STUDY ON VIBRATION RESPONSES OF QUARTER CAR SUSPENSION WITH PASSIVE AND SEMI-ACTIVE DAMPERS USING MATLAB

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IN

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ABSTRACT

Nowadays, in developing countries like India cars are most commonly used vehicles. One of the most important aspect in an automotive industry is considering the safety and comfort of the person. The main component used for safety and comfort purpose is suspension system of the vehicle as it controls the movement of the vehicle. In most of the vehicles passive suspension systems are generally used which is of low cost but gives less comfort on highly uneven surfaces. The main objective of this project is to introduce a different suspension system i.e, semi active suspension system which gives more comfort when compared to passive suspension systems. The Objective of this project is to develop a MATLAB/SIMULINK model of a Quarter-car suspension to analyze ride comfort and vehicle handling on the basis of person's body vibrational displacements and acceleration .The semi-active suspension system uses the varying damping force as control force. The ride comfort of person is initially analyzed by using a passive suspension system and then it is replaced with a controllable two state semi active dampers .A skyhook controller is used for controlling the damping force of the suspension system. The semi active suspension system and skyhook controller reduces the sprung mass displacements and acceleration thereby passenger comfort is increased.

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CHAPTER-1

1. INTRODUCTION

Vibration occurs when a system is displaced from a position of stable equilibrium. The system tends to return to this equilibrium position under the action of restoring forces (such as the elastic forces, as for a mass attached to a spring, or gravitational forces, as for a simple pendulum). The system keeps moving back and forth across its position of equilibrium. A system is a combination of elements intended to act together to accomplish an objective. For example, an automobile is a system whose elements are the wheels, suspension, car body, and so forth.

Most vibrations are undesirable in machines and structures because they produce increased stresses, energy losses, because added wear, increase bearing loads, induce fatigue, create passenger discomfort in vehicles, and absorb energy from the system. Rotating machine parts need careful balancing in order to prevent damage from vibrations.

Vibration can be desirable for example, the motion of a tuning fork, the reed in a woodwind instrument or harmonica, or mobile phones or the cone of a loudspeaker.

1.1. Causes of Vibrations

Identifying of the root cause of any problem helps us to tackle the same with great ease. This applies to vibration also. Most of the machines we use in our day to day life like the Mixer, Washing Machine, Vacuum Cleaner, etc. tend to indicate if something is wrong in them by means of vibration and noise (a major by-product caused by vibration).This article can provide you with at least some of the major contributors, which cause the change in vibration level of a machine. Let me discuss these now in detail.

1. Unbalance: This is basically in reference to the rotating bodies. The uneven distribution of mass in a rotating body contributes to the unbalance. A good example of unbalance related vibration would be the "vibrating alert" in our mobile phones. Here a small amount of unbalanced weight is rotated by a motor causing the vibration which makes the mobile phone to vibrate. You would have experienced the same sort

of vibration occurring in your front loaded washing machines that tend to vibrate during the "spinning" mode.

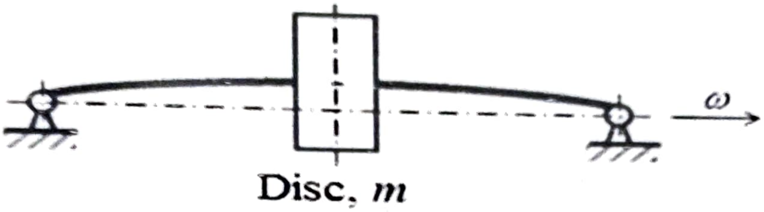


Fig.1.1 Unbalance of shaft

2. Misalignment: This is another major cause of vibration particularly in machines that are driven by motors or any other prime movers. A small figure is attached herewith to let you know about the types of misalignment.

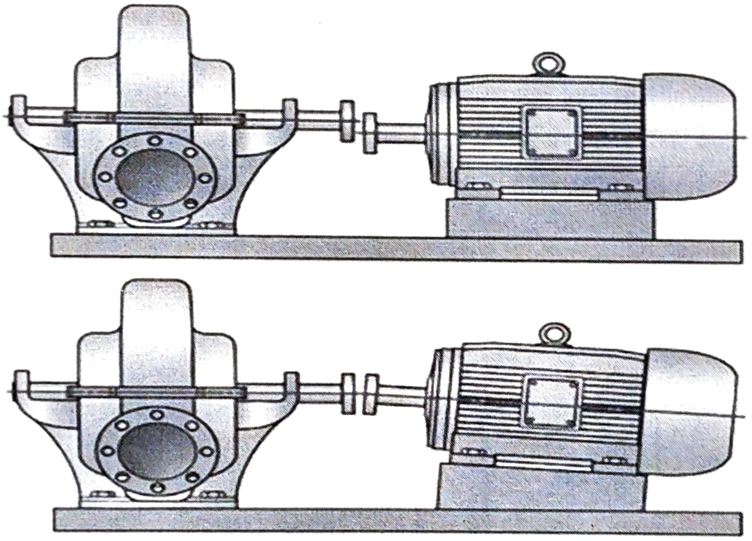


Fig.1.2. Misalignment of machine shaft

3. Bent Shaft: A rotating shaft that is bent also produces the the vibrating effect since it losses it rotation capability about its center.

4. Gears in the machine: The gears in the machine always tend to produce vibration, mainly due to their meshing. Though this may be controlled to some extent, any problem in the gearbox tends to get enhanced with ease. The major things that tend to cause excessive vibration in gears are

1. Misalignment of the gear axis
2. Gear teeth running out of contact
3. Wear and breakage of gear tooth.

5. Loose Foundations: This is a simple area where we fail to look into in any machine that vibrates. The improper mounting of the machine without holding it rigidly to the ground causes the machine to vibrate. The next time your water pump at home vibrates be sure to check out the foundation bolts of the motor before you proceed with further analysis.

1.2. Types of Vibration external agency

1. **Free vibration** occurs when a mechanical system is set off with an initial input and then allowed to vibrate freely. Examples of this type of vibration are pulling a child back on a swing and then letting go or hitting a tuning fork and letting it ring. The mechanical system then vibrates at one or more of its "natural frequency" and damps down to zero.

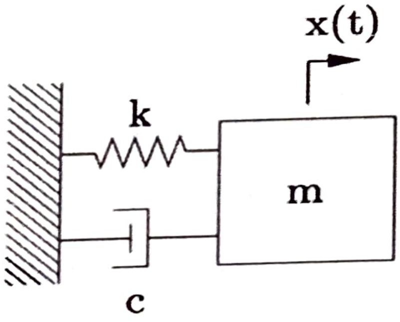


Fig.1.3. Free Vibration

2. **Forced vibration** is when a time-varying disturbance (load, displacement or velocity) is applied to a mechanical system. The disturbance can be a periodic, steady-state input, a transient input, or a random input. Examples of these types of vibration include a shaking washing machine due to an imbalance, transportation vibration (caused by truck engine, springs, road, etc.), or the vibration of a building during an earthquake.

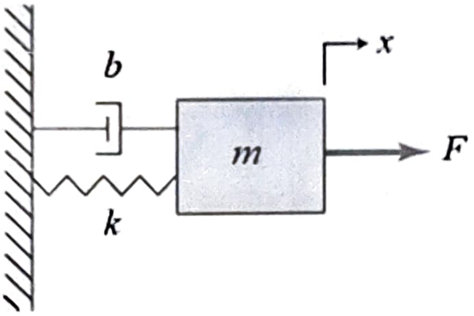


Fig.1.4. Forced Vibration

1.3 Suspension system

The suspension system of an automobile is one which separates the wheel/axle Assembly from the body. The primary function of the suspension system is to isolate the vehicle structure from shocks and vibration due to irregularities of the road surface.

1.3.1 Functions of suspension system

- To prevent the road shocks from being transmitted to the vehicle frame.
- To preserve the stability of the vehicle in pitching or rolling.
- To safeguard the occupants from road shocks.
- To provide good road holding while driving, cornering and braking.
- Maintain correct vehicle ride height
- Maintain correct wheel alignment

- Support vehicle weight
- Keep the tyres in contact with the road

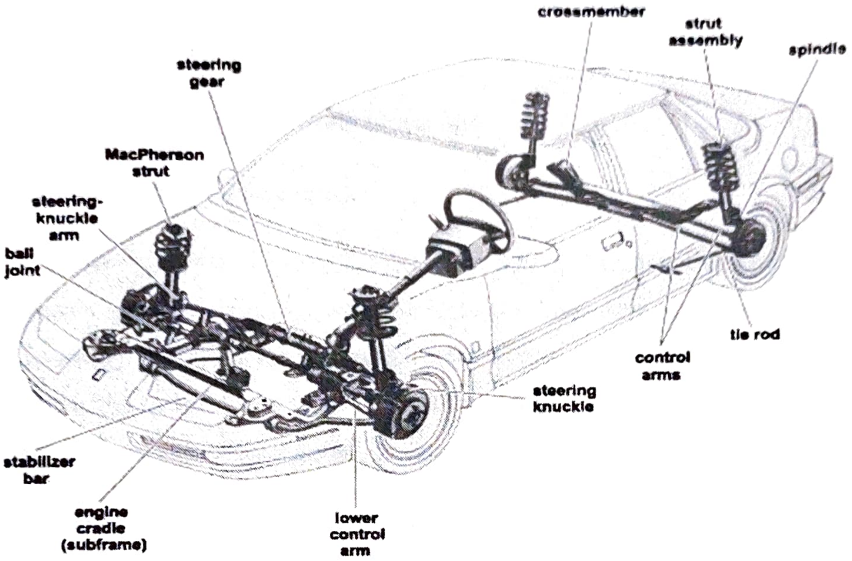


Fig. 1.5. Suspension system of car

1.4 Suspension System Types

Suspension is the system of tires, tire air, springs, shock absorbers and linkages that connects a vehicle to its wheels and allows relative motion between the two. Suspension systems serve a dual purpose contributing to the vehicle's road holding/handling and braking for good active safety and driving pleasure, and keeping vehicle occupants comfortable and a ride quality reasonably well isolated from road noise, bumps, and vibration ,etc. These goals are generally at odds, so the tuning of suspensions involves finding the right compromise. It is important for the suspension to keep the road wheel in contact with the road surface as much as possible, because all the road or ground forces acting on the vehicle do so through the contact patches of the tires. The suspension also protects the vehicle itself and any cargo or luggage from damage and wear.

A passive suspension system is conventional suspension system consist of non-controlled spring and shock-absorbing damper which means the damping criteria is fixed. Semi-active suspension system has equally same configuration as the passive suspension but with a controllable damping rate for the shock-absorbing damper. An active suspension is one in which the passive components are augmented by actuators that supply additional force.

1.5 Suspension Depending Upon Controller

1.5.1 Passive Suspension Systems

Passive vibration control involves an inherent compromise between low-frequency and high-frequency vibration isolation. Passive suspension system consists of an energy dissipating element, which is the damper, and an energy-storing element, which is the spring. Since these two elements cannot add energy to the system this kind of suspension systems are called passive.

Passive suspension systems are the most common systems that are used in commercial passenger cars. They are composed of conventional springs, and single or twin-tube oil dampers with constant damping properties. The designer pre-sets the fix damping properties to achieve optimum performance for the intended application. The disadvantage of passive suspension systems with constant damping characteristics is that setting the design parameters is a compromise between the ride quality and handling. Generally, softer dampers provide a more comfortable ride, while stiffer ones provide better stability and thus better road-handling. Passive suspension systems are tuned according to the expected operating conditions, but a compromise is always made between designing for the two opposing goals. Lot of common vehicles today uses passive suspension system to control the dynamics of a vehicle’s vertical motion as well as pitch and roll.

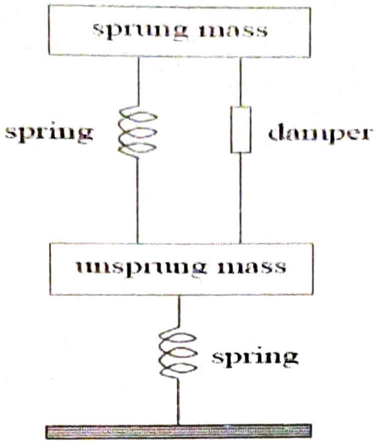


Fig. 1.6. Passive Suspension System

1.5.2. Active Suspension System

The active suspension and adaptive suspension/semi-active suspension are types of automotive suspensions that controls the vertical movement of the wheels relative to the chassis or vehicle body with an onboard system, rather than in passive suspensions where the movement is being determined entirely by the road surface, see Skyhook theory. Active suspensions can be generally divided into two main classes: pure active suspensions and adaptive/semi-active suspensions.

Active suspensions, the first to be introduced, use separate actuators which can exert an independent force on the suspension to improve the riding characteristics. The drawbacks of this design (at least today) are high cost, added complication/mass of the apparatus, and the need for rather frequent maintenance on some implementations. Maintenance can be problematic, since only a factory-authorized dealer will have the tools and mechanics with knowledge of the system, and some problems can be difficult to diagnose.

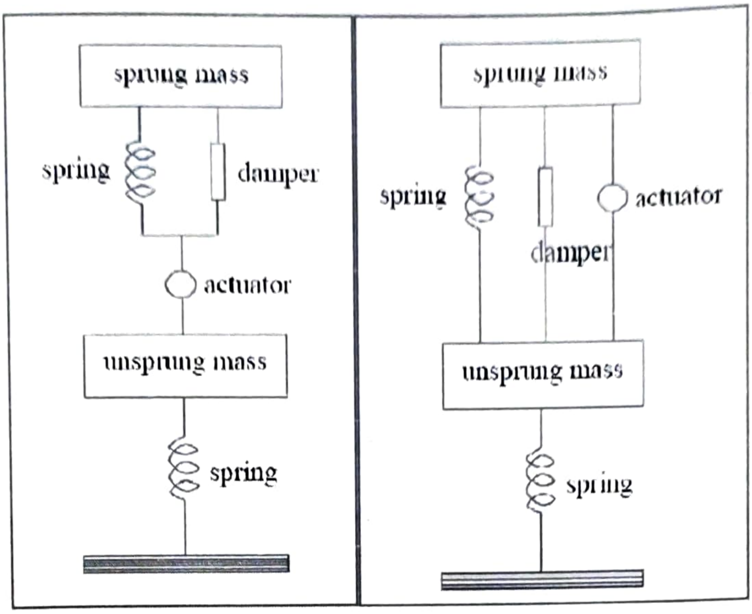


Fig.1.7. Active Suspension System

1.5.3. Semi Active Suspension System

Semi-active suspension is not to be confused with active suspension, nor any of the electronically adjustable systems currently available. In a fully active system, electromagnetic or hydraulic rams completely replace electronically adjustable systems such as BMW's ESA (Electronic Suspension Adjustment), Ducati's Electronic Suspension (DES), Ohlins Mechatronics and the system used on the MV Agusta F4 RR are often considered to be semi-active, which is true in some ways.

The continuous variable dampers have a characteristic that can be rapidly varied over a wide range. When the body velocity and damper velocity are in the same direction, the damper force is controlled to emulate the skyhook damper. The disadvantage of the continuous variable damper is that it is difficult to find devices that are capable in generating a high force at low velocities and a low force at high velocities, and be able to move rapidly between the two. Has introduced the control strategy to control the skyhook damper. The control strategy utilized a fictitious damper that is inserted between the sprung mass and the stationary sky as a way to suppress the vibration motion of the spring mass and as a tool to compute the desired skyhook force. Figure 2.3 shows the representation diagram of semi-active suspension system.

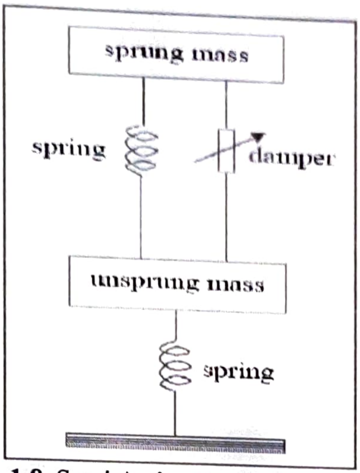


Fig .1.8. Semi Active Suspension System

Semi-active suspensions, which can achieve a ride comfort using less energy than active suspensions have been actively studied during the last decade. The Sky-Hook Control Law is adapted to many semi-active suspensions. The skyhook control strategy introduced by Karnopp et al is the most widely used control policy for semi-active suspension systems. The skyhook control can reduce the resonant peak of the body mass and thus achieve a good ride quality. But, in order to improve both the ride quality and the safety of vehicle, both the resonant peaks of the body and the wheel need to be reduced. The suspension stroke velocity and vertical velocity of a sprung mass are needed to realize this control law. Generally, these velocities are obtained by differentiating the signals measured with a stroke displacement sensor on suspension systems or integrating the signals measured with an acceleration sensor on a sprung mass.

CHAPTER-2

2. LITERATURE REVIEW

S. J. Chikhale [1] Scope of this paper is to prepare Quarter car model of vehicle suspension system in Matlab-SIMULINK and MSc-ADAMS. Mathematical model for quarter car is prepared with the help of State-Space representation. Then the quarter car model is developed in Matlab-SIMULINK and Msc-ADAMS. Vibration analysis is done by giving step input. Procedure and results are compared.

Ankita R. Bhise [2] Suspension system plays an important role in ride comfort and road holding. In this paper, the two degree-of-freedom quarter car model with passive and semi-active suspension system is designed using Matlab/Simulink. The semi-active suspension system is designed with MR damper. The control performance is compared between passive and semi-active suspension system. The results shows the vehicle response results obtained from step and sine of road input simulations. In conclusion we concluded that semi active system gives 93.9% and 63.7% better result for step and Half sine input respectively.

