

DESIGN AND VALIDATION OF CONTROLLER FOR SUSPENSION SYSTEM

Submitted in partial fulfilment of the requirements for the award of

Bachelor of Engineering degree in

Automobile Engineering

By

KAVVAMPALLY RAHUL (Reg. No. 40860002)



DEPARTMENT OF AUTOMOBILE ENGINEERING

SCHOOL OF MECHANICAL ENGINEERING

SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with grade “A++” by NAAC

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI – 600119

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of KAVVAMPALLY RAHUL (40800002) who carried out the project entitled "**DESIGN AND VALIDATION OF CONTROLLER FOR SUSPENSION SYSYEM**" under my supervision from November 2023 to April 2024.



Internal Guide

Dr. S. AROCKIA SUTHAN, M.E., Ph.D.



Head of the Department

Dr. V. K. BUPESH RAJA, M.E., Ph.D.

Submitted for Viva voce Examination held on 06/04/2024.



Internal Examiner



External Examiner

DECLARATION

I KAVVAMPALLY RAHUL (Reg. No. 40860002) hereby declare that the Project Report entitled **“DESIGN AND VALIDATION OF CONTROLLER FOR SUSPENSION SYSTEM”** done by me under the guidance of **Dr. S. Arockia Suthan, M.E., Ph.D.** at Sathyabama Institute of Science and Technology, Chennai, is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering degree in Automobile Engineering.

A handwritten signature in blue ink, appearing to read 'Rahul', with a horizontal line underneath.

DATE: 06.04.2024

SIGNATURE OF THE CANDIDATE

PLACE: CHENNAI

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ABSTRACT

The suspension system plays a vital role in enhancing vehicle stability, ride comfort, and safety by actively adjusting the damping forces in response to varying road conditions and vehicle dynamics. In this project, we propose a novel approach for the design and validation of a controller for a suspension system(active), aimed at optimizing ride quality and road handling performance. There are different types of suspension systems such as passive, semi-active and active suspension systems. Due to increased significance of vehicle comfort has paved the way for the development of various control algorithms to control the active suspension system. The design process starts with an in-depth analysis of the existing passive and active suspension systems, identifying their strengths and limitations. Subsequently, a comprehensive mathematical model of the vehicle dynamics is developed to facilitate the controller's design and analysis. We consider various control strategies, such as Proportional-Integral-Derivative (PID), Sliding mode controller, fuzzy logic controller, Model Predictive Control (MPC), and Adaptive Control, to determine the most suitable approach for our system. Active suspension system is applied to luxury vehicles to improve the vehicle dynamic performance by reducing the rolling, yawing, and pitching movements. This study highlights the modern control techniques that are employed in the suspension system by major manufacturers.

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LIST OF SYMBOLS AND ABBEREVIATIONS

m_h	Head mass
m_{ut}	Upper Torso mass
m_{lt}	Lower Torso mass
m_{tp}	Thighs and Pelvis mass
m_c	Seat and Cushion mass
m_f	Frame mass
m_s	Sprung mass
m_{us}	Unsprung mass
c_h	Damping coefficient of Head mass
c_{ut}	Damping coefficient of Upper Torso mass
c_{lt}	Damping coefficient of Lower Torso mass
c_{tp}	Damping coefficient of Thighs and Pelvis mass
c_c	Damping coefficient of Seat and Cushion mass
c_f	Damping coefficient of Frame mass
c_s	Damping coefficient of Sprung mass
c_{us}	Damping coefficient of Unsprung mass
k_h	Spring Stiffness of Head mass
k_{ut}	Spring Stiffness of Upper Torso mass
k_{lt}	Spring Stiffness of Lower Torso mass
k_{tp}	Spring Stiffness of Thighs and Pelvis mass
k_c	Spring Stiffness of Seat and Cushion mass
k_f	Spring Stiffness of Frame mass

k_s	Spring Stiffness of Sprung mass
k_{us}	Spring Stiffness of Unsprung mass

CHAPTER -1

INTRODUCTION

The suspension system is an integral component of any vehicle, playing a pivotal role in ensuring a smooth and controlled ride. It serves as the interface between the tires and the vehicle's body, responsible for absorbing shocks, maintaining tire contact with the road, and providing stability and comfort to passengers. In the world of automotive engineering, suspension systems are a subject of continuous evolution and innovation, driven by the pursuit of enhancing safety, handling, and ride quality. From the earliest horse-drawn carriages to today's high-performance sports cars and rugged off-road vehicles, the concept of suspension has been a fundamental aspect of vehicle design. Over time, suspension systems have become increasingly sophisticated, employing advanced materials, technologies, and engineering principles to meet the ever-growing demands of modern vehicles and their diverse applications. This comprehensive introduction will delve into the world of suspension systems, exploring their historical evolution, key components, functions, types, and the intricate interplay between them. We will also examine the crucial role that suspension systems play in ensuring vehicle stability, handling, and passenger comfort.

To appreciate the sophistication of today's suspension systems, it's essential to reflect on their historical evolution. The concept of suspension can be traced back to the earliest horse-drawn carriages, where simple wooden components were used to provide a more comfortable ride over uneven terrain. As the automotive industry began to take shape in the late 19th and early 20th centuries, suspension systems became an area of intense innovation and experimentation. One significant milestone was the introduction of leaf springs and solid axles, which revolutionized carriage and wagon design. Leaf springs, in particular, provided a flexible and shock-absorbing connection between the wheels and the carriage body. This innovation significantly improved ride comfort and laid the foundation for more advanced suspension technologies. As automobiles gained popularity, engineers started exploring independent suspension systems, where each wheel could move

independently. This development marked a significant departure from the rigid solid axles, enabling a smoother and more controlled ride. Over time, different types of springs, such as coil springs and torsion bars, came into use, each offering unique advantages in terms of ride quality and handling. The incorporation of dampers, commonly known as shock absorbers, further refined suspension systems. Dampers controlled the motion of springs, preventing excessive bouncing and enhancing vehicle stability. The ongoing evolution of materials and technologies in the automotive industry continued to drive innovation in suspension design, leading to the diverse range of suspension systems seen in vehicles today.

1.2 HISTORY OF SUSPENSION SYSTEM

Up until the early 1900s, streets were filled with horse-drawn carriages. But when Gottlieb Daimler and Carl Benz invented the automobile, they did so independently of each other in 1886. This created a whole new set of requirements compared to horse-drawn carriages, especially for the suspension, which had to be able to handle higher speeds without putting other people on the road in danger. Carl Benz and Gottlieb Daimler took different methods to this problem. Benz's Patent Motor Car was based on a bicycle and had a turning head and wire wheels, while Daimler's car was based on a wagon that had a steering system. Technology changed very quickly. Wilhelm Maybach, Daimler's clever design engineer, made the first "wire-wheel car" in 1889. Just like the Benz car, this one had a frame that had nothing to do with building carriages. The engines also got a lot better, getting stronger over time. This made the cars go faster, but it also made them heavier, which put new demands on the frame. In response, the design engineers came up with ideas that were more and more complex. Some of these changes were the growing use of coil springs, like on the back axle of the 1895 Daimler belt-driven car. Gottlieb Daimler did not figure out how to steer a four-wheeled car, but Carl Benz did. He came up with the "double pivot" turning method. Benz applied for a copyright on this new way of turning in 1893. It was first used in the Victoria model. The chain drive was finally replaced by the shaft drive at the start of the 20th century. The Benz Parsifal, which

was similar to the Mercedes Simplex, had a shaft drive in 1902. Because of the new drive system, the whole back axle assembly had to be redesigned. The axle gear unit now had a differential built in, which raised the unsprung masses. Because of this, the rear axle needed more suspension, so more dampers were added.

1.3 FUNCTIONS OF A SUSPENSION SYSTEM

The support system does a number of important things, such as

- To absorb shock and vibration: When a car drives over rough ground, the suspension system reduces the shock and vibration that it experiences. This makes the ride more comfortable for the people inside and helps keep the car's parts from getting damaged.
- To improve handling and stability: the suspension system helps keep the car stable and under control when turning corners, slowing down, and speeding up. This makes it easier to handle and safer.
- To maintain ride height: The suspension system helps keep the ride height steady, which is the space between the ground and the vehicle's wheels. This is important to keep the vehicle's ground clearance right and keep it from bottoming out on bumps.
- To keep the wheels aligned: The suspension system helps keep the wheels straight, which is important for ride quality and tire life.
- Reduce wear and tear on the vehicle: The suspension system helps to lessen damage to the tires, wheels, and other parts of the vehicle. These changes can help you save money on fixes and upkeep.
- Improve fuel efficiency: A well-kept suspension system can help increase gas mileage by lowering the amount of energy needed to move the car over rough terrain.
- Reduce noise and vibration: The suspension system helps to lessen the noise and vibration that gets into the cabin. This makes the ride more pleasant and relaxing.

- Improve safety: A good suspension system keeps the car stable and under control, which makes it safer. Because of this, crashes may not happen.

The support system can do more than just these simple things. It can also be used to do things like

- Off-road performance: Some cars have suspension systems that are made to be used off-road. The car can go over rough terrain because these suspension systems give it more ground clearance and flexibility.
- Sport handling: Some cars have suspension systems that are made to handle well in sports. Most of the time, these suspension systems are stronger and have less ground clearance than regular suspension systems. This makes the car easier to control at high speeds and around turns.
- Comfort: The handling systems in some cars are meant to make them more comfortable. Most of the time, these suspension systems are lighter and have more ground clearance than regular ones. This makes the ride more comfortable for the people inside, especially on rough roads.
- The suspension system is a complicated part of a car that is very important to its safety and performance.

1.4 TYPES OF SUSPENSION SYSTEM

There are two types of suspension system in a vehicle-

- i. Dependent suspension
- ii. Independent suspension
- iii. Passive suspension
- iv. Semi-active suspension
- v. Active suspension

1.4.1 *Dependent suspension*

A dependent suspension system in which the two wheels on the same axle are linked to each other by a solid beam or axle. When one wheel hits a bump, the other wheel will also be affected. Dependent suspension systems are typically used on rear-wheel drive vehicles, pickup trucks, SUVs, and commercial vehicles. They are also used on some front-wheel drive vehicles, but to a lesser extent.

There are two main types:

Leaf spring suspension: This type of suspension uses leaf springs to support the weight of the vehicle and absorb bumps. Leaf springs are made of a stack of long, flat metal leaves that are bolted together.

Coil spring suspension: This type of suspension uses coil springs to support the weight of the vehicle and absorb bumps. Coil springs are spiral-shaped metal springs that are compressed when the vehicle hits a bump.

1.4.2 *Independent suspension*

Independent suspension system is a system that allows wheels on the same solid axle to move independently of the others. When one wheel encounters a bump or irregularity in the road, it can move up and down without affecting the movement of the other wheels. This design offers several advantages for vehicle handling, comfort, and traction. The following are the pros of an independent suspension system:

Improved Ride Comfort: With independent suspension, each wheel can respond differently to bumps, potholes, and rough ground on the road. This makes the ride easier and more comfy for the people inside because the force on one wheel doesn't directly affect the others.

Better Handling: Independent suspension enhances a vehicle's handling characteristics by allowing each wheel to maintain better contact with the road

surface. This results in improved traction, stability, and cornering performance. It also reduces body roll during turns, contributing to better control.

Enhanced Traction: Each wheel can adjust to the terrain independently, which is particularly beneficial for off-road vehicles. It allows the wheels to maintain traction on uneven or slippery surfaces, enhancing the vehicle's off-road capability.

Reduced Unsprung Mass: Independent suspension typically has a lower unsprung mass (the mass not supported by the suspension) compared to other suspension types, like solid axles. This reduction in unsprung mass contributes to better wheel control, improved road contact, and more responsive handling.

Versatility: Independent suspension can be designed and tuned for various vehicle types and purposes, from sports cars to off-road trucks. Different configurations and setups can be used to meet specific performance and comfort requirements.

There are a number of different types of independent suspension systems, including:

There are a number of different types of independent suspension systems.

- **MacPherson strut:** The easiest and most popular type of independent suspension is the MacPherson spring. This part is used on the front axle of most new cars.
- **Double-wishbone:** Double-wishbone suspension is more complex and expensive than MacPherson strut suspension, but it offers better handling and performance. It is often used on the rear axle of high-performance cars and SUVs.
- **Multi-link:** Multi-link suspension is the most complex and expensive type of independent suspension. It offers the best handling and performance, but it is also the most heavy and expensive. It is often used on high-performance sports cars and luxury vehicles.

1.4.3 *Passive suspension system*

When there are bumps and other uneven parts in the road, a passive suspension system uses mechanical parts to smooth oscillations out. It does not use any external power, like hydraulics or electricity. Most of the time, suspension systems with passive parts are used. When a car hits a bump or other uneven surface on the road, the springs absorb energy and the damper dissipates the energy. This takes in the impact energy and keeps it from going to the frame or body of the car. The spring and damper are the two main parts of the passive suspension system. This kind of suspension system does not behave like an active suspension system. The dampers then control how much the springs bounce back, which keeps the car from shaking too much. The control bars keep the wheels on the road and help you control how they move. The control arms can turn and move around easily thanks to the ball joints. The steering rack is linked to the steering knuckles by tie rods. When the steering wheel is turned, the wheels turn with it. Many types of vehicles use passive suspension systems, such as cars, trucks, SUVs, vans, and buses.

1.4.4 *Semi-active suspension system*

Automotive suspension systems that change the braking force of the shock absorber based on information from the road surface that is always changing are called semi-active suspension systems. This is different from a passive suspension system, which uses springs and dampers to smooth out bumps and uneven roads in a set way. Several sensors in this system keep an eye on the vehicle's movements, including the speed of each wheel, the body's acceleration, and the vehicle's pitch and roll. The information from these devices is sent to a computer, which uses a control program to figure out what each shock absorber needs to work best. After that, the computer tells the motors in the shock dampers to change the damping force to match.

The skyhook damper system is the most popular type of mostly passive suspension system. There is no real skyhook damper, but there is a damper that is connected to a set place above the car. If the car goes over a bump, the skyhook damper will keep the car's body at the same height, no matter what the bump is. A semi-active

suspension system in the real world can't work as well as a skyhook damper, but it can get pretty close. The body roll, pitch, and sway of the car can be kept to a minimum by a semi-active suspension system that changes the braking force of the shock absorbers in real time. The ride is smoother, and the car handles better because of this.

1.4.5 Active suspension system-

A type of car suspension called an active suspension system control how the wheels and axles move up and down in relation to the body, or vehicle frame. It does this with an onboard control system. Normal passive suspension systems, on the other hand, only use springs and dampers to smooth out bumps and other imperfections in the road. Accelerometers, gyroscopes, and motion sensors are some of the tools that are used in active suspension systems to measure how the body of the car moves. The information is then sent to ECU, which uses a control program to figure out how much force should be applied to each wheel's suspension. The ECU then sends signals to actuators, which moves the vehicle to zero vertical displacement position.

Making an active suspension system is harder and costs more than making an inactive suspension system. Active suspension systems can also make a car heavier, which can make it use more gas and perform worse. Even though they have problems, active suspension systems are better than inactive suspension systems in a number of ways. Since active suspension systems are getting cheaper all the time, you can expect to see them in more types of cars.

These are some types of control systems that cars use. These are the kinds that are used based on the car. Most of the time, the active suspension system makes the ride smoother and more stable than the inactive and semi-active systems. The motors in the active suspension system are managed by a number of different control methods.

CHAPTER - 2

LITERATURE SURVERY

Gao, F.; Wang, K. The first part of this work looks at the transfer properties and how well the cab suspension blocks vibrations. The multi-body dynamics software ADAMS was used to make vibration models of the cab chassis and the whole car. It is used both finite elements and multi-body dynamics to look at the cab suspension's transfer characteristics, reaction, and separation feature based on the whole car. To make the cab suspension less likely to vibrate, genetic algorithm method was used to suggest changes and make the design better. The results of the study show that coil springs are only somewhat useful. The improvement plans called for getting rid of the coil spring and replacing it with an air spring and a crosswise damper. The plans show that the original cab's suspension was changed. It was a piecewise function method that was used to fit the air spring's properties. This way can directly show how stiff an air spring is in its working area, which makes it useful for designing and improving for different stages of use. At the same time, the cab suspension's damping characteristic curve was made. Because of the improvement of the changed suspension, the sound separation got a lot better. There was a lot less lateral and vertical shaking of the seat moving. The outcome shows that the improvement and change worked well and were done correctly.

Yu, J.-H.; Lee, et al., say that users of farm machines are subject to low frequency vibrations at work. A passive seat stabilization system on a spring-damper unit has been used for a long time to make driving more comfortable. However, the inactive device only blocks vibrations at a certain frequency while boosting vibrations at other frequencies. In real life, it can't really lower the whole frequency range of whole-body shaking, just the 1–7 Hz range. In order to fix this issue, a two-DOF (degree of freedom) active seat suspension system and its driver were created. They were able to reduce vibrations better than the inactive system across the full dangerous frequency range of whole-body vibration.

