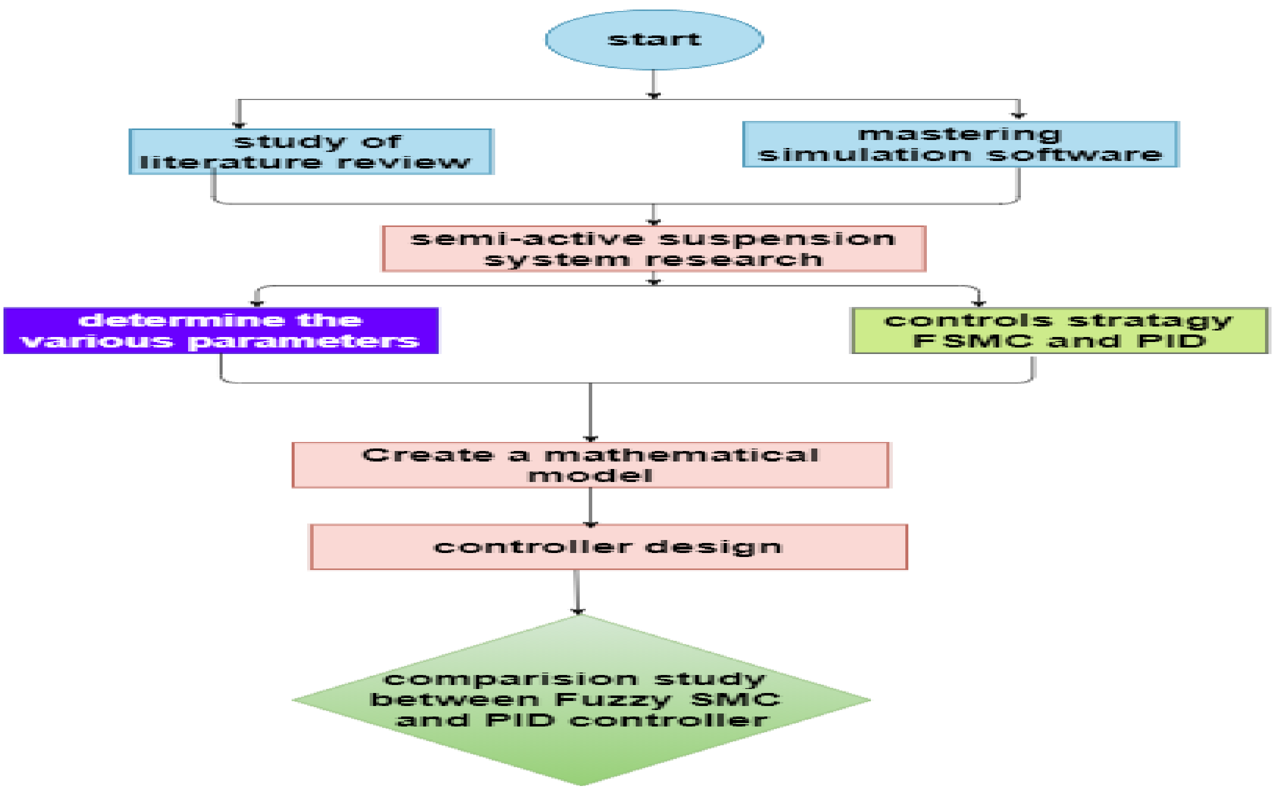

Figure 1.1 Research methodology flowchart

1.8.1 Diagram representation of proposed control scheme

Block diagrams are a visual depiction of a control system that may be used to simulate any simple or complicated system.

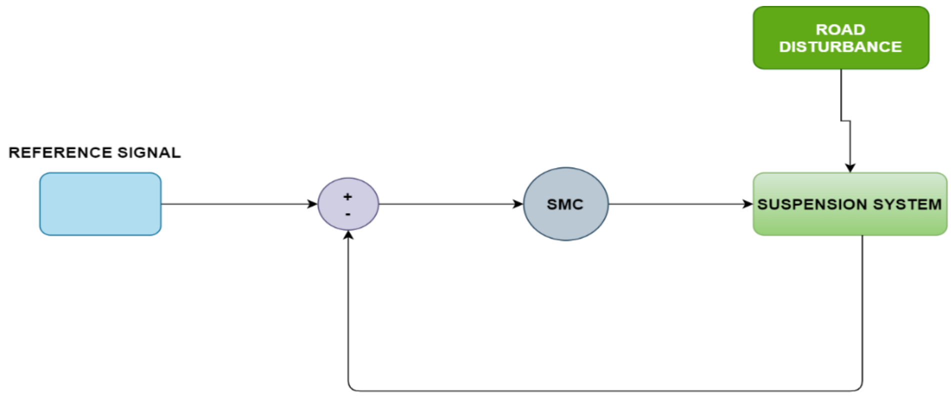

Figure 1.2 Semi-active suspension system block diagram

1.8.2 Flow chart for Execution of thesis work

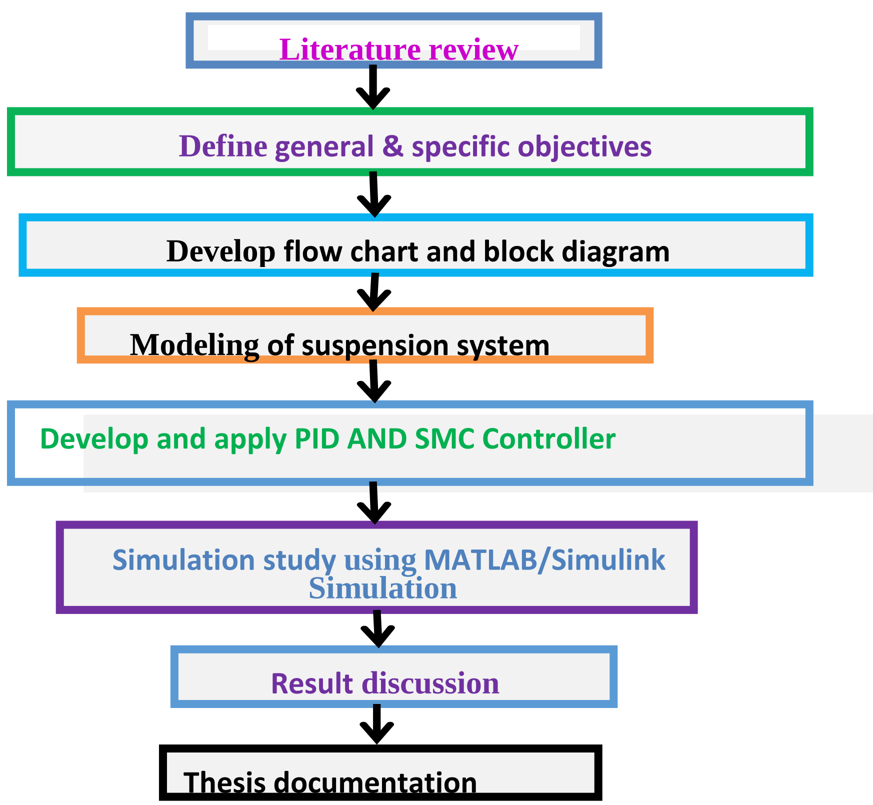

Figure 1.3 Flow chart semi-active suspension

1.9 Thesis organization

This thesis report is broken into five chapters, are discussed as highlight which are as follows:

- The first chapter of the thesis serves as the beginning. The study's findings are summarized in this chapter context, including its problem statement, research methodology, and the research's contribution to the thesis' organization.
- Semi-active suspension literature is reviewed in Chapter 2. Here, the classification of vehicle suspension, the performance criteria used to design suspension, and the model of the vehicle that it is associated with are explained in detail. Researchers and engineers presented an overview of semi-active suspension control in this chapter, and a research gap is identified.
- The vehicle ride modeling and validation are discussed in detail in Chapter 3. The mathematical model of the vehicle is described in detail in this chapter. A discussion of vehicle modeling assumptions and limitations is included as well. MATLAB-Simulink and by comparing the vehicle responses in MATLAB-Simulink, the quarter vehicle model in MATLAB-Simulink is validated**.**
- Chapter 4 is the controller design. This chapter will present and discuss the two controller SMC and SC.
- chapter 5 results and discussion
- The conclusion and recommendation are included in Chapter 6. It will cover the project's conclusion and future research recommendations.

CHAPTER 2

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

In order to address the control issue of a full vehicle active suspension system while accounting for nonlinearities in the spring and damper, unmodeled dynamics, and outside disturbances, we developed adaptive sliding mode control. To achieve convergence in finite time and closed loop stability, the control law. The Sliding Mode Control scheme will update the parameters utilizing the Lyapunov stability analysis. The suggested control strategy is made up of four comparable subsystems that are utilized to control the vehicle's four sides [4].

It develops an error-based layer contains control law for the total package based on the dynamics of the reference model's flaws [5] .

Nonlinearity and parameter uncertainty characterize magneto-rheological (MR) suspension systems, making it challenging to derive an accurate model for designing a model-based controller. To suppress the vibration of the MR suspension system, a novel sliding mode control (SMC) strategy based on the hybrid Taguchi genetic algorithm (HTGA) is proposed [6].

On the basis of the magnetorheological (MR) damper, control with sliding mode method (SMC) for semi-active air suspension is created to reduce vehicle vibration during driving circumstances. The system's semi-active air suspension's MR damper was assessed [7].

To control hydraulically driven nonlinear active suspension utilizing a whole automobile model, Sliding Model Control (SMC) has been proposed. Due to the complexity of the whole automobile mathematical model, the nonlinear effect in suspension, and the unexpected behavior of the hydraulic actuator, developing an effective classical controller for active suspension has proven difficult. The sliding mode controller (SMC) can deal with unknown parameters, nonlinearity, and a sophisticated mathematical model of a dynamic system. chattering for nonlinear sliding mode controllers is the chattering problem, which can be overcome by combining fuzzy logic with sliding mode control [8].

A fuzzy-based controller was used to construct a semi-active suspension control for a quarter car model. The quarter car model that will be utilized here is a 2 degrees-of-freedom nonlinear system that can be excited by different road profiles. The road model is employed as the control force is released by activating an electromagnetic shaker [9].

Proposing the sliding mode control approach by integrating PID in sliding mode variable structure to increase semi-active air suspension vehicle ride comfort. To verify the efficiency of this control technique, simulations in the time domain and frequency domain were used [10].

Ride comfort, body travel, road handling, and suspension travel are all factors to consider when designing a suspension system. Although no suspension system can maximize all of these characteristics simultaneously, an active suspension system can achieve a better balance between them. The goal of this study is to develop a reliable active suspension system control technique for a quarter-car model [11].

One of the design goals for automobile makers is to create vehicles that provide maximum driving comfort and handling stability [12].

A vehicle's suspension is the support system that connects the vehicle's body to its wheels. A suspension system's job is to support the vehicle's body and improve ride comfort. Because if the attenuation force becomes too big, the passenger will be subjected to an extremely unpleasant ride under high-frequency disturbances, and if the attenuation force becomes too little, the ride would feel unduly soft at low frequencies, care must be taken in the design of a suspension system [13].