Ram Mohan Rao et al [3] this paper describes the modeling, and testing of skyhook and other semi active suspension control strategies. The control performance of a three-degree-of-freedom quarter car semi active suspension systems is investigated using Matlab/Simulink, model. The objective of this paper is to present a comprehensive analysis of novel hybrid semi-active control algorithms and to compare the semi-active and passive systems in terms of human body vibrational displacements and accelerations. A theoretical model of the human seated model is developed in order to simulate the vertical motion of the Passenger in an omnibus when the vehicle passing over a speed bump. The mathematical model of these systems is presented. Ride comfort of off-road vehicles can be estimated by replacing the normal passive dampers in the vehicle suspension system with controllable, two-state, semi-active dampers.

The peak to peak method has been used to investigate the performance of different control methods. The simulation results show considerable differences between the results of passive and different schemes of semi active suspension system. This paper gave an overview of the simulation model which is developed in order to create a research environment for a variety of suspension systems. After discussing the general conditions for suspension Control and various control concepts, a parameter adaptive suspension control design is presented. In this connection, the potential of improvements for state space feedback in the case of road and body excitation is demonstrated by means of simulations. The variable damper obtains the best results in nearly the same size as an active suspension system.

Dawei Liu et al [4] in order to study the driving performance of semi-active suspension vehicle, a detailed multi-body driving dynamics model of the car were established by using SIMPACK software and a hybrid control strategy was worked out by means of Matlab/Simulink. The Simpack- Matlab co-simulation method was used to analyze the ride ability of semi-active suspension. The result showed that, the semi-active suspension based on hybrid control strategy could reduce the body vertical acceleration, roll angular acceleration, pitch angular acceleration and suspension dynamic deflection, and that was not under the condition of the wheel dynamic load increase. The semi-active suspension based on hybrid control strategy could reduce the vehicle body vibration and improve the ride comfort under the condition of the value of dynamic tire load not to be increased and Hybrid Control Strategy of sky hook control and ground hook control Study on Vehicle Semi Active Suspension Based on Multi-body Dynamics Theory and To improve dynamic performance control effect for semi active suspension vehicle with whole vehicle dynamics model as a control object and vertical, roll and pitch acceleration and suspension travel and tire dynamics load as control indexes, the hybrid control simulation was performed by taking grade C road as random input.

Galal Ali Hassaan [5] The object of this paper is to examine the dynamics of a car passing a circular bump for sake maintaining ride comfort for the passengers. Passive suspension elements are considered with suspension damping coefficient in the range 1 to 15 kNs/m. Car speed in the range 5 to 25 km/h is considered when passing the hump. Important phenomenon evolved from the analysis of the car dynamics which is performed using MATLAB. The mathematical model of the quarter-car model is derived in the state form and the dynamics are evaluated in terms of the sprung mass displacement and acceleration. The effect of suspension damping and car speed on the sprung-mass displacement and acceleration is examined. The study shows that for ride comfort the car speed has not to exceed 6.75 km/h when passing a circular hump depending on the suspension damping. A quarter-car model with passive elements was used in this study to investigate the car dynamics during passing a circular hump.

Rame Likaj et al [6] in this paper presented the comparison of two optimization algorithms: Sequential Quadratic Program (SQP) and Genetic Algorithms (GAs) for the optimal design of quarter car vehicle suspensions. During the optimization the three design criteria which have been used are; vertical vehicle body acceleration, dynamic tire load and suspension working space. For implementing a optimization will be chosen five design parameters: sprung and un-sprung mass, spring stiffness, damping coefficient and tire stiffness. Through the simulation in Matlab it will be shown that GA is more powerful tool to find the global optimal point, without any restrictive requirements on the gradient and Hessian Matrix, while SQP has local convergence properties. In order to overcome the permanent conflict between vehicle comfort and vehicle handling under different riding conditions and speed, the main focus of this research will be on minimising the vertical vehicle body acceleration subjected to a suspension working space and the dynamic tire load.

Based on the simulation results the optimum found by GAs at 19 generations, while by using the SQP the optimum is found after 47 iterations. As shown from the numerical simulation results the max amplitude of body displacement using optimized design variables is reduced for 9%, while maximal amplitude of body acceleration is reduced around 22%. Numerical experiments reveal the fact that to improve vehicle ride quality and satisfy the specified suspension working space and relative dynamic tire load, different vehicle speed and road irregularity have different requirements on the design variables, in particular, the un-sprung mass. It is recommended that to solve this vehicle speed and road irregularity related vehicle suspension design optimization problem, a multi-level optimization approach be applied. It is expected that by means of this multi-level optimization approach, the resulting solutions will compromise the conflicting requirements on design variables for vehicles traveling at different speed and on roads with different irregularity.

Andronic Florin et al [7] In this current article is simulated and analyzed the handling and ride performance of a vehicle with passive suspension system, quarter car model with two degree of freedom. Since, the equations of the system cannot be solved mathematically has developed a scheme in Matlab Simulink that allows analyzing the behavior of the suspension. The schema that was created in Matlab Simulink, were compared with the State space model and the Transfer function. In this paper simulated a passive suspension system, a system that is most commonly used. To verify the accuracy of modeling were used State Space and Transfer Function. Results obtained, using the three methods with the same parameters of the suspension system, are identical. Was used a step type signal for a broad application of the suspension system. This signal can be modified, for example, a sinusoidal or a required signal. The parameters of a passive suspension system are generally fixed, being chosen to achieve a certain level of compromise between road holding, load carrying and comfort.

Ahmad Zaim [8] The objective of this project is to increase comfort of the vehicle's passenger. In order to improve comfort and ride quality of a vehicles, there are four parameters need to be acknowledge. The four parameters are sprung mass acceleration, sprung mass displacement, unsprung displacement and suspension deflection. This project used a new approach in designing the suspension system which is semi-active suspension. The hydraulic damper is replaced by a magneto-rheological damper. A controller is developed for controlling the damping force of the suspension system. The actual concept of the controller is fictitious hence the realization model developed. The controller is called skyhook control. A modified skyhook controller also developed to further improve the suspension system. The semi-active suspension with modified skyhook controller reduces the sprung mass acceleration and displacement hence improving the passengers comfort.

S. Segla et al [9]. In the paper the performances of the passive suspensions are optimized and compared with the performances of active and semi-active suspensions (quarter car models) and In the paper optimization and comparison of passive, active, and semi-active vehicle suspension systems was presented. It was shown, that not only the active, but also semi-active suspension system is able to improve the ride comfort significantly compared with the classical passive suspension systems. Using the vibration absorber (split axle) and additional dampers between the engine and axle have improved the ride comfort only slightly. Using the relaxation damping even slightly worsened the ride comfort compared with the basic two-mass passive suspension system.

Thomas Gyllendahl et al [10] The goal of this work was to develop a vehicle suspension intended for an auto rickshaw. A variety of different suspension types were investigated and evaluated until two suspension types were chosen; one type for the front and one type for the rear. These suspension types were then simulated and tested in Siemens NX 8.0 in different critical scenarios to gain useful information. The information was then evaluated to draw a conclusion if the developed suspension obtained good performance. The final solution was simulated and partly verified. A suspension suitable for an auto rickshaw could be a leading link front suspension and trailing arm rear suspension in combination with a sway bar. This report concludes that such a solution would have sufficient performance and still be cheap enough for the tough Indian market. The three-wheel configuration in a delta shape has flaws when it comes to vehicle dynamics and handling as it is more unstable compared to a four wheel configuration. The three wheel set up although have some positive attributes as it is very cheap and is a combination of both a two and a four wheeled vehicle.

The objective of this thesis was to develop a vehicle suspension intended for an auto rickshaw with improved handling and dynamic characteristics. The development of an auto rickshaw suspension was accomplished and data from simulations of the auto rickshaw and its suspension was obtained. The work resulted in an overall suspension solution including parts as leading link suspension for the front, trailing arm suspension with sway bar for the rear and suitable dampers and springs.

P. Srinivas Rao [11] An auto rickshaw is a three wheeled motor vehicle with one front steering wheel. Auto rickshaws are most commonly found in developing countries as they are a very cheap form of transportation due to low price, low maintenance cost, and low operation costs. Auto rickshaws needs to be developed to take the step into the 21-century. To develop a new product in the modern world one of the most important challenges is safety of the users. As for the automotive industries this challenge has a great importance since the outcome can be devastating. One important category from the safety point of view is the vehicle suspensions, as the suspensions control the movement of the wheels and thus keeping the vehicle on the road .Suspension system design is a challenging task for the auto-mobile designers in view of multiple control parameters, complex objectives and stochastic disturbances. The objective of this project is to develop a MATLAB/SIMULINK model of one third auto-rickshaw suspension to analyze the ride comfort and vehicle handling. A theoretical model of the human seated model is developed in order to simulate the vertical motion of the Passenger in an auto rickshaw when the vehicle passing over various road disturbances. This project used a new approach in designing the suspension system which is semi-active suspension. The semi active suspension system uses a varying damping force as a control force. Ride comfort of off-road vehicles can be estimated by replacing the normal passive dampers in the vehicle suspension system with controllable, two-state, semi-active dampers. Skyhook controller is developed for controlling the damping force of the suspension system. Comprehensive analysis of passive and semi-active suspension system in terms of human body vibrational displacements and accelerations has been done. The semi-active suspension with skyhook controller reduces the sprung mass acceleration and displacement hence improving the passengers comfort.

Mr. Amit A. Hingane 1 , Prof. S. H. Sawant2 [12] In this paper, a brief introduction to vehicle primary suspension system is presented along with analysis of a semi-active suspension system with Bingham model for MR damper. Isolation from the forces transmitted by external excitation is the fundamental task of any suspension system. The heart of a semi-active suspension system is the controllable damper. In this paper, the ride and handling performance of a specific vehicle with passive suspension system is compared to semi-active suspension system. The body suspension wheel system is modeled as a two degree of freedom quarter car model. Simulation is carried out using MATLAB/Simulink. The developed design allows the suspension system to behave differently in different operating conditions, without compromising on road-holding ability. Controller has been developed for semi active suspension. The result shows improvement over passive suspension method.

CHAPTER-3

3. MATLAB/SIMULINK

3.1 Introduction

MATLAB stands for Matrix Laboratory. The very first version of MATLAB, written at the University of New Mexico and Stanford University in the late 1970s was intended for use in Matrix theory, Linear algebra and Numerical analysis. Later and with the addition of several toolboxes the capabilities of MATLAB were expanded and today it is a very powerful tool at the hands of an engineer. Typical uses of MATLAB include:

- Math and Computation
- Algorithm development
- Modeling, simulation and prototyping
- Data analysis, exploration and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building

Simulink is a software package for modeling, simulating, and analyzing dynamical systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Systems can also be multi rate, i.e., have different parts that are sampled or updated at different rates.

For modeling, Simulink provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations. With this interface, you can draw the models just as you would with pencil and paper. Simulink includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors. You can also customize and create your own blocks.

Models are hierarchical. This approach provides insight into how a model is organized and how its parts interact. After you define a model, you can simulate it, using a choice of integration methods, either from the Simulink menus or by entering commands in MATLAB's command window. The menus are particularly convenient for interactive work, while the command-line approach is very useful for running a batch of simulations. Using scopes and other display blocks, you can see the simulation results while the simulation is running. In addition, you can change parameters and immediately see what happens, for "what if" exploration. The simulation results can be put in the MATLAB workspace for post processing and visualization. And because MATLAB and Simulink are integrated, you can simulate, analyze, and revise your models in either environment at any point.

For the project, Simulink from MATLAB is used to model the block diagram of the suspension system. The equations will be converted into block diagram by using MATLAB Simulink Library block function. Modeling must be precisely following the required equations in order to avoid error thus giving the correct results during the simulation. For simulation, the complete Simulink diagram must modeled first in order to represent the real suspension system configuration.

3.2 MATLAB SIMULINK LIBRARY

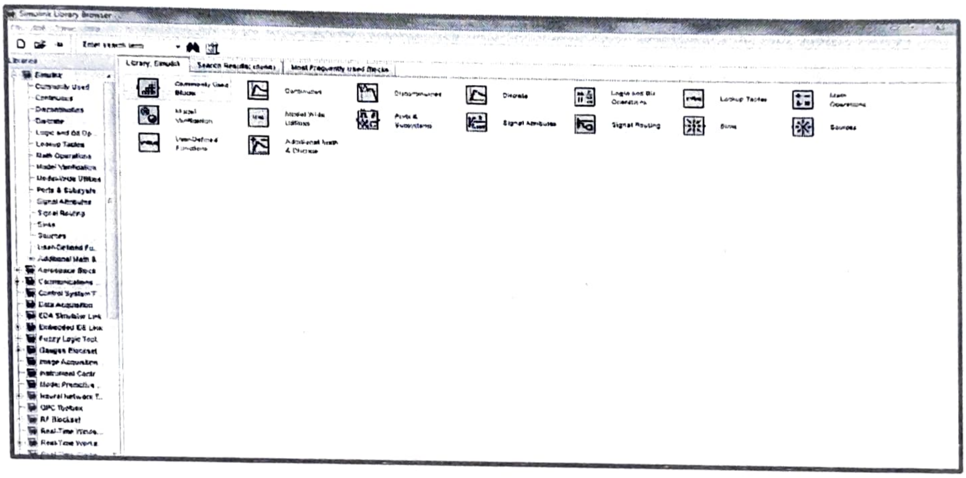
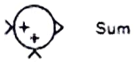


Fig.3.1. Simulink Library

1. **Sum Block:** The Sum block performs addition or subtraction on its inputs. This block can add or subtract scalar, vector, or matrix inputs. It can also collapse the elements of a signal.



2. **Bus Creator:** The Bus Creator block combines a set of signals into a bus. To bundle a group of signals with a Bus Creator block, set the block's **Number of inputs**

parameter to the number of signals in the group. The block displays the number of ports that you specify. Connect the signals to be grouped to the resulting input ports.

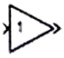

Bus Creator

3. **Constant Block:** The Constant block generates a real or complex constant value. The block generates scalar, vector, or matrix output, depending on the dimensionality of the **Constant value** parameter and the setting of the **Interpret vector parameters as 1-D** parameter. Also, the block can generate either a sample-based or frame-based signal, depending on the setting of the **Sampling mode** parameter.

Constant

The output of the block has the same dimensions and elements as the **Constant value** parameter. If you specify a vector for this parameter, and you want the block to interpret it as a vector, select the **Interpret vector parameters as 1-D** parameter. Otherwise, the block treats the **Constant value** parameter as a matrix.

4. **Gain Block:** The Gain block multiplies the input by a constant value (gain). The input and the gain can each be a scalar, vector, or matrix.



Gain

You specify the value of the gain in the **Gain** parameter. The **Multiplication** parameter lets you specify element-wise or matrix multiplication. For matrix multiplication, this parameter also lets you indicate the order of the multiplicands. The gain is converted from doubles to the data specified in the block mask offline using round-to-nearest and saturation. The input and gain are then multiplied, and the result is converted to the output data type using the specified rounding and overflow modes.

5. Integrator Block: The Integrator block outputs the integral of its input at the current time step. The following equation represents the output of the block y as a function of its input u and an initial condition y_0, where y and u are vector functions of the current simulation time t.

Simulink software can use a number of different numerical integration methods to compute the Integrator block's output, each with advantages in particular applications. Use the **Solver** pane of the Configuration Parameters dialog box (see Solver Pane) to select the technique best suited to your application.

Simulink software treats the Integrator block as a dynamic system with one state, its output. The Integrator block's input is the state's time derivative. The selected solver computes the output of the Integrator block at the current time step, using the current input value and the value of the state at the previous time step. To support this computational model, the Integrator block saves its output at the current time step for use by the solver to compute its output at the next time step. The block also provides the solver with an initial condition for use in computing the block's initial state at the beginning of a simulation run. The default value of the initial condition is 0. The block's parameter dialog box allows you to specify another value for the initial condition or create an initial value input port on the block.

6. Scope Block: The Scope block displays its input with respect to simulation time.

The Scope block can have multiple axes (one per port) and all axes have a common time range with independent *y*-axes.

All the data input to the Scope, preserve axis settings from one simulation to the next, limit data displayed, and save data to the workspace.

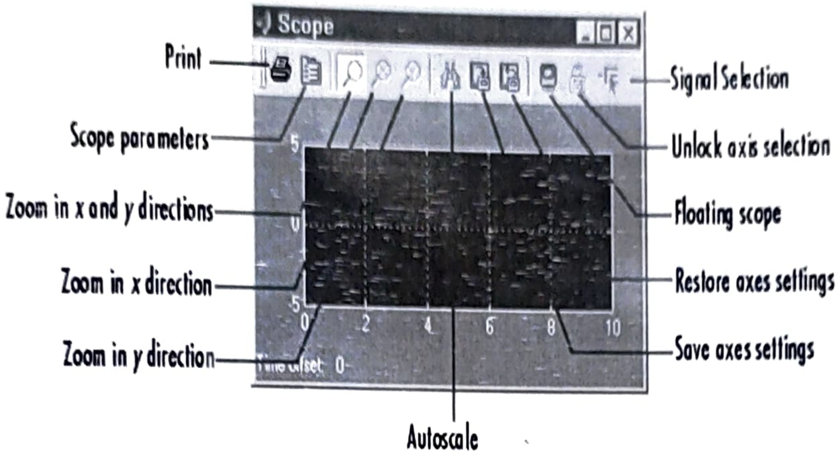
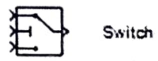
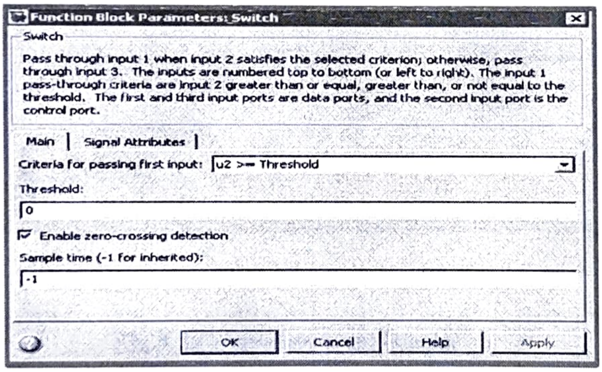


Fig .3.2 Scope OutPut Box

7. Switch Block: The Switch block passes through the first input or the third input based on the value of the second input. The first and third inputs are called *data inputs*. The second input is called the *control input*.



