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# Performance Evaluation of Active Suspension for Passenger Cars Using MATLAB

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***ABSTRACT :*** *The aim of this study are to obtain a mathematical model for the passive and active suspension systems for quarter car model and construct an active suspension control for a quarter car model subject to excitation from a road profile using PID controller. Current automobile suspension systems using passive components only by utilizing spring and damping coefficient with fixed rates. The purpose of the suspension system is to improve passenger comfort while providing good road handling characteristics subject to different road profile. Passive suspensions only offer compromise between these two conflicting criteria. Active suspensions possess the ability to reduce the traditional design as a compromise between handling and comfort by directly controlling the suspensions force actuators. In this study, the active suspension system is proposed based on the Proportional Integral Derivative (PID) control technique for a quarter car model for the enhancement of its road handling and comfort. Comparison between passive and active suspensions system are performed by using road profile as an input. The performance of the active suspension system is evaluated by comparing it with passive suspension system. The performance of these will be determined by performing computer simulations using the MATLAB and SIMULINK toolbox. The simulation is enhanced with 3-D animation of car going on bump created in VRML.*

***Keywords -*** *Active suspension system, PID Controller, Simulink, Quarter car model, Virtual reality animation*

## I. INTRODUCTION

A car suspension system is mechanism that physically separates the car body from the wheels of the car. Basically the suspension system comprises of spring, damper and various links; spring stores potential and kinetic energy while damper dissipates the energy. The purpose of the suspension system is to provide good level of ride comfort along with smooth handling of a car. The main function of the car suspension system is to isolate the car body from vibrations due to uneven road surface and also inertial disturbances associated with cornering and braking or acceleration while keeping the wheels in contact with road surface. The suspension system must also be able to minimize vertical force transmitted to passengers for their comfort and safety. These objectives can be achieved by minimizing the vertical car body acceleration. A heavily damped suspension will obtain good vehicle handling and adhesion but the car operator may find harsh ride or it may physically damage the car. Whereas lightly damped suspension will obtain more comfortable ride but would significantly reduce the stability of a car at turns, lane changes, etc. The traditional suspension of automobiles can have a tradeoff between these two conflict criteria, by providing spring and damping coefficients with predetermined rates. Thus to satisfy all of these requirements, it is necessary to change a damping factor dynamically with respect to a road situation.

The suspension system can be classified into Passive, Semi-active and Active suspension system according to external power input to the system. A passive suspension system is a conventional suspension system consists of non-controlled spring and shock absorbing damper whereas the semi-active suspension system has the damper with two or more selectable damping rates. In general the passenger cars today use passive suspension system. Active suspensions differ from the conventional passive suspensions in their ability to inject energy in to the system, as well as store and dissipate it. Generally, the vehicle suspension models are divided into three types namely quarter car, half car and full car models. A vehicle is generally modeled as a rigid body. Although there are interactions between body structure and all wheels, often a reduced order model representing a half-car or a quarter-car model is used for theoretical analysis and active suspension design.

The passive suspension system is an open loop control system. It only designs to achieve certain condition. The characteristic of passive suspension are fixed and cannot be adjusted by any mechanical part. Therefore, the performance of the passive suspension depends on the road profile. In other way, active suspension can gave better performance of suspension by having force actuator, which is a close loop control system. The force actuator is a mechanical part that added inside the system that controlled by the controller. Controller will calculate either add or dissipate energy from the system, from the help of sensors as an input. Sensors will give the data of road profile to the controller. Therefore, an active suspension system shown is Fig. 1 is needed where there is an active element inside the system to give both conditions so that it can improve the performance of the suspension system. In this study the main objective is to observe the performance of active suspension by using PID controller and passive suspension.