In comparison to the sliding-mode controller with standard exponent reaching law, this study intends to offer an enhanced sliding-mode control scheme with variable rate reaching law for semi-active car suspension systems, which can eliminate chattering problems in high frequency. while taking into account the sliding-mode reaching segment characteristics, which can dynamically change the reaching rate to suppress chattering in closed-loop control systems [14].

For semi-active control of buildings under earthquake excitations, a new Adaptive Sliding Mode Control (ASMC) approach is presented. The suggested method has the significant advantage of being model-free, which allows it to deal with structural model uncertainties, large nonlinearities in the behavior of Magnetorheological (MR) dampers, and the random character of earthquake excitations. [15].

Semi-active suspension system is a promising solution for improving suspension system performance by applying an appropriate resistive damper controller. The ability to manage the modifying incoming current applied on the magnetorheological damper[16].

Body motions, such as vertical vibrations and roll dynamics, have an impact on the comfort factor and can only be improved by passive vehicle components to a limited extent. Improved ride comfort can be achieved by using active components rather than passive components [17].

The developed controller significantly improves the passive suspension's efficiency in terms of performance criteria (in the frequency domain). Furthermore, the controller's synthesis incorporates nonlinear actuator dynamics, which are typically avoided in reported work, enhancing the relevance of research outcomes because the controller is synthesized from a suspension model that is closer to reality [18].

Initially, we'll look at the semi-active suspension control problem, where some sensors or actuator (damper leakage) faults are considered. A model of an LPV will be described, taking into account an actuator fault represented as some varying parameters, from a vehicle's semi-active nonlinear damper in a quarter-car model [19].

The multiple fuzzy control system, as opposed to the classic fuzzy PID control system that measures road slope and takes changing road conditions into account [20].

Create an effective control method for a vehicle's suspension system. The objective of a vehicle's suspension system is to provide a more comfortable ride and better handling with road vibrations. In parallel with the damper, a nonlinear hydraulic actuator is coupled to the passive suspension system. The proposed controller is used to manage a quarter-car suspension system, and the results are compared to a passive suspension system model and an input road profile. The developed controller performs well according to simulation findings [21].

Road holding and comfort are essential but conflicting goals in semi-active suspension control. it is applied to the semi-active suspension control to get the best possible results [22].

Many parts of suspension connect from vehicle to its parts are referred to as the suspension system. Suspension systems have two functions: first, they retain the car's braking system and road holding/handling for effective active safety and second, they make the car ride comfortable by separating the rider from the jarring, vibrations, and noise of the road, among other things. The aim of this to control and PID to evaluate a quarter car Model for suspension control that experiences vibration stimulation from random road profiles [23].

The safety determine the suspension mechanism's performance, Car body displacement and wheel deflection performance can be used to measure it. The proposed PID controller improves the effectiveness of wheel and body displacement, according to the results [24].

A quarter model of an automobile is used to simplify the suspension system design into a one-dimensional mass spring-damper system. On the basis of time response, its open-loop performance is noticed, indicating that the car suspension exhibits oscillations with a long settling period. A closed-loop system is utilized to solve this problem. [25].

The technique ensures both the stability of a sliding mode and the stability of the entire system.

The suggested process takes into account several stages. The actuator between the sprung and unsprung masses is used in the first phase to control the suspension dynamics. The current of the servo valve is then controlled by taking into account the spool valve displacement dynamics [26].

Since this decade, the vehicle semi-active suspension with magneto-rheological damper (MRD) has been a popular topic, and it can be difficult to create a strong control synthesis that takes load variation into account. For the quarter-vehicle suspension with the magneto-rheological (MR) damper, a new semi-active controller based on sliding mode control (SMC) strategies and the inverse model is proposed in this paper. The ideal skyhook suspension is used as the control reference model, and the vehicle sprung mass is taken into account as an uncertain parameter[27].

The purpose of this essay is to describe the steps involved in developing system that uses sliding mode control (SMC). In this regard, the sliding mode was chosen as a controlling approach, and the design was employed to estimate the road profile[28].

The strong stabilization problem remains an unresolved problem in the framework of nest algebra, and no adequate and necessary condition has been identified to characterize the plant that can be strongly stabilized [29].

A design model of the dynamical process to be regulated is used to build the controller. Using a fuzzy modeling approach, the design model is derived from the truth model[30].

2.1 Successfully isolate the sprung mass from vibrations

A soft suspension spring is typically necessary whereas a firm suspension spring is recommended to provide great road holding ability at a frequency close to the natural frequency of the unsprung mass, this is to achieve good vibration isolation for the sprung mass over a wide frequency range (the "wheel hop" frequency). In order to properly isolate the sprung mass from vibration performance in the high-frequency region, a low damping ratio is preferred. A high damping ratio is required to reduce the amplitude of the sprung mass's vibration at a frequency close to its natural frequency. Since the parameters of a typical (passive) suspension .The system's spring and shock absorber are fixed and cannot be modified in line with the vehicle's operating conditions. it is unable to satisfy these competing needs. The force in the actuator is regulated to improve ride, handling, and performance based on the signals collected by the sensors and the prescribed control method.

According to the findings of the literature research, many strategies have been used to improve performance. Vibration isolator, passive suspension, gain scheduling controller, SC, As a result, a more efficient integration of SMC control that needs Control of Semi-active Dampers in Automotive in order to solve control requirement due to the inherent limitations of control techniques. In order to solve such limitations it is proposed controlling of semi active automotive damper by using sliding mode controller.

The goal of proposed problem is to create a controller with the same that meets certain defined stability and performance characteristics over the whole set of possible parameter trajectories. The advantage of control theory over conventional control is that the resulting controllers are gain-scheduled automatically without the need for gain interpolation techniques. Additionally, it guarantees qualities like cool, performance, and robustness, which are challenging to obtain using conventional design methods.

Need of SMC for the performance and robustness of sliding mode control of Suspensions that are semi-active are outstanding. The variable structure control method-based Sliding Mode Controller (SMC) can manage uncertain parameters, complex mathematical models, and chattering effects in active suspension. Adding SC we can get superior to analytical performance a control scheme and a sliding mode controller (SMC) are constructed and formulated. The performance of the SMC that results is assessed. The results reveal that when SC control is paired with a sliding mode controller, the SMC's "chattering" is significantly decreased. It is also demonstrated that the suggested sliding mode controller's performance is steady and robust in the presence of parameter uncertainty.

This chapter summarizes into these suspensions. Comparison study is investigated using SC and SMC controlling system and compare them and make it conclusion which controller is best performance are discussed.

2.2 Summary of related literature

A suspension with low rigidity and soft damping, known as 'soft' suspension, on the other hand, provides adequate body isolation from road unevenness and good ride comfort. However, this technology is incapable of efficiently controlling the motions of the vehicle's body and wheels. As a result, ride comfort and decent handling must be mutually exclusive when constructing standard passive suspensions. The tradeoff between ride comfort and vehicle handling is not possible with a passive suspension. It either provides good comfort at the expense of handling, or the opposite is true. Because of this, people started looking into other strategies like suspension, both active and semi-active offer a good middle ground between the competing demands.

This study examined a novel method for modeling, simulating, and controlling suspension methods that support both riding comfort and road holding capabilities. The work provided a control-oriented PID quarter car semi-active suspension system using a parametric technique. Next, SMC & SC safety ability was developed using the quarter car hybrid model.

For the comfort of passengers and drivers, sliding mode control approach (SMC) for semi-active suspension is suggested. When compared to passive suspensions, semi-active suspensions have a greater potential for improving important vehicle characteristics like ride comfort, road holding, and vehicle handling. The proposed plan is applying the linear parameter varying control to semi-active suspension system with the comparison between stabilizing control and sliding mode control. From the three controller sliding mode controller is best performance because PID is also unstable.

CHAPTER 3

MODELING OF SEMI ACTIVE SUSPENSION

Other researchers' work in this area has been reviewed in order to select an appropriate method for developing a slightly active suspension system. The model with developed after the MATLAB-Simulink model was accepted. MATLAB-Simulink is used to create a similar vehicle model, which was then used to create a semi-active suspension system. Semi-active suspension control method are numerous, but only a few of them are suitable for heavy-duty vehicles.

The dynamic tire forces and ride comfort of a vehicle were taken into account in this study, which is a departure from the majority of control system. To Compare SMC performance with SC controller and show the improvement of non-linear SMC scheme. This thesis study has followed the necessary design steps. For this semi-active suspension damper all necessary considerations are addressed. The problem that arises due to the controllers was not dependent on any particular system attribute or control purpose can be solved through this thesis.

In comparison to active suspension systems, semi active suspension systems use less energy and improve vehicle stability during transit. In contrast to the fixed conventional active [31] and passive [32] systems, the system uses a damper whose characteristics can be adjusted externally via controllers. A quarter car model [33] can be used to describe the design of the semi active system, with the masses categorized as sprung (ms/m1) and unsprung mass (mus/m2). The suspension system dampens the sprung mass, while the unsprung mass is made up of the mass of the vehicle's components like brakes and steering wheel. The system is made up of nonlinear springs that connect the sprung and unsprung masses and are characterized by stiffness constants, as shown in Figure 3 a damper with a stiffness constant of c0 occurs between the tire and the sprung mass. The overall contribution of the tire damper, on the other hand, is frequently overlooked due to its minor impact on performance [34].

A variable damper exists between the sprung and unsprung masses in a semi active system, which is regulated by an external control unit. To depict abnormalities in the road surface, a road profile w through tire contact is utilized. give the nonlinear forces on the tire and spring[35], [36].

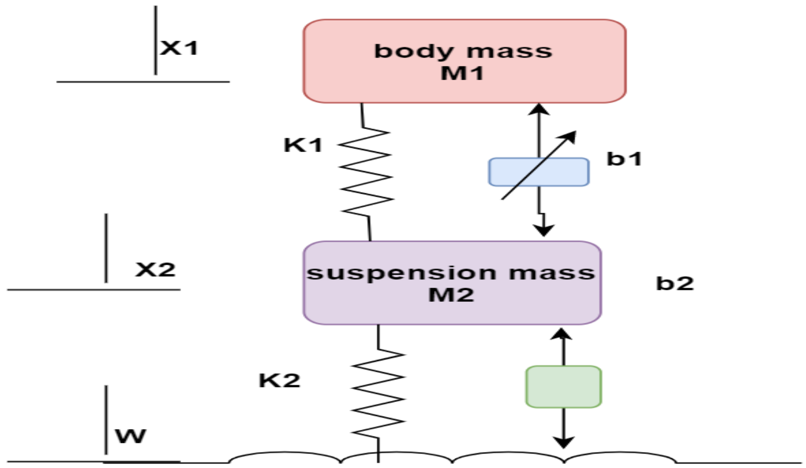

Figure 3.1 suspension system for Semi-active

3.5 Suspension System definitions

A suspension system isolates a car's occupants from outside noises while supporting a load from above. The springs are the flexible components of the suspension system. These parts have the capacity to hold the energy that is applied as loads and deflections. When a spring's length is reduced, it can absorb energy and bend. When a tire hits a barrier, the spring absorbs the energy of the upward motion and propels it forward. Spring, on the other hand, observes this energy for a short period of time before releasing it by returning to its original posture. When a spring releases stored energy, it does so swiftly and with such power that the spring's end usually stretches too far. The spring will oscillate, contract, and expand in a series of phases until it has released all of its energy. The natural frequency of the spring and suspension will influence the speed of the oscillations. A damper's purpose is to limit how much the sprung mass bounces. Furthermore, it made sure that by vibrating at its natural vibration frequency, the wheel assembly always made contact with the road.