The Main pane of the Switch block dialog box appears as follows:



Switch

Pass through input 1 when input 2 satisfies the selected criterion; otherwise, pass through input 3. The inputs are numbered top to bottom (or left to right). The input 1 pass-through criteria are input 2 greater than or equal, greater than, or not equal to the threshold. The first and third input ports are data ports, and the second input port is the control port.

Criteria for passing first input: u2 >= Threshold

Threshold: 0

☑ Enable zero-crossing detection

Sample time (-1 for inherited): -1

Fig.3.3 Parameters and dialog box

3.3 Building a Simple Model for damper, spring and mass system

This example shows how to build a model using many of the model building commands and actions.

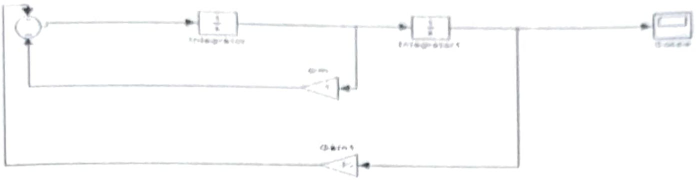


Fig.3.4 Block Diagram for Damper, Spring, And Mass Vibrating System

The model integrates differential equations for simple damper, spring and mass vibration system and displays the result. The block diagram of the model looks like this.

To create the model, first type Simulink in the MATLAB command window. On Microsoft Windows, the Simulink Library Browser appears as below.

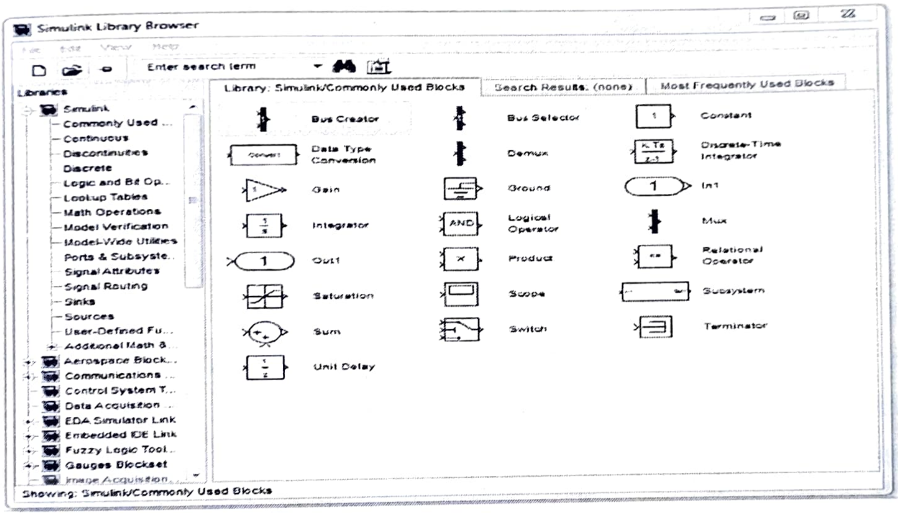


Fig.3.5. Commonly Used Blocks

To create a new model, select Model from the new submenu of the Simulink library window's File menu. To create a new model on Windows, select the New Model button on the Library Browser's toolbar.

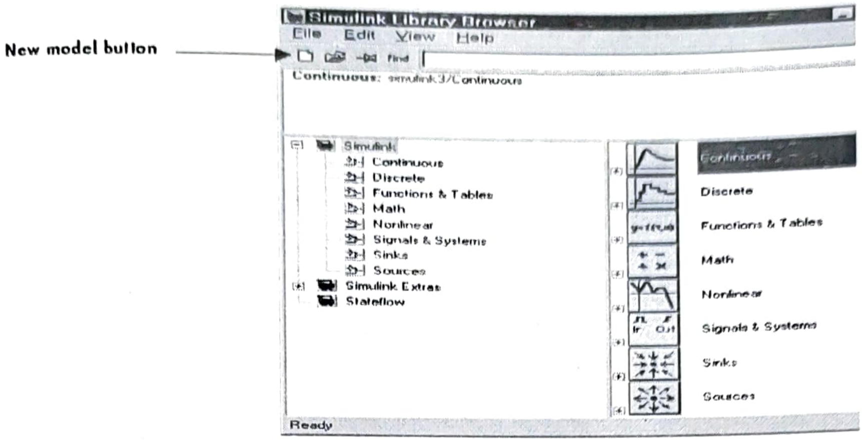
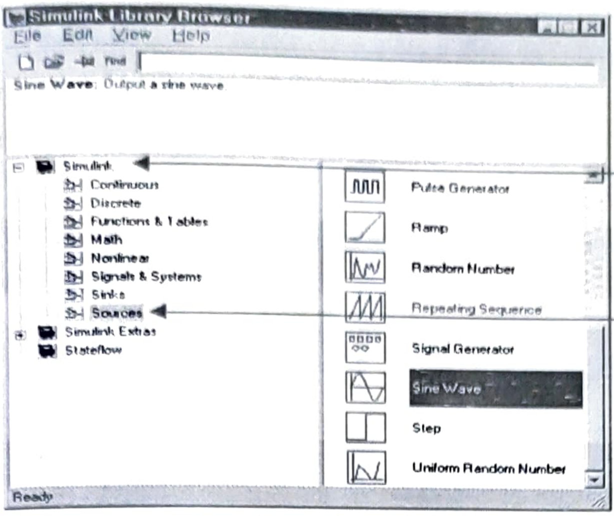


Fig.3.6. Simulink Browser

To create this model, you will need to copy blocks into the model from the following Simulink block libraries:

- Sources library (the Sine Wave block)
- Sinks library (the Scope block)
- Continuous library (the Integrator block)
- Math library (the Gain block)

To copy the Sine Wave block from the Library Browser, first expand the Library Browser tree to display the blocks in the Sources library. Do this by clicking on the Sources node to display the Sources library blocks. Finally, click on the Sine Wave node to select the Sine Wave block. Here is how the Library Browser should look after you have done this.



Simulink library

Sources library

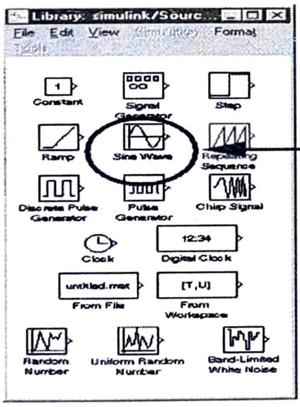
Sine Wave block

Fig.3.7. Simulink Library Browser

Now drag the Sine Wave block from the browser and drop it in the model window. Simulink creates a copy of the Sine Wave block at the point where you dropped the node icon.

To copy the Sine Wave block from the Sources library window, open the Sources window by double-clicking on the Sources icon in the Simulink library window. (On Windows, you can open the Simulink library window by right-clicking the Simulink node in the Library Browser and then clicking the resulting Open Library button.)

Simulink displays the Sources library window



The Sine Wave block

Fig. 3.8. Source Library

Copy the rest of the blocks in a similar manner from their respective libraries into the model window. You can move a block from one place in the model window to another by dragging the block. You can move a block a short distance by selecting the block, then pressing the arrow keys.

With all the blocks copied into the model window, the model should look something like this.

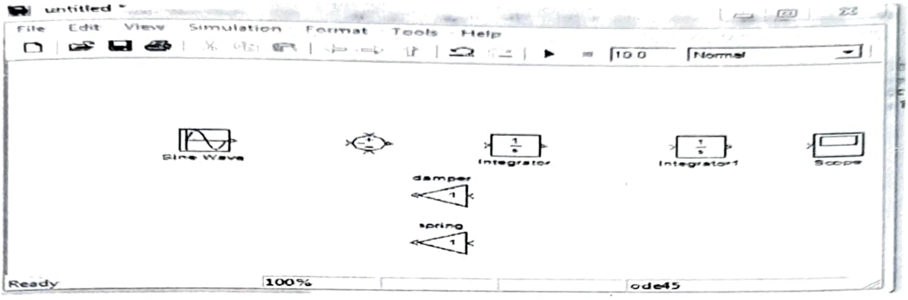
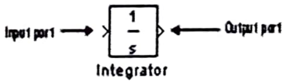


Fig.3.9. Model Creation

If you examine the block icons, you see an angle bracket on the right of the Sine Wave block. The > symbol pointing out of a block is an output port. if the symbol points to a block, it is an input port . A signal travels out of an output port and into an input port of another block through a connecting line. When the blocks are connected, the port symbols disappear.



Now it's time to connect the blocks. Connect the Sine Wave block to the top input port of the Gain block. Position the pointer over the output port on the right side of the Sine Wave block. Notice that the cursor shape changes to cross hairs.

Connect all blocks in the same way. The model appears as follows

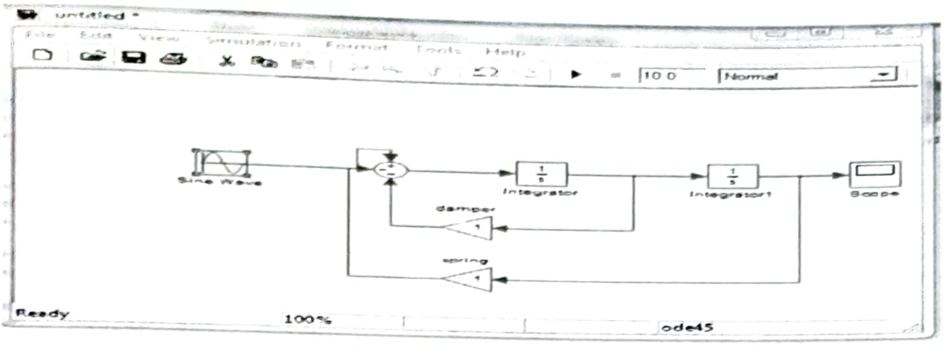


Fig.3.10. Model Creation Step 2

Now, open the Scope block to view the simulation output. Keeping the Scope window open, set up Simulink to run the simulation for 10 seconds. First, set the simulation parameters by choosing Simulation Parameters from the Simulation menu. On the dialog box that appears, notice that the *Stop time* is set to 10.0 (its default value).

Close the Simulation Parameters dialog box by clicking on the *OK* button. Simulink applies the parameters and closes the dialog box.

Choose Start from the Simulation menu and watch the traces of the Scope block's input.

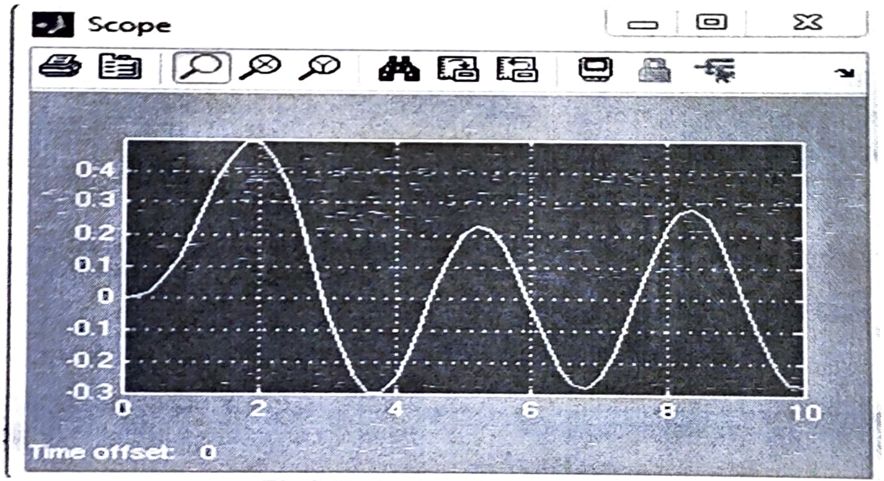


Fig.3.11. Out Put Responses

The simulation stops when it reaches the stop time specified in the Simulation Parameters dialog box or when you choose Stop from the Simulation menu.

To save this model, choose *Save* from the File menu and enter a filename and location. That file contains the description of the model.

3.4 TOOL BOX AND THEIR FUNCTIONS

Table.3.1

TOOL BOX	FUNCTIONS
Statistics and Machine Learning Toolbox	• Visualize Distribution of Channel Data with a Box Plot • Find Mean of Data Ignoring NaN Values
Curve Fitting Toolbox	• Visualize Linear Fit to Scattered Thing Speak Data • Visualize Wind Speed as a Function of Ambient Temperature and Pressure
Control System Toolbox	• Compute Linear Response Characteristics
Signal Processing Toolbox	• Remove and Visualize Outliers in Your Data • Remove Outliers in Your Data
Mapping Toolbox	• Visualize Path Traversed in Vector Maps • Visualize Path Traversed in NASA Map
Data feed Toolbox	• Retrieve Current Financial Data Using Data feed Toolbox
Financial Toolbox	• Visualize Simple Moving Average of Your Data • Create a Candle Plot with Customized Date Axis • Plot the MACD Indicator

CHAPTER-4

4. PROBLEM DETECTION

4.1 Problem Statement

Passive suspension system is very common in the 4-wheeler car. The main problem for passive suspension system is it cannot give comfort to the Person without sacrificing the traction force between the tire and the road. Figure shows the relation of ride comfort and vehicle stability in a vehicle passive suspension system design. The passive suspension system performance also is variable subject to road profile and added person's weight. It is because passive suspension system has fixed spring constant and damping coefficient thus its damping force is not adjustable. This project developed a vehicle suspension system as semi-active suspension system that can adjust its damping force by replacing standard hydraulic damper with a continuously adjustable damper or on and off adjustable damper to overcome the problem. The main focus is to make the vehicle passenger feel more comfortable without sacrificing the vehicle handling abilities.

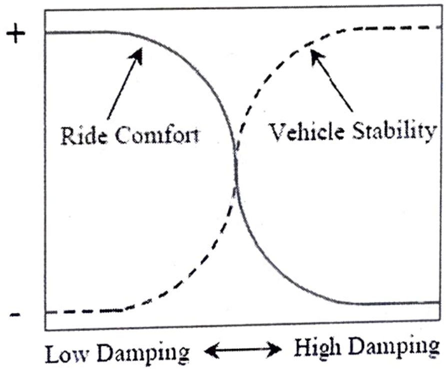


Fig. 4.1 Passive Suspension Design Compromise

4.2 Dynamic model of one third of quatar-car model

Physical models for the investigation of vertical dynamics of suspension systems are most commonly built on the quarter-car model.

4.2.1 Passive system model along with seat

The piecewise linear model of the passive viscous damper used in the simulation is shown in the Fig.2.

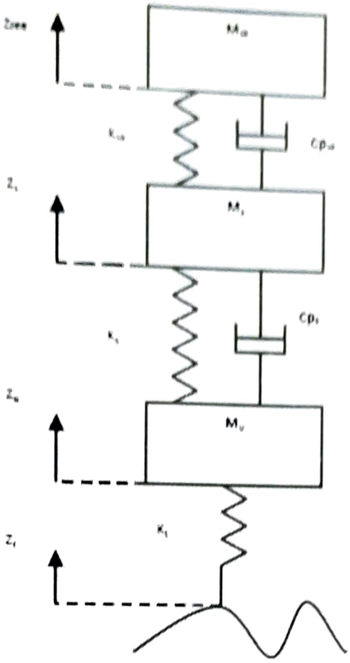


Fig. 4.2 A One-fourth of a car (Passive Model)

If Zse is the vertical displacement of the seat, Z_s is the vertical displacement of the sprung mass, Z_u is the vertical displacement of the unsprung mass and Z_r is the road displacement. The masses of the seat, sprung and unsprung are M_{se}, M_s,and M_u respectively. The corresponding spring stiffness, damping coefficient under the seat are K_{se}, Cp_{se}.Suspension damping and stiffness are indicated as Cp_s and K_s. The tyre stiffness is noted as K_t.

Equation of motion for combined occupant and seat mass is given as

$$\mathbf{Mse}\,\ddot{Z}se + \mathbf{Kse}\,(\mathbf{Zse} - \mathbf{Zs}) + \mathbf{Cpse}(\dot{\mathbf{Z}}\mathbf{se} - \dot{\mathbf{Z}}\mathbf{s}) = 0$$

Equation of motion for sprung mass is

$$\mathbf{Ms}\ddot{\mathbf{Z}}\mathbf{s} + \mathbf{Ks}(\mathbf{zs} - \mathbf{Zu}) + \mathbf{Cps}(\dot{\mathbf{Z}}\mathbf{se} - \dot{\mathbf{Z}}\mathbf{s}) - \mathbf{Kse}(\mathbf{Zse} - \mathbf{Zs})$$

$$-\mathbf{Cpse}(\dot{\mathbf{Z}}\mathbf{se} - \ddot{\mathbf{Z}}\mathbf{s}) = 0$$

Similarly, the equation for unsprung mass is

$$Mu\ddot{Z}s + Kt(Zu - Zr) - Ks(Zs - Zu) - Cps(\dot{Z}s - \dot{Z}u) = 0$$

4.2.2 Semi-Active Model

Semi-active suspension systems are the adaptation of the damping and or the stiffness of the spring to the actual demands. Figure 6 shows a schematic diagram of a one-fourth of car semi-active suspension control system. The common concept of semi-active springs is based on a system containing an air spring or hydro pneumatic system.