In [1], the effects of seat suspension on vehicle performance of a quarter car model for a given road input are explored using different approaches. The approach namely, Analysis by equation of motion using mathematical blocks available in Simulink for the quarter car model is utilized in this paper. In [2], a skyhook surface sliding mode control method was proposed and applied to the control on the semi-active vehicle suspension system. In [3], order reduction issues for a vehicle active suspension system are reviewed throughout its modeling with H-infinity controller design and controller refinement. In [4], the H∞ control problem for active vehicle suspension systems is allocated with actuator time delay. The nonlinear mathematical model and the robust control technique of the hydraulically actuated active suspension system for a quarter car model are assessed in [5].

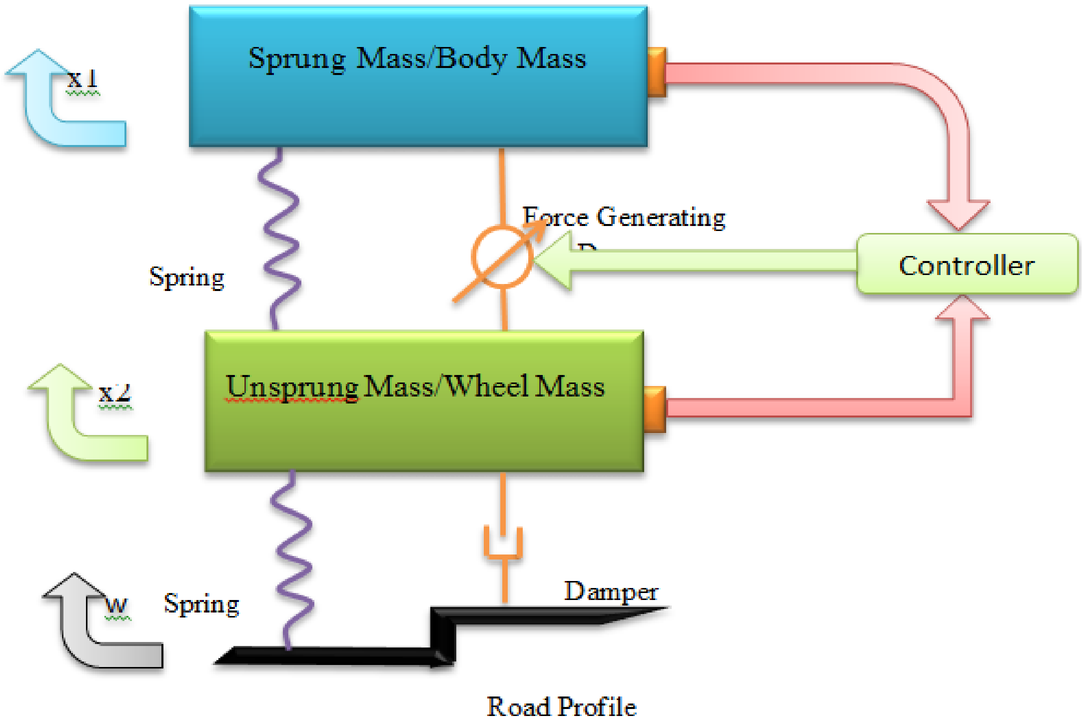


Fig. 1 Active Suspension System

## II. MATHEMATICAL MODELLING FOR A QUARTER CAR MODEL

### 1. Basic Idea

The quarter-car implies a model of a quarter of a four wheeled vehicle. A quarter car models consist of a sprung mass supported on a suspension system which has stiffness and damping characteristic. The suspension system is connected to the unsprung mass of the axle. Quarter-car model in Fig. 2 is often used for suspension analysis. The equations of motions for quarter car model are found by adding vertical forces on the sprung and unsprung masses. The spring, shock absorber and a variable force-generating element placed between the sprung and unsprung masses constitutes suspension. From the quarter car model, the design can be expend into full car model. The main focus is to provide background for mathematical modeling of a quarter car model. The dynamic model, which can describes the relationship between the input and output, enables one to understand the behavior of the system.