Wheel assemblies and the control geometry that governs their movement are also mechanical elements in a suspension system. To stabilize the vehicle in corners by minimizing roll, simple linkages and multi-purpose components such as transverse torsion bars are used.

3.6 Car Suspension

On a soft-surfaced road, a suspension system is not necessary to offer ride comfort for a vehicle's occupants. However, there are many different types and degrees of road surface roughness, making the use of a required to protect the car from the jarring discomfort caused by unevenness of the road. In order to ensure optimum vehicle ride stability, suspension systems must also maintain consistent contact between tires and the road. When the vehicle is turning, accelerating, or braking, this ability is especially critical. In a nutshell, the suspension of a vehicle delivers ride quality and driving safety. There are also important for preventing high tire forces that harm the pavement on the road surface.

The road surface roughness causes shock-excitations, which are absorbed by the springs. When the suspension hits a bump, the spring compresses and stores the shock's energy. It then increase and gradually discharges the energy absorbed to the body of the vehicle. A damper, in the other way of expression is used to diffuse the vibration of the system. When the suspension hits a bump, the damper absorbs a portion of the force of shock directly. It regulates the activity of the springs in this way. Similarly, springs and dampers manage vehicle body motion generated by driving movements.

Steel springs, which coil, torsion bar, and leaf springs, are utilized in most automobiles' suspension systems. Some cars also use pneumatic and hydro-pneumatic springs. The next sections will go into the specifics of these systems. Hydraulic dampers are the most common type of damper in automobile suspension systems. Hydraulic dampers use a similar working principle.

The two main roles of suspension systems, comfortable ride and vehicle control, will be discussed in the following sections. In addition, the limitations of traditional suspensions in fulfilling these roles will be examined, as well as possible remedies.

3.6.1 Ride Comfort

The main objective of a car's suspension system is to ensure a smooth ride. The ride comfort of a car is a crucial component in determining how comfortable its occupants will be on the road.

The foundation of a vehicle's ride comfort is its suspension system. Suspension systems have a frequency range that is lower than 25 Hz. "Ride comfort" in vehicle dynamics refers only to this portion of the frequency range [37]. The car's body's dynamic behavior (i.e. sprung mass) has a significant impact on ride comfort.

Vibrations of the vehicle body should be assessed in two directions: vertical (i.e. heave) and horizontal (i.e. roll, pitch, and yaw) in order to quantify the ride comfort of a vehicle. The entire sample time is (T), the acceleration of sprung mass is (a), and the time is (t). This test must be carried out in both directions. However, merely the body vertical acceleration (i.e. heave) is frequently assessed to simplify the measurement.

3.6.2 Vehicle Control

Handling is a vehicle feature that allows for stable and safe driving by maintaining a constant touch between the road surface and tires. When performing actions like cornering, braking, or accelerating, a vehicle's handling capability is critical. In these extreme settings, poor handling diminishes the vehicle's control ability and may jeopardize passenger safety. As a result, handling is regarded as a crucial feature for automobiles, and it is regarded as the primary goal of employing suspensions in vehicles, aside from ride comfort. Wheel and vehicle body vibrations both have an impact on the connected the road and car tire. Road roughness has the most impact on vertical wheel motion, while vehicle directional changes have the most impact on body motion. Vehicle movements are regarded as the most difficult test for a vehicle's handling characteristics Centrifugal forces, for example, propel vehicles around corners.

A critical handling state is also formed when a vehicle brakes or accelerates quickly. Extra traction forces on the tires are required in this situation, however tire contact force cannot be created adequately due to weight movement from back to front or vice versa. As previously stated, car suspension serves two key functions: vehicle handling and ride comfort. There are, however, several methods for assessing handling indirectly. Tire contact forces that are stable provide good handling, whereas tire force variations that are high reduce the vehicle's handling performance.

3.7 Functions of a Vehicle Suspension

The speed of the car will decide how comfortable the ride is. The disruption causes the passengers to experience acceleration forces, which puts pressure on the load and the vehicle. These disturbances, which were brought on by the uneven road profile, must be kept apart from the vehicle body by the suspension system. Passengers in cars catch up on these acoustic interruptions, and noise comfort worsens as a result.

3.8 Types of Suspension System

Suspension systems are divided into three categories. They are as follows:

1) Suspension that is passive

2) Suspension that is semi-active

3) Suspension in active

3.8.1 Passive Suspension

The system of passive suspension is the most common type of suspension system. One of the elements is damper, while the other is spring. The dampers' job in this passive suspension is to disperse energy, while the spring's job is to accumulate it.

The force storage capacity of a spring is frequently stated in terms of its design function. Machines frequently use springs to lower peak loads, kinetic energy from moving components is stored during deceleration and released during acceleration. The spring will compress when a load is applied until the force generated by compression equals the load. The spring will oscillate briefly around its starting position whenever an outside force disturbs the load. This oscillation can be absorbed by dampers, so it only jumps briefly. This is the primary problem with this kind of suspension system since ride comfort and competent steering parameters change with variety road surfaces. This is due to the fixed damping coefficient and spring stiffness. The semi-active suspension system can increase the performance of a passive suspension system.

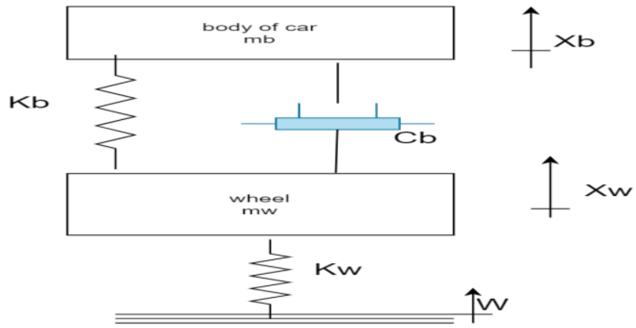

Figure 3.2 Passive suspension system

3.8.2 Semi-active Suspension

The component in the semi-active suspension system is the same as the component in the above figure and when external energy is necessary, it serves the same purpose a suspension that is active suspension system. The ability to change the damping coefficient distinguishes a dynamic suspension system from a passive suspension system. The actuator is only able to dissipate power rather than supply it because to adjustments made to the fully active suspension. The actuator then transforms into a continuously variable damper, allowing it to monitor force demand signals regardless of the immediate velocity applied across it. Despite it's this suspension system has a low system price, a light system weight, and uses little energy. By limiting sprung mass acceleration and displacement, this suspension improves ride quality. Semi-active suspension systems allow the damping or stiffness of the spring to be adjusted to the desired response.

It can adjust the vehicle height in response to weight and disturbance loading variations. This technology responded to internal loading without generating any energy. Semi-active suspension typically has a bandwidth of 0-5 Hz. Using actuator magnetorheological (MR) fluid dampers, skyhook control, relative control, and many more types of semi-active suspension have been designed and introduced. In comparison to active suspension, this type of suspension has the disadvantage of just dissipating kinetic energy from disturbances rather than generating energy for the system. As a result, it's only useful for low-frequency and low-speed vibrations. [38]

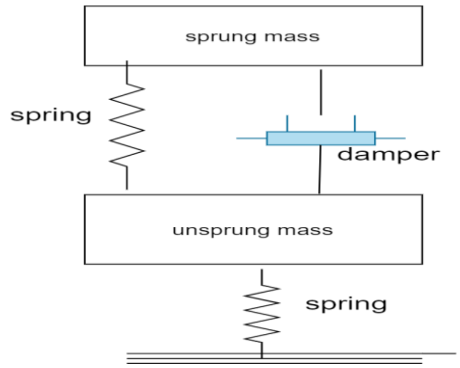

Figure 3.3 the system of semi-active suspension

3.8.3 The Benefits of Using a Semi-Active Suspension System

Semi-active quarter car suspension systems use much less energy than fully active suspension systems. Power usage solely for the purpose of modifying the semi-active device's real-time dissipative force properties. Power is used to modify the area of the piston orifice in a variable opening damper, for example, or to change the current in an MR damper's electromagnetic coil. Vibrational forces are not directly countered by external power. Semi-active suspension systems also have the advantage of not causing the suspension system to become unstable. This is because they do not actively give energy to the vibratory suspension system; instead, they solely dissipate energy from it.

3.8.4 Active Suspension

There are a variety of performance criteria that must be met while analyzing a suspension system. Body acceleration, suspension travel, and wheel deflection are three performance criteria that should be carefully considered when building a suspension system. The performance of the active suspension system can be improved by including the suitable controller into the system

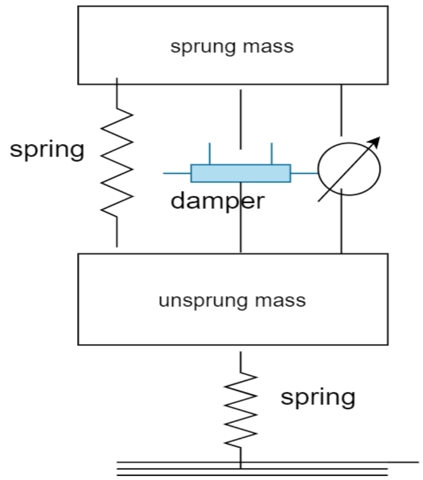

Figure 3.4 active system

3.8.5 Modelling and application of MR dampers

The adaptive change of suspension properties is possible using MR dampers. It can be done at a considerably lower cost because altering settings in semi active devices uses far less energy than generating force in active ones. The MR damper's behavior is significantly nonlinear due to the complicated structure of the MR fluid. The force response is affected by both kinematic and control current excitations, as well as the housing temperature. It is advised that at least a portion of the behavior of such phenomena be described and mapped before using MR dampers in vibration control systems. The use of a reference MR damper model is required for simulation-based research and validation of control methods, while partial linearization of MR damper behavior using inverse modeling increases vibration control quality. [33]

3.8.6 Performance of Suspension System

The passenger's comfort is determined by a number of elements, including the driver's safety and the driving environment. Vibration, which is uncontrollable. The sole factor considered in this work is vibration. Taken into account it can be determined by the distance between the road disturbance and the house. The main system the better the isolation, the more comfortable the passengers will be. The mass acceleration sprung the passenger's comfort is represented by Y s. the smaller. The higher the sprung mass acceleration, the more comfortable the passenger will be.