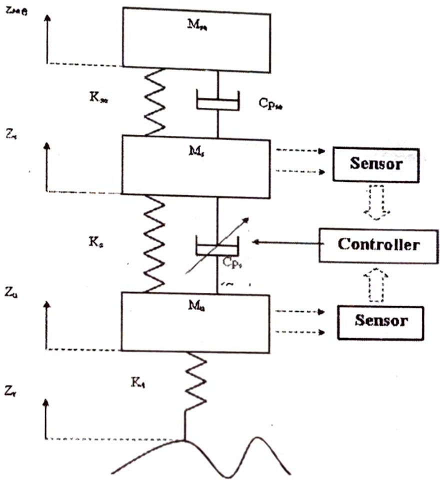


Fig.4.3 A One fourth Of a car Semi-Active Suspension Control System:

4.3 Semi active control strategies

There are different controls strategies adopted under the semi active suspension system, each one having its own characteristics.

4.3.1 Limited Relative Displacement Control Method

The ideal goal of an optimal suspension is to minimize the sprung mass relative displacement and acceleration. However, these two criteria are in conflict. In general, a suspension system with a small relative displacement corresponds to a high sprung mass acceleration, and a large relative displacement corresponds to a low sprung mass acceleration. For this reason, the control strategy is set in a way that the damper is switched to a high damping ratio when the relative displacement is higher than a specific value and a low damping value otherwise. This on–off control law can be expressed as

$$\zeta_s = \begin{cases} \zeta_{max} & |Z_s - \ Z_u| \geq 0 \\ \zeta_{min} = 0 & |Z_s - \ Z_u| < 0 \end{cases}$$

Where

ζs is the equivalent damping ratio of the suspension system.

$$\zeta_S = \frac{C_{PS}}{\sqrt[2]{K_S M_S}}$$

This method can limit the relative displacement of the suspension by adjusting two parameters, ζ max and ζ min. This is a simple approach and the results are matching with skyhook control .Therefore they are not presented here. In this paper simulations are run for skyhook (SH) and modified skyhook (MSH) methods only.

4.3.2 Skyhook Control Method

Skyhook control is a popular and effective vibration control method because it can dissipate system energy at a high rate.

It is typically classified as continuous skyhook control and on-off skyhook control. The on-off Skyhook controller is usually simpler and better suited for the industrial applications. In this study, on-off skyhook control is implemented. The control law can be described as follows:

This strategy indicates that if the relative velocity of the body with respect to the wheel is in the same direction as that of the body velocity, then a maximum damping force should be applied to reduce the body acceleration. On the other hand, if the two velocities are in the opposite directions, the damping force should be at a minimum to minimize body acceleration. This control strategy requires the measurement of the absolute Velocity of body.

4.3.3 Skyhook Controller

Semi-active dampers allow for the damping coefficient, and therefore the damping force, to be varied between high and low levels of damping. Early semi- active dampers were mechanically adjustable by opening or closing a bypass valve. The only power required for the damper is the relatively small power to actuate the valve. For this research, a magneto-rheological damper which varies the damping by electrically changing the magnetic field applied to the magneto-rheological fluid is used. With a semi-active damper, the 2DOF model modifies to Figure 2.6, where the damping coefficient, Controllable, can be varied in time. This configuration is referred to as a semi-active suspension.

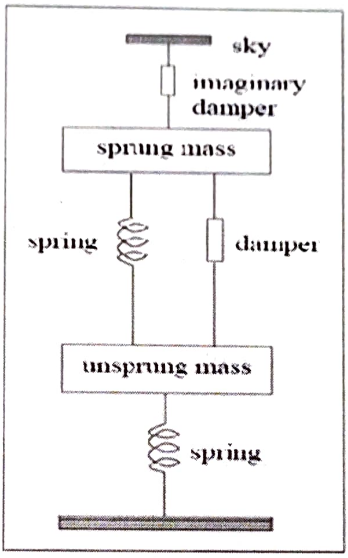


Fig.4.4. 2dof Skyhook Damper Configuration

Once it is decided that a semi-active damper is used, the means of modulating the damper such that it emulates a skyhook damper must be determined. We first define the velocity of the sprung mass relative to the unsprung mass, V_{12}, to be positive when the sprung mass and unsprung mass are separating (i.e., when V_1 is greater than V_2) for the systems. Now assume that for both systems, the sprung mass is moving upwards with a positive velocity V_1. If we consider the force that is applied by the skyhook damper to the sprung mass, we notice that it is in the negative.

X_1direction

or,

$$F_{sky} = -C_{sky} V_1$$

Where, F_{sky} is the skyhook force and C_{sky} is the skyhook damping coefficient. Next, is to determine if the semi-active damper is able to provide the same force. If the sprung and unsprung masses in Fig. 3.1 are separating, then the semi-active damper is in tension. Thus, the force applied to the sprung mass is in the negative X_1 direction, or

$$F_{controllable} = -C_{controllable} V_{12}$$

Where $F_{controllable}$ is the force applied to the sprung mass. Since we are able to Generate a force in the proper direction, the only requirement to match the skyhook suspension is

$$C_{controllable} = C_{sky}$$

To summarize, if V_1 and V_{12} are positive, CONTROLLABLE should be defined as in equation above. Now consider the case in which the sprung and unsprung masses are still separating, but the sprung mass is moving downwards with a negative velocity V_1. In the skyhook configuration, the damping force will now be applied in the upwards, or positive, X_1 direction. In the semi-active configuration, however, the semi-active damper is still in tension, and the damping force will still be applied in the downwards, or negative, direction. Since the semi-active damping force cannot possibly be applied in the same direction as the skyhook damping force, the best that can be achieved is to minimize the damping force. Ideally, the semi- active damper is desired to be set so that there is no damping force, but in reality there is some small damping force present and it is not in the same direction as the skyhook damping force. Thus, if V_{12} is positive and V_1 is negative, we need to minimize the semi-active damping force.

We can apply the same simple analysis to the other two combinations of V_1 and V_{12}, resulting in the well-known semi-active skyhook control policy:

$$\begin{cases} V_1V_{12} > 0 & F_{SA} = C_{SKY}V_1 \\ V_1V_{12} < 0 & F_{SA} = 0 \end{cases}$$

Where, F_{SA} is the semi-active skyhook damper force. Equation (4) implies that when the relative velocity across the suspension (V_{12}) and the sprung mass absolute velocity (V_1) have the same sign, a damping force proportional to V_1 is desired.

The skyhook damper configuration attempts to eliminate the trade-off between resonance control and high frequency isolation common to passive suspensions . Consider the arrangement . The damper is connected to an inertial reference in the sky. Clearly, this arrangement is fictitious, since for this configuration to be implemented, the damper would have to be connected to a reference point which is fixed with respect to the ground but can translate with the vehicle. Such a suspension mounting point does not exist. The end goal of skyhook control is not to physically implement this system, but to command a controllable damper to cause the system to respond in a similar manner to this fictitious system.

In essence, this skyhook configuration is adding more damping to the sprung mass and taking away damping from the un-sprung mass. The skyhook configuration is ideal if the primary goal is isolating the sprung mass from base excitations, even at the expense of excessive un-sprung mass motion. An additional benefit is apparent in the frequency range between the two natural frequencies. With the skyhook configuration, isolation in this region actually increases with increasing C_{sky}.

4.4 Methodology

This project starts with title confirmation with the reseacher of the project. Then the project background, problem statement, objectives and the scopes of the project is discussed with reseacher in order to understand what the overall project is about. Literature review is then conducted in order to investigate past researches in the areas related to this project. Literature review is important as it helps to understand more about the project as well as to get more information about the data and results that can help or used in this project.

After getting enough information about the project, the modeling of the Simulink diagram is started. Firstly, is to model the 2DOF passive suspension system Simulink diagram in MATLAB. The modeling is done by following the equation of motion for the 2DOF passive suspension system. The next process is modeling the skyhook controller Simulink diagram according to the equation that is sourced from the journal. The Simulink diagram of MR damper then is developed and modeled. The MR damper is developed by following the mechanical model formulation of the Bingham method.

The next step is creating the Simulink diagram of semi-active suspension system with skyhook controller. This is achieved by replacing the hydraulic damper in passive suspension system with the MR damper and attached the skyhook controller. Simulink diagram of semi-active suspension system with modified skyhook controller is created after that by adding the modified skyhook controller Simulink diagram to the previous semi-active suspension system with skyhook controller.

After completing all the Simulink diagrams needed for this project, the simulation processes are done in the MATLAB. The results of the simulation then are analyzed and discussed briefly. The final step is writing the final report of the project which includes all five chapters starting from introduction, literature review, methodology, results analysis and the conclusion. The summary of all the methodology above can be summarized into a methodology flowchart which is shown in Figure 3.1 at the next page. All the methodology processes are following the timeline in the Gantt chart which is attached in the appendix.

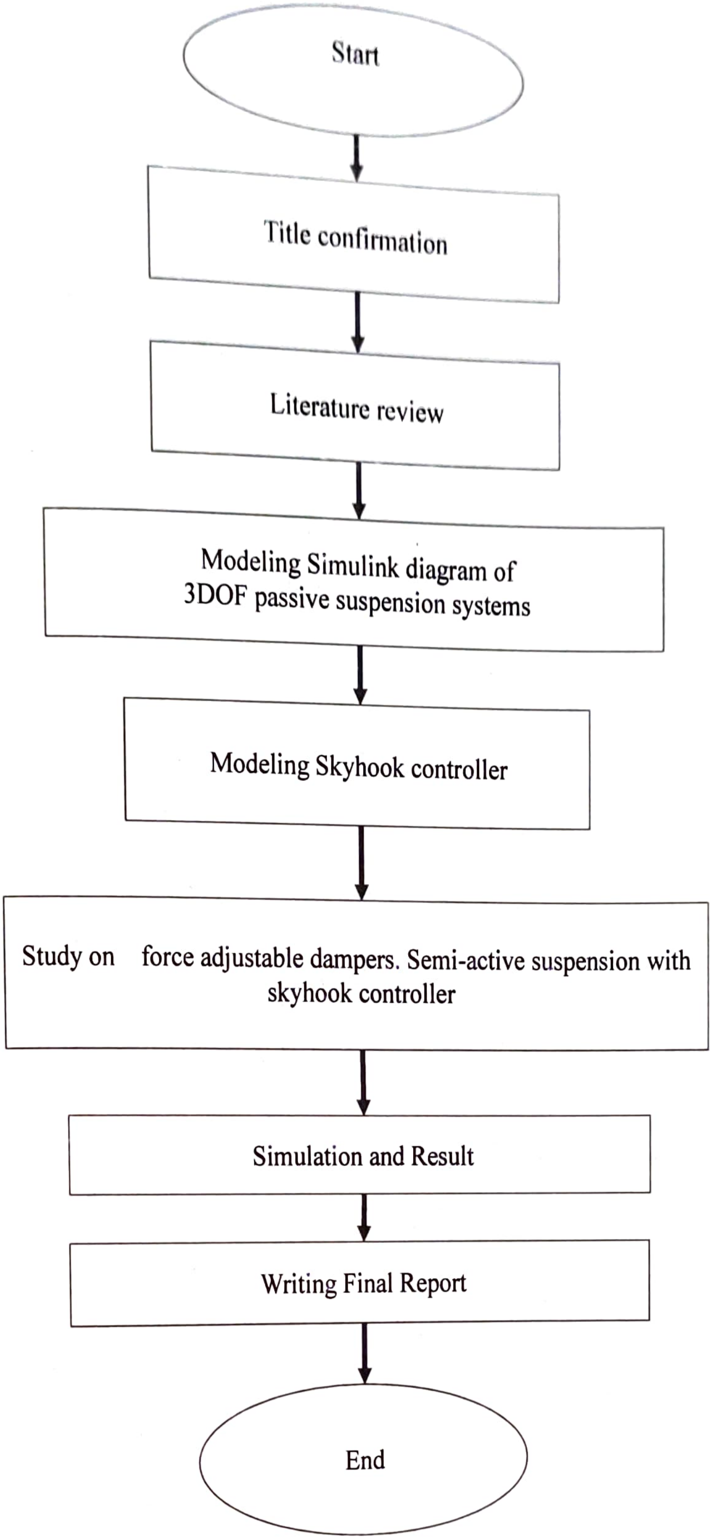


Fig.4.5 Methodology Flowchart

4.5 Modeling and Simulation Software

The software that is used to create the Simulink diagram and running the simulation is MATLAB. MATLAB stands for Matrix Laboratory. The very first version of MATLAB, written at the University of New Mexico and Stanford University in the late 1970s was intended for use in Matrix theory, Linear algebra and Numerical analysis. Later and with the addition of several toolboxes the capabilities of MATLAB were expanded and today it is a very powerful tool at the hands of an engineer. Typical uses of MATLAB include:

- Math and Computation
- Algorithm development
- Modeling, simulation and prototyping
- Data analysis, exploration and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building.

4.6 Implementation using Matlab/Simulink

The Simulink block diagram for passive suspension system by means of state space approach. The various matrices are entered in to the simulink block and the response for the given input is obtained. Skyhook and modified skyhook controllers are implemented to estimate the passenger comfort when the vehicle passing over the bump with a speed of 40kmph.

In this Simulink block diagram an on-off switch is used to actuate control policy. This switch has three input ports which are numbered from top to bottom and one output port. The first and third input ports are data ports and second input port is control port. As per the control algorithm policy, signal passes through input one when input two satisfies the selected criteria; otherwise it passes through input three. In this way the damper switches back and forth between two possible damping states, high damping and low damping. In this analysis, equivalent damping ratio ζ_S value is varied between 0.11 to 0.45 for case and 0.11 to 0.6 for second case. This is to check whether the same results are obtained through adjustment of parameters within the range of maximum and minimum limits.