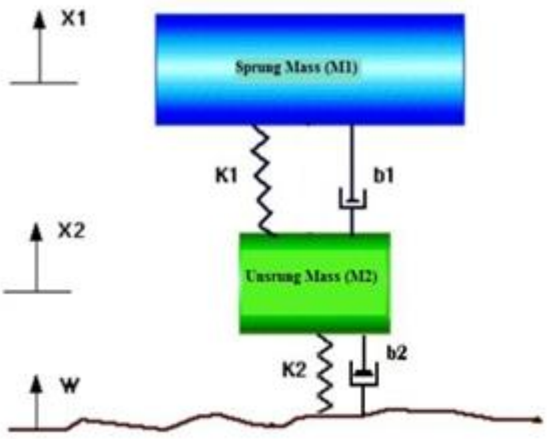


Fig. 2 A quarter car model

## 2. Problem Description

Fig. 3 shows a basic two-degree-of freedom system representing the model of a quarter-car. In this Model, the sprung mass is represented by $M1$, while tire and axles are shown by the unsprung mass $M2$. The suspension system consists of a passive spring $K_1$ and a damper $b_1$. The tire is modeled as a linear spring with stiffness $K_2$ and a linear damper $b_2$ . The passive elements will guarantee a minimal level of performance and safety, while the active element will be designed to further improve the performance. This combination will provide some degree of reliability. Parameters of Quarter Car Model for Simple Passenger Car are given in Table 1.

Table 1 Parameters for Quarter Car Model

| Parameter No. | Parameter Name | Parameter Value | Parameter Unit |
|---|---|---|---|
| **1** | $M1$ | 241.5 | Kg |
| **2** | $M2$ | 41.5 | Kg |
| **3** | $k1$ | 6000 | N/m |
| **4** | $k2$ | 140000 | N/m |
| **5** | $b1$ | 300 | Ns/m |
| **6** | $b2$ | 1500 | Ns/m |

## 3. Quarter Car Model for Mathematical Modeling

The governing equations of the quarter car suspension system are presented. The free body diagram for the car model is shown in Fig. 3. Equation of motion from Fig. 2 for Sprung mass is given below:

For $M1$,

$$M1\,\ddot{x}1 + k1(x1 - x2) + b1(\dot{x}1 - \dot{x}2) = 0 \qquad (1)$$

$$M1\,\ddot{x}1 = -k1(x1 - x2) - b1(\dot{x}1 - \dot{x}2) \tag{2}$$

$$\ddot{x}1 = \frac{-k1(x1 - x2) - b1(\dot{x}1 - \dot{x}2)}{M1} \tag{3}$$

Similarly, from Fig. 2, Equation of Motion for unsprung mass is given below:
For $M2$,

$$M2\ddot{x}2 + k2(x2 - w) + b2(\dot{x}2 - \dot{w}) + k1(x2 - x1) + b1(\dot{x}2 - \dot{x}1) = 0 \tag{4}$$

$$M2\ddot{x}2 = -k2(x2 - w) - b2(\dot{x}2 - \dot{w}) - k1(x2 - x1) - b1(\dot{x}2 - \dot{x}1) \tag{5}$$

$$\ddot{x}2 = \frac{-k2(x2 - w) - b2(\dot{x}2 - \dot{w}) - k1(x2 - x1) - b1(\dot{x}2 - \dot{x}1)}{M2} \tag{6}$$