The second component that influences suspension system performance is road holding. It is the vehicle's ability to maintain contact with the road and maximize wheel tracking in the face of road unevenness, as well as to ensure road contact regardless of the road profile or load transfer condition. The suspension deflection, which can be expressed as Ys-Yu, is used to determine road holding in this study. There is a trade-off between passenger comfort and road holding, it has been demonstrated. As a result, the engineer must build an adequate suspension system in order to minimize it and get the intended effect [39].

3.8.7 Semi-Active Suspension System with Two Degrees of Freedom

The car suspension system's job is to support and isolate the vehicle body and payload from road disturbances while also maintaining traction between the tires and the road surface. With minimal power demand, the SA suspension system can provide both reliability and versatility, including passenger ride comfort. For the SA suspension system, a two-degree-of-freedom concept focusing on passenger ride comfort performance is proposed [40].

3.8.8 MR Damper

The MR damper is made of MR fluid, which is a type of controlled fluid that can change its behavior from liquid to semi-solid when exposed to the damper. Critical performance properties of the MR damper are continuous controllability, rapid response, and low energy consumption, and tem, stability. Due to its special characteristics, MR dampers have been demonstrated to be appropriate for semi-active energy-dissipating uses in suspension applications. By adjusting the power dissipate to coils mounted on the piston, MR dampers' viscous damping coefficient can be adjusted.[41]

The suspended particles, which are a few micrometers in size, are made of ferromagnetic material with a high saturation magnetization, which is usually pure iron. In order to prevent coagulation in the MR fluid, the polarizable particles are also purposely coated by polymers or silica. The fluid can be employed in a variety of operational modes, including flow, shear, and squeeze [42] with flow mode being used for linear MR dampers.

While the MR damper piston is moving, MR fluid flows via gaps designed into the piston. Coils are situated near the gaps and are supplied with control current via wiring. When particles of MR fluid are exposed to a magnetic field created by piston coils, they get polarized and form a chain-like structure along the magnetic field lines and perpendicular to the flow direction.

The passenger of MR fluid via piston gaps is stopped by chains of polarizable particles. As a result, changes in the damping characteristics of the MR damper can be seen on a macroscopic scale [43].

3.9 Semi-active suspension modeling

A damper is a device that absorbs unwanted vibrations. By converting kinetic energy to heat energy, it reduces vibration. When the damper is compressed and extended, the piston, which is made up of orifices, moves through the fluid inside the damper. High pressure is created as the fluid passes through the small orifices, converting the kinetic energy of the moving piston to thermal energy of the fluid. As a result, damping is induced, which reduces vibration in the system.

Any suspension system would be incomplete without dampers. They are also the component of the suspension that is the least understood and most perplexing. The dampers' primary purpose is to manage the transient behavior of the vehicles sprung and unsprung masses. This is achieved by dampening the energy stored in the springs as a result of suspension movement. The damper provides a force that is determined by the damper's piston velocity. Shock absorbers are another name for dampers. Semi-active dampers are electro-mechanical control devices that can change the damping coefficient between its maximum and minimum values as well as in between. With a modest quantity of power supplied, this variable in damping coefficient results in a variation in dissipated energy. There are three different types of semi-active dampers [44]. Electro-rheological (ER) and Magneto-rheological (MR) dampers are three types of semi-active dampers.

A traditional semi-active damper's most common purpose is to vary the bypass cross-section area that connects the two chambers of the damper's piston, resulting in numerous performance curves from a single damper. The following are the primary characteristics of vehicles with semi-active suspensions

• The damper can only dissipate energy;

• The damper has a nonlinear behavior that must be considered during the control design phase.

New approaches have recently been developed to deal with these constraints individually [45][46][47] Recent developments are described in this work to:

Controller for an automotive suspension system with a Magneto-Rheological semi-active damper is designed using the entire model. Depending on the requirements, this controller seeks to improve ride comfort and/or road holding.

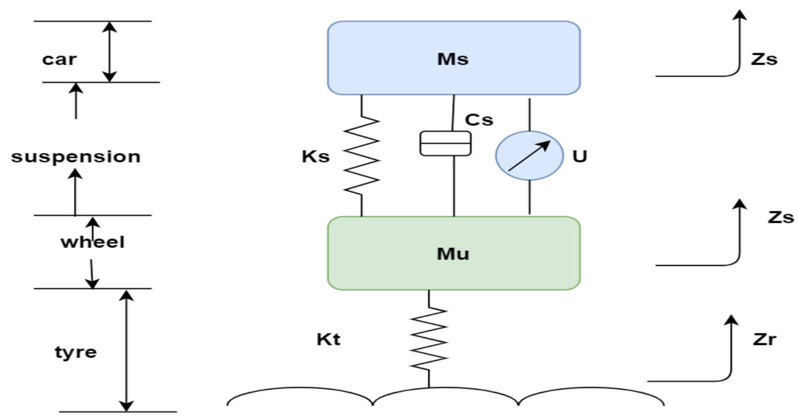

Figure 3.5 model of semi-active suspension

Mechanical equation:

$$M_s\ddot{Z}_s + K_s(Z_s - Z_u) + C_s(\dot{Z}_s - \dot{Z}_u) + u(t) = 0$$

$$M_s\ddot{Z}_s + (Z_s - Z_u) + C_s(\dot{Z}_s - \dot{Z}_u) = -u(t)$$

$$M_u\ddot{Z}_u + K_s(Z_u - Z_s)C_s(\dot{Z}_u - \dot{Z}_s) + k_t(Z_u - Z_r) = u(t)$$

The state equation

$$\dot{x}(t) = Ax(t) + Bu(t) + B_w W(t).$$

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ -\frac{ks}{ms} & 0 & -\frac{Cs}{Ms} & \frac{Cs}{Ms} \\ \frac{Ks}{mu} & -\frac{kt}{Mu} & \frac{Cs}{Ms} & -\frac{Cs}{Mu} \end{bmatrix} \begin{bmatrix} x_1\\ x_2\\ x_3\\ x_4\end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{Ms} \\ \frac{1}{Mu}\end{bmatrix} U + \begin{bmatrix} 0\\ -1\\ 0\\ 0\end{bmatrix} W$$

Selecting state variables:-

$$x_1(t) = (Z_s(t) - Z_u(t)$$

$$x_2(t) = Z_u(t) - Z_r(t)$$

$$x_3(t) = \dot{Z}_s(t)$$

$$x_4(t) = \dot{z}_u(t)$$

The above equation consider road roughness as disturbance and input to system

So we have:

$$A=\begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ -\frac{ks}{ms} & 0 & -\frac{Cs}{Ms} & \frac{Cs}{Ms} \\ \frac{Ks}{mu} & -\frac{kt}{Mu} & \frac{Cs}{Ms} & -\frac{Cs}{Mu} \end{bmatrix} B=\begin{bmatrix} 0 \\ 0 \\ -\frac{1}{Ms} \\ \frac{1}{Mu} \end{bmatrix} Bw=\begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \end{bmatrix}$$

$$C=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, D=\begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix}$$

MS = Body mass/Sprung mass (kg)

Mu = Suspension mass/Un − spring mass (kg)

Ks = coefficient of suspension spring (m)

Kt = coefficient of tyre material (m)

Cs = damping coefficient (N.s/m)

3.9.1 Semi-active suspension for quarter cars parameters

The quarter vehicle model parameter sets, which constitute a conventional parameter set for automotive applications, are those that have been taken into account. A quarter-car model on a passenger car is built, simulated, and analyzed using these parameter settings.

Table 3.1 Quarter car semi active suspension vehicle parameters

S.NO	Parameter	Definition	values	Units
1	*Ms*	(sprung mass)	504.5	Kg
2	*Mu*	(un-sprung mass)	62	Kg
3	*Ks*	Coefficient of suspension spring	13100	N/m
4	*Kt*	Coefficient of tyre material	252000	N/m
5	*Cs*	Damping coefficient of the dampers	400	N-s/m

CHAPTER FOUR

CONTROLLER DESIGN

4.1 CONTROLLER

A controller is a device that keeps track of and physically adjusts the working the parameters of a dynamical system. The relevance of the control system has grown in recent decades as the complexity of the system under control has expanded, as has the need to attain optimum system performance. Figure 8 shows a block diagram of a closed-loop car suspension system.

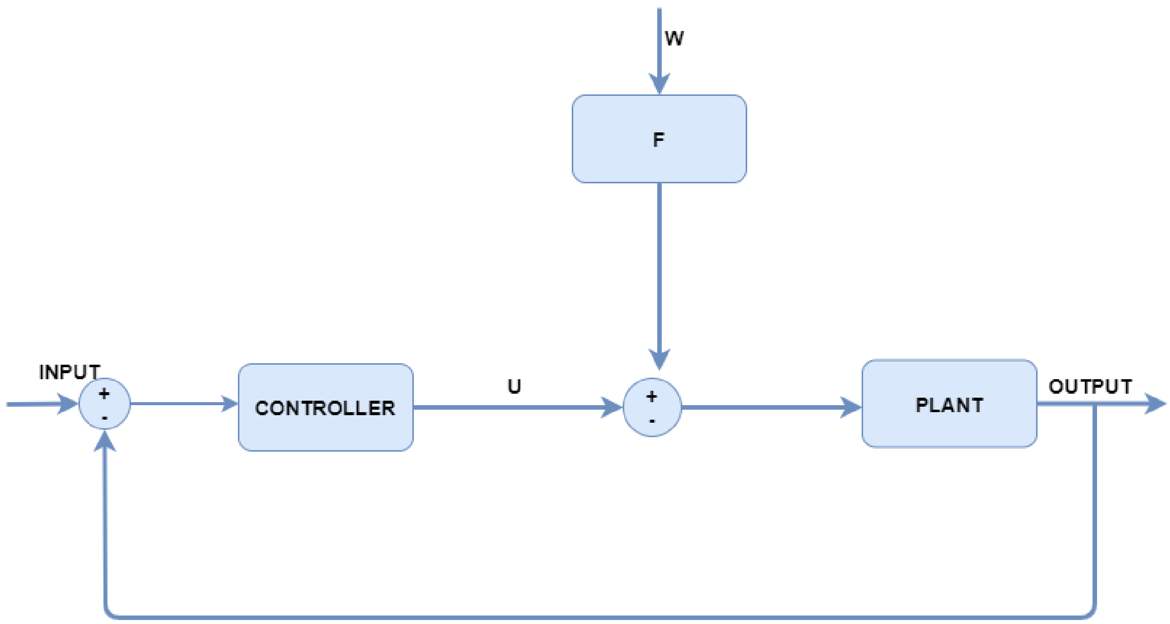

Figure 4.1 Step response of an automobile suspension system in a closed loop

The proportional-integral-derivative (PID) controller is utilized in this paper to increase the system's response.

A primary study topic has been optimizing vehicle handling, driving pleasure, passenger comfort, and effective and efficient isolation of road noise and vibration in suspension systems. The application of several controllers to regulate vibration in the automotive suspension system is presented in this study. A 1/4 model of an automobile is used to simplify the suspension system design into a one-dimensional mass spring-damper system. On the basis of time response, its open-loop performance is noticed, indicating that the car suspension exhibits oscillations with a long settling period. A closed-loop system is utilized to solve this problem.