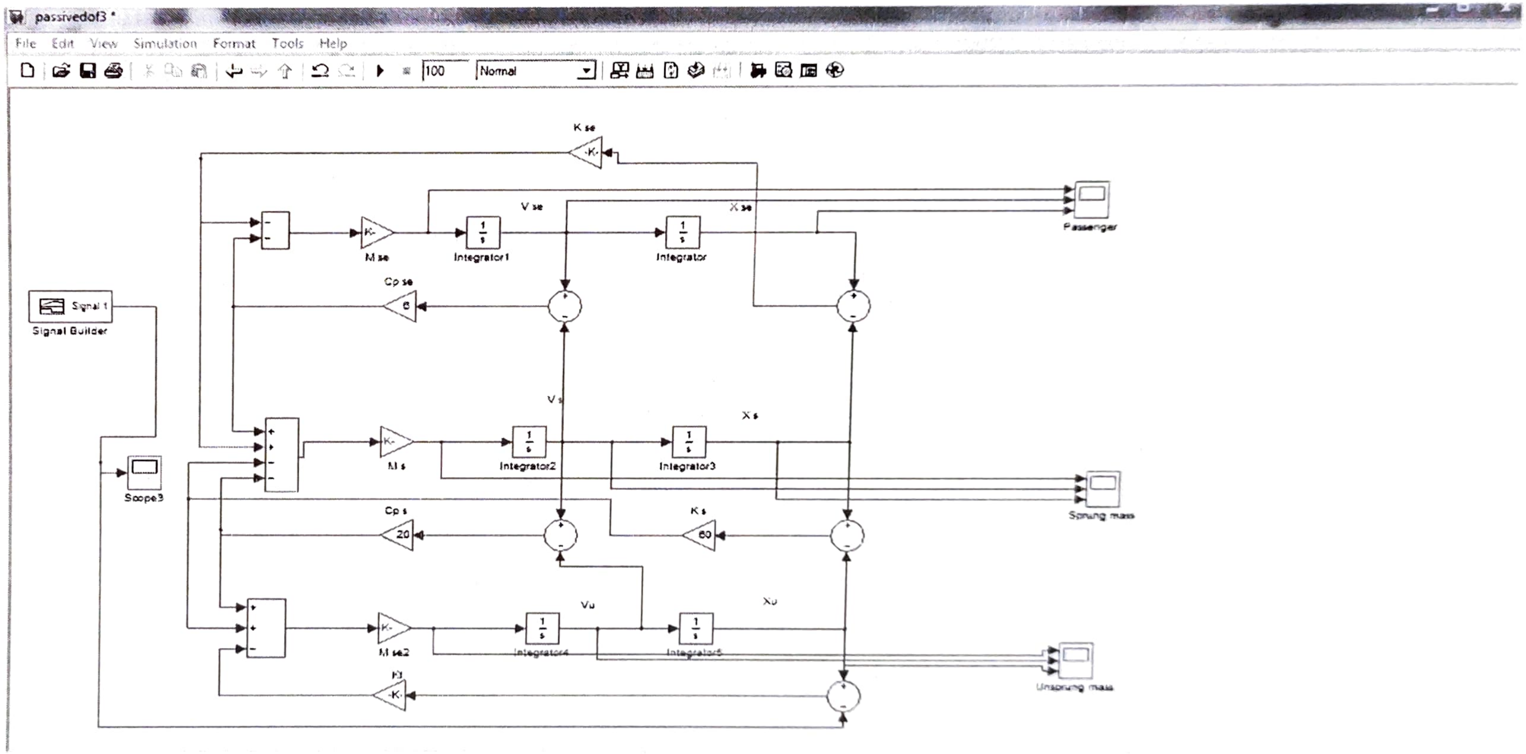


Fig.4.6. Passive Simulink block diagram

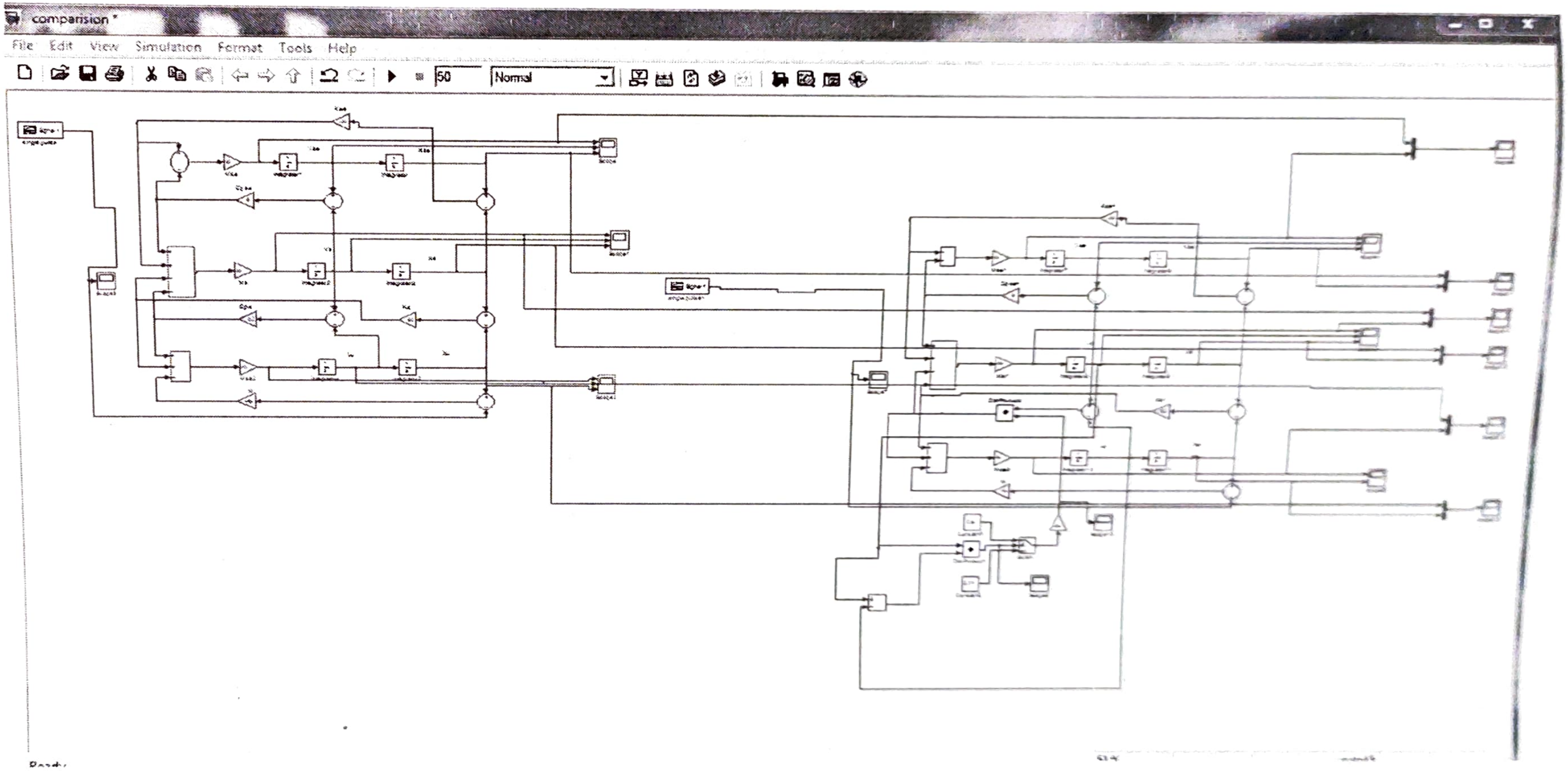


Fig.4.7. Passive/semi-active Simulink block diagram

CHAPTER-5

5. RESULTS AND DISCUSSION

Here, MATLAB/Simulink is used as a computer aided control system tool for modelling the non-physical quarter car with its modelling as, all included in one analysis loop passive system and semi-active suspension system. The vehicle parameter considered for the analysis given in table for the response of the system observed in 35 sec. scale. The simulation results for the semi-active suspension system with skyhook control policy show apparent trade-off in between displacement ,velocity and acceleration. The semi-active suspension system response of the skyhook control peak to peak displacement is less when compared with passive systems. The seat peak to peak accelerations of the vehicle are increased at the cost of peak to peak reduction of displacement between the passive and semi-active. The important finding for semi-active suspension system with skyhook control and passive is the response of the both seat and sprung mass dies out faster in semi-active system.

Table .5.1.Parameters of the car

Body mass(sprung mass)	8200kg
Mass of the wheel/axle assembly(unsprung mass)	400kg
Person's and seat mass	100kg
Suspension damping	5KNs/mm
Suspension stiffness	0.4MN/mm
Persons seat Damping	6KNs/mm
Persons seat Stiffness	0.1MN/mm
Tire stiffness	2MN/mm

5.1 Different Input signal

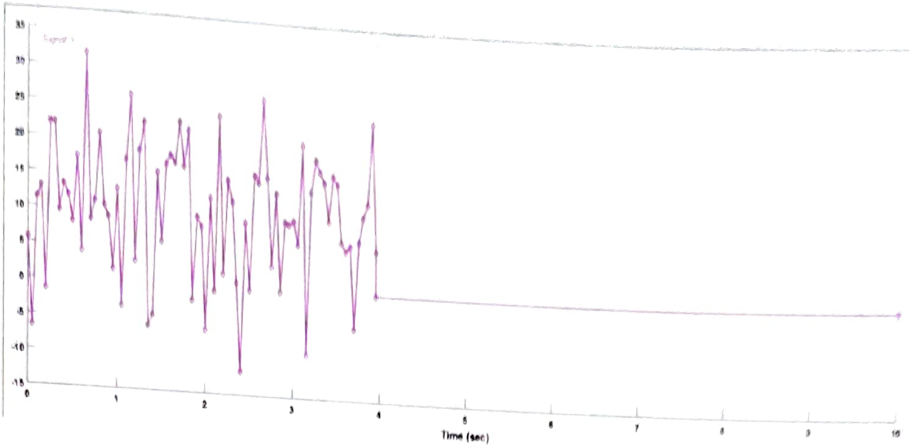


Fig. 5.1. Input signal for Random spectrum with 20 frequency

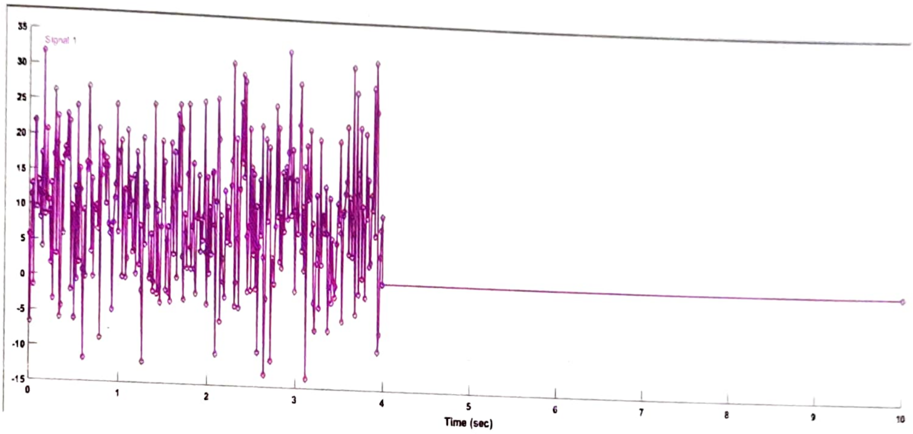


Fig. 5.2. Input signals for Random spectrum with 80 frequency

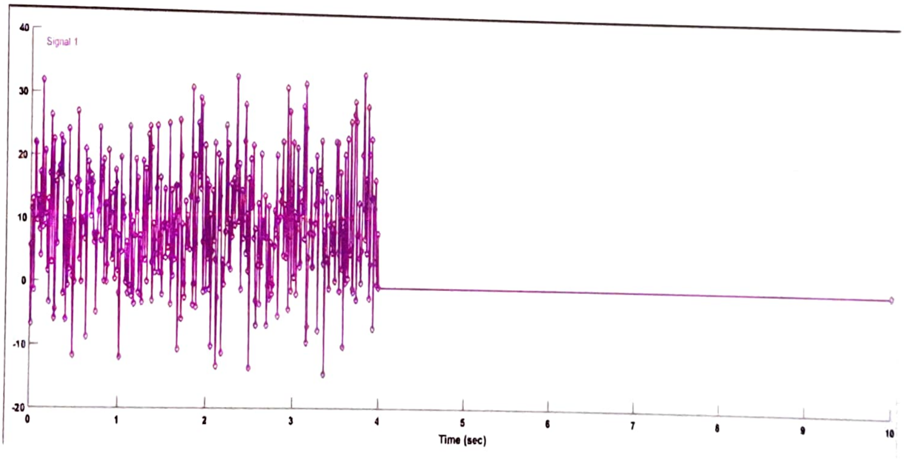


Fig. 5.3 Input signals for Random spectrum with 100 frequency

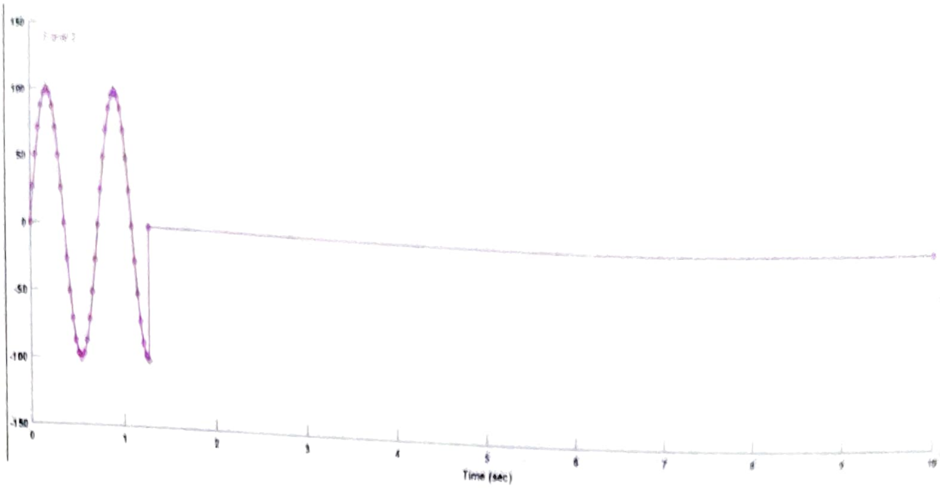


Fig. 5.4 Input signals for sinusoidal bump with 100 amplitude

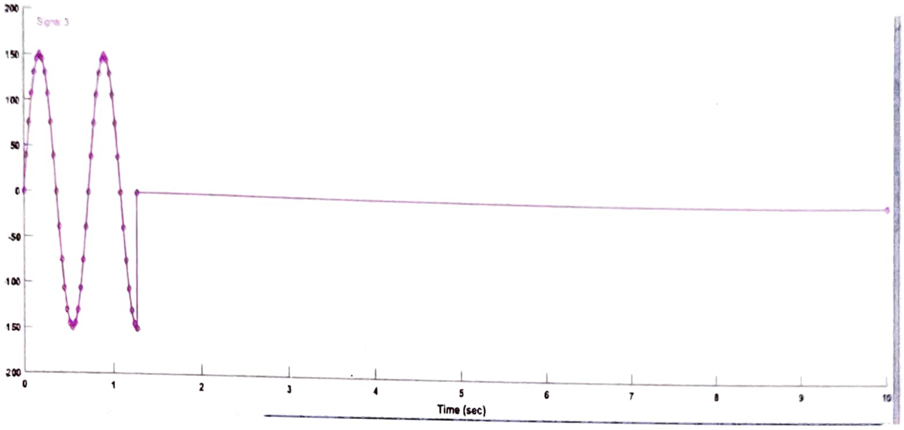


Fig. 5.5 Input signals for sinusoidal bump with 150 amplitude

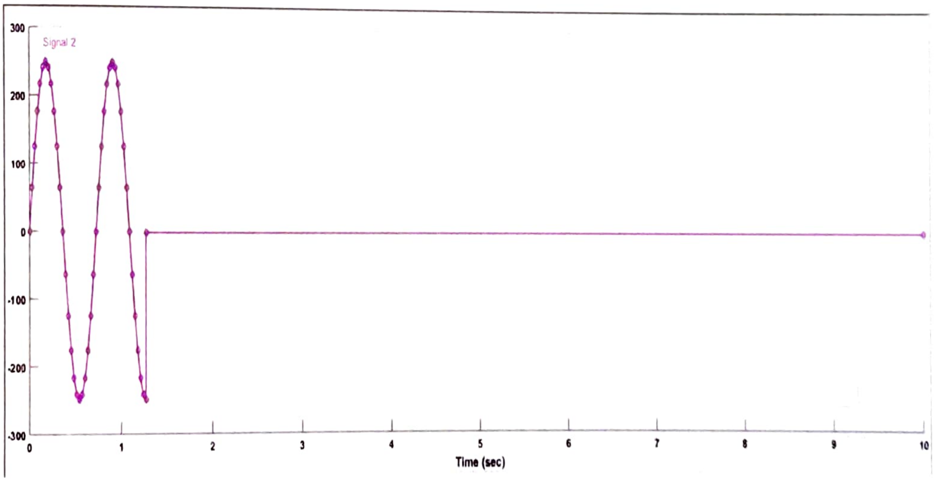


Fig. 5.6 Input signals for sinusoidal bump with 250 amplitude

5.2 Equivalent Damping Ratio In Between 0.0436 and 0.6

5.2.1 Random spectrum/bump with 20 frequency (passive system)

Table .5.2. Displacement and Time values

Input	Controller	Max. persons displacement (mm)	Time (sec)	Max. sprung mass displacement (mm)	Time (sec)	Max. Unsprung mass displacement (mm)	Time (sec)
Random spectrum with 20 frequency(5 kmph)	Passive	27.7	2.8	27	2.86	43	0.7

Table.5.3. Acceleration and Time values

Input	Controller	Max. persons Acceleration (mm/s^2)	time (sec)	Max. sprung mass Acceleration (mm/s^2)	Time (sec)	Max. Unsprung mass Acceleration (mm/s^2)	Time (sec)
Random spectrum with 20 frequency(5 kmph)	Passive	1920	2.17	2080	2.15	94*10^3	2.11

a.**Simulation Responses**

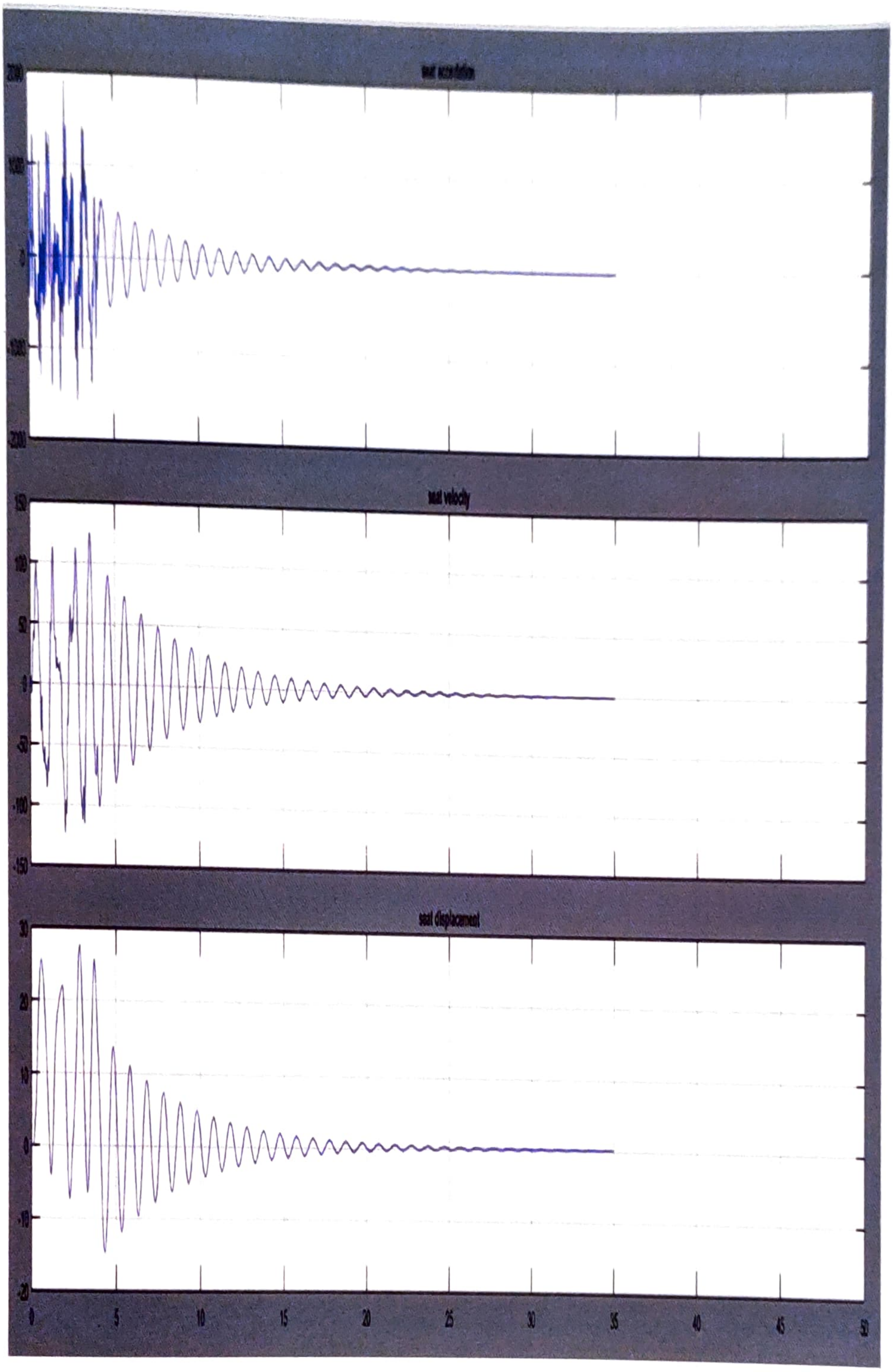


Fig.5.7. seat acceleration, velocity and displacement for 20 frequency random spectrum