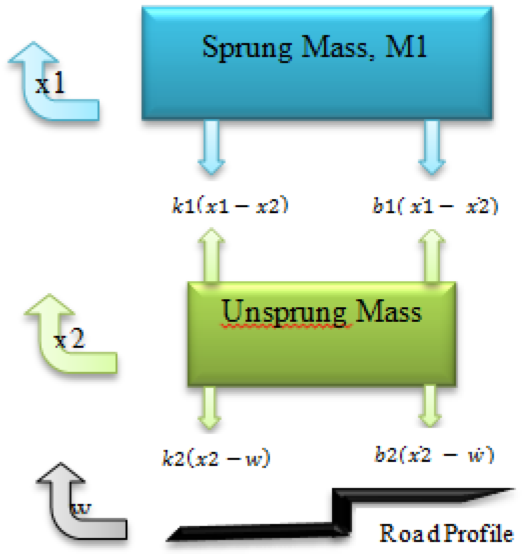


Fig. 3 Free Body Diagram for Quarter Car

## III. CONTOLLER DESIGN USING PROPORTIONAL INTEGRAL DERIVATIVE (PID)

### 1. Basic Concept of PID Controller

The main objective of this section is to design PID controller for the active suspension system. In optimal control, the attempts are done to find controller that can provide the best possible performance. The PID approach of vehicle suspension control is widely used in background of many studies in vehicle suspension control. The strength of PID approach is that the factors of the performance index can be weighted according to the designer's desires or other constraints using it. In this study, the PID method is used to improve the road handling and the ride comfort for a quarter car model. The controller structure adopted in this study is shown in Fig. 4. Thus, for designing a PID controller, the following steps are executed to obtain a desired response:

1. Obtain an open-loop response and determine what needs to be improved
2. Add a proportional control to improve the rise time

3. Add a derivative control to improve the overshoot
4. Add an integral control to eliminate the steady-state error
5. Adjust each of $K_p$, $K_i$ and $K_d$ until a desired overall response is obtained.

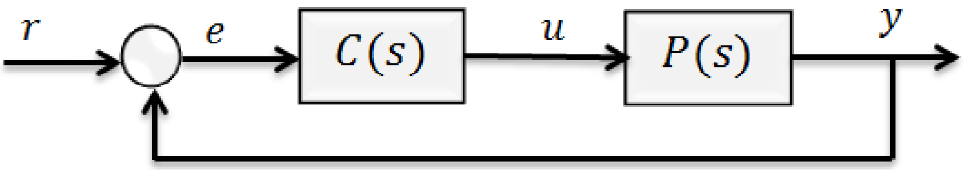


Fig. 4 Unity Feedback System for PID Controller

The effects of each of controller parameters, $K_p$, $K_i$ and $K_d$ on a closed-loop system are summarized in the table below. Note that these correlations may not be exactly accurate, because $K_p$, $K_i$ and $K_d$ are dependent on each other. In fact, changing one of these variables can change the effect of the other two. For this reason, the table should only be used as a reference for determining the values for $K_p$, $K_i$ and $K_d$.

Table 2: Effect of Controller Parameters on Closed loop System

| Controller Response | Rise Time | Overshoot | Settling Time |
|---|---|---|---|
| $k_p$ | Decrease | Increase | Small change |
| $k_i$ | Decrease | Increase | Increase |
| $k_d$ | Small change | Decrease | Decrease |

**2. PID Controller Design Using MATLAB**

The PID controller can be designed in MATLAB using the *Transfer Function* directly. MATLAB's *pid* controller object is also applied to generate an equivalent continuous-time controller. Thus, the tuning of PID controller can be done using following steps-:

1. Generate Transfer function to find $K_p$, $K_i$ and $K_d$.
2. Import the obtained parameters to Linear Time-invariant System to confirm the tuning base.
3. Tune the PID controller.

## IV. SYSTEM MODELLING

**1. Design Using Simulink**

A quarter car model shown in Fig. 2, is used for designing an Active Suspension System, as enlightened earlier. Designing an automatic suspension system for a car turns out to be an interesting control problem. When the suspension system is designed, a Quarter car model (one of the four wheels) is used to simplify the problem to a one dimensional spring-damper system. Here, w, x2, x1 are the vertical displacement of road, unsprung mass, sprung mass respectively.