According to Logan Mullinix and Madhu V. Shurpali, the comfortable ride is the person sitting in it depends on how well the suspension blocks vibrations. They have tested how well the suspension seat blocks vibrations so far by moving it around on a Six-Axis shaker table with different displacement curves. In this study, it is described how a Multi-Body Dynamics (MBD) model can be used to test how comfortable a suspension seat is to ride in. The model was checked using data collected while a prototype spring seat was being tested. When the expected sound transmissibility from the model was compared to test results, they were found to be about 80% the same. By making this model, a lot less testing will be needed, which can cut down on the time it takes to make a product even more. It's also possible to test the seat's comfort early on in the planning process since the model can be made from 3D solid geometries. This means that the design team can change the design of the suspension seat early on in the process, instead of having to make changes that take more time and resources later on.

Arunachalam, K.; Jawahar et al., the design of automotive suspension has been a balance between three factors that are at odds with each other: grip on the road, load carrying, and passenger comfort. In the last 30 years, more and more complex electrical control parts have been added to car suspensions, which have changed the limits of what can be compromised. The first part of this study talks about the different types of support systems. In the second part, the road problems are talked about. Next, the need for and background of the warning system are given. It also listed the gear the system would need and two different ways the peek sensor could be set up. It is also shown how to make the road surface from the sample camera. Based on what has been written, it can be said that active suspension with preview control will work well on Indian roads.

Cutini, S. and Cinquemani, S. Uneven roads and dirt often cause serious whole-body shaking in people who drive construction trucks like wheel loaders, excavators, and others. Most work trucks don't have cabin stability unless they have tires and seats. In particular, these last ones are very important because they control the vehicle's natural rhythms and sound types. So, over the years, tires have been given extra care and different technologies have been used. This paper looks at several

different ways to find out how comfortable construction truck drivers are. In particular, tests done outside as required by the standards to measure the shocks that workers feel throughout their bodies are compared to tests done inside using a four-posttest rig that were made on the spot. There are four sets of tires that are all the same size but are made of different materials. Tires were chosen to look at possible changes, pros and cons of methods that were used.

Wang, X.; Zhao, Y. Recently, people have become interested in studying how well industrial car seating systems control low-frequency vibrations, since they are a big part of keeping people safe and reducing vibrations. This piece talks about the latest changes in active seat springs for cars. It goes into great depth about the features of active seat suspension motors and the control methods that go with them. Furthermore, the ability of active seat suspension systems to control and lower vibrations is also looked at. There is also talk about how machine learning, specifically artificial neural network (ANN) control methods, could be used to help make active seat support systems that reduce vibrations.

Abd El-Nasser S. Ahmed; Ahmed S. Ali. This paper discusses the development and analysis a PID controller. It emphasizes the significance of suspension systems in enhancing ride comfort, road handling, and vehicle stability. The study compares passive and active suspension systems, highlighting the limitations of passive systems in providing a balance between road handling and comfort due to fixed spring and damping coefficients. Active suspension systems are designed to directly control suspension force actuators, offering improved performance by adjusting parameters based on operating conditions. The paper also has mathematical models for the active suspension system, including the addition of hydraulic actuators and control systems. The study concludes by highlighting the prospective comfort and road handling properties using the PID controller and suggests future work focusing on alternative control methods and model validation.

Jeen Lin; Ruey-Jing Lian. In the study, researchers proposed an enhanced fuzzy sliding mode controller (EFSMC) for an active suspension system and systematically compared its performance with traditional fuzzy controllers and the

fuzzy sliding mode controller (FSMC). The objective of research is to enhance the control performance of suspension by addressing the dynamic effects associated with vehicle body acceleration and tire bouncing during tire rotation that impact ride comfort and road-holding capability. The researchers designed a friendly graphical user interface (GUI) for the intelligent controllers to facilitate the implementation in the suspension system control process. Experimental results demonstrated that the EFSMC outperformed the traditional controllers (TFC and FSMC) in terms of suppressing the acceleration of the vehicle body and reducing the tire deflection, thus improving the ride quality and road-holding ability of the car. Additionally, the EFSMC exhibited smoother control voltage, better performance, and enhanced the life of the system structure as compared to the traditional controllers. The study notably contributed to advancing the understanding of intelligent control strategies for active suspension systems and demonstrated the superior performance of the EFSMC.

Deshpande; B. Mohan. The research paper focuses on the development and validation of a road input observer-based SMC for active systems. This approach focuses on figuring out how much bumpiness comes from the springs and shocks being unpredictable, how the weight in the car changes load variations, and how bumpy the road - all without needing to directly track the weight of the wheels and parts connected to unsprung mass. This describes the difficulty of making a car ride smoother without sacrificing its ability to handle corners distinctly (good road holding). All this needs to be achieved while keeping the suspension system within its design constraints (rattle space limitations). The paper demonstrates the effectiveness of the proposed method through simulations for different road profiles and load variations, as well as validation on an experimental setup. The active suspension system with the proposed sliding mode control scheme and disturbance observer significantly reduces the acceleration of the sprung mass, thereby improving ride comfort. This is achieved without the need to measure the states of the unsprung mass and without requiring prior knowledge of uncertainty bounds. The scheme is shown to work satisfactorily under various loading conditions and road profiles, with a single controller. The efficacy of the scheme is verified through

both simulations and experimental validation, showing marked improvement in ride comfort and stability compared to passive suspension systems.

T. Yuvapriya; P. Lakshmi. The research paper focuses on the design, analysis, and experimental validation of a Fractional Order Terminal Sliding Mode Controller (FOTSMC) on an Active Suspension System (ASS). The study aims to reduce vibrations and increase ride comfort for vehicle passengers. The proposed FOTSMC is compared with other controllers, including terminal sliding mode controller and sliding mode controller, and tested with various road inputs. The study examines the performance of the controllers, analyzes ride comfort according to ISO 2631–1 standard, and tests the stability of the system. The results indicate that the FOTSMC outperforms other controllers in terms of reducing vibration and enhancing ride comfort. The experimental results demonstrate that the proposed FOTSMC significantly reduces body acceleration (BA) and control forces compared to other controllers across different road profiles. The FOTSMC provides better transient and steady-state behavior, reduces root mean square (RMS) values of BA, and exhibits better performance in terms of Frequency Weighted RMS (FWRMS) and Vibration Dose Values (VDV) of BA. Additionally, the stability of the designed controllers is proven with respect to Lyapunov's theory, and the phase plane analysis shows that system trajectories converge to the origin, indicating stability.

T. Yuvapriya. The research paper focuses on enhancing the ride comfort of heavy-duty vehicles (HDV) by evaluating the effectiveness of control techniques such as proportional integral and derivative (PID) controller, sliding mode controller (SMC), and fractional order sliding mode controller (FOSMC). The study emphasizes the significance of the FOSMC in eliminating steady-state error and chattering effects while enhancing the ride quality and stability of HDVs, as compared to SMC and PID controllers.

The mathematical modeling of a HDV with two degrees of freedom is developed and simulated in MATLAB/Simulink environment. The performance of the designed controllers is evaluated in terms of time domain, frequency domain, ride comfort analysis as per ISO 2631, and stability analysis. The FOSMC demonstrated superior

results in reducing suspension deflection and body acceleration of HDV, thereby enhancing ride quality and providing effective vibration suppression. The study also compares the performance of FOSMC with existing PID controllers and validates the stability of the vehicle under different road profiles, such as step, random, and sinusoidal inputs. The results indicate that FOSMC significantly outperforms PID and SMC in reducing vibration and improving ride comfort for passengers. Additionally, the FOSMC is proven to be effective in meeting both steady-state and transient response criteria.

T. Yuwapriya; S. Rajendiran. This research paper explores the use of Fractional Order Sliding Mode Controller (FOSMC) and Sliding Mode Controller (SMC) to suppress vibration in a full vehicle model (FCM). The study aims to reduce the impact of vibrations caused by road irregularities on the human body, paying particular attention to the root mean square (RMS) values of vehicle body acceleration (BA), yaw acceleration (PA) and rolling acceleration (RA), and considering the human body perception range Power spectral density (PSD) within. Research results show that FOSMC performs well in suppressing vibrations when faced with different road disturbances, compared to SMC and passive suspension systems (PSS). Through comparative analysis, the paper confirms the effectiveness of FOSMC in improving passenger comfort and emphasizes the importance of vibration suppression for complete car models.

Dr. Rajnish Katarne; Dr. Satyendra Sharma. The research paper reviews the active hybrid suspension system and aims to highlight the various damping systems available, focusing on parameters like performance, feasibility, capacity, and safety. The paper emphasizes the need for an active hybrid suspension system with controlled damping actions that utilize unused energy dissipated during damping actions to provide better ride comfort and vehicle handling abilities.

The review covers various proposed concepts and control mechanisms for active suspension systems, including the use of passive dissipate heat, skyhook control, electromagnetic actuation mechanisms, and magnetic shock absorbers for energy regeneration. It also discusses the performance characteristics of

magnetorheological (MR) dampers and the use of fuzzy PID controllers for improved damper performance. Furthermore, the paper explores the development of regenerative suspension systems, the application of hybrid artificial intelligence techniques in designing semi-active suspension systems, and the use of linear motor in adjustable shock absorbers to form hybrid active semi-active suspension systems (HASAS). It also delves into the modeling and force tracking control of non-linear hydraulic actuator systems in active suspension systems. The research paper concludes with an optimization analysis of damper controlling systems based on four parameters, suggesting that electromagnetic damping systems may be a suitable choice for further evaluation in the active suspension system.

T. Yuvapriya; S. Rajendiran. The paper explores the importance of suspension systems in vehicles and their evolution from the horse-drawn carriage era to modern automobiles. It outlines the key components of a suspension system, including tires, tire air, springs, shock absorbers, and linkages, which allow relative motion between the vehicle and its wheels while supporting road handling and ride quality. The essence of suspension is to keep the road wheel in contact with the road surface, thus affecting ride comfort and stability. The paper delves into the influence of vehicle parameters on car simulation, addressing the trade-off between comfort and safety for passive suspension systems and how semi-active/active suspension systems aim to resolve or reduce this trade-off. Furthermore, it discusses the role of shock absorbers in controlling the impact and recoil movement of a vehicle's springs and suspension, thus ensuring the vehicle's stability and safety on the road.

CHAPTER - 3

AIM AND SCOPE

3.1 AIM OF THE PROJECT

The aim of the project is to design a new and advanced controller algorithm that can actively adjust the suspension damping forces in response to changing road conditions and vehicle dynamics. To evaluate and compare different control strategies, such as PID, MPC, and Adaptive Control, to determine the most effective approach for achieving improved ride comfort, stability, and handling characteristics.

3.2 SCOPE OF THE PROJECT

A vehicle suspension system is a system of components that connects the vehicle body to the wheels. It is responsible for absorbing the bumps and vibrations caused by uneven road surfaces, and for keeping the tires in contact with the road. A well-designed suspension system can improve ride comfort, handling, and safety. Suspension systems can be classified into two main types: passive and active. Passive suspension systems use springs and dampers to absorb bumps and vibrations. Active suspension systems use actuators to actively control the suspension system's response to road conditions. Passive suspension systems are the most common type of suspension system used in vehicles today. They are relatively simple and inexpensive to manufacture, and they are reliable. However, passive suspension systems can only do so much to absorb bumps and vibrations, and they can sometimes lead to a rough ride. Active suspension systems are more expensive and complex than passive suspension systems, but they can offer a number of advantages. Active suspension systems can provide a smoother ride, improve handling, and reduce body roll. They can also be used to improve fuel economy by keeping the vehicle at a constant height.

3.2.1 Control Algorithms for Suspension Systems

The control algorithm for a suspension system is responsible for determining the appropriate force to apply to each actuator. The control algorithm must consider a number of factors, including the vehicle's speed, the road conditions, and the desired ride quality. There are a number of different control algorithms that can be used for suspension systems. Some of the most common control algorithms include Proportional-integral-derivative (PID) control, Linear quadratic regulator (LQR) control, Model predictive control (MPC), Sliding mode controller (SMC), fuzzy logic controller and many more. The choice of control algorithm for a suspension system depends on a number of factors, including the desired performance, the cost, and the complexity of the implementation.

3.2.2 Scope for Future Research

- i. Developing new control algorithms that can provide even better performance, especially in terms of ride comfort and handling.
- ii. Developing control algorithms that are more robust to noise and disturbances.
- iii. Developing control algorithms that are more efficient and can be implemented on low-cost hardware.
- iv. Developing new suspension system designs that are more compatible with active suspension control.

CHAPTER - 4

MATERIALS AND EXPERIMENTAL METHODS

4.1 METHODOLOGY

The proposed method is to design a controller technique for the active suspension system. The active suspension system consists of a component called an actuator. This actuator adjusts the suspension system such that the vertical movements and the Whole-body vibrations are decreased significantly. Different control algorithms are proposed by the researchers for varying purposes. Some of these algorithms are PID, LQR, SMC, adaptive controller, hybrid controller etc. These types of controllers are designed using the MATLAB/Simulink software. MATLAB ("MATrix LABoratory") is a high-level, interactive programming and numerical computing environment that is widely used in various fields, including engineering, mathematics, science, and finance. Developed by MathWorks, MATLAB is known for its extensive functionality and user-friendly interface. Simulink was used in conjunction with MATLAB to find the results for random road input.

The methodology for designing a controller for an active suspension system.

- Model the suspension system.
- Define the control objectives.
- Design the controller.
- Implement the controller.
- Tune the controller.

7 DOF model quarter car model was used in the project. This system considers the mass of vehicle such as sprung mass and unsprung mass along with the mass of the driver. This system evaluates the change in the displacements and acceleration for different parts of the driver. The mathematical models for passive and active suspension systems are derived to find out the differences between these systems.

The Simulink model for passive suspension system was created using Simulink software.

Table 4.1 The linear quarter car seat-suspension-driver model parameters for 7DOF quarter car model

m_h	5.32	c_h	415	k_h	325000
m_{ut}	29.04	c_{ut}	4860	k_{ut}	179000
m_{lt}	8.89	c_{lt}	4650	k_{lt}	164000
m_{tp}	13.05	c_{tp}	2050	k_{tp}	85000
m_{sc}	1	c_{sc}	230	k_{sc}	18550
m_f	16.68	c_f	790	k_f	32500
m_s	285	c_s	720	k_s	25500
m_{us}	45	c_{us}	195000	k_{us}	19500

4.1.1 PID CONTROLLER

Proportional integral derivative, or PID, is a type of device used in industrial settings to control temperature, pressure, flow, and speed among other process factors. This controller uses a loop of controlled feedback device to regulate each process variable. With this kind of control, a system may be directed toward a goal point or kept level. It is utilized virtually universally for controlling temperature and in many chemical reactions, automation, and scientific operations. Closed-loop feedback is employed in this controller to keep the actual output from a technique, such as near the goal. This page discusses the PID controller design and the many control modes that are employed, including P, I, and D. PID control algorithm is used for active suspension system which is placed between the sprung mass and unsprung mass.

$$u(t) = k_p e(t) + k_i \int e(t). dt + k_d [d/dt e(t)]$$

$$e(t) = r(t) - y(t)$$

PID Control: $K_P \in [2000, 15000]$, $K_I \in [10, 150]$, $K_D \in [15000, 50000]$

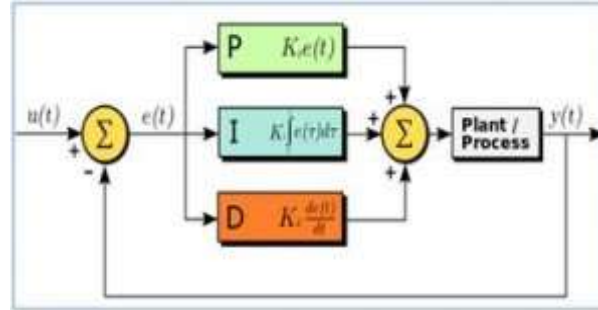


figure 4.1. Block diagram of PID control

4.2 MATHEMATICAL MODELS OF SUSPENSION SYSTEM

4.2.1 PASSIVE SUSPENSION SYSTEM

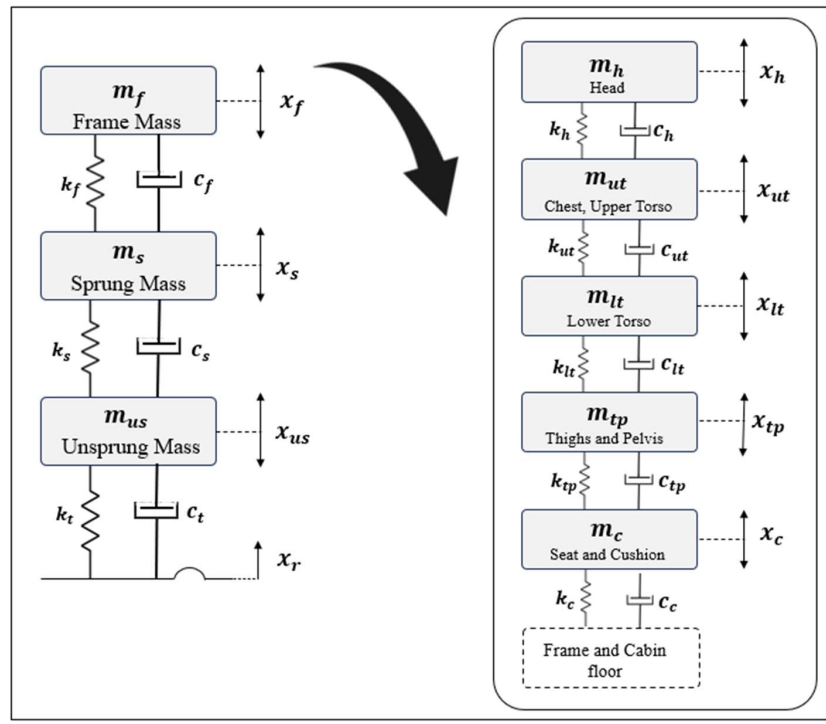


Figure. 4.2 7 DOF of Passive suspension system

1. Head mass equation –

$$m_h \ddot{x}_h + c_h (\dot{x}_h - \dot{x}_{ut}) + k_h (x_h - x_{ut}) = 0$$

$$m_h \ddot{x}_h = -c_h (\dot{x}_h - \dot{x}_{ut}) - k_h (x_h - x_{ut})$$

2. Upper torso mass Equation –

$$m_{ut} \ddot{x}_{ut} + c_{ut} (\dot{x}_{ut} - \dot{x}_{lt}) + k_{ut} (x_{ut} - x_{lt}) - c_h (\dot{x}_h - \dot{x}_{ut}) - k_h (x_h - x_{ut}) = 0$$

$$m_{ut} \ddot{x}_{ut} = c_h (\dot{x}_h - \dot{x}_{ut}) + k_h (x_h - x_{ut}) - c_{ut} (\dot{x}_{ut} - \dot{x}_{lt}) - k_{ut} (x_{ut} - x_{lt})$$