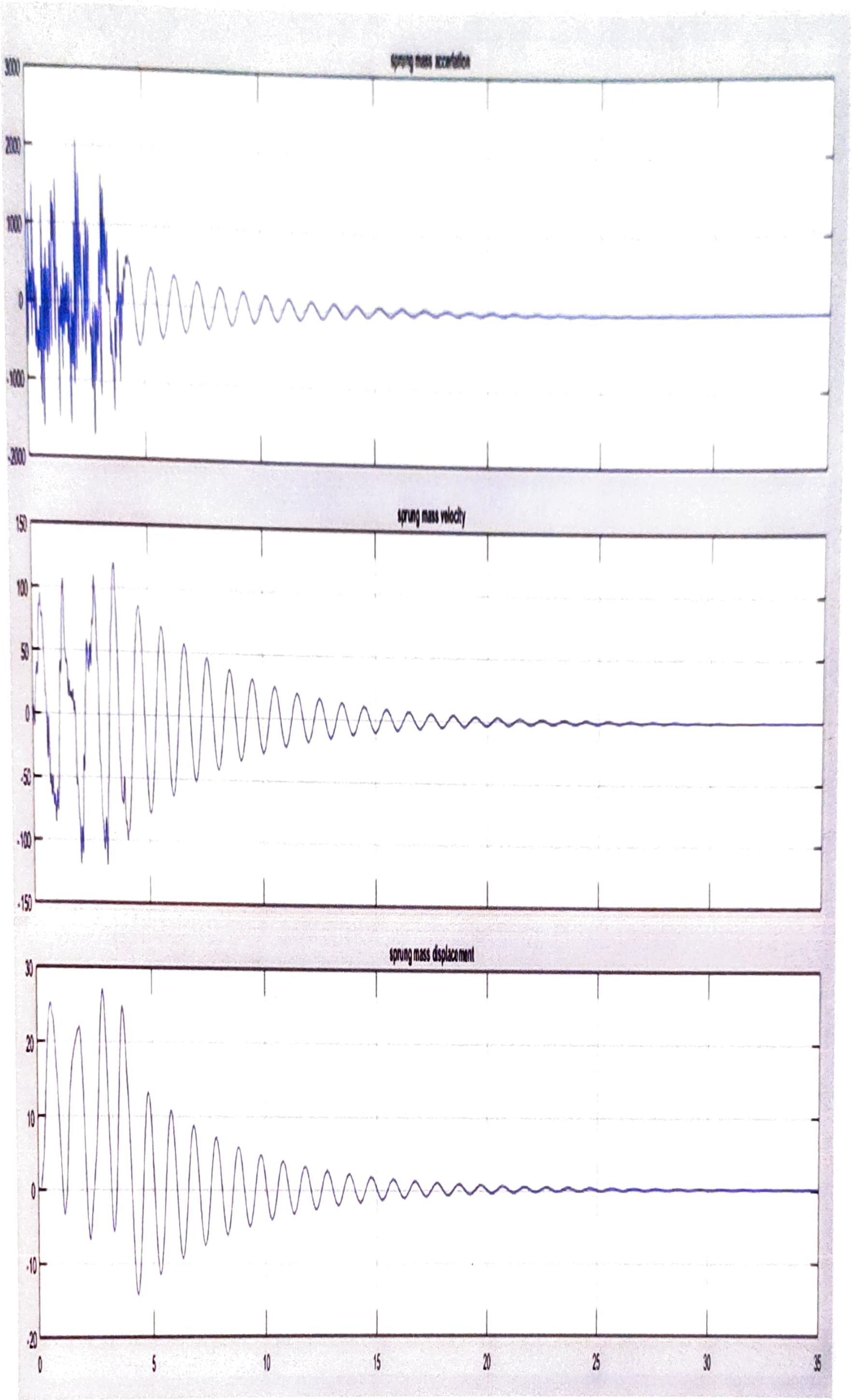


Fig.5.8. sprung mass acceleration, velocity and displacement for 20 frequency random spectrum

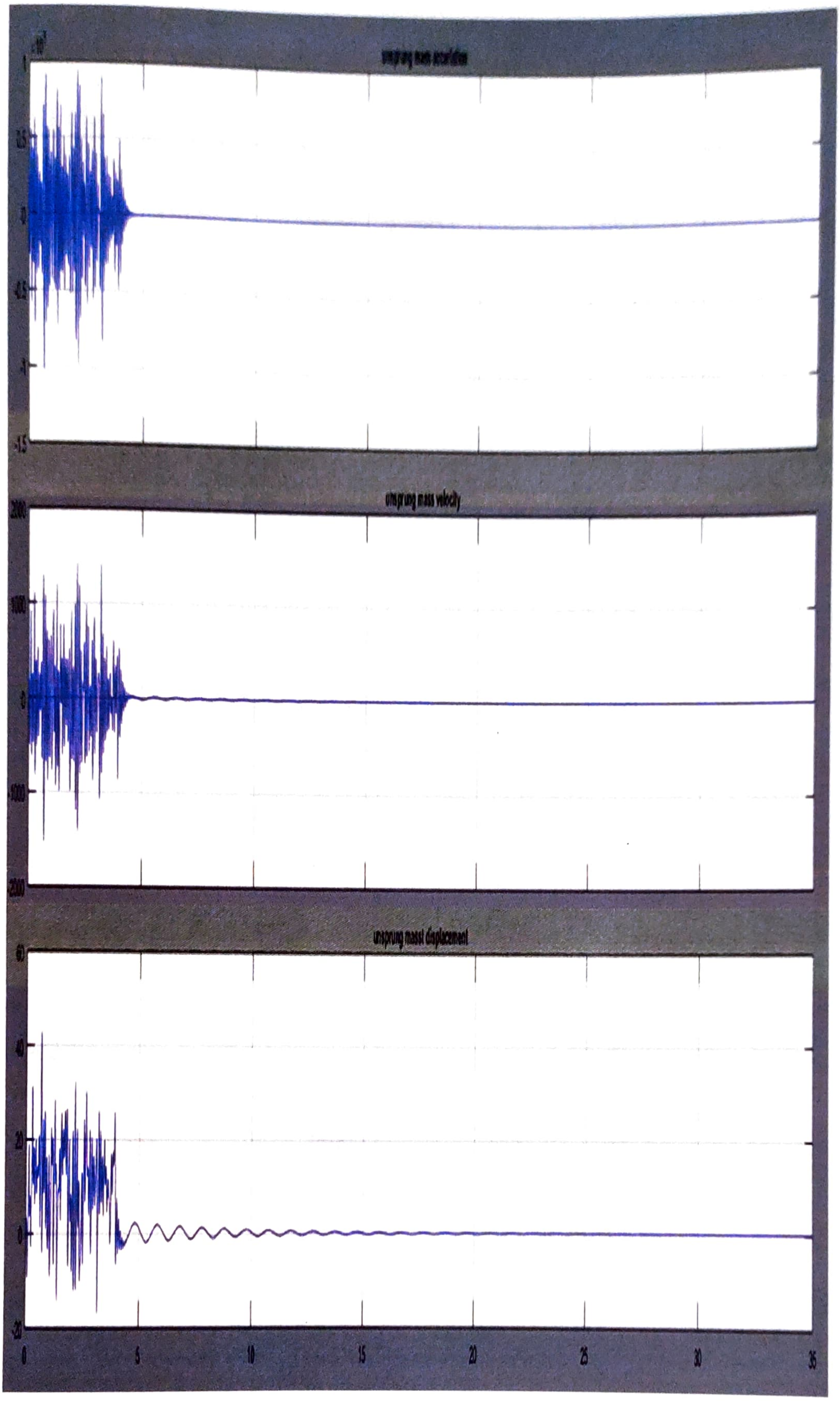


Fig .5.9. unsprung mass acceleration, velocity and displacement for 20 frequency random spectrum

5.2.2 Random spectrum with 80 frequency

Table 5.4. Displacement and Time values

Input	Controller	Max. persons displacement (mm)	Time (sec)	Max. sprung mass displacement (mm)	Time (sec)	Max. Unsprung mass displacement (mm)	Time (sec)
Random spectrum with 80 frequency(5k mph)	Passive	16.5	0.5	17	0.5	31.5	2.78

Table.5.5. Acceleration and Time values

Input	Controller	Max. persons Acceleration (mm/s^2)	Time (sec)	Max. sprung mass Acceleration (mm/s^2)	Time (sec)	Max. Unsprung mass Acceleration (mm/s^2)	Time (sec)
Random spectrum with 80 frequency(5k mph)	Passive	1800	2.77	2370	3.66	2.285*10^5	2.68

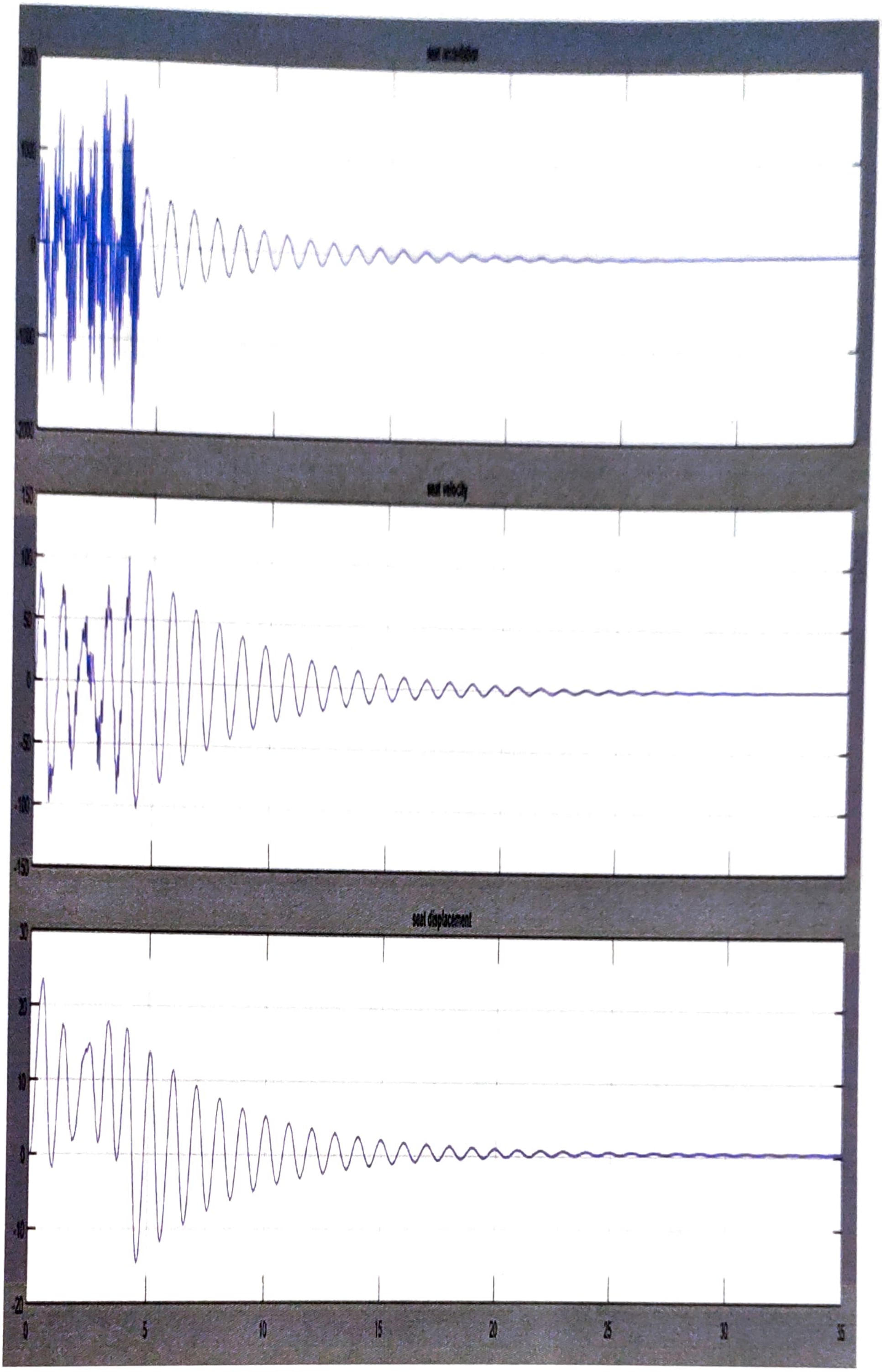


Fig5.10. Seat acceleration, velocity and displacement for 80 frequency random spectrum

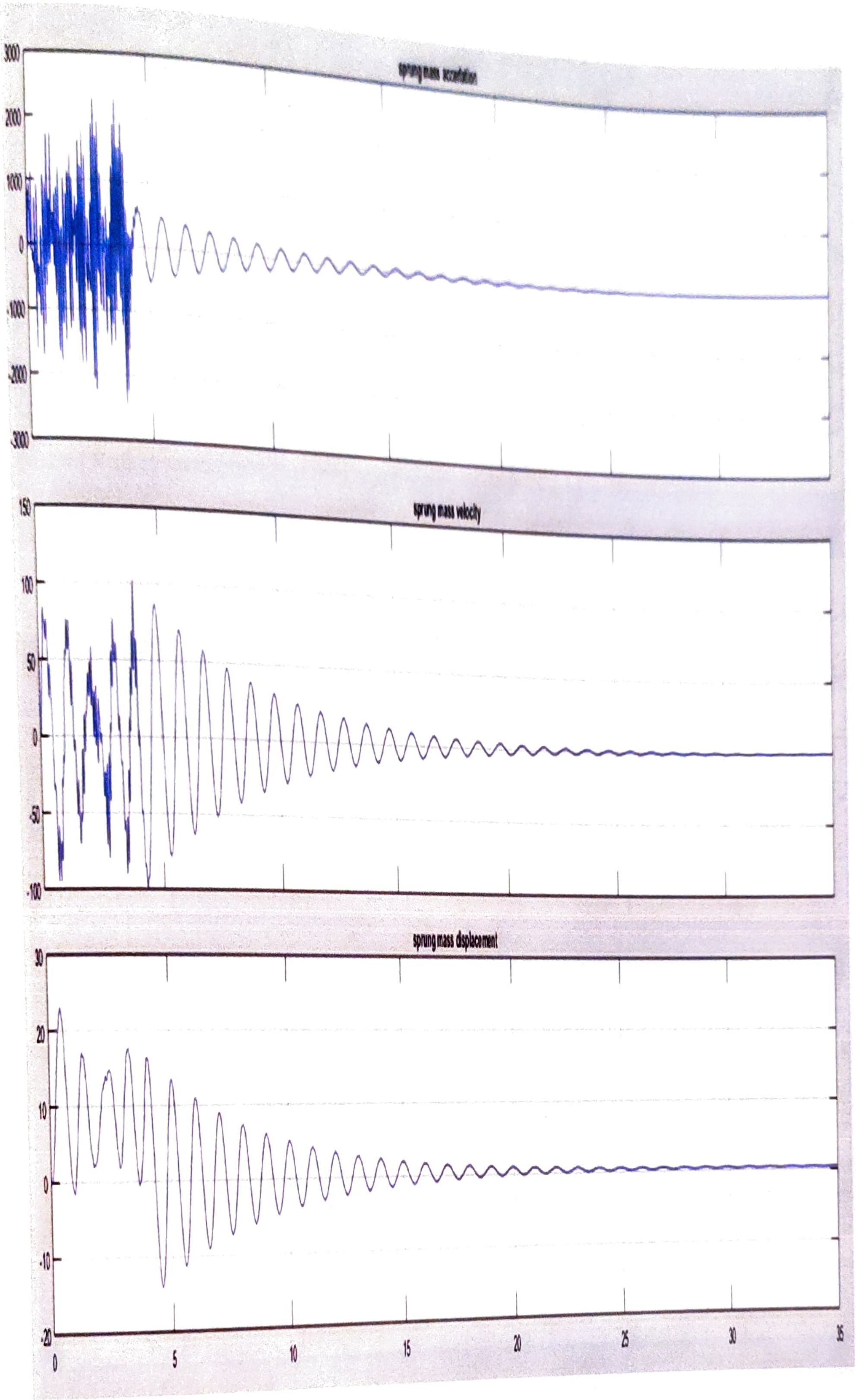


Fig.5.11. Sprung mass acceleration, velocity and displacement for 80 frequency random spectrum