Model Parameters Are given as follows:

- Sprung or body mass (M1) = 241.5 kg
- Un-sprung or Wheel assembly mass (M2) = 41.5 kg
- Spring constant or stiffness of suspension system (k1) = 6000 N/m
- Spring constant or stiffness of wheel assembly (k2) = 140000 N/m
- Damping constant or coefficient of suspension system ($b1$) = 300 Ns/m
- Damping constant or coefficient of wheel assembly (b2) = 1500 Ns/m

**1.1 Design requirements**

A good car suspension system should have satisfactory road holding ability, while still providing comfort when riding over bumps and holes in the road. When the car is experiencing any road disturbance (i.e. pot holes, cracks, and uneven pavement), the car body should not have large oscillations, and the oscillations should dissipate quickly Since the distance (**x1-w)** is very difficult to measure, and the deformation of the tire (**x2-w**) is negligible, we will use the distance (**x1-x2)** instead of (**x1-w)** as the output in our problem. Keep in mind that this is estimation. The road disturbance (**w**) in this problem will be simulated by a step input. This step could represent the car coming out of a pothole.

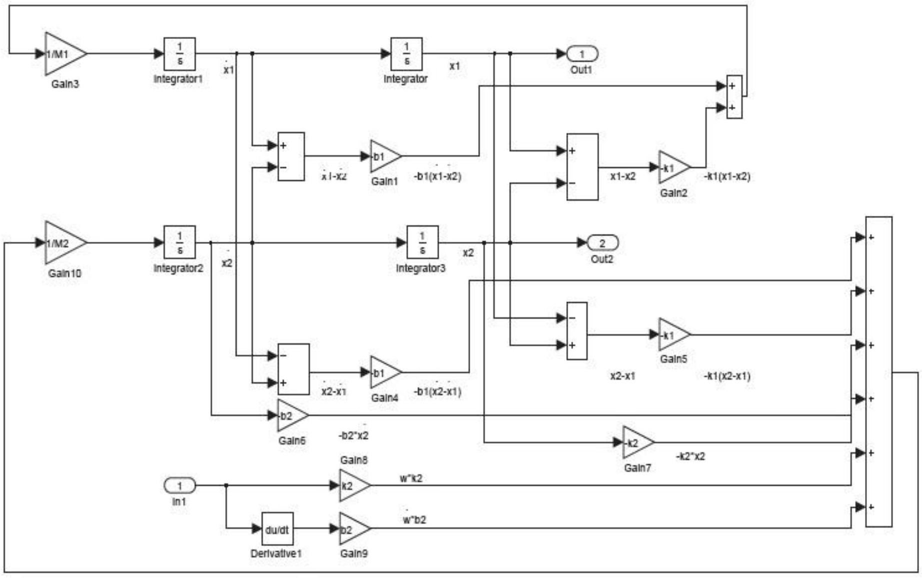


Fig. 5 Simulink Model for Passive Suspension System

### 1.2 Equations of Motion

Equations of motion for sprung and unsprung mass are given from Equation (1) through Equation (6). Now, referring to Fig. 2 and Equation (1) and Equation (4), the parameters used in the system modeling are given as follows:

$x1 - x2$ = Suspension travel, $\dot{x1}$ = Car Body Velocity, $\ddot{x1}$ = Car Body Acceleration,

$x2 - w$ = Wheel Deflection and $\dot{x2}$ = Wheel Velocity

Using Equation (1) and Equation (4), the Simulink model of the suspension system is designed. The model consists of the basic blocks from the Simulink library. Fig. 5 represents the Simulink model for the suspension system.

### 2. Design Using Virtual Reality Animation

Passive and Active model of quarter car suspension system is first developed using Simulink method as discussed in earlier sections. The data generated from these Simulink models are used to manipulate the virtual reality objects. The virtual world of a car going on a road bump on a straight road is created using standard Virtual Reality Modeling Language (VRML) technology. The scene is kept simple to avoid the system lagging. The *camera position* is set to a quarter views that enable the observer to analyze motion of a car. For that purpose, the *static viewpoint* is set. To interface the Simulink block diagram with the virtual world, VR sink block from Virtual Reality Toolbox is used. To define the association between Simulink model and virtual world, the VR signal expander is used as interfacing element.