The PID controller compares the system output to a user-defined setpoint before producing an error signal. The output is then changed in an effort to lessen the erroneous signal that is driving the system. Three terms proportional (*P*), integral (*I*), and derivative (*D*), each with its own gaincalculated independently from the error signal are multiplied to produce the driving signal. As a feedback loop controller, the proposed system employs a Proportional Integral Derivative (*PID*). An error signal is fed into this closed loop to alter the input in order to get the output to the desired set of points. The gain parameters are taken into account when adjusting the controller to reduce overshoot and settling time.

$$u(t) = k_p e(t) + k_i \int e(t)dt + kd \frac{d\big(e(t)\big)}{dt} u(t)u(t)$$

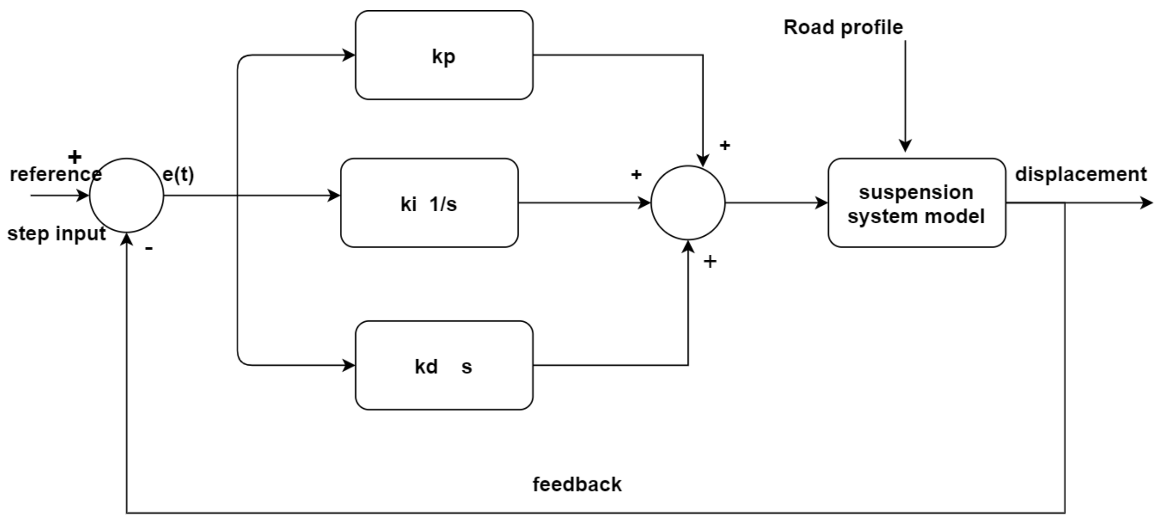

Figure 4.2 Schematic Diagram for PID Controller applied on Suspension System

From this study, the PID controller gain results obtained by trial and error and the effect of each PID controller components ($k_{p\,,}k_i\ and\ K_d$) where the findings have been shown in table 1. Then the whole activities of the controller simulated in using MATLAB software and Simulink environment. PID Controller when $c(s) = k_{p,} + \frac{k_i}{S} + K_d\ S$

A proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism widely employed in industrial control systems; the PID controller is the most regularly used feedback controller.

When a *PID* scheme is used to perform control actions and C(s) the transfer function of the *PID* controller has a form, $c(s) = K_p + \frac{K_i}{S} + K_d\, S$ the way to produce the controller for the automobile suspension system is detailed in this section.

The proportional, integral, and derivative values, designated *P*, *I*, and *D*, are used in the *PID* controller computation, which is frequently referred to as three term control. The reaction to the present error is determined by the proportional value, the integral value is determined by the sum of recent errors, and the derivative error has been changing. The weighted sum of these three activities is utilized to regulate the process using a control element like a car suspension system's disturbances.

$$U(t) = K_p e(t) + K_i \int e(t)dt + K_d\ \frac{de(t)}{dt} \qquad (4.1)$$

Where

K_p , K_i, K_d Proportional gain, Integral gain and Derivative gain respectively

e(t) = set point- plant output

$e(t) = y_{ref} - y$ Represents the change among the existing value y and relative reference value y_{ref} of the system.

The transfer function of *PID* controller given as follows:

$$\frac{U(s)}{E(s)} = G_{pid}(s) = K_p + \frac{K_i}{S} + K_d\, S \qquad (4.2)$$

$$G = K_p\, S \left(\frac{K_p\, S + K_{i+K_d}\, S^2}{K_p\, S^2} \right) \qquad (4.\ 3)$$

$$G_{pid}(s) = K_p\, S \left(\frac{\frac{K_p S}{K_i} + \frac{K_d\, S^2}{K_i} + 1}{\frac{K_p\, S^2}{K_i}} \right) \qquad (4.4)$$

Where

$G_{pid}(s)$ =Transfer function of *PID* controller

T_c =Time constant of *PID* controller

K_p =Proportional gain of *PID* controller

K_i = Integral gain of *PID* controller and

K_d = Derivative gain of *PID* controller

Serial connections are used to link the state-space formatted simplified *PID* controller model. Axle displacements, which are thought of as outputs, are fed back into the input to create double-closed loops, and smooth road surfaces, which are thought of as reference inputs, are regarded zeros. These two factors, along with the disturbance, make up the input to the plant.

A changing damping stiffness coefficient damper is used in the semi-active suspension system, which is powered by an external power source and controlled by an embedded controller with a set of sensors. The controller determines the level of damping necessary based on the road profile, and then adjusts the damper to provide the desired damping. The results of a Proportional Integral Derivative (*PID*) controller were compared to those of a similar passive suspension system for various types of road disturbances. The trial and error method is used to determine the values of proportionality constants K_p , K_i and K_d for the developed *PID* controller.

Table 4.1 Parameter value of PID controller

K_p	1.602
K_i	2.369
K_d	-0.094

4.1.1 Profile of sliding mode control (SMC)

The sliding control approach is a well-known and simple robust control mechanism. It is predicated on the assertion that first order systems are significantly simpler to regulate. Let $e = x - x_d$ be the tracking error of the variable x, where x_d is the desired value for x which is given to the controller. Furthermore, let us define a time varying surface$e = x - x_d$, for a first-order problem, by the scalar equation: $s = \lambda e + \dot{e}$.

Based on the input function$y = \sin(0.25 * \pi * u)$, u<8

Y=0 otherwise

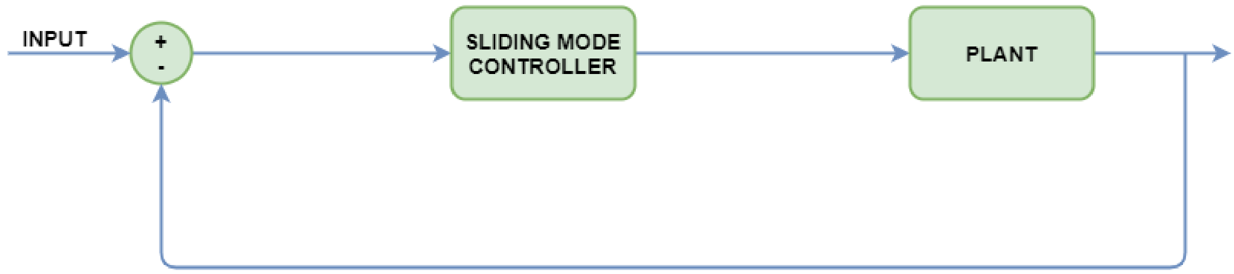

Figure 4.3 slide mode and plant block diagram

A sliding mode state that is asymptotically stable can be created using dynamic errors between the modified MR quarter-vehicle suspension system and the sliding mode control (SMC) synthesis method is:-

- Applicable to linear and nonlinear dynamical systems
- Directly considers robustness issues as part of the design process.
- Also called variable structure control (due to switching nature of control law).
- Used for many applications including power systems and robotics.
- One of the most researched control design technique. Many variations, e.g. twisting SMC, super twisting SMC, terminal SMC, adaptive SMC, and event triggered SMC etc.

In this study, the sliding-mode control theory is adopted to design the controllers because of its robustness.

The vehicle semi-active suspension with magneto-rheological damper (MRD) has been a hot topic since this decade, in which the robust control synthesis considering load variation is a challenging task. In this paper, a new semi-active controller based upon the inverse model and sliding mode control (SMC) strategies is proposed for the quarter-vehicle suspension with the magneto-rheological (MR) damper, wherein an ideal skyhook suspension is employed as the control reference model and the vehicle sprung mass is considered as an uncertain parameter. According to the asymptotical stability of SMC, the dynamic errors between the plant and reference systems are used to derive the control damping force acquired by the MR quarter-vehicle suspension system.

The evaluation results illustrate that the proposed SSMC can greatly suppress the vehicle suspension vibration due to uncertainty of the load, and thus improve the ride comfort and handling safety.

The basic concepts, mathematical and design aspects of sliding mode control. It is shown that the main advantages of sliding mode control are order reduction, decoupling design procedures, disturbance rejection, insensitivity to parameter variations, simple implementation by means of conventional power converters. The methods of suppressing chattering, caused by discrete-time implementation and unmodeled dynamics, are given.

The primary goals of a vehicle's suspension system are to improve riding comfort and road input handling. The main goal of this study is to use a sliding mode controller to increase passenger comfort by reducing vibration in the automotive suspension. The theoretical framework for semi active suspensions mechanism for a quarter-car model that is excited by road profiles. The Sliding mode control is used to create semi active suspension system for a quarter-car model. The effectiveness of the MATLAB and the SIMULINK toolbox are used to simulate the evaluation of sliding mode control.

A problem with conventional (first-order) sliding mode control is attenuation of the chattering effect. However sliding mode control provides effective tools for the reduction or even practical elimination of the chattering, without compromising the benefits of the standard sliding mode

4.1.2 STABLIZING CONTROLLER

It is commonly known in the control literature that the existence of a delay in some control scheme may induce instability or bad performances. At the same time, there exist simple dynamical systems (second-order oscillators) for which a delay in the output feedback control law may induce a stabilizing effect. Suppose p is stable. Then the set of all stabilizing controllers in figure can be described as $k = Q(I - PQ)^{-1}$ stabilizing controller is used as lead compensator.

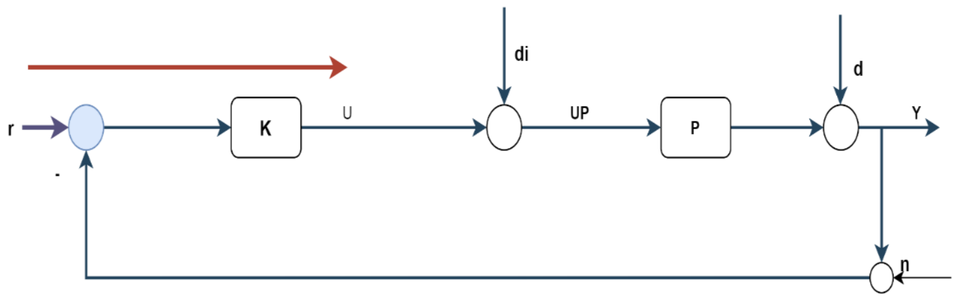

Figure 4.4 the set of all stabilizing controller

For any Q in the set of stable transfer matrices and $I = P(\infty)Q(\infty)$ nonsingular. Proof

$K = Q(I - PQ)^{-1}$ $= K(I - PQ) = Q$ $Q = K(I + PK)^{-1}$ System is stable.