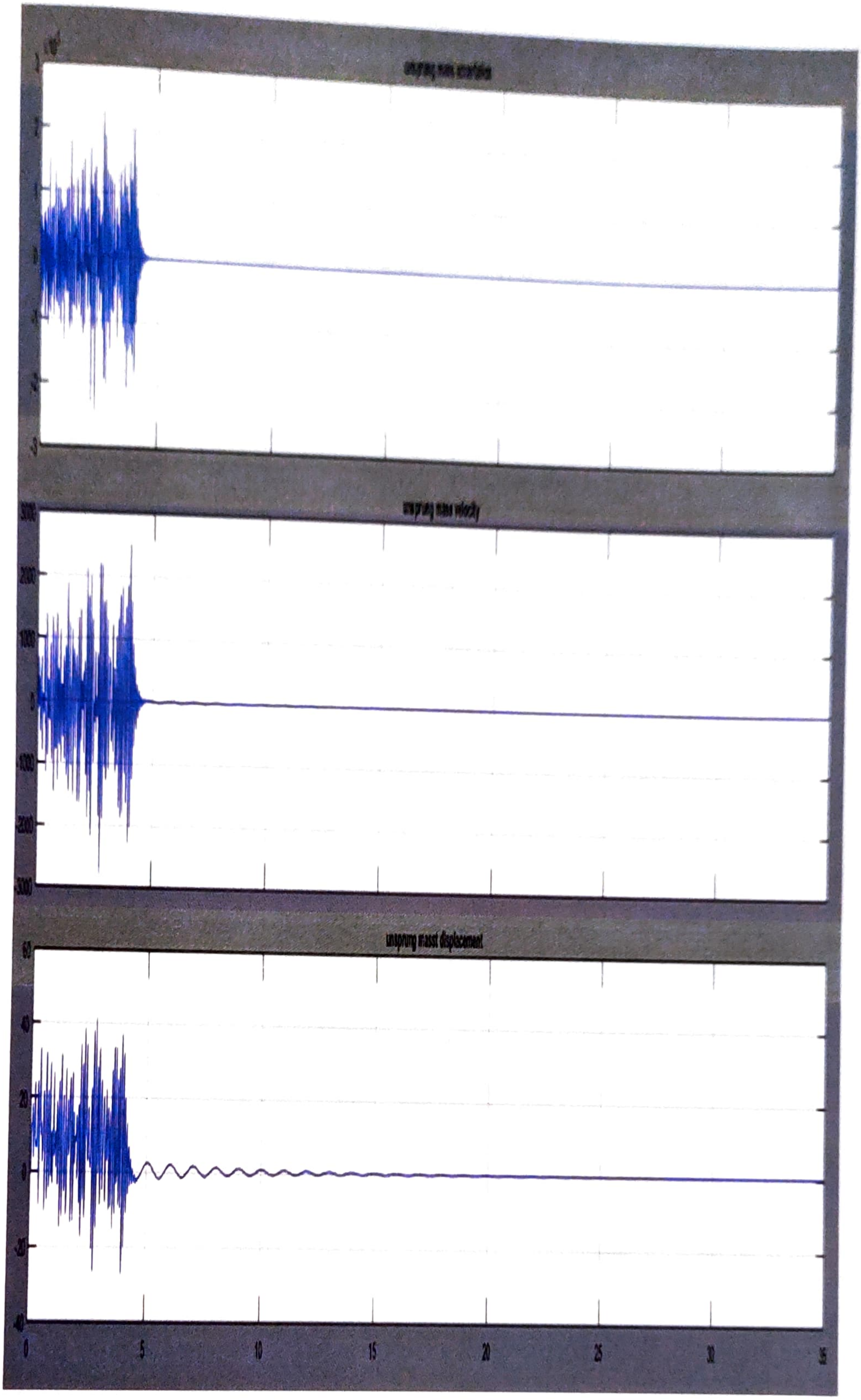


Fig.5.12. Unsprung mass acceleration, velocity and displacement for 80 frequency random spectrum

5.2.3 Random spectrum with 100 frequency

Table. 5.6 Displacement and Time values

Input	Controller	Max. persons displacement (mm)	Time (sec)	Max. sprung mass displacement (mm)	Time (sec)	Max. Unsprung mass displacement (mm)	Time (sec)
Random spectrum with 100 frequency(5 kmph)	Passive	18.5	3.3	20.3	3.4	38.5	2.25

Table 5.7. Acceleration and Time values

Input	Controller	Max. persons Acceleration (mm/s^2)	Time (sec)	Max. sprung mass Acceleration (mm/s^2)	Time (sec)	Max. Unsprung mass Acceleration (mm/s^2)	Time (sec)
Random spectrum with 100 frequency(5kmph)	Passive	1603	3.83	2180	2.23	20*10^4	2.15

a.Stimulink responses

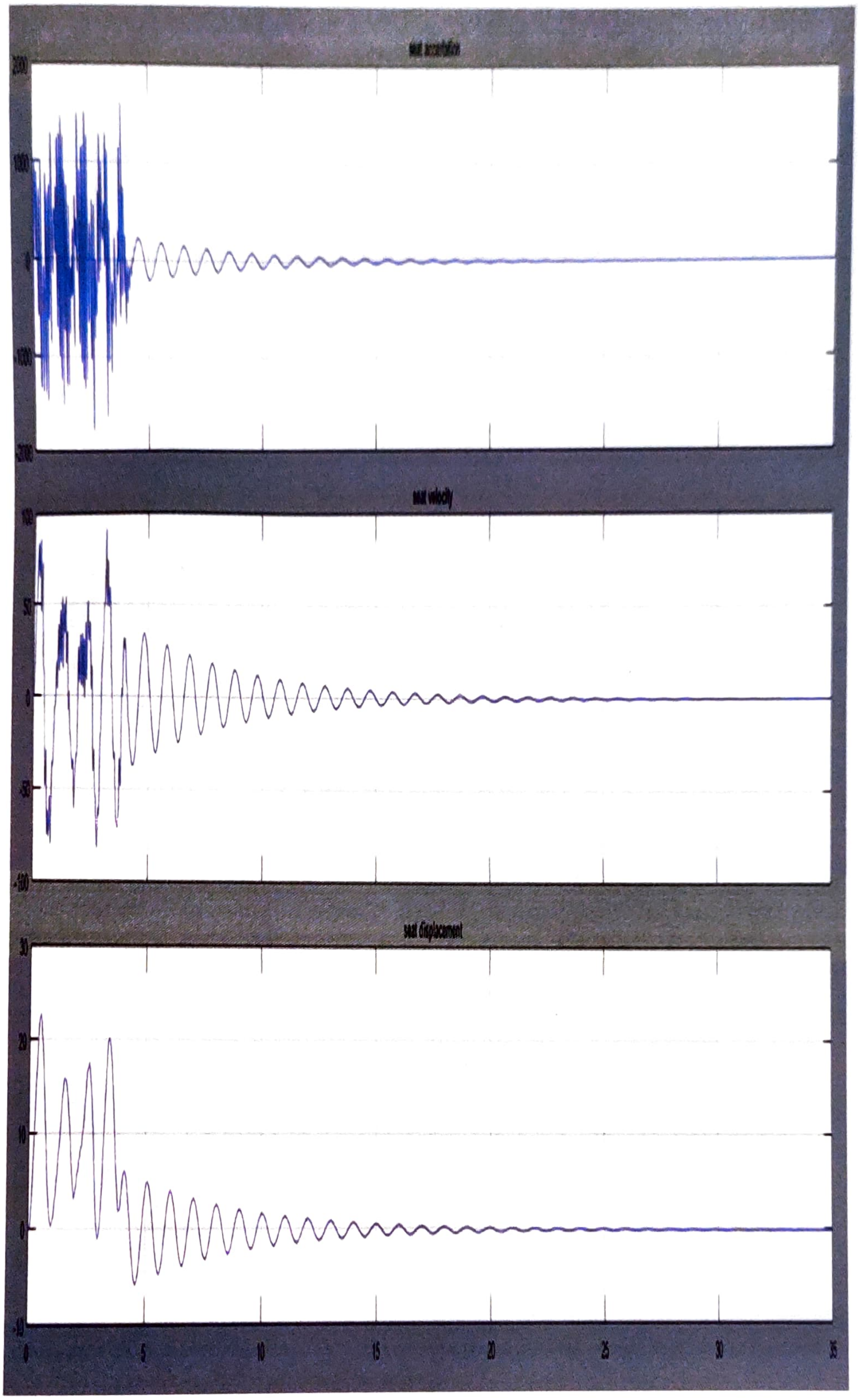


Fig5.13. Seat acceleration, velocity and displacement for 100 frequency random spectrum

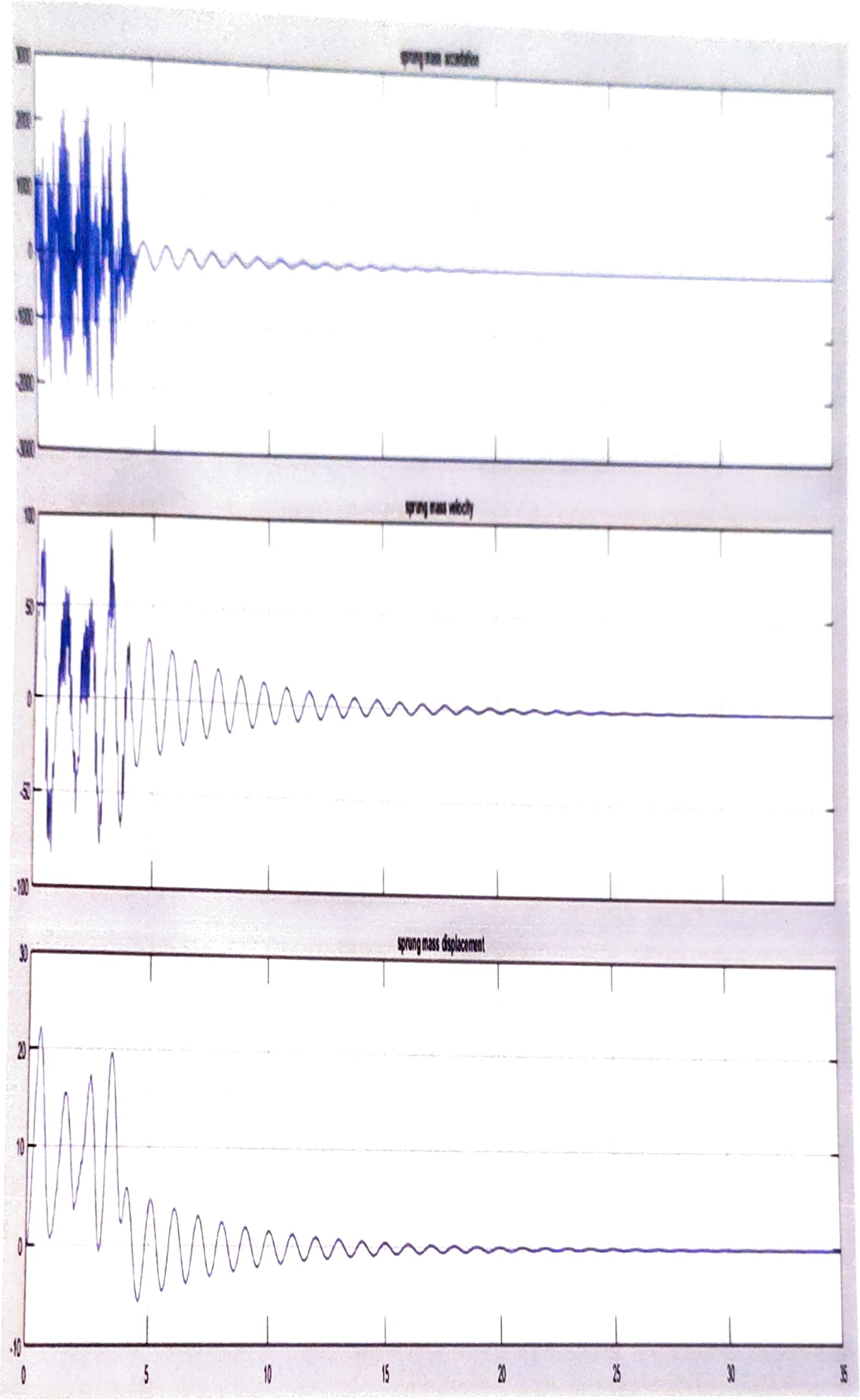


Fig5.14. Sprung mass acceleration, velocity and displacement for 100 frequency random spectrum

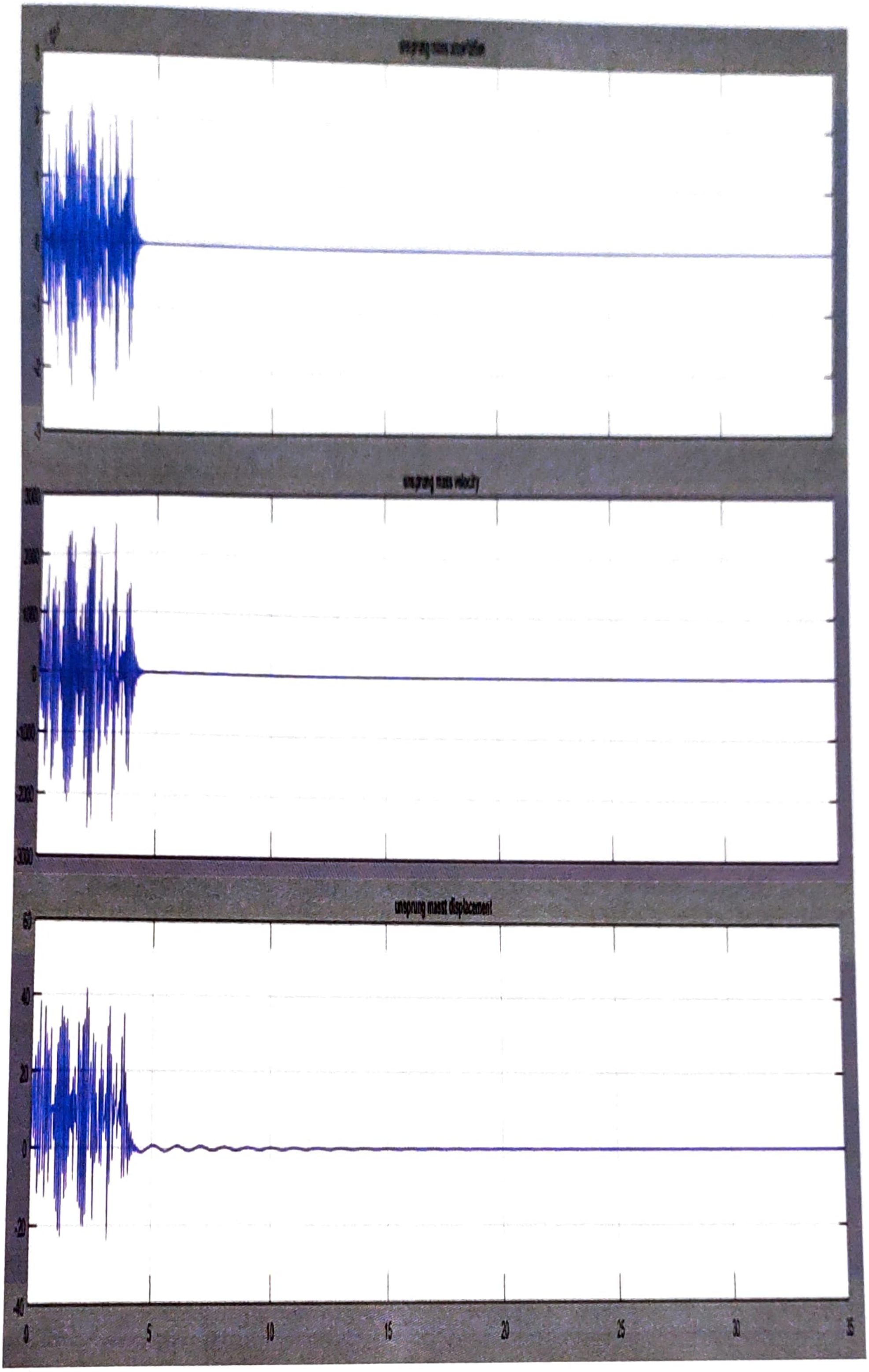


Fig5.15.Unsprung mass acceleration, velocity and displacement for 100 frequency random spectrum

5.2.4 Sinusoidal 2 peak bump having 100 amplitude

Table 5.8 Seat Displacement, velocity, acceleration and Time values

Input	Controller	Max. persons displacement (mm)	Time (sec)	Max. passenger velocity (mm/sec)	Time (sec)	Max. passenger acceleration (mm/s²)	Time (sec)
Sinusoidal bump (5 kmph)	Passive	246	1.238	1767.7	1.038	1.2251 *10^4	0.843
	Semi active	222.7	1.238	1746	1.038	1.1132 *10^4	0.843

5.2.5 Sinusoidal 2 peak bump having 150 amplitude

Table 5.9 Seat Displacement, velocity, acceleration and Time values

Input	Controller	Max. persons displacement (mm)	Time (sec)	Max. passenger velocity (mm/sec)	Time (sec)	Max. passenger acceleration (mm/s²)	Time (sec)
Sinusoidal bump (5 kmph)	Passive	369	1.24	2652	1.037	1.8377 *10^4	0.83
	Semi active	189.5	1.24	2157.56	0.99	1.558* 10^4	0.83

5.2.6 Sinusoidal 2 peak bump having 250 amplitude

Table 5.10 Seat Displacement, velocity, acceleration and Time values

Input	Controller	Max. persons displacement (mm)	Time (sec)	Max. passenger velocity (mm/sec)	Time (sec)	passenger Max. acceleration (mm/s^2)	Time (sec)
Sinusoidal bump (5 kmph)	Passive	615	1.24	4420	1.04	3.063*10^4	0.845
	Semi active	316	1.24	2379	0.95	2.523*10^4	0.845

a.**Simulation Responses: For 100 amplitude sinusoidal 2peak bump**

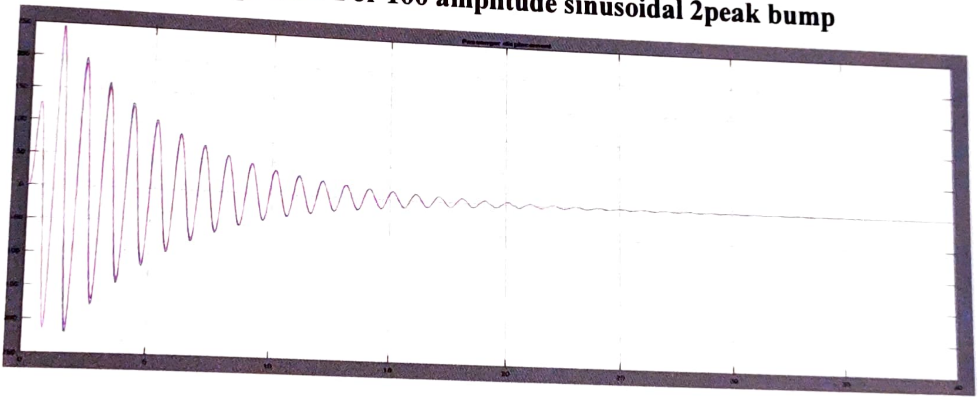


Fig5.16. Seat displacement for 100 amplitude sinusoidal bump (comparison between passive and semi active systems)