## V. RESULTS AND DISCUSSION

### 1. Analysis of Active Suspension System Using Simulink

Simulation based on the mathematical model for quarter car by using MATLAB/SIMULINK software will be performed. Performances of the suspension system in term of ride quality and car handling will be observed, where road disturbance is assumed as the input for the system. Parameters that will be observed are the car body travel, wheel deflection and the car body acceleration for quarter car. Force generated by damper in case of Active PID controlled system also observed for Controller Accuracy. The aim is to achieve small amplitude value for car body travel, wheel deflection and the car body acceleration. The steady state for each part also should be fast.

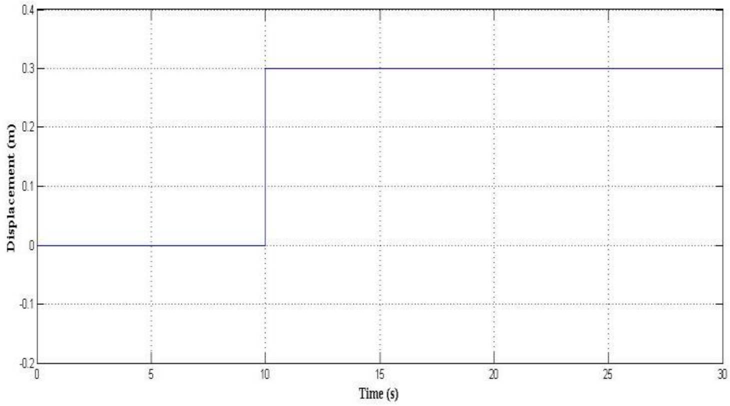


Fig.6 Road with Bump

### 1.1 Comparison between Passive and Active Suspension for Quarter Car Model

Computer simulation work is based on the Equation (4) has been performed. Comparison between passive and active suspension for quarter car model is observed. For the PID controller, the various parameters such as $K_p$, $K_i$ and $K_d$ can be set as per the requirement by the PID tuning method discussed in section III.

### 1.2 Effect of the road bump on Active and Passive suspension system

In this section, the performance comparison is established between the quarter car Active suspension system using PID controller and Passive suspension system, evaluated under Road bump shown from Fig. 7 through Fig. 10. Excitation Force and Generated Force by the actuator are shown in Fig. 7. The Excitation Force gets cancelled by the Generated Force. This indicates the efficiency of the PID controller. By comparing the performance of the Passive and Active suspension system using PID control technique it is clearly realized that Active suspension can give lower or almost no peak over shoot (amplitude) and faster settling time. Body Travel can reduce the amplitude and settling time compare to passive suspension system. Body Displacement is used to represent ride quality as shown in Fig. 8.