3. Lower torso mass equation –

$$m_{lt} \ddot{x}_{lt} + c_{lt} (\dot{x}_{lt} - \dot{x}_t) + k_{lt} (x_{lt} - x_t) - c_{ut} (\dot{x}_{ut} - \dot{x}_{lt}) - k_{ut} (x_{ut} - x_{lt}) = 0$$

$$m_{lt} \ddot{x}_{lt} = c_{ut} (\dot{x}_{ut} - \dot{x}_{lt}) + k_{ut} (x_{ut} - x_{lt}) - c_{lt} (\dot{x}_{lt} - \dot{x}_t) - k_{lt} (x_{lt} - x_t)$$

4. Thighs and pelvis mass equation –

$$m_t \ddot{x}_t + c_{tp} (\dot{x}_t - \dot{x}_c) + k_{tp} (x_t - x_c) - c_{lt} (\dot{x}_{lt} - \dot{x}_t) - k_{lt} (x_{lt} - x_t) = 0$$

$$m_t \ddot{x}_t = c_{lt} (\dot{x}_{lt} - \dot{x}_t) + k_{lt} (x_{lt} - x_t) - c_{tp} (\dot{x}_t - \dot{x}_c) - k_{tp} (x_t - x_c)$$

5. Seat cushion mass equation –

$$m_c \ddot{x}_c + c_c (\dot{x}_c - \dot{x}_f) + k_c (x_c - x_f) - c_{tp} (\dot{x}_t - \dot{x}_c) - k_{tp} (x_t - x_c) = 0$$

$$m_c \ddot{x}_c = c_{tp} (\dot{x}_t - \dot{x}_c) + k_{tp} (x_t - x_c) - c_c (\dot{x}_c - \dot{x}_f) - k_c (x_c - x_f)$$

6. Frame mass equation –

$$m_f \ddot{x}_f + c_f (\dot{x}_f - \dot{x}_s) + k_f (x_f - x_s) - c_c (\dot{x}_c - \dot{x}_f) - k_c (x_c - x_f) = 0$$

$$m_f \ddot{x}_f = c_c (\dot{x}_c - \dot{x}_f) + k_c (x_c - x_f) - c_f (\dot{x}_f - \dot{x}_s) - k_f (x_f - x_s)$$

7. Sprung mass equation –

$$m_s \ddot{x}_s + c_s (\dot{x}_s - \dot{x}_{us}) + k_s (x_s - x_{us}) - c_f (\dot{x}_f - \dot{x}_s) - k_f (x_f - x_s) = 0$$

$$m_s \ddot{x}_s = c_f (\dot{x}_f - \dot{x}_s) + k_f (x_f - x_s) - c_s (\dot{x}_s - \dot{x}_{us}) - k_s (x_s - x_{us})$$

8. Unsprung mass equation –

$$m_{us} \ddot{x}_{us} + c_t (\dot{x}_{us} - \dot{x}_r) + k_t (x_{us} - x_r) - c_s (\dot{x}_s - \dot{x}_{us}) - k_s (x_s - x_{us}) = 0$$

$$m_{us} \ddot{x}_{us} = c_s (\dot{x}_s - \dot{x}_{us}) + k_s (x_s - x_{us}) - c_t (\dot{x}_{us} - \dot{x}_r) - k_t (x_{us} - x_r)$$

4.2.2 ACTIVE SUSPENSION SYSTEM

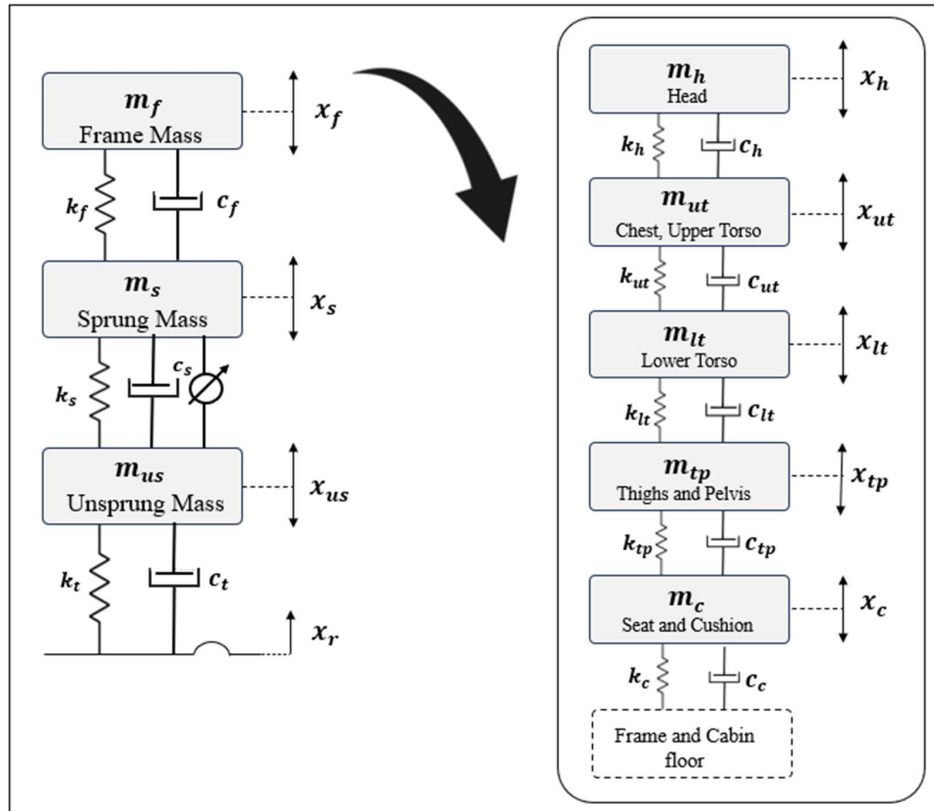


Figure. 4.3 7 DOF of Passive suspension system

1. Head mass equation –

$$m_h \ddot{x}_h + c_h (\dot{x}_h - \dot{x}_{ut}) + k_h (x_h - x_{ut}) = 0$$

$$m_h \ddot{x}_h = -c_h (\dot{x}_h - \dot{x}_{ut}) - k_h (x_h - x_{ut})$$

2. Upper torso mass Equation –

$$m_{ut} \ddot{x}_{ut} + c_{ut} (\dot{x}_{ut} - \dot{x}_{lt}) + k_{ut} (x_{ut} - x_{lt}) - c_h (\dot{x}_h - \dot{x}_{ut}) - k_h (x_h - x_{ut}) = 0$$

$$m_{ut} \ddot{x}_{ut} = c_h (\dot{x}_h - \dot{x}_{ut}) + k_h (x_h - x_{ut}) - c_{ut} (\dot{x}_{ut} - \dot{x}_{lt}) - k_{ut} (x_{ut} - x_{lt})$$

3. Lower torso mass equation –

$$m_{lt} \ddot{x}_{lt} + c_{lt} (\dot{x}_{lt} - \dot{x}_t) + k_{lt} (x_{lt} - x_t) - c_{ut} (\dot{x}_{ut} - \dot{x}_{lt}) - k_{ut} (x_{ut} - x_{lt}) = 0$$

$$m_{lt} \ddot{x}_{lt} = c_{ut} (\dot{x}_{ut} - \dot{x}_{lt}) + k_{ut} (x_{ut} - x_{lt}) - c_{lt} (\dot{x}_{lt} - \dot{x}_t) - k_{lt} (x_{lt} - x_t)$$

4. Thighs and pelvis mass equation –

$$m_t \ddot{x}_t + c_{tp} (\dot{x}_t - \dot{x}_c) + k_{tp} (x_t - x_c) - c_{lt} (\dot{x}_{lt} - \dot{x}_t) - k_{lt} (x_{lt} - x_t) = 0$$

$$m_t \ddot{x}_t = c_{lt} (\dot{x}_{lt} - \dot{x}_t) + k_{lt} (x_{lt} - x_t) - c_{tp} (\dot{x}_t - \dot{x}_c) - k_{tp} (x_t - x_c)$$

5. Seat cushion mass equation –

$$m_c \ddot{x}_c + c_c (\dot{x}_c - \dot{x}_f) + k_c (x_c - x_f) - c_{tp} (\dot{x}_t - \dot{x}_c) - k_{tp} (x_t - x_c) = 0$$

$$m_c \ddot{x}_c = c_{tp} (\dot{x}_t - \dot{x}_c) + k_{tp} (x_t - x_c) - c_c (\dot{x}_c - \dot{x}_f) - k_c (x_c - x_f)$$

6. Frame mass equation –

$$m_f \ddot{x}_f + c_f (\dot{x}_f - \dot{x}_s) + k_f (x_f - x_s) - c_c (\dot{x}_c - \dot{x}_f) - k_c (x_c - x_f) = 0$$

$$m_f \ddot{x}_f = c_c (\dot{x}_c - \dot{x}_f) + k_c (x_c - x_f) - c_f (\dot{x}_f - \dot{x}_s) - k_f (x_f - x_s)$$

7. Sprung mass equation –

$$m_s \ddot{x}_s + c_s (\dot{x}_s - \dot{x}_{us}) + k_s (x_s - x_{us}) - c_f (\dot{x}_f - \dot{x}_s) - k_f (x_f - x_s) - f = 0$$

$$m_s \ddot{x}_s = c_f (\dot{x}_f - \dot{x}_s) + k_f (x_f - x_s) - c_s (\dot{x}_s - \dot{x}_{us}) - k_s (x_s - x_{us}) + f$$

8. Unsprung mass equation –

$$m_{us} \ddot{x}_{us} + c_t (\dot{x}_{us} - \dot{x}_r) + k_t (x_{us} - x_r) - c_s (\dot{x}_s - \dot{x}_{us}) - k_f (x_s - x_{us}) + f = 0$$

$$m_{us} \ddot{x}_{us} = c_s (\dot{x}_s - \dot{x}_{us}) + k_s (x_s - x_{us}) - c_t (\dot{x}_{us} - \dot{x}_r) - k_t (x_{us} - x_r) - f$$

Table 4.2 Nomenclature

Nomenclature	
m_s	Mass of sprung mass
m_{us}	Mass of unsprung mass
m_h	Head mass
m_{ut}	Upper torso mass
m_{lt}	Lower torso mass
m_{tp}	Thighs and Pelvic mass
m_{sc}	Seat and cushion mass
m_f	Frame mass
z_s	Vertical displacement of sprung mass
z_{us}	Vertical displacement of unsprung mass
z_r	Road input
k_s	Spring stiffness
c_s	Damping coefficient of spring
k_t	Tire stiffness
c_t	Damping coefficient of tire

4.3 CONTROL TECHNIQUES FOR ACTIVE SUSPENSION

In an active suspension system, the controller plays a pivotal role in managing and optimizing the performance of the system. The controller is essentially the brain of the active suspension system, responsible for processing various inputs such as vehicle speed, acceleration, road conditions, and driver inputs, and generating appropriate commands to adjust the suspension parts. These adjustments aim to enhance ride comfort, vehicle stability, and handling characteristics by actively controlling the damping force, spring stiffness, and ride height of each individual wheel. One of the key functions of the controller is to continuously analyze sensor data to assess the dynamic state of the vehicle and the road surface. This involves monitoring parameters such as wheel displacement, vehicle body acceleration, and chassis pitch and roll rates. By accurately sensing these variables, the controller can anticipate changes in road conditions and vehicle dynamics, allowing it to proactively adjust the suspension settings to mitigate the effects of disturbances such as bumps, potholes, or cornering forces.

The controller utilizes sophisticated algorithms and control strategies to determine the optimal suspension response in real-time. These algorithms consider various factors including driver preferences, vehicle dynamics, and ride comfort requirements. For instance, the controller may employ predictive control techniques to predict upcoming road irregularities and adjust the suspension settings to minimize vehicle motion and improve ride quality.

Another important aspect of the controller's role is to maintain vehicle stability and control during dynamic maneuvers such as cornering, braking, and acceleration. By modulating the damping force and spring stiffness of each wheel independently, the controller can actively counteract body roll, pitch, and dive, thereby improving the vehicle's handling characteristics and reducing the risk of loss of traction or rollover.

In addition to enhancing ride comfort and vehicle dynamics, the controller also plays a crucial role in improving overall vehicle efficiency and energy consumption. By actively managing the suspension system, the controller can optimize the distribution of forces within the vehicle chassis, minimizing energy losses due to

vibrations, oscillations, and unnecessary motion. This not only improves fuel efficiency but also extends the lifespan of suspension components and reduces maintenance costs.

4.3.1 Robust H_∞ Controller

Zamas and Francis introduced the H_∞ controller as a controller approach in 1990. Developed in the frequency domain, the H-Controller is an optimal control theory that addresses stability issues in feedback design. It is more advantageous than conventional controllers and has been employed extensively in a variety of research disciplines and applications because of the numerical optimization methods. It is used to provide the building with excellent stability even when there are sounds and disturbances present.

It may be used to give the plant a high level of stability performance in the current noisy and disruptive environment. However, it necessitates extensive control work and a high degree of mathematical comprehension.

The figure illustrates the configuration of H_∞ controller, in which $P(s)$ is the generalized plant. The external input is represented by ' w ' and the output is represented by ' z '. The main objective of the H_∞ controller is to determine a feedback controller gain that minimizes the output. The purpose of this controller is to mitigate the persistent oscillation in the active-suspension system, hence minimizing the oscillations of the body and enhancing its stability.

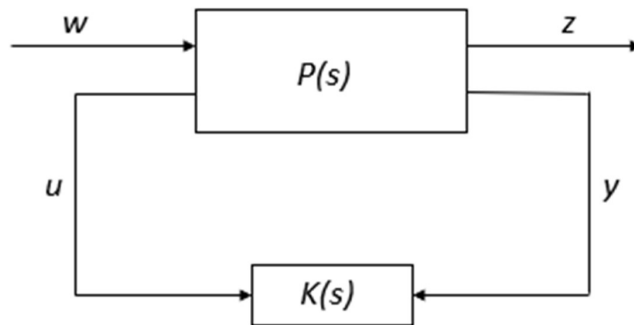


Figure. 4.4 Plant model of controller

To create a very exact dynamic model that includes all system uncertainties, the active-suspension system model considered the passenger dynamic model as well as the sitting suspension system model. The sturdy controller was engineered to fulfill certain requirements, including minimal body acceleration to provide optimal riding comfort even in the face of road disruptions. To maintain seat safety, the seat deflection cannot be more than the suspension's maximum permitted stroke.

4.3.2 Preview Controller

Preview controller is a type of control algorithm used widely in vehicles having an active-suspension system. This controller was introduced in the year 1968 by Bender. Preview controller is further classified into wheelbase and lookahead. The lookahead controller works by collecting the data present in front of the vehicle and this data is fed to the wheels of the active-suspension system. It also utilizes the front axle dynamic characteristics and modifies the parameters of the rear axle to stabilize the vehicle.

In the active-suspension unit, preview control of data was applied, and instead of using road disturbances to determine the force of actuator, the dynamic information of vehicle suspension was used. The quarter vehicle suspension model was proposed in conjunction with a single DOF seat suspension model in experimental testing to evaluate the suggested control approach. The experimental test was performed with varying vehicle speeds over a bumpy and randomly excited road profile. It is demonstrated that a notable 10 dB decrease in acceleration is attained over the 0–18 Hz frequency range. Additionally, a fuzzy logic controller improved the preview information from the wheels, front left suspension, and front axle to handle actuator constraints and friction. The preview controller guarantees great performance in reducing the vertical movements of a vehicle.

4.3.3 Sliding mode controller

Sliding mode controller is also known as variable structure control (SVC). For its robust characteristics against disturbances, this controller is extensively utilized in active-suspension systems. The development of this controller was initiated in the late 20th century by a research group comprising Utkins, Itkis, and Emelyanov. The sliding mode controller is a control concept that involves the switching of feedback control between continuous structures utilizing high frequency switching algorithms. The system moves across a surface known as the sliding surface. The advantage of sliding mode controller over other types of is its robustness against the road disturbances and vibrations of the vehicle. However, SMC has chattering problems which are observed commonly with applications related to design.