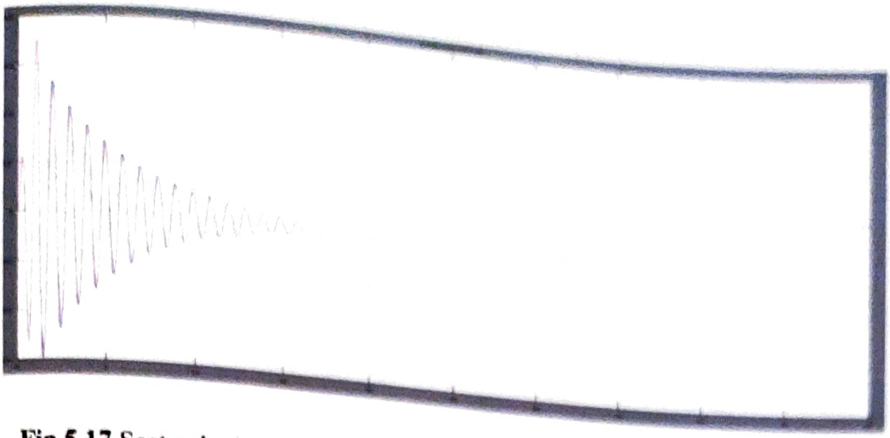


Fig.5.17.Seat velocity for 100 amplitude sinusoidal bump (comparison between passive and semi active systems)

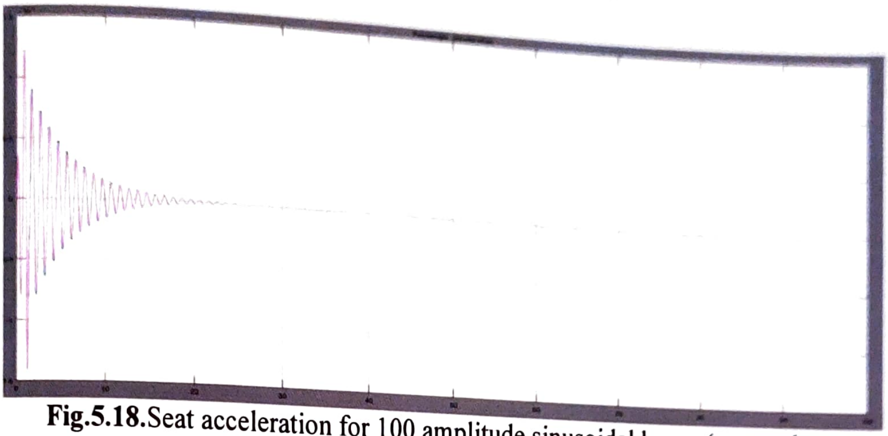


Fig.5.18. Seat acceleration for 100 amplitude sinusoidal bump (comparison between passive and semi active systems)

a.Simulation Responses: For 150 amplitude sinusoidal 2peak bump

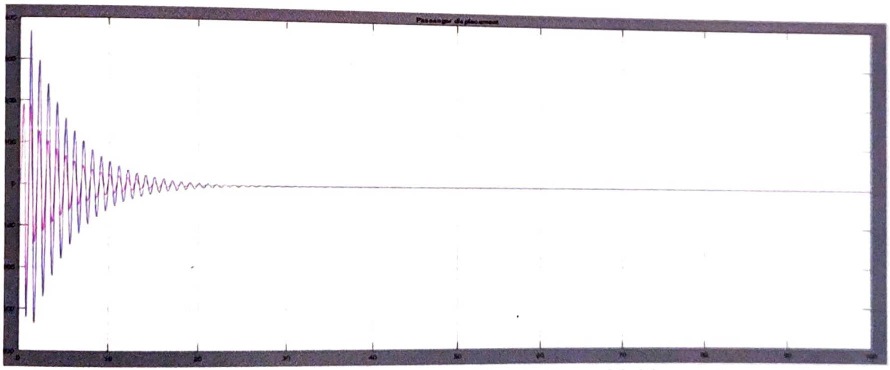


Fig.5.19. Seat displacement for 150 amplitude sinusoidal bump (comparison between passive and semi active systems)

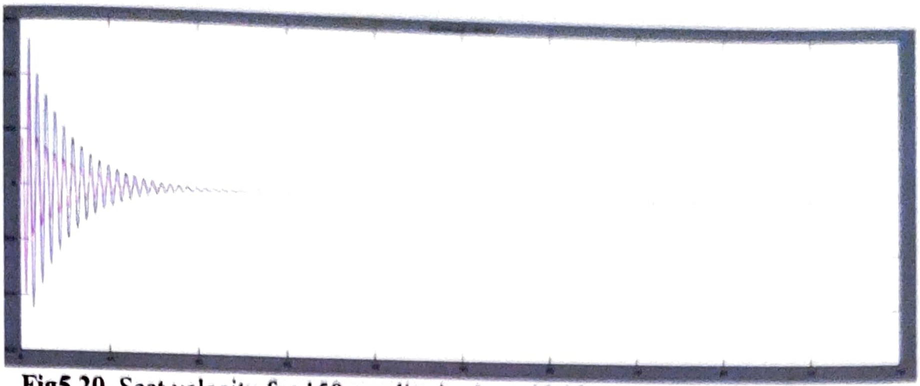


Fig5.20. Seat velocity for 150 amplitude sinusoidal bump (comparison between passive and semi active systems)

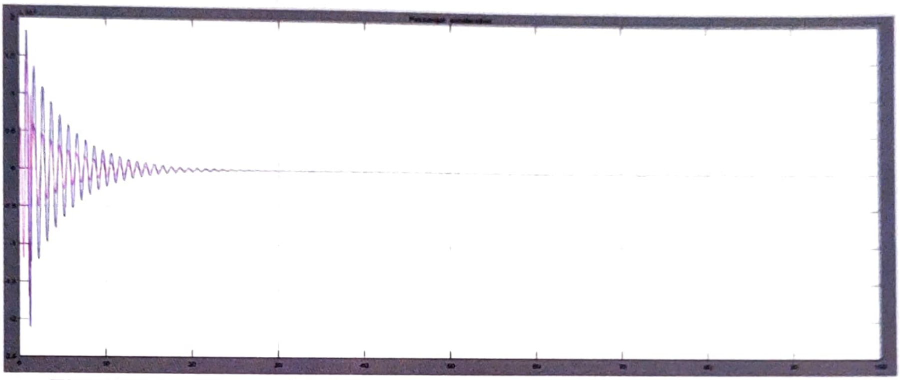


Fig5.21. Seat acceleration for 150 amplitude sinusoidal bump (comparison between passive and semi active systems)

a.**Simulation Responses: For 250 amplitude sinusoidal 2peak bump**

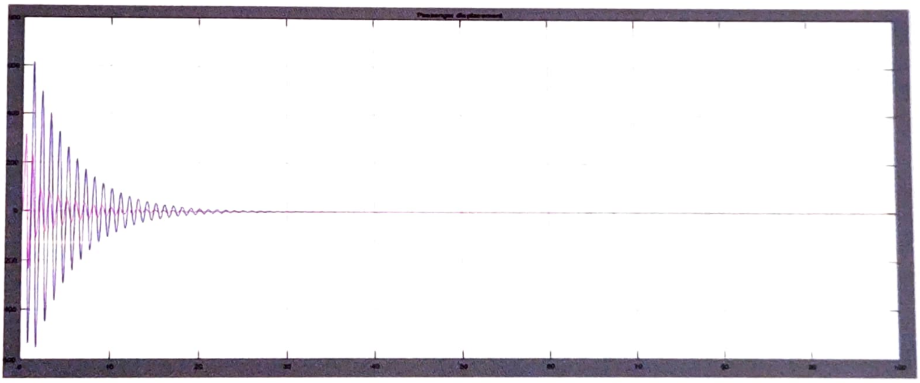


Fig5.22. Seat displacement for 250 amplitude sinusoidal bump (comparison between passive and semi active systems)

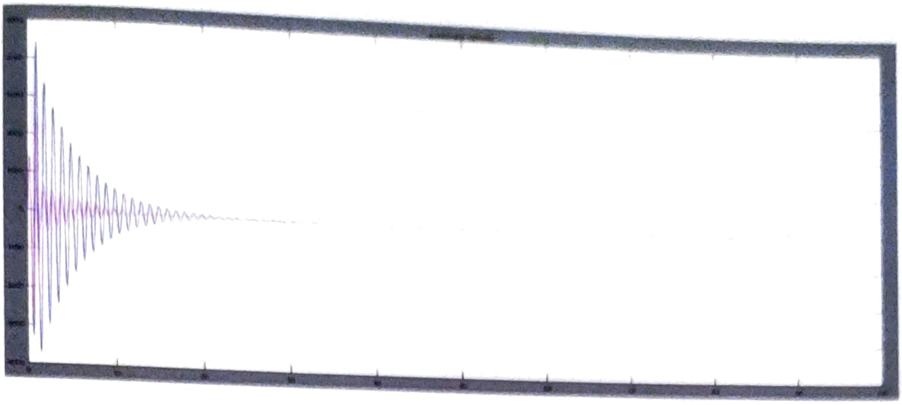


Fig 5.23. Seat velocity for 250 amplitude sinusoidal bump (comparison between passive and semi active systems)

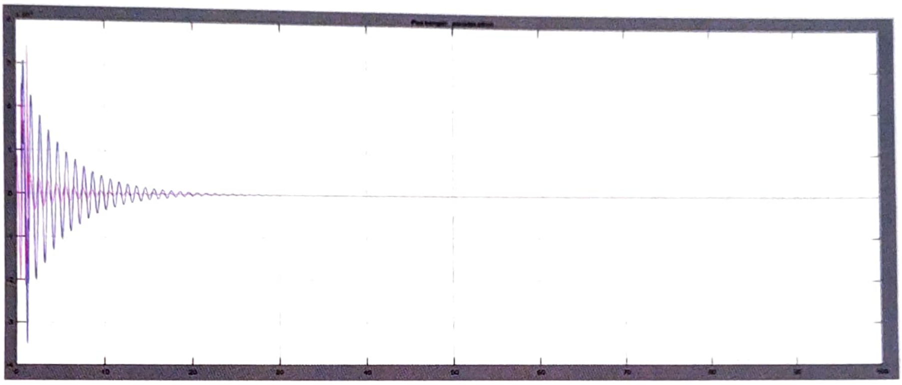


Fig 5.24. Seat acceleration for 250 amplitude sinusoidal bump (comparison between passive and semi active systems)

CHAPTER-6

6. CONCLUSIONS

One fourth model of a car (automobile) with passive and semi active suspension system has been simulated for random disturbances and double bump disturbance by using MATLAB/SIMULINK.

Comparison between passive and semi active suspension system with different valves of on-off skyhook control has been done.

The simulation results show considerable differences between the results of passive and different schemes of semi active suspension system.

1. Semi active suspension with skyhook controller gives lower values of maximum sprung mass acceleration than passive suspension for given road inputs.

2. Also settling time for the persons under semi active system less than passive suspension system.

3. It can be observed that the skyhook control can achieve substantial reduction of peak displacement for passenger than that of passive suspension.

4. Hence suspension model with semi active suspension provides good persons comfort and vehicle stability than passive suspension system

REFERENCES

1. **S.J. Chikhale, Dr.S.P.Deshmukh** " Comparative Analysis of Vehicle Suspension System in Matlab-SIMULINK and MScADAMS with the help of Quarter Car Model " PG student, Dept. of Mechanical Engineering, SAE, Kondhawa, Pune, India1 Professor, Dept. of Mechanical Engineering SAE, Kondhwa, Pune, India.

2. **Ankita R. Bhise , Rutuja G. Desai, Mr. R. N. Yerrawar, Dr. A.C. Mitra, Dr. R. R. Arakerimath** "Comparison Between Passive And Semi-Active Suspension System Using Matlab/Simulink" (Department of Mechanical, MES College of Engineering, Pune) ,(Research scholar, Dept. of Mechanical Engineering, Dr. DYPIET, Primpari, Pune, India), (Department of Mechanical, G H Raisoni College of Engineering & Research Pune , India).

3. **T. Ram Mohan Rao , G. Venkata Rao, k.Sreenivasa Rao and A. Purushottam**" Analysis Of Passive And Semi Active Controlled Suspension Systems For Ride Comfort In An Omnibus Passing Over A Speed Bump" IJRRAS 5 (1) October 2010 Rao & al. Analysis of Passive & Semi Active Controlled Suspension Systems.

4. **Dawei Liu, Huanming Chen , Rongchao Jiang and Wei Liu** "Study of Driving Performance of Semi-active Suspension Based on Hybrid Control Strategy" 2010 Second WRI Global Congress on Intelligent Systems.

5. **Galal Ali Hassaan** "Car Dynamics using Quarter Model and Passive Suspension,
Part I: Effect of Suspension Damping and Car Speed" International Journal of Computer Techniques — Volume 1 Issue 2, 2014.

6. **Ramë Likaj, Ahmet Shala, Mirlind Bruqi & Mehmet Qelaj** "Optimal Design Of Quarter Car Vehicle Suspension System" 14th International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology" TMT 2010, Mediterranean Cruise, 11-18 September 2010.

7. **Andronic Florin , Manolache-Rusu Ioan-Cozmin and Pătuleanu Liliana** "Pasive Suspension Modeling Using Matlab, Quarter Car Model, Imput Signal Step Type" TEHNOMUS - New Technologies and Products in Machine Manufacturing Technologies.

8. **Ahmad Zaim Solehin Bin Che Hasan** "Modelling And Simulation Of Modified Skyhook Control For Semi-Active Suspension" Universiti Malaysia Pahang.
9. **S. Segla, S. Reich** "Optimization and comparison of passive, active, and semi-active vehicle suspension systems" 12th IFToMM World Congress, Besançon (France), June18-21, 2007.

10. **Thomas Gyllendahl and David Tran** "Development of an auto rickshaw vehicle suspension" Luleå University of Technology Department of Engineering Sciences and Mathematics.

11. **P. Srinivasa Rao, M. Ramkrishna, M. Amareswari Reddy, V.S.C Varma**, "VIBRATION ANALYSIS OF SEMI ACTIVE SUSPENSION SYSTEM FOR AN AUTO RICKSHAW BY USING MATLAB/SIMULINK" Department of Mechanical Engineering Anits, Visakhapatnam.

12. **Mr. Amit A.Hingane, Prof. S. H. Sawant, Prof.S.P.Chavan,Prof. A.P.Shah** "Analysis of Semi active Suspension System with Bingham Model Subjected to Random Road Excitation Using MATLAB/Simulink" ,(PG Student,Mechanical Engineering Department, Dr. J.J. Magdum College of Engg. Jaysingpur, India) ,(Asso.Professor, Mechanical Engineering Department, Dr. J.J. Magdum College of Engg. Jaysingpur, India) ,(Asst.Professor,Mechanical Engineering Department, Dr. J.J. Magdum College of Engg. Jaysingpur, India.

13. **K.Rajeswari, P.Lakshmi** "Simulation of Suspension System with Intelligent Active Force Control" 2010 International Conference on Advances in Recent Technologies in Communication and Computing.

14. **Shu-wei Liu, Gang-Li and Liang-Hao** "Optimization Research of Vehicle Damper Matching Parameters" 2013 International Conference on Mechatronic Sciences, Electric Engineering and Computer (MEC) Dec 20-22, 2013, Shenyang, China.

15. **Thanh-Tung Tran, Chiaki Horil and Hiroshi Hasegawa** "Integrated Inerter Design And Application To Optimal Vehicle Suspension System" International Journal of Computer-Aided technologies (IJCAx) Vol.1,No.2/3,October 2014.

16. **A. Mitra, N. Benerjee, H. A. Khalane, M. A. Sonawane, D. R. Joshi and G.R. Bagul** "Simulation and Analysis of Full Car Model for various Road profile on a analytically validated MATLAB/SIMULINK model" IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) ISSN(e) : 2278-1684, ISSN(p) : 2320–334X, PP : 22-33 www.iosrjournals.org.

17. **Hongkun Zhang, Hermann Winner, and Wenjun Li** "Comparison between Skyhook and Minimax Control Strategies for Semi-active Suspension System" World Academy of Science, Engineering and Technology 31 2009.

18. **Likaj, R.; Shala, A.; Bruqi, M. and Bajrami, Xh.**" Optimal Design And Analysis Of Vehicle Suspension System" Daaam International Scientific Book 2014 Pp. 087-108.

19. **Cebon, D., Besinger, F. H., and Cole, D. J.,** Control strategies for semi-active lorry suspensions. Proc.Inst. Mech. Engrs, Part D: J. Automobile Engineering, 1996, 210, 161–178.

20. **Wilson, D. A., Sharp, R. S., and Hassan, S.** A., The application of linear optimal control theory to the design of Active automotive suspension. Veh. System Dynamics, 1986, 15, 105– 118.