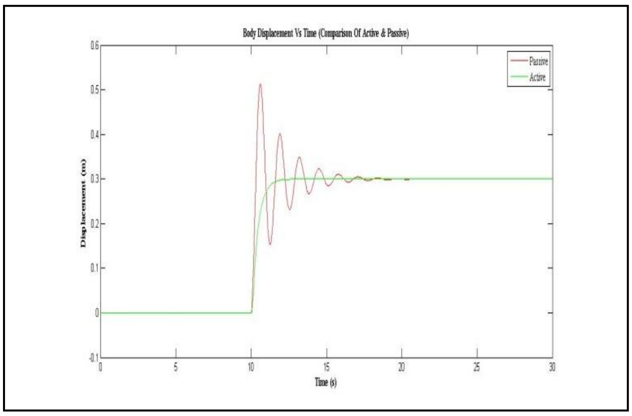


Fig. 7 Excitation Force and Force Generated

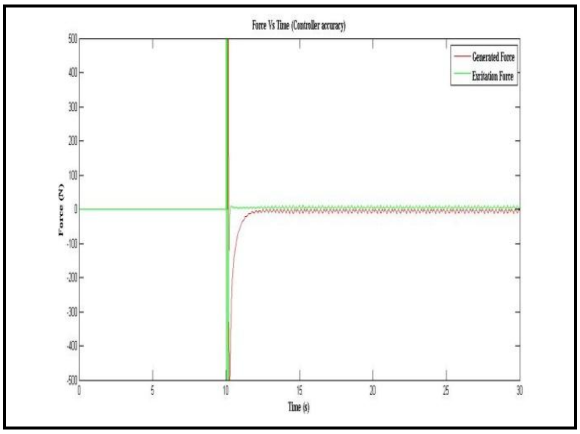


Fig. 8 Body Displacement

PID controller design approach has been examined for the active system. Suspension travel in active case has been found reduced to more than half or almost null of their value in passive system. By including an active element in the suspension, it is possible to reach a better compromise than that of using purely passive elements.

The potential for improved ride comfort and better road handling using PID controller design is examined. MATLAB software programs have been developed to handle the control design and simulation for passive and active systems.

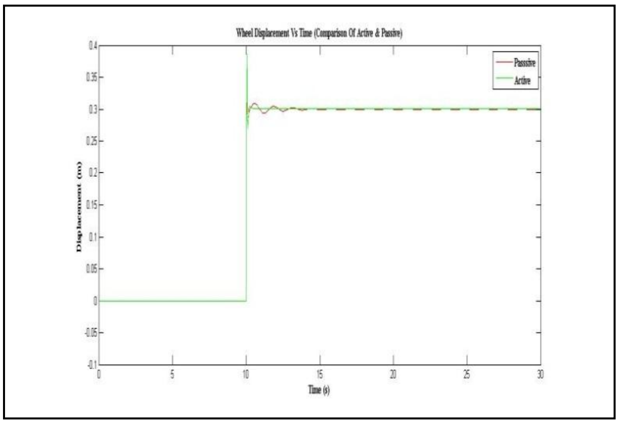


Fig. 9 Body Acceleration

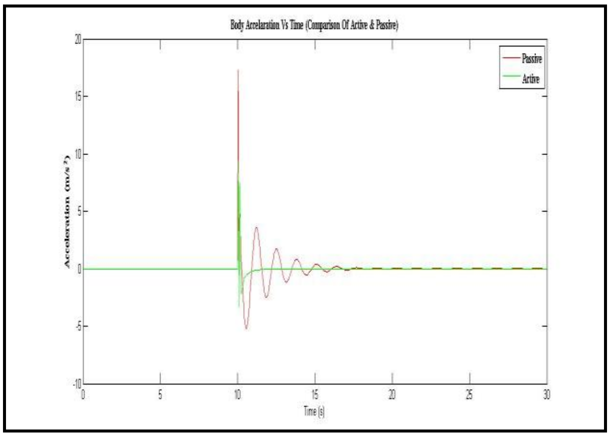


Fig. 10 Wheel Displacement

## 2. Analysis of Active Suspension System Using Animation

To realize the effect of Road variation on the Passive and Active suspension System built in Simulink and Virtual Reality animation at a time, the Virtual Reality canvas with graphs is used. Thus, the following window shown in Fig. 11 is generated to observe that effect. The window comprises the animation of both the systems along with the graphs of Displacement Vs. time just below the animation window of each of the suspension system. By comparing the performance of the passive and active suspension system using the Virtual Reality canvas with graphs it is clearly understood that active suspension can give lower or almost no peak over shoot (amplitude) and faster settling time.