Regarding the rapid convergence time, the TSMC outperforms the typical sliding mode controller. In order to reduce chattering, the switching gain of the disturbance observer was decreased. The state observer was utilised to calculate the precise velocity, and to guarantee correct estimation outcomes, a complementary filter was employed to merge the data. The TSMC was meticulously built to address any disturbances that may arise from the reduction of the model, which involves reducing it from a 6 DOF (degrees of freedom) to a 1 DOF active seat model. The active seat suspension's performance was evaluated under random vibration conditions utilizing ISO 2631-1 and the acceleration Power Spectral Density (PSD). An implementation of a non-singular type sliding mode controller was utilised to reduce quantities such as lateral acceleration and roll vibration. The disturbances are estimated using a disturbance observer within the sliding mode controller. The cascade control method utilised SMC (Sliding Mode Control) to accurately measure the stiffness and force, while a proportional controller was employed to adjust the actuator locations.

4.3.4 Hybrid controller

For some research purposes, hybrid controllers were introduced where two or more control techniques are used to produce robust performances which further improve the ride comfort and safety of driver and passengers. Hybrid controller was proposed

to combine the core advantages of the different control strategies to improve the performance of control systems. A hybrid controller, combining PID and fuzzy logic, was created in order to mitigate vertical vibrations in a vehicle. The hybrid fuzzy PID controller has been enhanced by combining PD and integral components to optimize controller performance. The active seat suspension was enhanced by implementing a combination of STSMC and ANFIS, referred to as ASTSMC, in order to improve the ride comfort. This type of controller consists of two signals. One signal is specifically developed to monitor the behavior of the active car suspension, while the other signal is utilized to ensure that the plant remains on the sliding surface. This signal is referred to as a discontinuous control signal. The calculation of the slope of the SMC, which determines the sliding surface, necessitates the use of the ANFIS result. The active suspension is determined based on the ISO 2631-1 standard, and the suggested method effectively decreases the overall vibration impact on the vehicle.

4.3.5 Fuzzy Interference System

These controllers are a form of artificial intelligence that utilize neural networks. An Adaptive Neuro Fuzzy Interference System (ANFIS) is a model that integrates the methods of fuzzy logic theory and neural network technique. The fuzzy logic controllers analyze the data from different sensors to find optimal solutions, while the neural networks learn from the actuators' ways to enhance the accuracy of these solutions. ANFIS is composed of five levels. The initial layer is responsible for receiving inputs referred to as error 'e' and the derivative of the error 'de'. The signals must undergo a fuzzification step. Layer 2 produces the result of multiplying the input signals together. The node in the second stratum is stationary. The third layer includes a stationary node with a normalizing layer. Layer 4 is responsible for carrying out the defuzzification process, which is a layer that can adapt. The last layer consists of a stationary node that produces the output for the ANFIS controller. ANFIS has been utilized in vehicles to enhance the driver's riding comfort. This technology was suggested as a means to consistently regulate the suspension system of the seat. This control technology was employed in three instances: active vehicle main suspension, active control system, and active seat suspension.

4.3.6 Model Predictive Controller

Model Predictive controller is a control method used in active-suspension systems. It is a robust control method in which it utilizes iterative computing and optimizes performance due to uncertainty parameters. This control method is also aided with the information of the road using cameras and sensors which is known as road disturbance. The aim of MPC design is to process a model so that the output is calculated based on the input.

MPC is a type of control in which an open-loop optimal control problem with a finite or infinite horizon is solved to determine the current control action at each sampling time. Using the present state of the plant as the beginning state and applying the first control in the sequence to the plant, this approach yields an optimum control sequence. The entire process is then repeated at the subsequent sampling moment.

4.3.7 Linear Quadratic Regulator (LQR)

A Linear Quadratic Regulator (LQR) is a control algorithm used in engineering and control systems to optimize the performance of a linear system. It's particularly useful in situations where the system dynamics are known and can be modelled linearly. In an LQR, the goal is to minimize a cost function that typically includes two components: a quadratic error term and a control effort term. The quadratic error term penalizes the deviation of the system's output from a desired trajectory, while the control effort term penalizes the magnitude of the control input. The LQR computes the optimal control law by solving a Riccati equation associated with the linear dynamical system. Once the optimal control law is determined, it can be applied to regulate the system towards the desired state while minimizing the cost function.

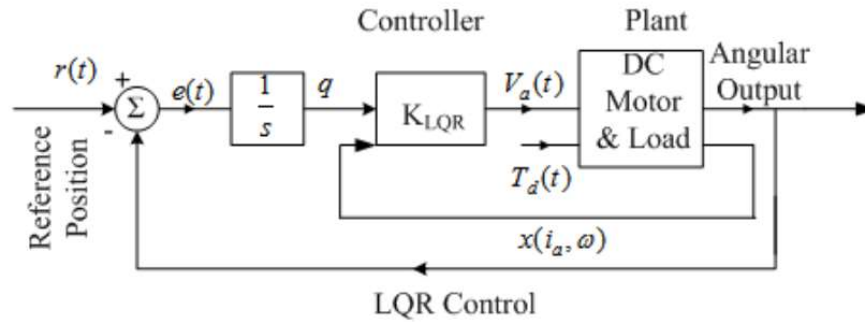


Figure 4.5. Linear Quadratic Regulator (LQR) control system.

LQR is widely used in various engineering applications such as aerospace, robotics, and automotive control systems due to its effectiveness in achieving optimal performance.

4.3.8 Skyhook Damping Controller

A Skyhook damping controller is a type of control system used in the field of structural engineering, particularly in the design of vibration isolation systems for buildings, bridges, and other structures.

The concept of skyhook damping originates from the idea of attaching a hypothetical mass to a structure via an idealized massless spring and damper system. This "skyhook" mass experiences the same vertical velocity as the structure itself. By applying control algorithms based on the relative velocity between the structure and the ground (or sky), the skyhook damping controller can effectively reduce unwanted vibrations.

In practical implementations, sensors are used to measure the relative velocity between the structure and the ground. The control algorithm then adjusts damping forces applied to dampers within the system. By optimally tuning these damping forces, the skyhook damping controller can significantly reduce vibrations transmitted to the structure, improving its overall stability and performance.

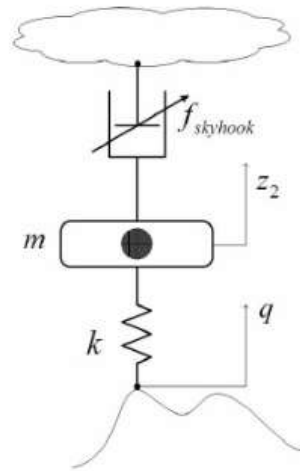


Figure 4.6. *Ideal Skyhook control scheme*

Skyhook damping controllers are commonly employed in seismic isolation systems for buildings, where they help mitigate the effects of earthquakes and other dynamic loads. They are also used in vehicle suspension systems to enhance ride comfort and vehicle stability.

4.3.9 Fractional Order Controller

A Fractional Order Controller (FOC) is a controller utilized in control systems that integrates notions from fractional calculus into its design. Unlike traditional integer-order controllers, which use integer-order differential equations, fractional-order controllers utilise fractional-order differential equations to describe system dynamics.

The use of fractional calculus allows FOCs to capture more complex system behaviours and dynamics that integer-order controllers might overlook. By incorporating fractional-order dynamics, these controllers can provide better performance, stability, and robustness, particularly in systems with non-linearities or time delays.

FOCs have applications across various fields, including engineering, physics, biology, and finance. They are used in systems such as robotics, process control,

biomedical devices, and signal processing. Designing FOCs involves determining the fractional order parameters and tuning them to achieve desired control objectives. While more complex than integer-order controllers, FOCs offer advantages in dealing with intricate system dynamics and can lead to improved control performance in many applications.

4.3.10 Neural Network Controller

A Neural Network Controller (NNC) is a controller utilized in control systems that utilizes artificial neural networks (ANNs) to govern and oversee system behaviour. ANNs are models that are created by emulating the structure and behaviour of biological neural networks seen in the human brain.

In an NNC, the neural network is trained using data from the system it is intended to control. Through the process of training, the neural network learns the relationship between input signals (such as sensor data) and output signals (such as control actions). This enables the NNC to adapt and respond to changing system dynamics in real-time.

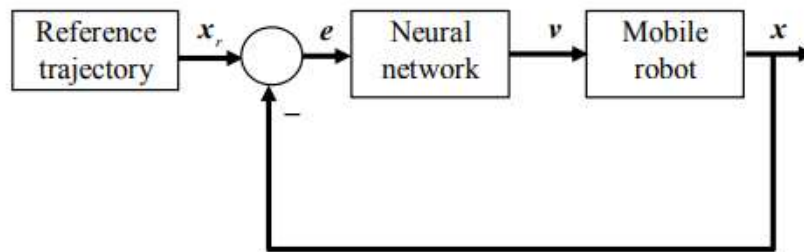


Figure 4.7 *Mobile robot motion control system*

One of the key advantages of NNCs is their ability to handle complex, non-linear, and uncertain systems. They can approximate highly non-linear functions and adapt to changes in system behaviour without requiring explicit mathematical models.

NNCs find applications across various domains, including robotics, industrial automation, process control, autonomous vehicles, and more. They offer flexibility, adaptability, and the potential for high-performance control in diverse and

challenging environments. Designing an NNC involves several steps, including data collection, network architecture design, training, and validation. Careful tuning and training are essential to ensure the NNC performs effectively and reliably in controlling the target system.

4.3.11 Terminal Sliding mode controller

A Terminal Sliding Mode Controller (TSMC) is a type of control system to set the behaviour of dynamic systems, particularly those with uncertain or varying parameters. TSMC is a variation of the conventional sliding mode control (SMC) technique, which is known for its robustness against model uncertainties and disturbances. In a TSMC, the control law is designed to drive the system state onto a sliding manifold within a finite time, known as the reaching phase. Once the system reaches the sliding manifold, a terminal control law is activated to ensure that the system remains on the manifold indefinitely, maintaining stability and achieving desired performance.

TSMC offers several advantages, including robustness to uncertainties, disturbances, and model inaccuracies. Additionally, it provides finite-time convergence properties, meaning the system state reaches the desired state within a finite time, regardless of initial conditions or disturbances. Applications of TSMC span various fields, including aerospace, automotive, robotics, and power systems. It is particularly useful in systems where precise tracking, disturbance rejection, and robust performance are crucial requirements.

Designing a TSMC involves selecting appropriate sliding surfaces, designing reaching and terminal control laws, and tuning controller parameters to achieve desired performance specifications while ensuring stability and robustness.

4.4 DESIGNS OF CONTROLLER

The sliding mode control technique offers an effective approach to control the time varying systems such as disturbances and parameter differences. The sliding mode controller is designed by considering the sliding surface as the difference of suspension deflection between the sprung mass and unsprung mass, the velocity of the car body is taken to calculate the sliding surface. In quarter car model the control forces are given to the actuators to eliminate the vertical deflections caused due to road disturbances. The Lyapunov's function considered to design the sliding mode controller is $V = \frac{1}{2} s^2$, where s is the sliding surface of the controller.

$$V = s\dot{s} < 0 \quad \text{i.e., } \dot{s} = 0$$

For designing the control force for actuator, the state variables y_1 and y_2 are chosen and these are defined by,

The difference of sprung and unsprung mass

$$y_1 = x_s - x_{us}$$

The velocity of the car body is

$$y_2 = \dot{x}_s$$

4.4.1 Sliding Mode Controller (SMC)

SMC is designed to achieve desired ride quality and stability in vehicles. The SMC design technique consists of two parts. The first step is to create a switching function to ensure the sliding motion meets specifications for design. The second step involves selecting a control rule that aligns with the switching function and the system state. The designed SMC is evaluated for random road disturbances. The produced vibrations are controlled by applying control force generated by the actuators in the opposite direction to eliminate road disturbances.

The suspension deflection (y_1) and car body velocity (y_2) are chosen as state variables to design SMC. The Lyapunov function used for Sliding mode controller is $V = 1/2 s^2$. The vibration reaches the least value when the equation (9) is satisfied. To design SMC, sliding surface (s) is considered as:

$$s = y_2 + \lambda y_1$$

By differentiating the above equation, we get,

$$\dot{s} = \dot{y}_2 + \lambda \dot{y}_1$$

$$0 = \dot{y}_2 + \lambda \dot{y}_1$$

The control force (f_a) is designed by using the state variables (Equations 10 and 11) to substitute in Equation 14 and simplified.

$$f_a = k_1(x_s - x_{us}) + c_1(\dot{x}_s - \dot{x}_{us}) - \lambda m_s(\dot{x}_s - \dot{x}_{us}) - k \text{sign}(s)$$

k_1 and c_1 are spring stiffness and damping coefficient of the suspension system. $\text{sign}(s)$ is the switching function of sliding surface and k is a positive constant, which brings the system to sliding surface and converges to zero.

4.4.2 Terminal Sliding Mode Controller (TSMC)

The chattering effect is observed in conventional Sliding mode controller which affects the dynamic behavior of the suspension system. Terminal Sliding mode controller is designed to reduce the chattering effect by reducing the overall oscillations and system trajectories that arrive at the final sliding surface in a finite time. The terminal sliding mode controller ensures a finite time closed loop convergence to equilibrium. Terminal sliders offer resilience against parametric uncertainty without the need for high frequency switching control like traditional sliders. The limited time closed loop convergence to equilibrium is enforced by the terminal sliding mode controller. The author shows that, unlike traditional sliders,

terminal sliders offer robustness to parametric uncertainty without requiring the use of high frequency switching. This section covered the development of the idea of terminally sliding surfaces from basic principles as well as the control synthesis of non-linear systems.

The system moves with the sliding mode at $s = 0$ as per equation 9. The sliding surface for terminal SMC is defined as

$$s = x_2^{\frac{p}{q}} + \lambda x_1$$

On differentiating, we get,

$$\dot{s} = \dot{x}_2 + \lambda \frac{q}{p} x_1^{2-p/q}$$

$$0 = \dot{x}_2 + \lambda \frac{q}{p} x_1^{2-p/q}$$

Actuator force is calculated by substituting the state variables in the above equation.

On simplifying the equation, we get the actuator force as:

$$f_a = k_1(y_1 - y_2) + c_1(\dot{y}_1 - \dot{y}_2) - \lambda \frac{q}{p} m_s(\dot{y}_1 - \dot{y}_2)^{2-p/q} - k \text{sign}(s)$$

4.4.3 Fractional Order Sliding Mode Controller (FOSMC)

Fractional calculus is a frequently employed method for converting integer order calculus into non-integer order calculus, when the order might exist in a non-integer form. Although there are several definitions for fractional calculus, Caputo fractional calculus is the one that is most frequently applied. The objective of the FOSMC is to lower the maximum peak overshoot and steady state error, which enhances the system's transient responsiveness. SMC is the source of state variables used in the design of FOSMC. The sliding surface for FOSMC is chosen as:

$$s = D^{\alpha-1}x_2 + \lambda x_1$$

where D represents the Differentiation and α is the fractional order of the Differentiation (D),

On differentiating the s, we get,

$$\dot{s} = D^{\alpha-1}\dot{x}_2 + \lambda\dot{x}_1$$

The sliding surface is valued as '0' to achieve the least oscillation during the operation.

$$0 = D^{\alpha-1}\dot{x}_2 + \lambda\dot{x}_1$$

The actuator force f_a , for the system is defined as,

$$f_a = k_1(y_1 - y_2) + c_1(\dot{y}_1 - \dot{y}_2) - D^{\alpha-1}\lambda m_s(\dot{y}_1 - \dot{y}_2) - ksign(s)$$

4.4.4 Fractional Order Terminal Sliding Mode Controller (FOTSMC)

The development of FOTSMC was inspired by the compelling advantages of using TSMC with fractional order SMC. In order to achieve accurate and quick tracking, this method incorporates fractional derivative elements into TSMC equations, particularly for FCM that have Active Suspension system installed. FOTSMC exhibits the capacity to quickly reduce tracking errors to zero, guaranteeing stability in a little amount of time.

Additionally, it successfully reduces chattering effects, which improves passenger comfort. FOTSMC is a recommended option for control strategy design because it ensures resilience and stability in FCM systems by adding fractional order derivatives and terminal power values.

$$s = (D^{\alpha-1}x_2)^{\frac{p}{q}} + \lambda x_1$$

s is substituted with zero to attain the least vibrations and is differentiated to produce:

$$0 = \dot{x}_2 + \lambda \frac{q}{p} (D^{1-\alpha}x_2)^{\frac{p}{q}} x_1^{2-p/q}$$

By substituting the state variables (Equations (10) and (11)), the actuator force f_a is derived as follows:

$$f_a = k_1(y_1 - y_2) + c_1(\dot{y}_1 - \dot{y}_2) - \lambda \frac{q}{p} m_s (D^{1-\alpha})^{p/q} \cdot (\dot{y}_1 - \dot{y}_2)^{2-p/q} - k \text{sign}(s)$$

CHAPTER - 5

RESULTS AND DISCUSSIONS

The passive suspension was created in the MATLAB/Simulink software. A 7 degree of freedom quarter car model was created which considered the masses of head, upper torso, lower torso, pelvic and thighs, leg mass, sprung and unsprung mass. For road input, random road profile was generated in Simulink. Class c road profile was generated to find the results for the given input parameters.

Random road input was generated for continuous 20 seconds.