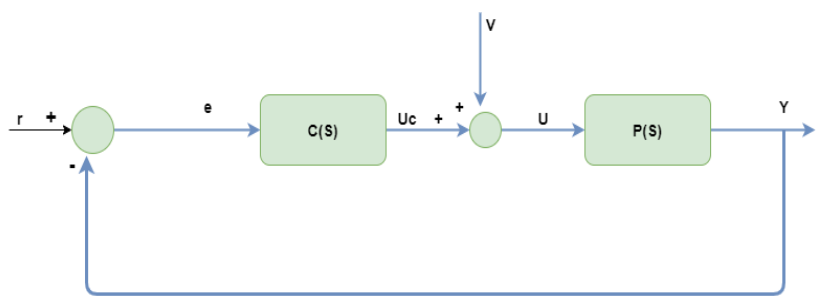

Figure 4. 5 Strong Stabilization Problem

We say that C strongly stabilizes P if

C is stable and the closed-loop system (C, P) is also stable.

Why strong stabilization?

- Simultaneous stabilization of two plants is equivalent to strong stabilization of another plant.
- Robustness to sensor failures in the feedback path.
- The capability to test the stand-alone controller off-line.

CHAPTER FIVE

RESULTS AND DISCUSSION

This presents the Simulink model of the vehicle suspension system modeled mathematically in chapter three. The designed controller parameters are given numerical values. The model of quarter car suspension systems are developed in the computer Simulink model with a controller. The expected behavior of the system under the influence of a suggested control system is simulated and observed using this model, and the simulation results are displayed as graphs. In order to demonstrate the intended results, the results have been discussed in terms of the chosen vehicle suspension system's performance.

5.1 Simulink model , performance of the controller and vehicle suspension

The proposed work overall vehicle suspension system with controller is created in the MATLAB software to examine and analyze how well the desired controller performs under the intended controller action.

Based on the given mathematical modelling (dynamic equation) the Simulink block of semi active suspension system is created.

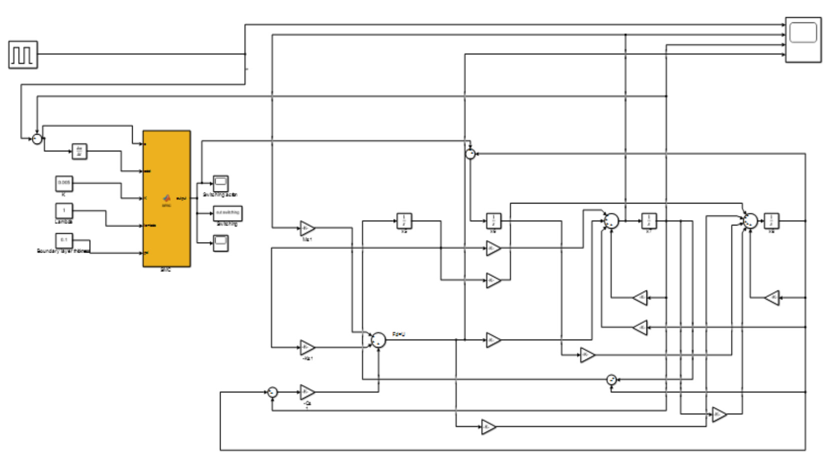

Figure 5.1 Simulink model of semi active suspension system having a SMC controller