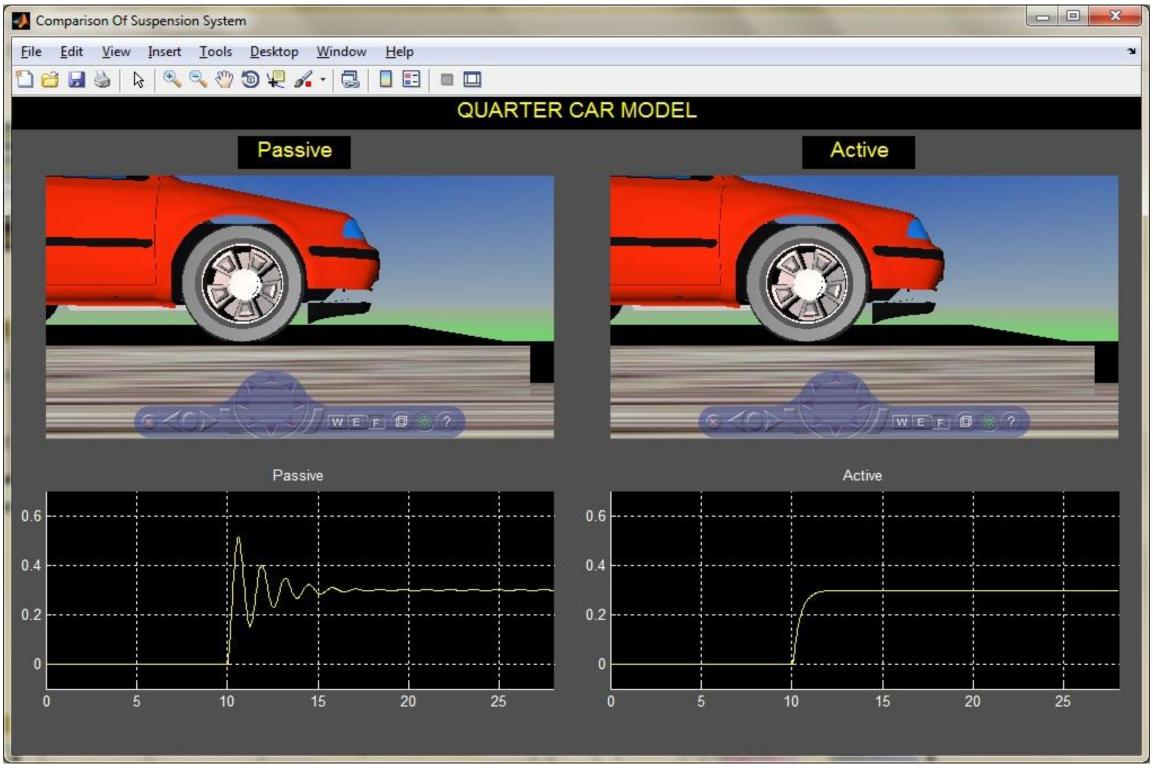


Fig. 11 Virtual Reality Canvas with Graph for comparison of Active and Passive system

## VI. CONCLUSION

The methodology was developed to design an Active suspension for a passenger car by designing a controller, which improves performance of the system with respect to design goals compared to Passive suspension system. Mathematical modeling has been performed using a two degree-of-freedom quarter car model for Passive and Active suspension system considering only bounce motion to evaluate the performance of suspension with respect to various contradicting design goals. PID controller design approach has been examined for the Active suspension system. Suspension travel in active case has been found reduced to more than half or almost null of their value in passive system. By including an active element in the suspension, it is possible to reach a better compromise than that of using purely passive elements. The potential for improved ride comfort and better road handling using PID controller design is examined. The development of the Quarter car in the virtual environment can provide an insight into the actual condition when a car hits the road bump, thus provides more intuitive way to compare or verify the system. This will allow user to imagine and relate to the real plant that being modeled in better way as well as it will help in rapid prototyping. The objectives of this project have been achieved. Dynamic model for linear quarter car suspensions systems has been formulated and derived. Only one **type of controller is used to test the systems performance which is PID.**

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