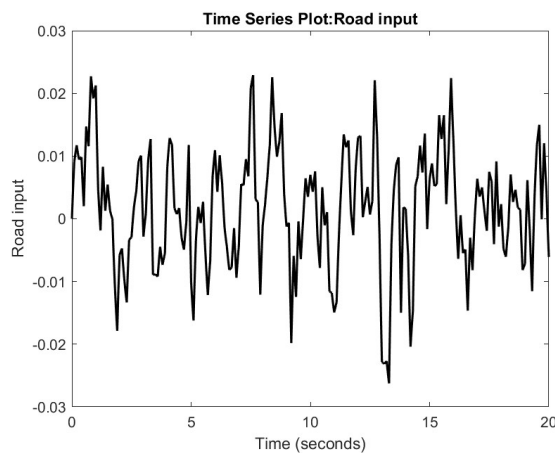


Figure. 5.1 Class C Road disturbances

It was observed that the employed passive suspension system had significantly reduced the acceleration and also the displacements. As shown in the graphs, there is sudden drop in acceleration between the unsprung mass and sprung mass. The acceleration was minimal throughout the time compared to the unsprung mass acceleration. The graphs for 7 degrees of freedom are shown below.

The acceleration vs domain time for 20 seconds is shown below for different degrees of freedom. The active suspension system shows excellent results compared to passive suspension system.

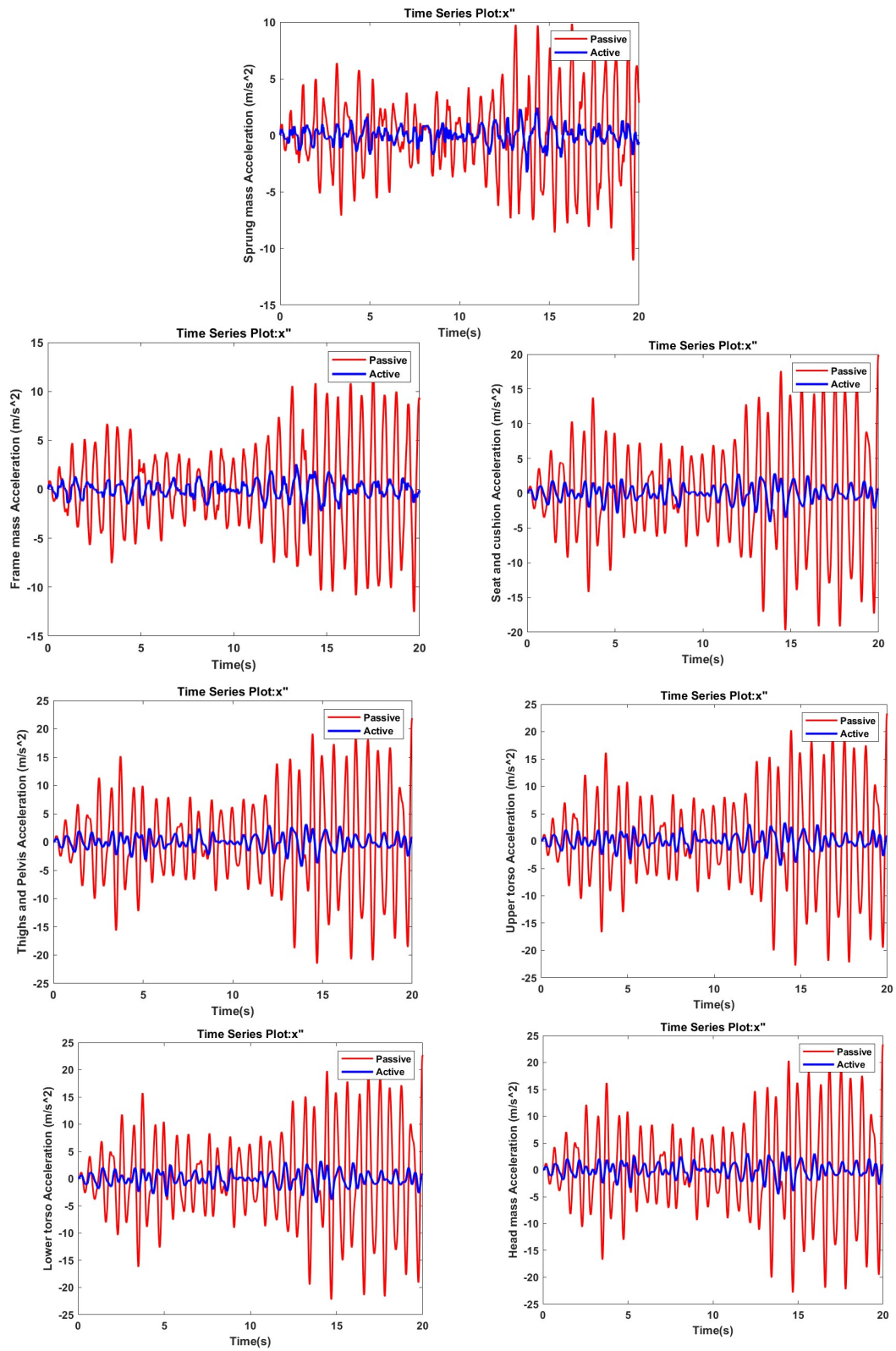


Figure 5.2 Active vs Passive Acceleration

5.1 Sliding mode controller

Sliding mode controller is also known as variable structure control (SVC). For its robust characteristics against disturbances, this controller is widely used in active suspension systems. This controller was proposed during the late 20th century by a research group consisting of Utkins, Itkis and Emelyanov. The concept of sliding mode controller is based on switching the feedback control between continuous structures using high frequency switching algorithms. The system slides along a surface which is called sliding surface, the controller impulses the system to attain the sliding surface within a spiculated time and changes its phases to on and off or forward and reverse. The advantage of sliding mode controller over other types of is its robustness against the road disturbances and vibrations of the vehicle. However, SMC has chattering problems which are observed commonly with applications related to design.

A modified Terminal Side Mode Controller (TSMC) was utilized to build a sliding mode controller in the active seat suspension. In terms of the quick convergence time, the TSMC is superior than the standard sliding mode controller. The switching gain of the disturbance observer was lowered in order to lessen chattering. The absolute velocity was estimated using the state observer, and to guarantee correct estimation findings, a complementary filter was utilized to fuse the data. The TSMC was designed with exceptional concern for disruptions resulting from the simplification of the model from a 6 DOF to 1 DOF active seat model. Under random vibration, the performance of the active seat suspension was assessed using ISO 2631-1 and the acceleration PSD. According to the testing findings, the suggested controller reduced RMS acceleration by 54.6% when compared to the vibration reduction of a properly adjusted passive seat suspension.

A non-singular type sliding mode controller was implemented to decrease the quantities like lateral acceleration and roll vibration, and the disturbances are calculated using disturbance observer in sliding mode controller. In cascade control type, SMC was employed for tracking the stiffness and force and a proportional controller was used to change the actuator positions.

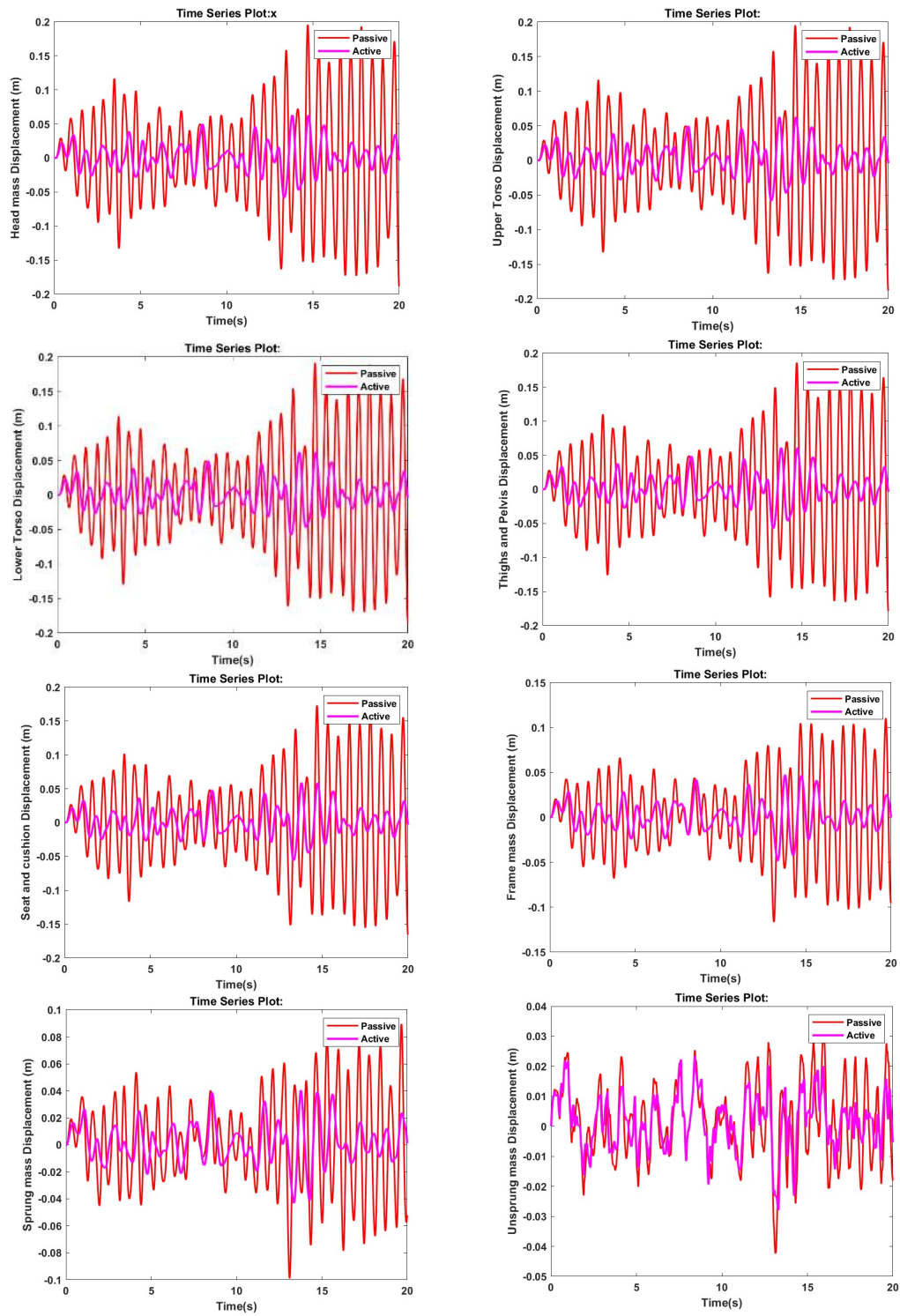


Figure 5.3 *Active vs Passive Displacement*

5.2 Proposed Controller

The proposed controller is simulated using MATLAB/ Simulink and the model parameters are listed in the table below. The controller is designed by the trial-and-error method. The control systems such as SMC, TSMC, FOSMC and FOTSMC are connected to the conventional suspension-system between the sprung mass and unsprung mass. The parameters of terminal controllers are defined as $p = 23$, $q = 25$, the sliding surface λ is taken as 0.9. The switching gain (k_1) is chosen as 0.3 for proposed controller and 1 for other control methods. The value of α for FOSMC and FOTSMC is 0.85.

The controllers are simulated in personal laptop using MATLAB R2023b software and the results of systems are taken from the software. The proposed controller is validated with two types of input profiles using Simulink tool i.e., Random Road input and step input. Initially the suspension-system is designed by taking 7 degree of freedom system which are, unsprung mass, sprung mass, seat and cushion mass, thighs and pelvic mass, lower torso, upper torso, and head mass. The system is designed using equations 1 to 8. Random road input of class C is employed as source to the system to study the behaviour of the 7 DOF system. This is generated using Random number block in Simulink. The behavior of passive and active models is plotted. The graph below shows the comparison between passive and active models sprung mass acceleration. The passive system has more vertical oscillation after the input compared to active system, the vibrations and vertical movements are damped in active suspension. The PID control method is used in an active suspension-system for validating the systems.

5.1.1 Step Input

Initially the suspension model is tested with PID control method to observe the behaviour of the system, during which it showed positive results for active systems. The conventional Sliding Mode controller is designed in Simulink as base controller as per equation 15. The step input is generated using library in Simulink. The step

block is differentiated and connected to the unsprung mass to produce disturbance to the suspension-system. The sample time is taken as 0.1 in the step block while keeping the initial value as 0 and final value as 1. The step time is also taken as 1. The displacement reached maximum to 0.035m and it is maintained as constant road input for 10 seconds which is validated for this time. The standard step input is shown below.

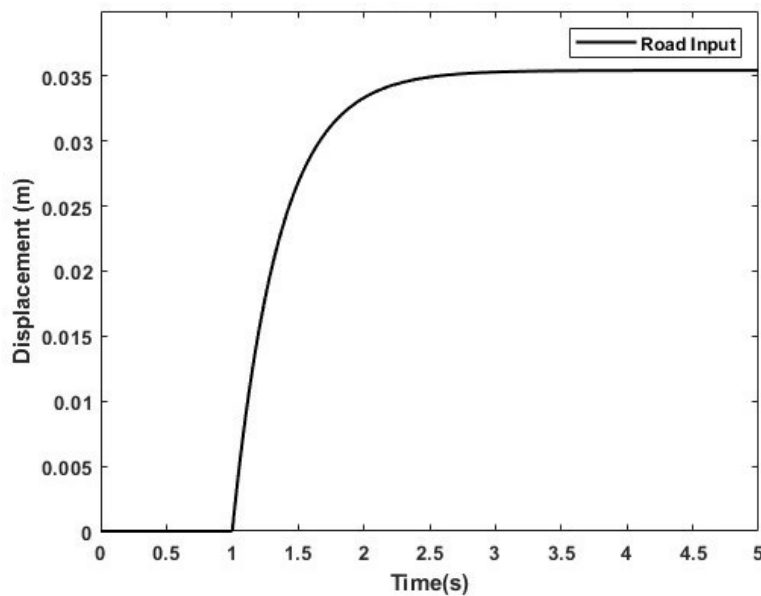


Figure 5.4 Step Input

The graph below illustrates the dynamic behavior of the suggested controller in comparison to the standard sliding mode controller. As depicted in the diagram, the input is provided at 1 second, at which point the passive suspension-system exhibits the highest acceleration in comparison to other points in time. The passive system achieved an acceleration of roughly 5.7 m/s^2 , whereas the active suspension-system, specifically the Sliding mode controller, achieved an acceleration of around 1.6 m/s^2 . The proposed controller exhibits the lowest acceleration compared to the other two control methods. The proposed controller has an acceleration that is below 0.6 m/s^2 . The graph represents the acceleration of the sprung mass of the 7DOF system. As it is shown, the proposed controller is observed to be nearly zero after 2 seconds and it attained zero level within milliseconds.

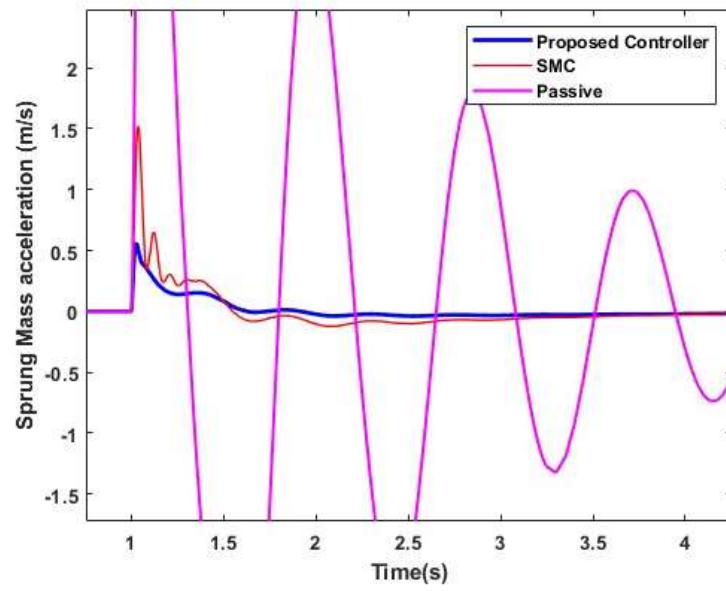
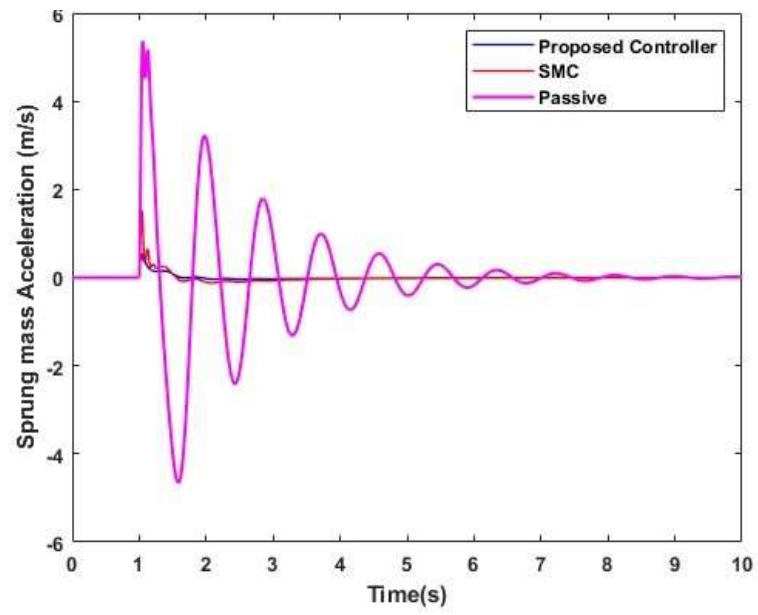


Figure 5.5. Control forces for Step input.