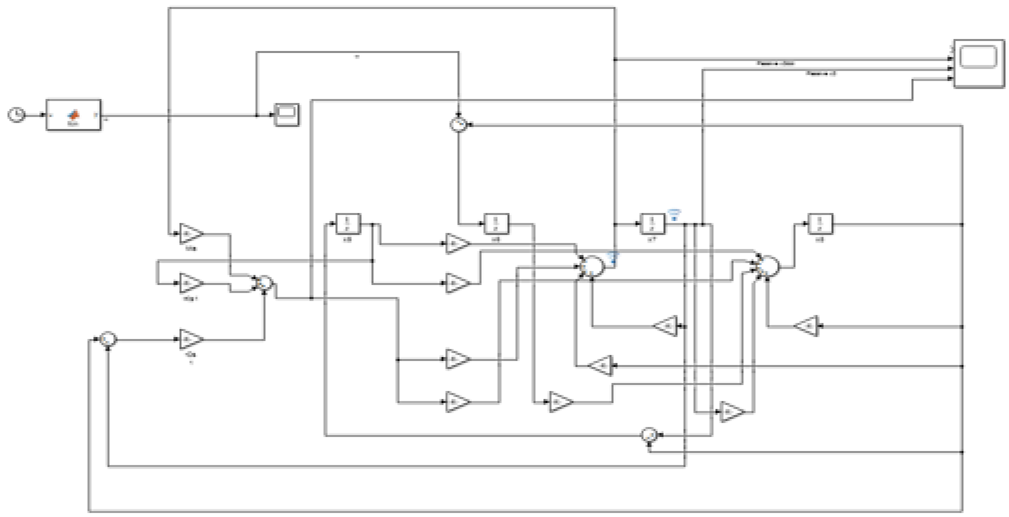

Figure 5.2 Simulink model of semi active suspension system without controller

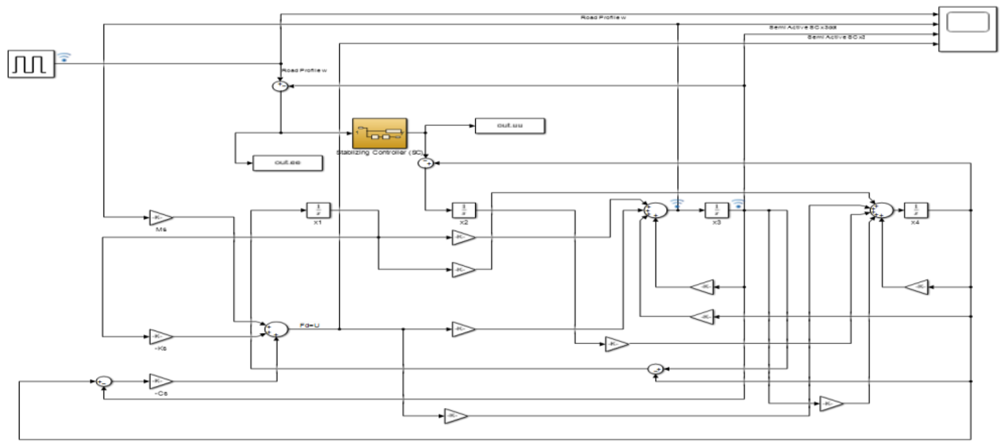

Figure 5.3 Stabilizing control semi active suspension

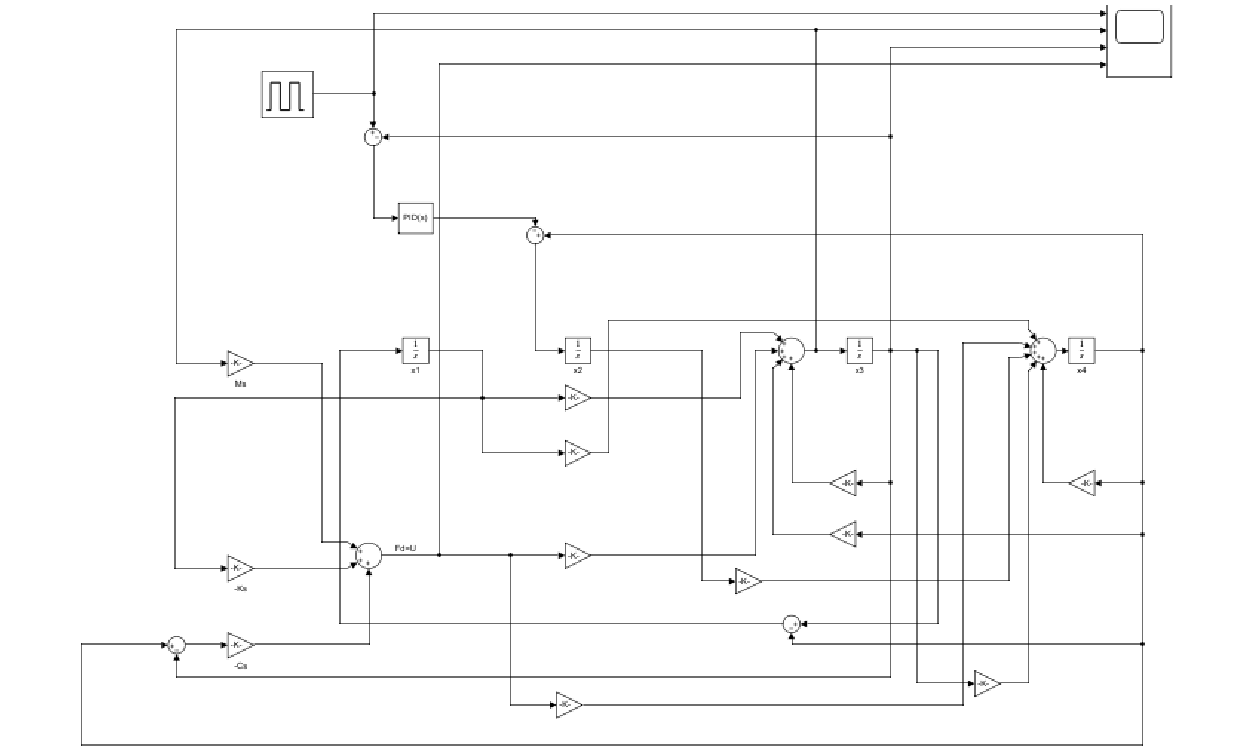

Figure 5.4 Semi active suspension with PID controller

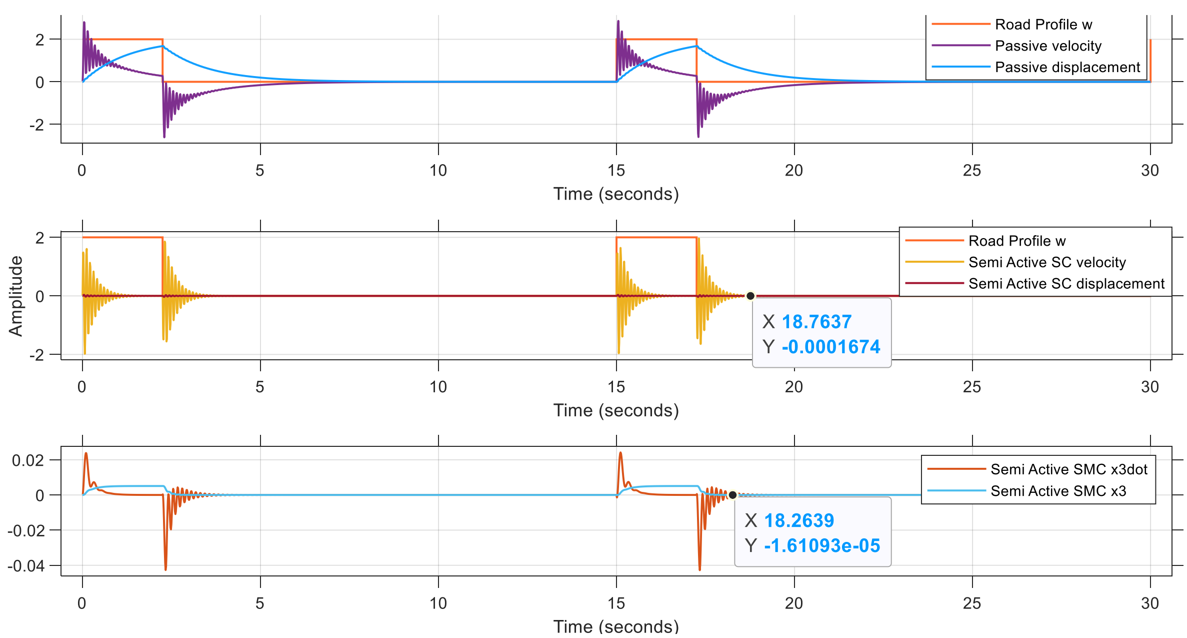

Figure 5.5 semi active SMC Vs semi active SC different road profile

	Settling time	% improvement	
Semi active SC	18.76		
Semi active SMC	18.26	2.73	SMC better performance than SC

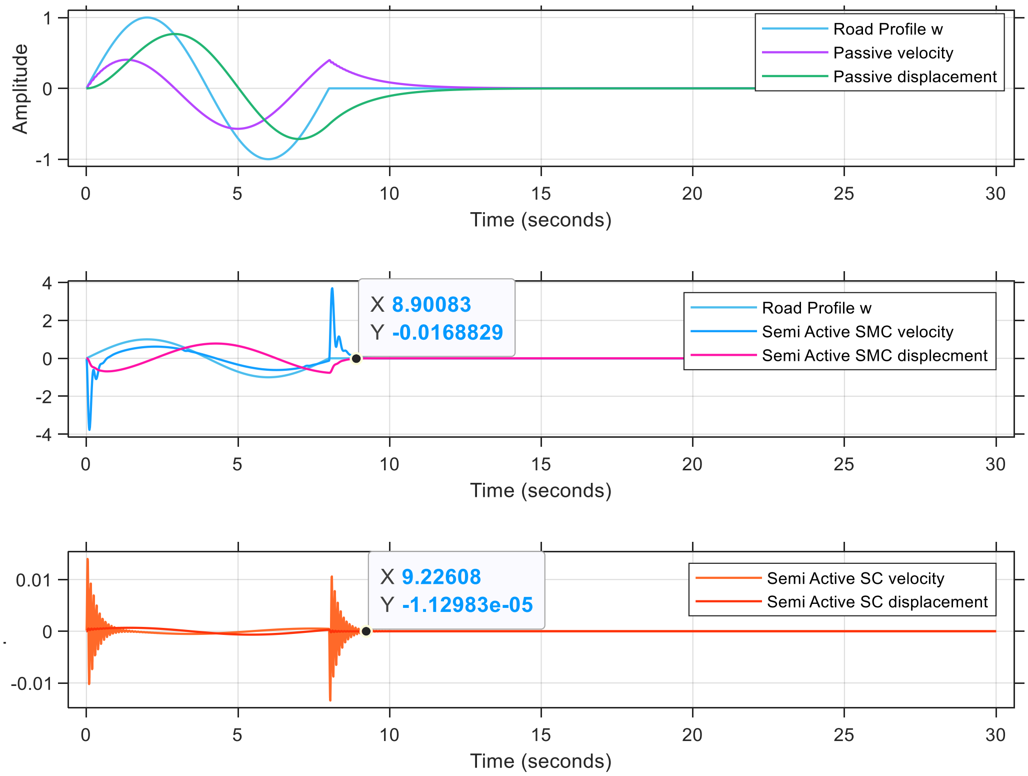

Figure 5.6 semi active SMC Vs semi active SC different road profile

	Settling time	% improvement	
Semi active SC	9.22		
Semi active SMC	8.9	3.65	SMC better performance than SC

From the figure 18 shows semi active SC the settling time is 9.22 sec and SMC 8.9 sec. so SMC IS improved in around 3.65%.

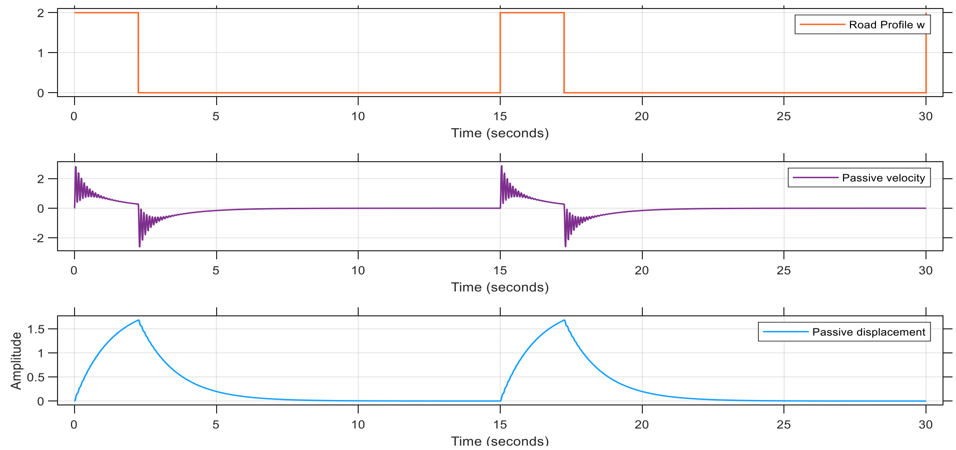

Figure 5.7 semi active suspension without controller

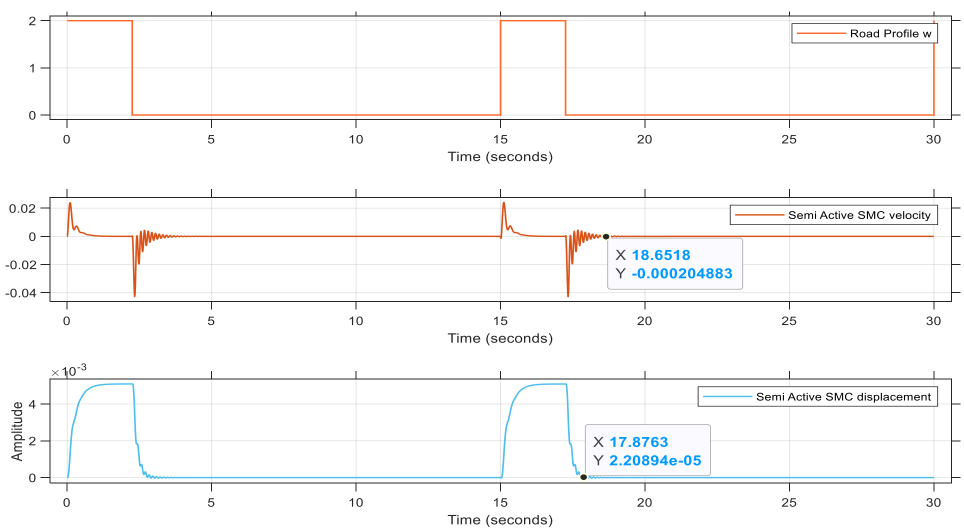

Figure 5.8 semi active velocity and displacement slide mode control based

	Settling time	% improvement	
Semi active SMC velocity	18.65		
Semi active SMC displacement	17.87	4.36	SMC in displacement

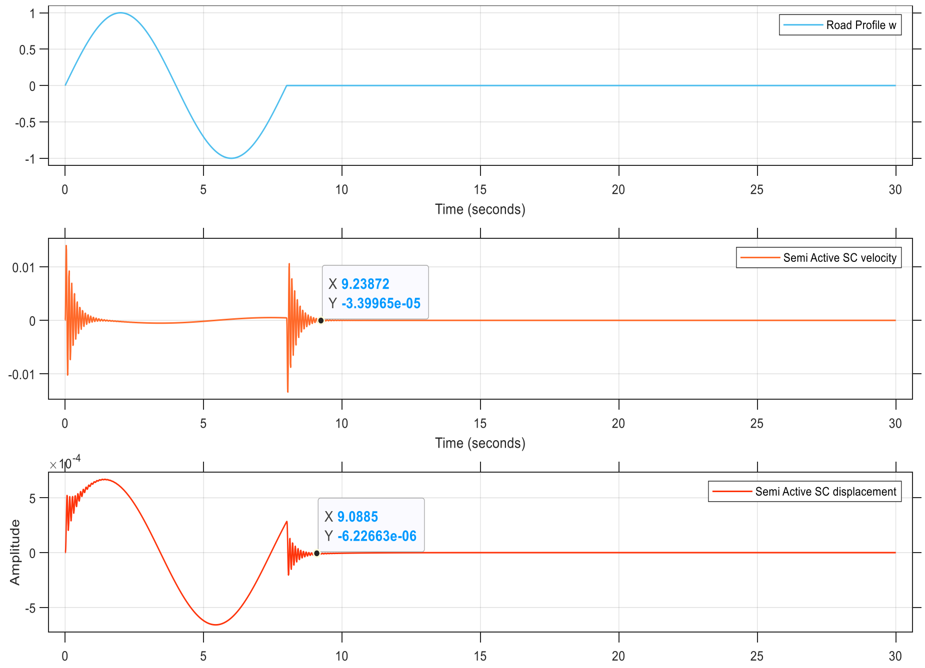

Figure 5.9 stabilizing control semi active suspension with velocity and displacement

	Settling time	% improvement	
Semi active SC velocity	9.23		
Semi active SC displacement	9.08	1.65	SC in displacement