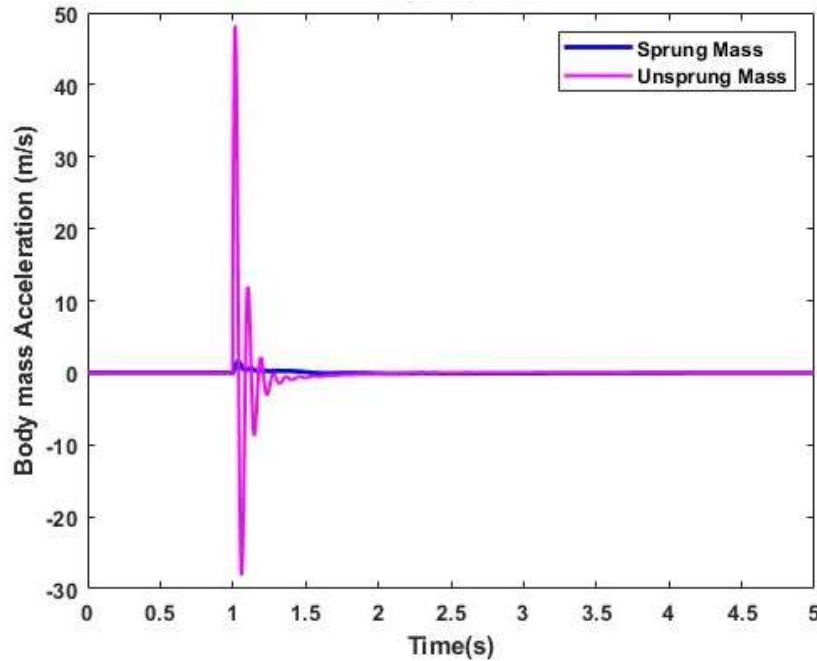


Figure 5.6. Comparison between sprung and unsprung mass of 7DOF system

The above graph compares the body mass acceleration between the sprung mass and unsprung mass of the 7-DOF system. The peaks of the sprung mass were significantly dropped after using the proposed controller in the suspension-system. The acceleration for the unsprung mass reached 48 m/s^2 at 1s, where the step input is given. The acceleration of the sprung mass is 0.6 m/s^2 which when compared to unsprung mass, great difference is observed. Also, the unsprung mass takes more time to reach siding surface condition. Figure 9 represents the difference between proposed controller and conventional controller, it is clearly shown that the peaks of acceleration of proposed controller are less than the SMC. Also, the proposed controller remained closer to the sliding surface after rise in acceleration due to the step input. This controller is achieved by altering the k value in switching function to the lower values. The force given to the unsprung mass can be multiplied after the actuator force by value to gain the least vibration. The comparative analysis of performance indices demonstrates that the suggested controller enhances the percentage of reduction in values of BA, hence confirming the effectiveness of the new controller.

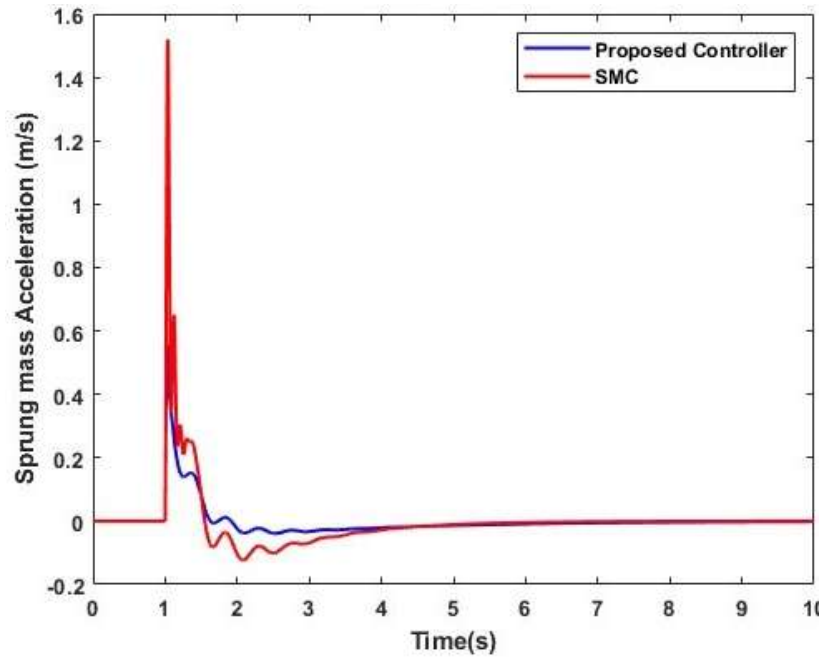


Figure 5.7. Comparison between Conventional SMC and proposed controller

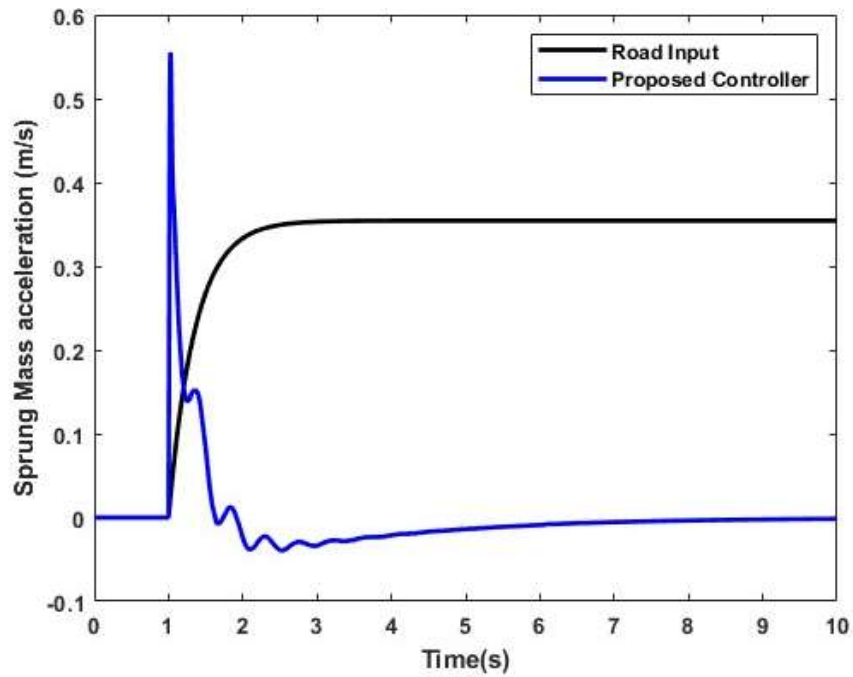


Figure 5.8. Comparison between Road Input(Step Input) and proposed controller

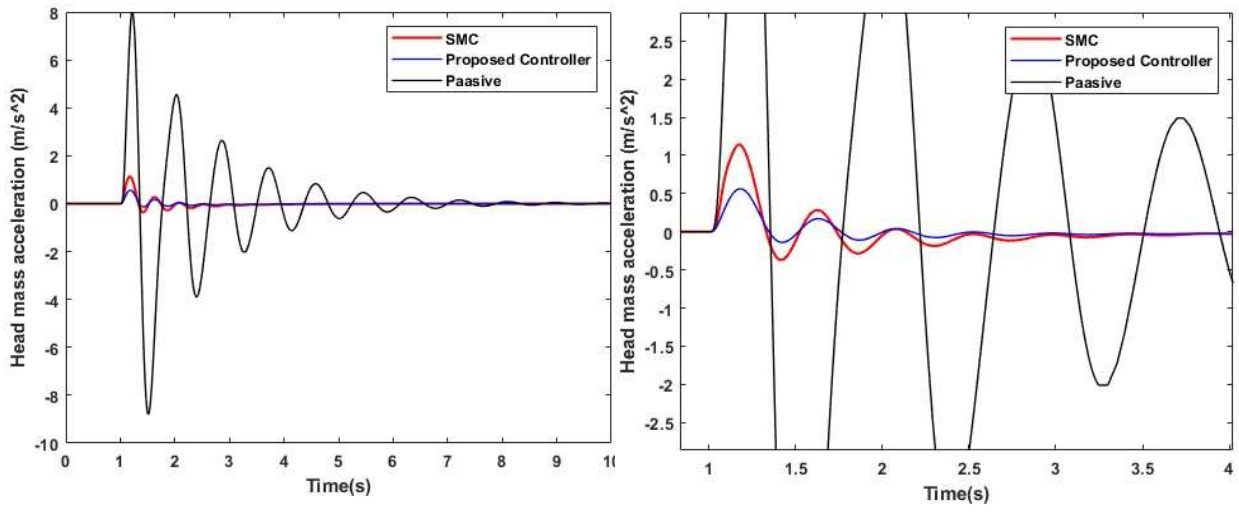


Figure 5.9. Head mass acceleration – Step Input

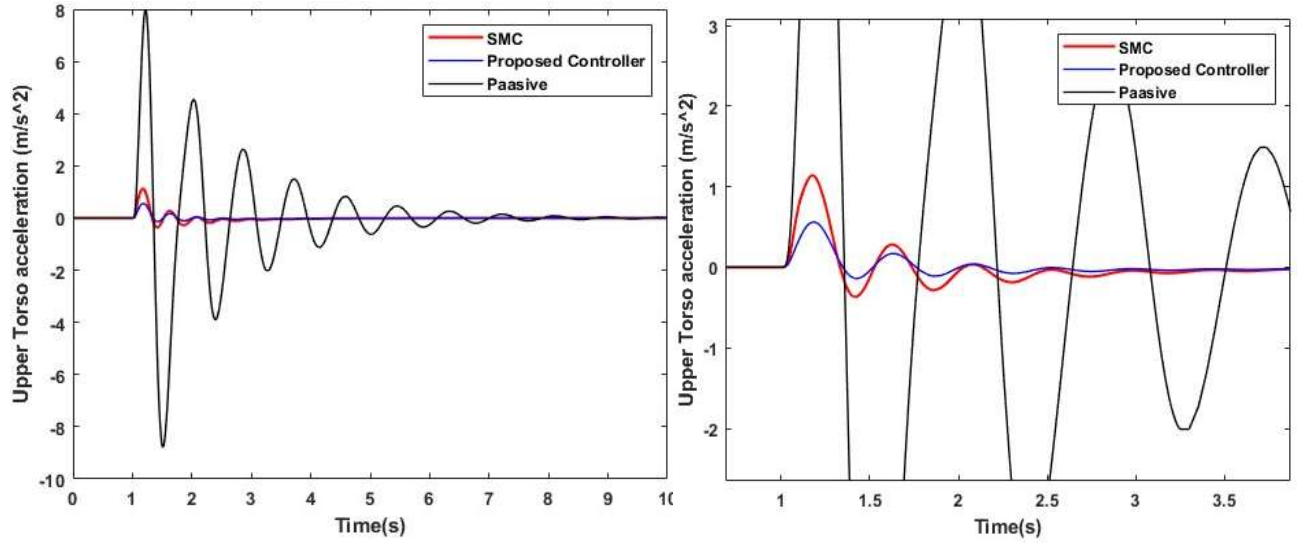


Figure 5.10 Upper Torso acceleration – Step Input

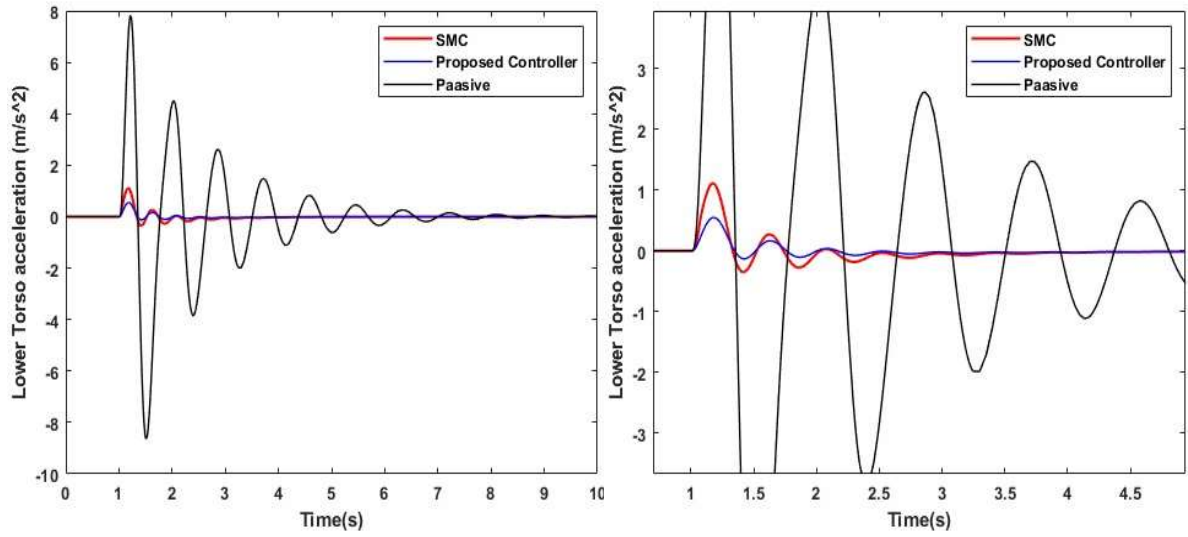


Figure 5.11 Lower Torso acceleration – Step Input

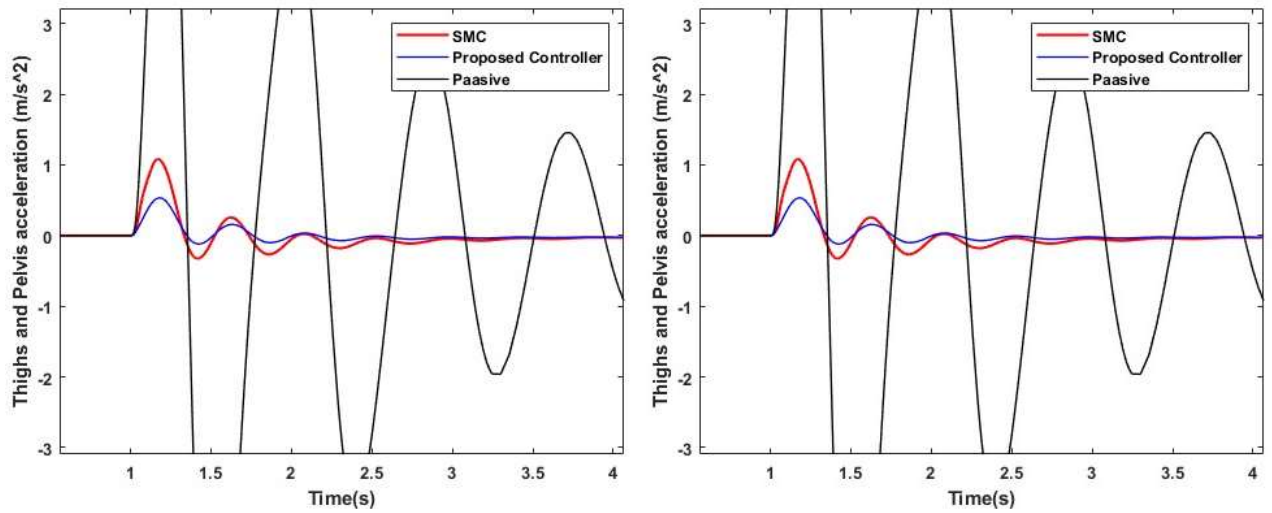


Figure 5.12 Thighs and Pelvis acceleration – Step Input

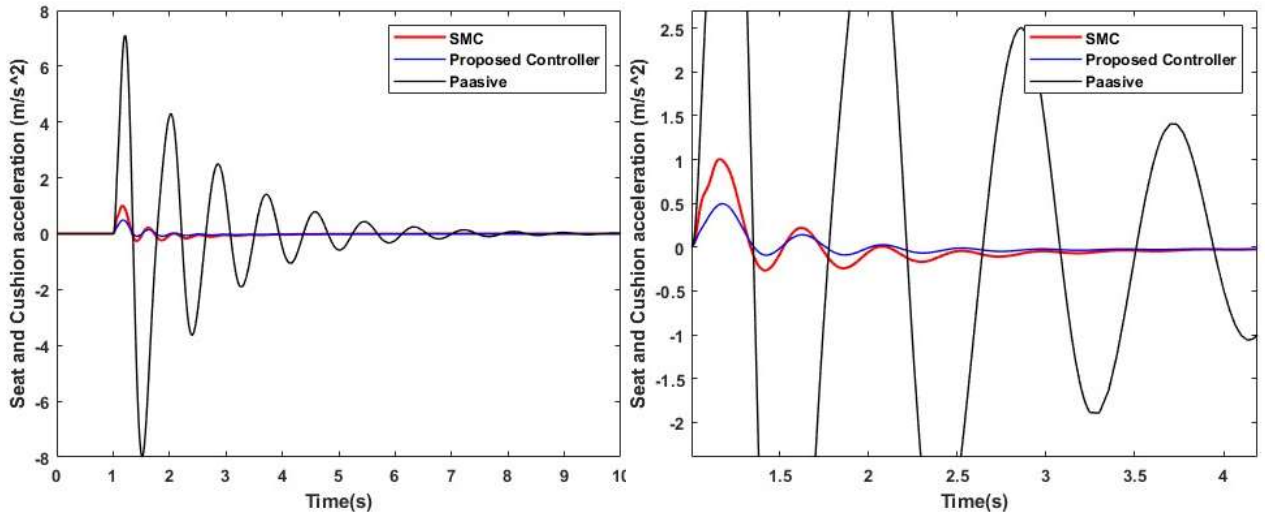


Figure 5.13 *Seat and Cushion acceleration – Step Input*

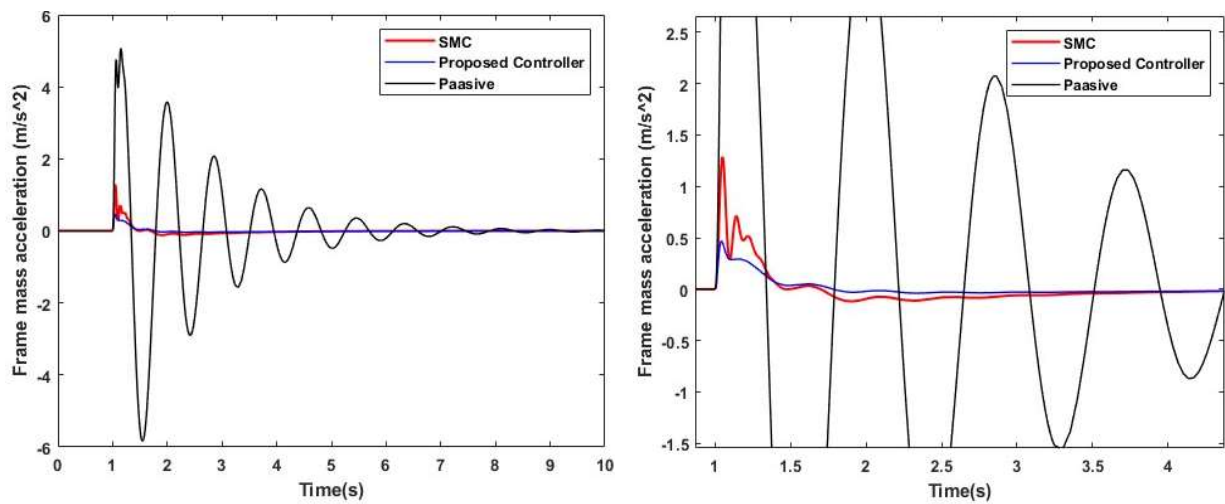


Figure 5.14 *Frame mass acceleration – Step Input*

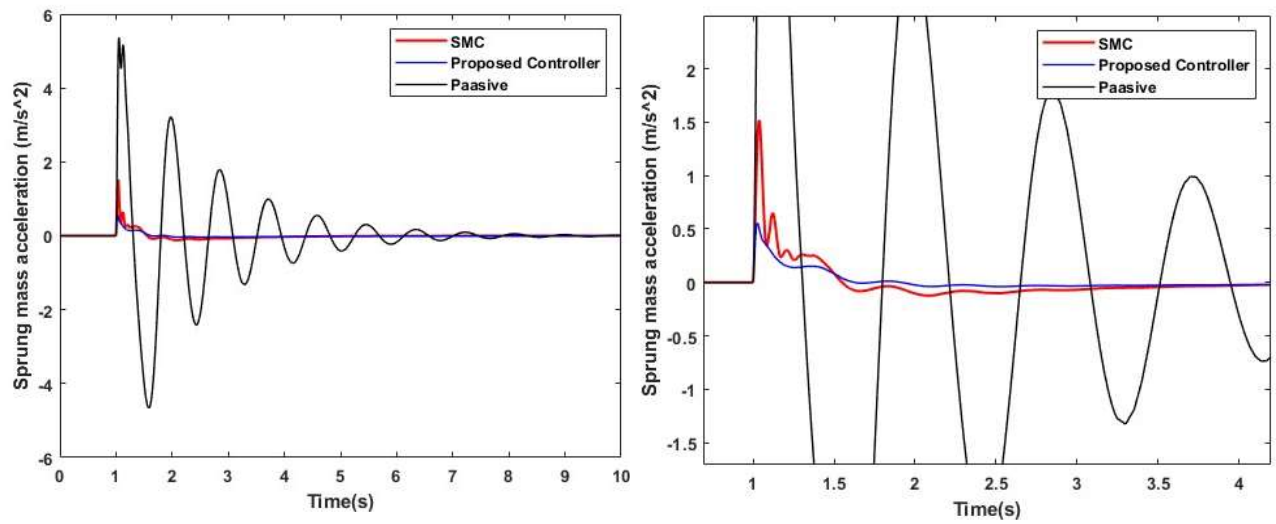


Figure 5.15 *Sprung mass acceleration – Step Input*

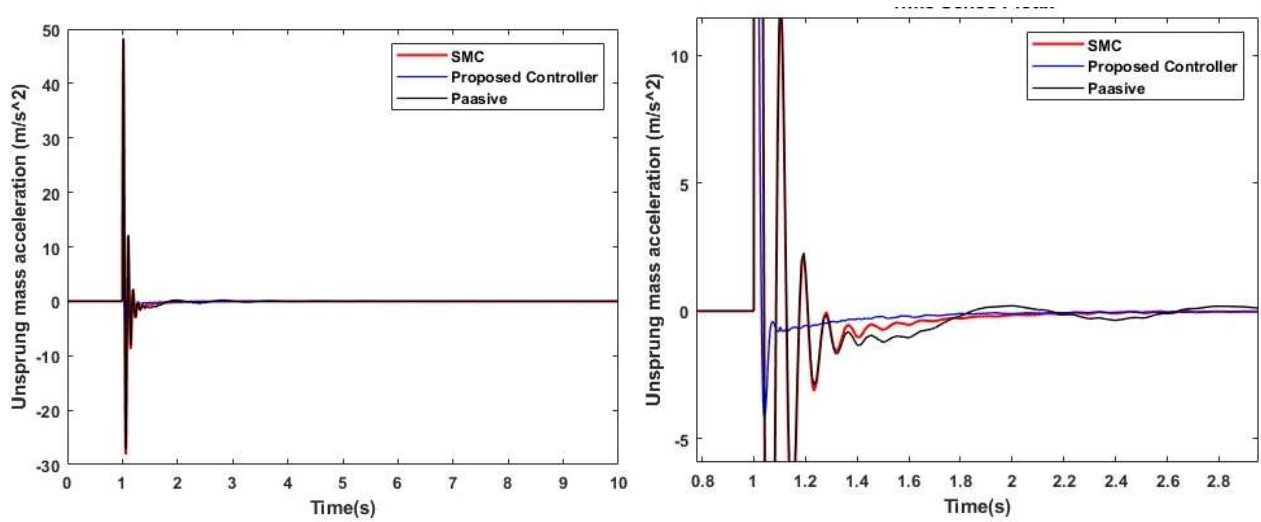


Figure 5.16 *Unsprung mass acceleration – Step Input*

5.2 Random Road Input

Random road input is used in various fields of engineering and research, particularly in the study of structural dynamics, vehicle dynamics, and transportation engineering. It involves the generation of random profiles or characteristics of road surfaces to simulate real-world road conditions. By generating random road profiles, the suspension-systems can be validated by researchers. The Random Road is designed as per ISO 8608 and used for simulation of the suspension-system with proposed controller. Uniform Random Number block is used to produce the random road source to the suspension model. The minimum and maximum value is taken as '-1' to '1' while sample time is taken as 0.1.

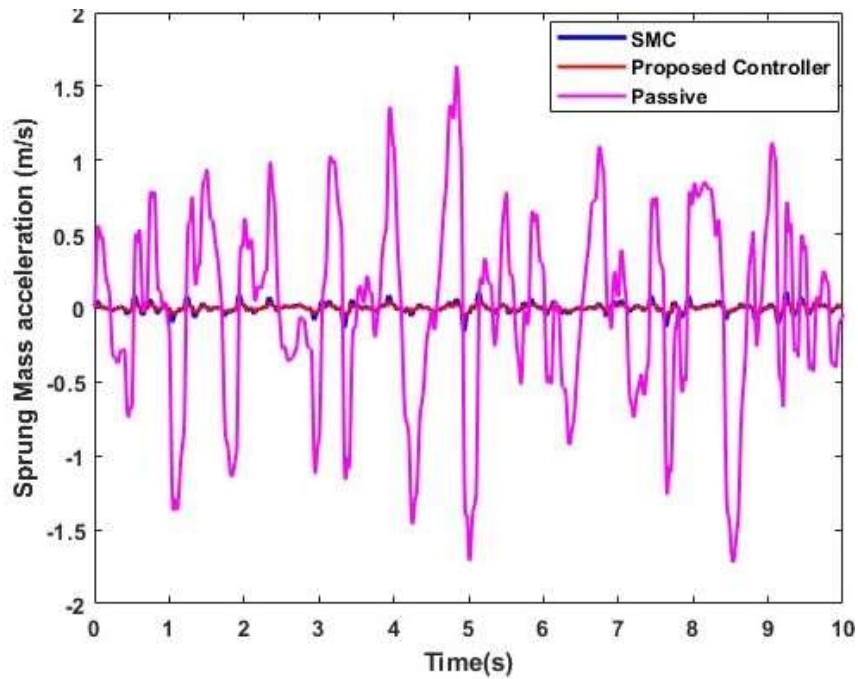


Figure 5.17a. Control forces for Random Road Input

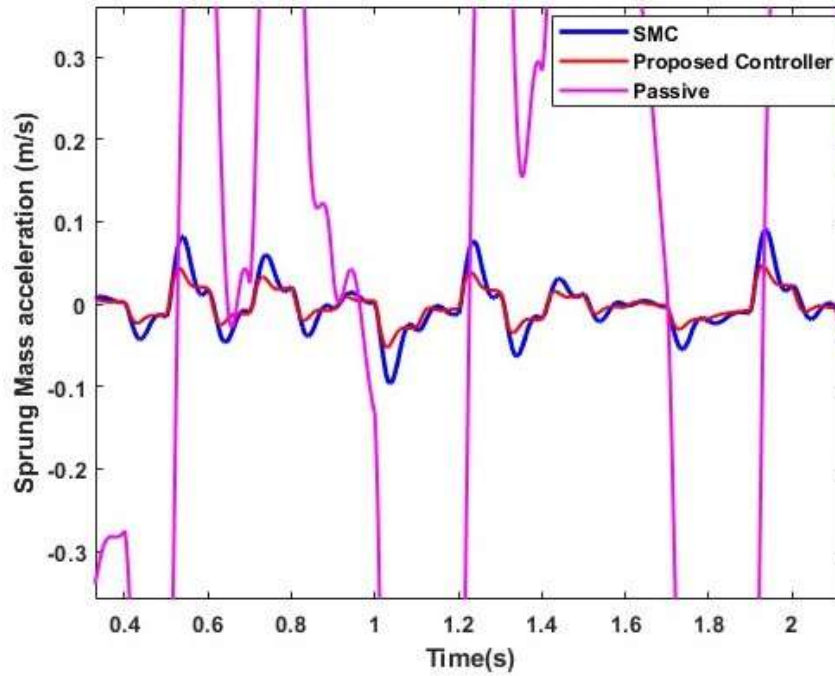


Figure 5.17b. Control forces for *Random Road Input*

The dynamic behaviour of the suspension-systems is shown in figures 10a and 10b. It is the comparison of sprung mass between the passive system, SMC, and proposed controller. As it is observed in fig 10b, the proposed controller has lesser peaks than the conventional SMC and the PC remains closer to the sliding surface. The passive suspension-system reached maximum peak of 1.6 m/s^2 while the active systems are near 0.1 m/s^2 . The active systems surpassed 98% vibrations when compared to passive systems.

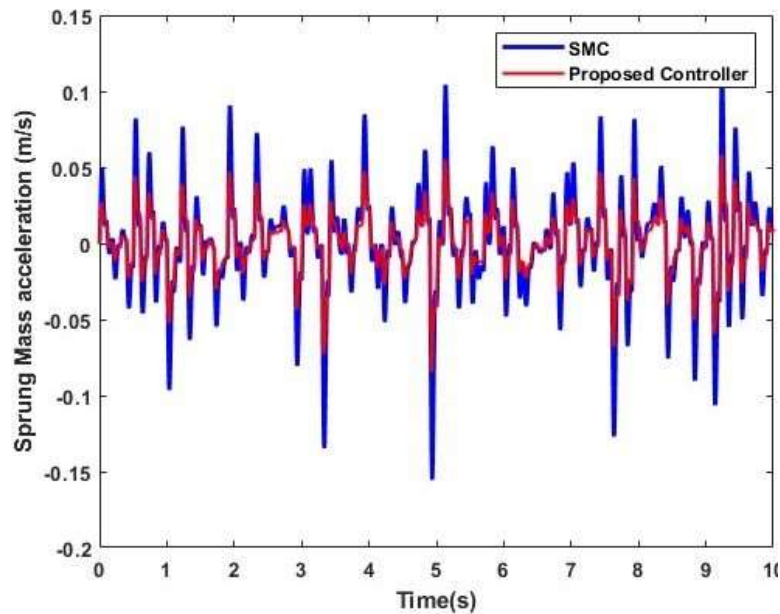


Figure 5.18. *SMC vs Proposed Controller*

Figure 11 is the comparison between the conventional SMC and proposed controller. As observed, the peaks of SMC are at the highest and lowest points at a specific time whereas the results of the new controller are shown to be near to the siding surface which is defined to be zero. The acceleration for the SMC lies between the values of -0.15 and 0.1 and -0.9 to 0.7 for the proposed controller. There is an improvement of nearly 40% when compared to with SMC and sixteen times more effective to passive suspension-system.