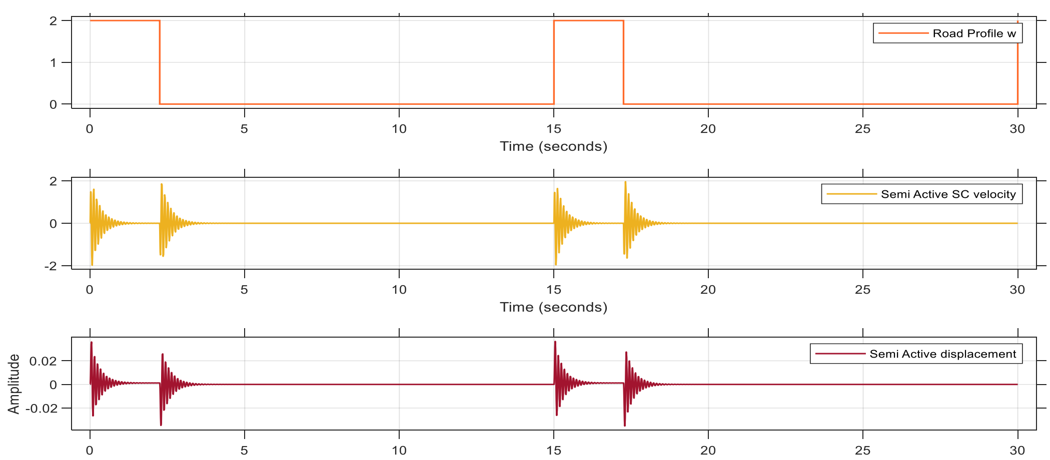

Figure 5.10 semi active suspension stabilizing control

Semi-active suspension system

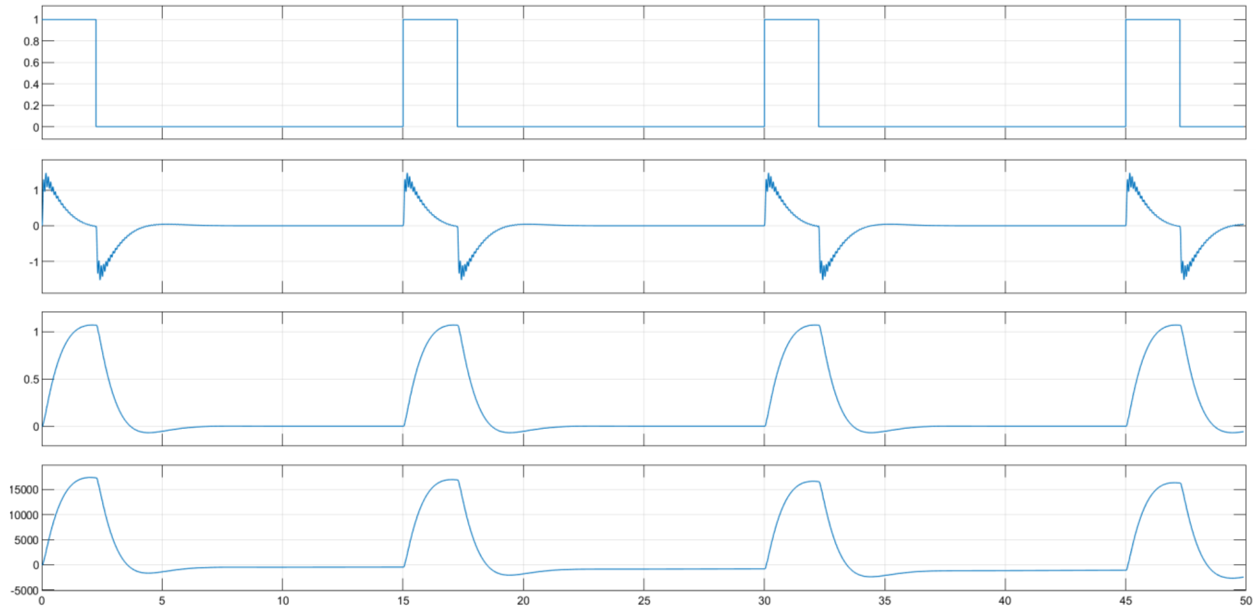

Figure 5.11 PID controller response for semi-active suspension system

Y1= Reference signal (Desired vertical velocity of chassis)

Y2 =vertical acceleration of chassis (m^3/s)

Y3 = vertical velocity of chassis (m^2/s)

Y4 = Input force (N-m)

X= Time in seconds

The *PID* controller disturbance rejection response for the semi-active suspension system is shown in Figure 25. The disturbance signal is given as a sequence of pulse signal (*Y1*). The deviation in vertical velocity of chassis is given in *Y3* and its corresponding vertical acceleration of chassis is given in *y2*. The input force spent for the disturbance rejection process is given in *Y4*.

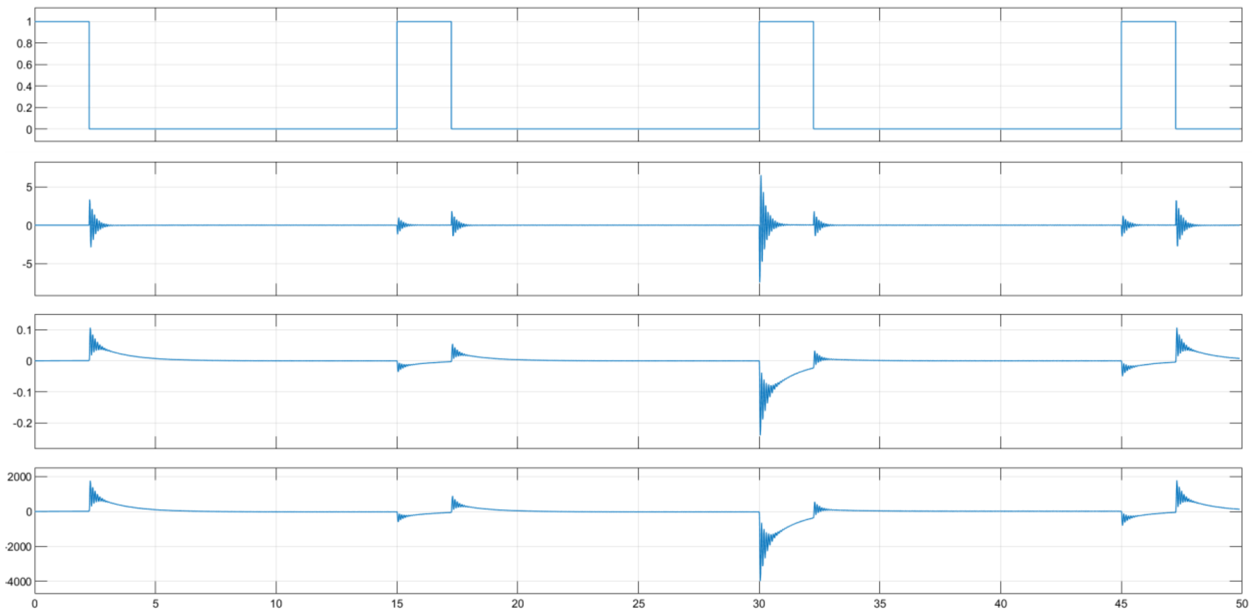

Figure 5.12 Sliding mode controller response for semi-active suspension system

The sliding mode controller disturbance rejection response for the semi-active suspension system is shown in Figure 2. The disturbance signal is given as a sequence of pulse signal (*Y1)*. The deviation in vertical velocity of chassis is given in *Y3* and its corresponding vertical acceleration of chassis is given in *y2.* The deviation in the velocity and acceleration is less compared to *PID* controller. The input force spent for the disturbance rejection process is given in *Y4*. Also, the input force is less compared to *PID* controller.

5.4 DISCUSSION

From the above Simulink block the system get pulse generator as an input for road profile to the stabilizing controller and sliding mode controller in different system parameters and pulse is input for the stabilizing control for the stable of vehicles direction in order to reduce the vehicles bump height.

The sliding mode controller disturbance rejection response for the semi-active suspension system is shown in the figure above. The disturbance signal is given as a sequence of pulse signal .The deviation in vertical velocity of chassis is given in velocity and its corresponding displacement given in displacement. The deviation in the velocity and displacement is less compared to stabilizing and sliding mode controllers. The input force spent for the disturbance rejection/stabilizing control process is given. Also, the input force is less compared to stabilizing and sliding mode controllers. The disturbance rejection performance of the sliding mode controller is better than stabilizing controller.

The simulation analysis was completed in MATLAB using the Simulink models for the quarter-car semi-active suspension system. The performance parameter was chosen to be the suspension velocity and the displacement of the car's body mass (body travel) in terms of linear displacement. The highway both systems regarded disruption as input.

They are in three states: without a controller, stabilizing controller and sliding mode controller. As the above figure shows, Performance of sliding mode controller is less over shoot while stabilizing controller theory can't decrease the acceleration glowing. SMC is reviewed in the previous results and discussed about its robustness.

This robust controller is more accurate and efficient. In suspension system, because of some uncertainties in vehicle dynamics and road conditions, only a robust controller can do well. Road profile is given as input for the simulation. Also, the input force is less compared to sliding mode controllers. The disturbance rejection performance of the sliding mode controller is better than *PID* and stabilizing controller. For the *PID* response is the system becomes unstable to make it stable stabilizing controller is used.

A thorough comparison between the semi-active and passive suspension systems was conducted. By creating a controller that enhances system performance, an approach for building an semi active suspension for a passenger car was devised. So based on the out put semi active suspension is less bump height, the road and ride safety is very high.

The nonlinear controller based on sliding mode controller is one of many types of controllers in this study. The goal is to reduce the acceleration that is given to the vehicle's mass center. The simulation results demonstrated that the created controller may reduce the vibration loads generally delivered on the rough road. Results indicated that while employing sliding mode can drastically alter systems, control effort quickly increases in this mode.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

This thesis's objective is to design and simulate a controller for a vehicle suspension system in order to compare its performance to other controllers. There has been discussion about the suspension system's mathematical model. Stablizing and SMC controllers, two different types of controllers, are designed in this study. To test and show the controller performance of the suspension defined regulated parameters for the desired position and speed of the vehicles, a MATLAB Simulink simulation of the vehicle suspension system is used..

Semi-active suspensions have a greater potential for improving important vehicle characteristics like ride comfort, road holding, and vehicle handling. In this work, a mathematical model of the semi-active suspension system is developed. First, a conventional stabilizing controller is designed. In addition a sliding mode controller and PID is designed. The performance of the controllers is analyzed. In order to evaluate the disturbance rejection performance of the controllers a sequence of function is given as the road disturbance signal as input. Among all the controllers the sliding mode controller disturbance rejection performance is better than the other controller performances.

The modeling approach of a nonlinear semi active suspension model yields the constants of the linear model. For road holding and ride comfort, respectively, the sliding surface is made up of suspension deflection/displacement and suspension velocity. The linear model is employed to assess the effectiveness of the suggested SMC. While going over the speed bump, the suggested SMC can decrease sprung mass acceleration for frequency responses without increasing tire deflection. The proposed SMC may still deliver the intended performance in the presence of parameter uncertainty caused by the increased sprung mass and deteriorating suspension.so sliding mode controller is perform best performance than *PID* and stabilizing controller.

6.2 Future Scope

The following aspects may be considered as a future work

- Adaptive fuzzy sliding mode controller may be designed for the time varying semi-active suspension system.
- Robust H infinity approach based control scheme may be designed for semi-active suspension system with constraints.

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Appendix: Parameters of semi active suspension system used in the SMC Simulink model.

%% Constants

% Mass of vehicle body (kg)
MS = 504.5;
%Mass of the tyre and suspension (kg)
Mu = 62;
% Coefficient of suspension spring (N/m)
Ks = 13100;
%Coefficient of tyre material (N/m)
Kt = 252000;
% damping coefficient of the dampers (N-s/m)
Cs = 400;