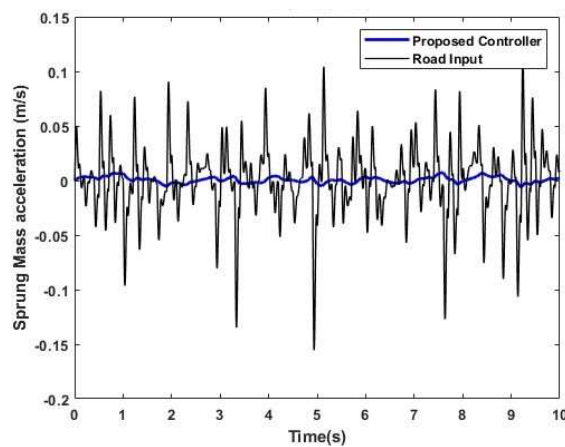


Figure 5.19 *Road Input vs Proposed Controller*

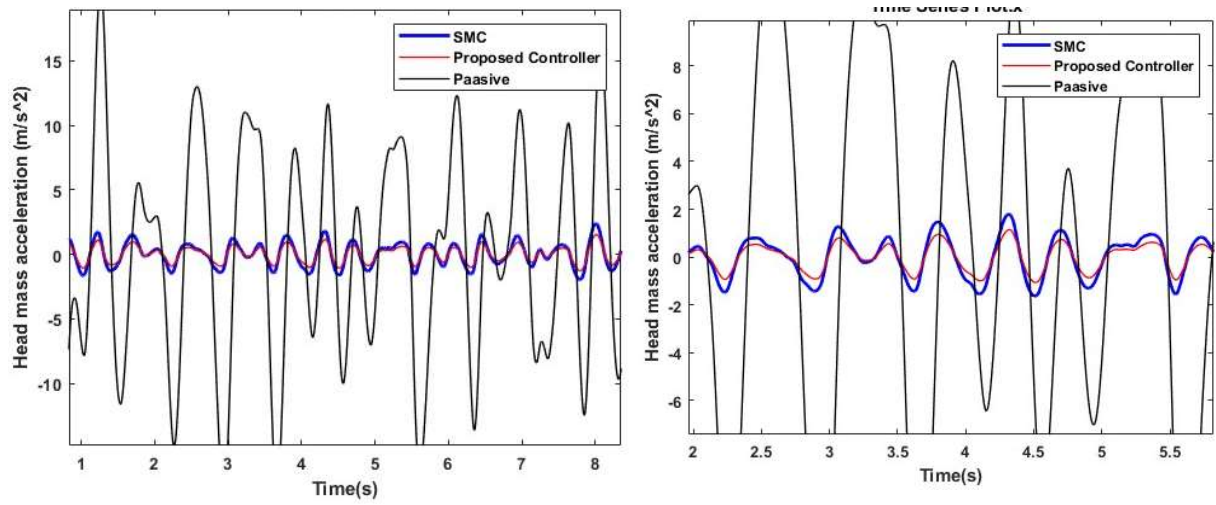


Figure 5.20 . Head mass acceleration – Random Road Input

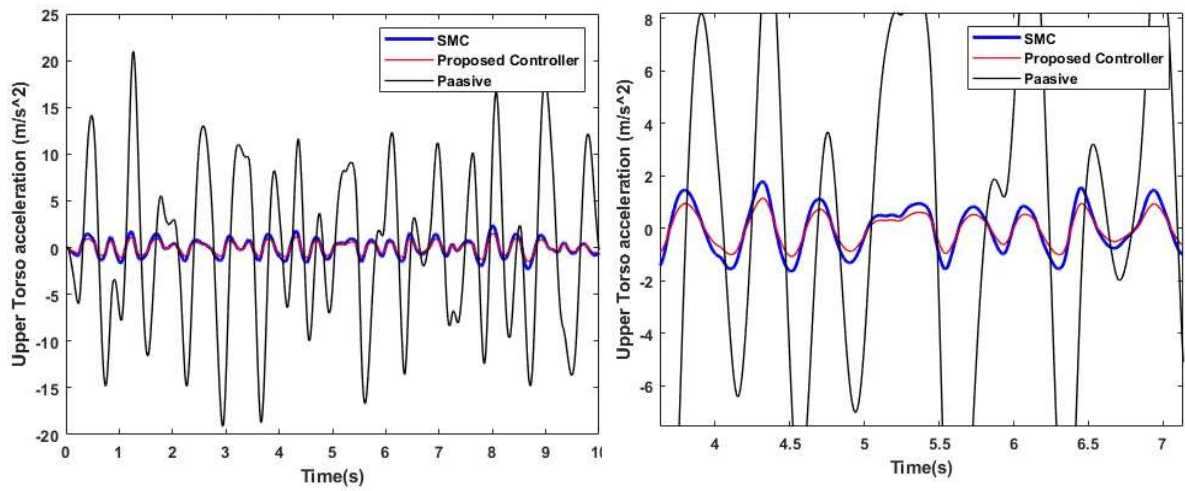


Figure 5.21 Upper Torso acceleration – Random Road Input

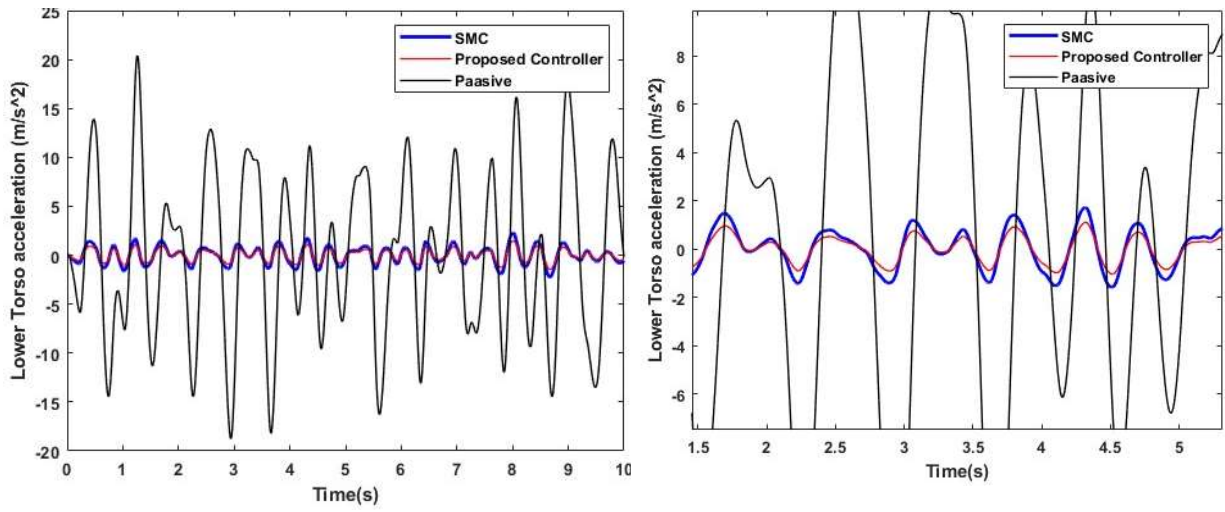


Figure 5.22 . Lower Torso acceleration – Random Road Input

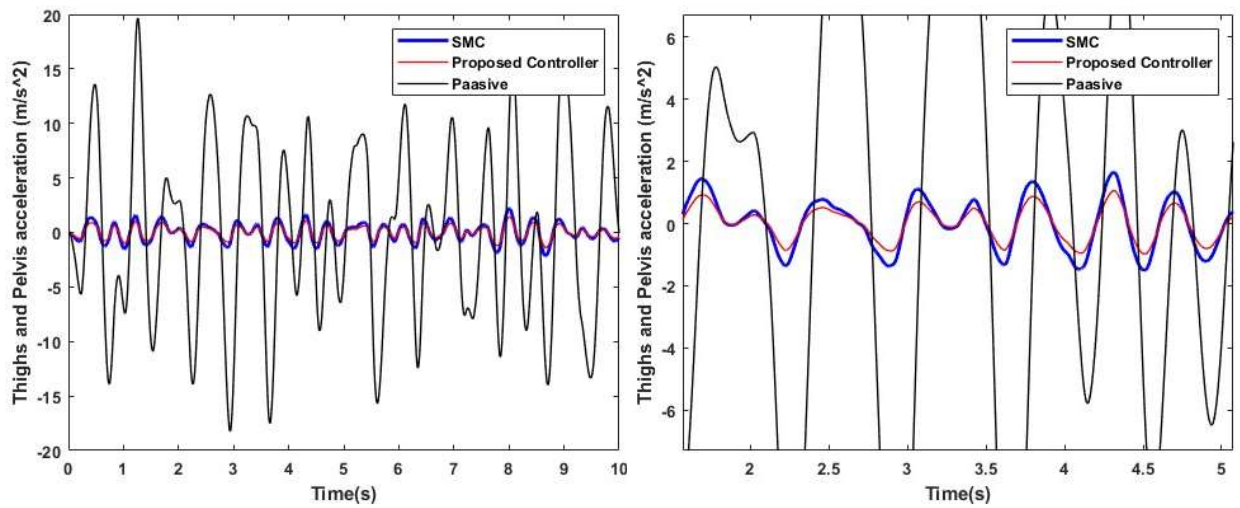


Figure 5.23 Thighs and Pelvis acceleration – Random Road Input

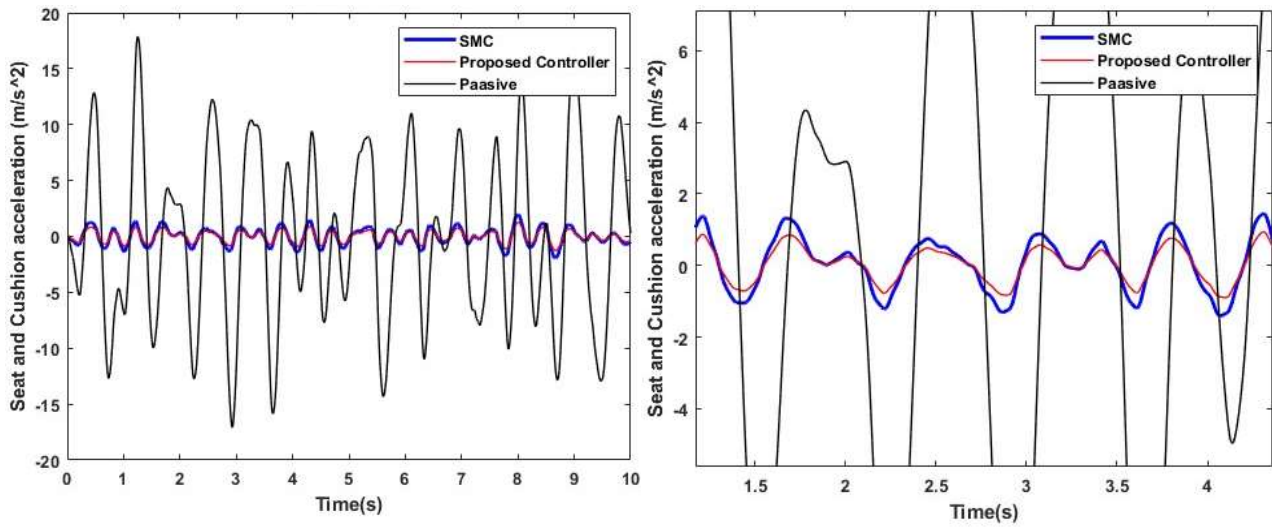


Figure 5.24 *Seat and cushion acceleration – Random Road Input*

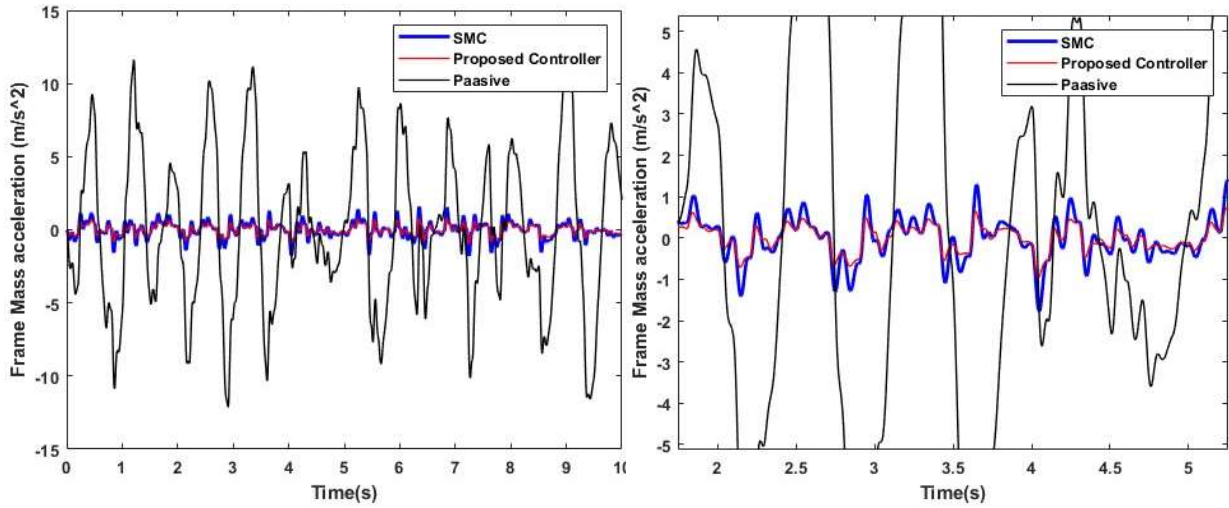


Figure 5.25 *Frame mass acceleration – Random Road Input*

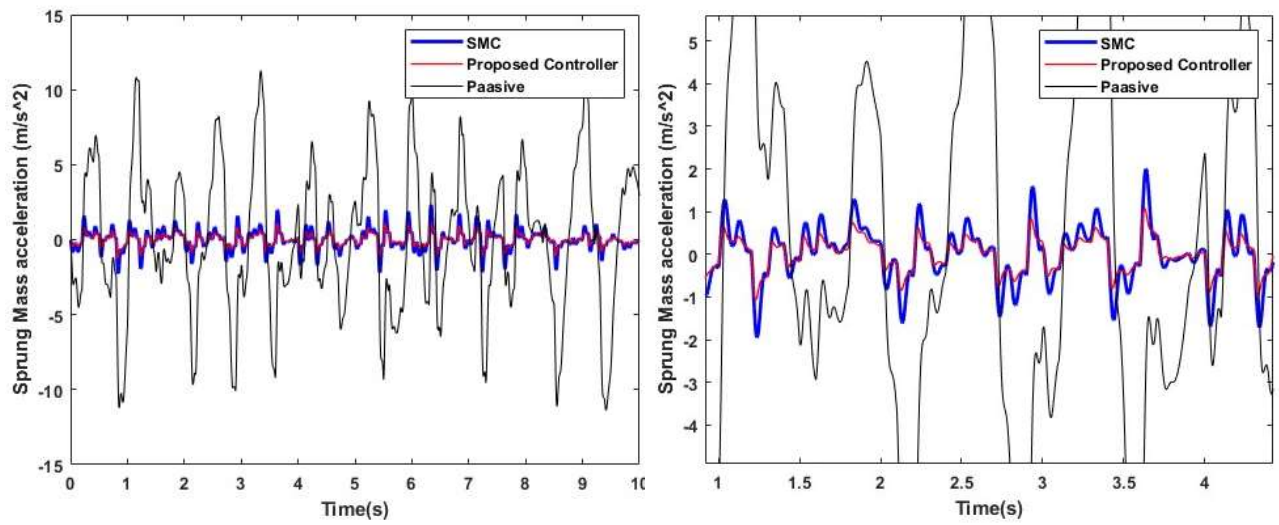


Figure 5.26 Sprung mass acceleration – Random Road Input

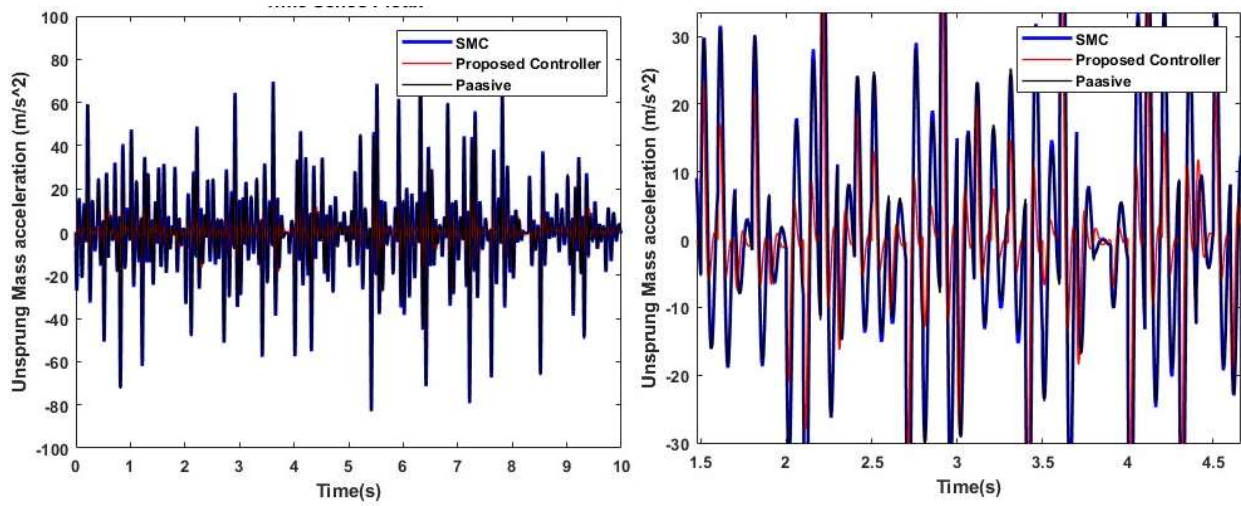


Figure 5.27 Unsprung mass acceleration – Random Road Input

CHAPTER – 6

SUMMARY AND CONCLUSION

6.1 SUMMARY

The suspension system in a vehicle is a critical component that affects its ride quality, handling, and safety. The suspension system is responsible for absorbing bumps and irregularities in the road surface, keeping the tires in contact with the road, and maintaining a stable platform for the vehicle. It consists of a number of components, including springs, shock absorbers, control arms, and linkages. Springs work to absorb the energy of bumps, while shock absorbers control the rebound of the springs. Control arms and linkages connect the suspension components to the vehicle frame and wheels. The types of suspension systems are classified into passive, semi-active and active suspension system. The active suspension system consists of an actuator which continuously changes its parameters to maintain its stability. The suspension controller is a device that monitors and adjusts the suspension system in real time. The controller uses sensors to measure the vehicle's speed, acceleration, and position. It also uses sensors to measure the suspension system's displacement and velocity. The suspension controller uses this information to adjust the suspension system's stiffness and damping. This allows the controller to optimize the suspension system for different driving conditions and road surfaces. The controllers are of many types which differ by control algorithms.

6.2 CONCLUSION

The suspension system is one of the most important components of a vehicle, as it is responsible for providing a comfortable and safe ride. It also plays a vital role in handling and performance. In recent years, there has been a growing interest in developing new and innovative suspension systems that can improve ride quality, handling, and safety. One of the most promising areas of research in suspension system design is the use of control algorithms. Control algorithms can be used to adjust the behavior of the suspension system in real time, based on road conditions

and vehicle dynamics. This can lead to significant improvements in ride quality, handling, and safety.

In this project, we develop and evaluate a new control algorithm for suspension systems. The algorithm is based on a model of the suspension system and a set of performance objectives. The algorithm uses real-time feedback from sensors to adjust the behavior of the suspension system in order to achieve the desired performance objectives. The results of our evaluation show that the new control algorithm can significantly improve the ride quality, handling, and safety of a vehicle. The algorithm also improved the handling of the vehicle, making it more responsive and easier to control. Overall, the results of this project are promising. We have shown that control algorithms can be used to significantly improve the performance of suspension systems. This work has the potential to lead to the development of new and innovative suspension systems that can make vehicles safer and more enjoyable to drive.

This study is focused on designing the more efficient SMC for quarter car model and it is simulated using MATLAB/Simulink. The mathematical models of control strategies such SMC, FOSMC, TSMC, and FOTSMC are produced in this research which can be used for further analysis of the suspension-systems.

The simulation results provided evidence of the efficacy of the Proposed Controller in minimizing traffic congestion and improving vehicle stability compared to the conventional SMC strategy. The comparative examination of performance measures shows that the proposed controller enhances the percentage of decrease in BA values, hence confirming the effectiveness of the new controller. Proposed Controller achieved a significant reduction in suspension deflection and sprung mass acceleration, translating to a more comfortable ride for passengers.

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