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Design and Development of Quarter Car Suspension Test Rig Model and It's Simulation

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Abstract:
For this modern fast pace world transportation being the backbone of society, the fact of luxury and comfort has also become of utmost interest for many people. The competition in automobile industries put the standards on higher level concerned about vehicle suspension as it is directly related to human health and comfort.
As the vehicle suspension is concerned, it varies from one vehicle to another and from one application to another. These various suspension systems are designed accordingly with the desired effects and performances. The testing and calibrating facilities for these suspension systems are available at their manufacturers and some purposefully established organizations only. This project is hence carried so as to develop a simplified and cost effective suspension system testing setup. The setup is made as a quarter car setup, the reduced model from a full car, to reduce the cost of development and the complications in its design and manufacturing.
The work involved was from selection of suspension system to final readings and analyses. The McPherson strut independent suspension system was selected, as nowadays it is being most popular suspension system in passenger cars. The procedure for development was analytical as well as experimental. Hence the initial mathematical model was developed and the analytical results were taken on Matlab 10, as an analytical solver. In later stages the experimental setup is developed and the actual readings were taken for various inputs; finally both experimental and analytical results are compared for reliability of experimental setup.

1. Introduction

The main functions of an automotive suspension system are to provide vehicle support, stability and directional control during handling maneuvers and to provide effective isolation from road disturbance. These different tasks result in conflicting design requirements. Directional control and stability requires a suspension that is neither very stiff nor very soft. Insensitivity to external loads requires a stiff suspension, whereas good ride comfort demands a soft suspension.
In a conventional passive suspension system, the designer is faced with the problem of choosing the suspension stiffness and damping parameters, which inevitably involves a difficult compromise in view of the wide range of conditions over which a vehicle operates.
Ride and handling performances of a vehicle suspension system often present engineers conflicting design goals. For decades, engineers have studied active control for vehicle suspension systems to resolve this conflict. The intent of the system is to replace the classical passive elements by a controlled system that can supply unlimited force to the system. This type of active suspension system has proven capable of achieving improvement over passive systems
The different methods of measurement of vibrations in cars are studying the dynamics of motions, preparing the state space equations, conversion of acceleration inputs in velocity and displacement and analyze the frequency response in graphical form and also simulating the system using the matlab software. Measurement of tire dynamics, degrees of freedom of the suspension components such as Mcpherson strut, control rods, lower arm, upright, car body frame.
A car suspension system is the mechanism that physically separates the car body from the wheels of the car. The performance of the suspension system has been greatly increased due to increasing vehicle capabilities. Various performance characteristics to be considered in order to achieve a good suspension system. Suspension consists of the system of springs, shock absorbers and linkages that connects a vehicle to its wheels. In other meaning, suspension system is a mechanism that physically separates the car body from

the car wheel. The main function of vehicle suspension system is to minimize the vertical acceleration transmitted to the passenger which directly provides road comfort.

Any suspension system has the ability to store, dissipate and to introduce energy to the system. It may vary its parameters depending upon operating conditions. There are three types of suspension system; passive, semi-active and active suspension system. Traditional suspension consists springs and dampers are referred to as passive suspension, then if the suspension is externally controlled it is known as a semi active or active suspension.

The passive suspension system is an open loop control system. It only designs to achieve certain condition only. The characteristic of passive suspension are fix 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 control 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.

2. Objectives

Currently, the desired functions of a quarter-car rig include the ability to mount several different designs of actual car suspensions, having the ability to perform a wide range of tests, which include body loads on the sprung mass.

- The objective for this work is to study and develop a test facility that can improve the state-of-the-art in indoor vehicle suspension simulation testing on a quarter-car vehicle.
- The objective is to design and develop a quarter car suspension test rig model and to perform its simulation.
- In summary, a new quarter-car test rig has been designed and built. In an attempt to prove the concept, a well known control scheme, not currently used for this application, is applied to the problem of replicating vehicle response signals. Finally the comparison of both analytical simulation and experimental results was done.

3. Methodology

To achieve these tasks the following approach is taken. Current quarter-car test rigs and the state of indoor testing in general are first evaluated. The approach is to develop a quarter-car test rig that addresses many of the shortcomings found with the state-of-the-art while trying to minimize expense. Before this with known data the analytical simulation is carried out on Matlab and the results were recorded. Then comparison is to be done with the actual test results.

Since the days of horse-drawn spring carriages, people have strived for making rides comfortable by isolating the car body from road irregularities. Today's "carriage" isolation could consist of passive and/or active spring and dashpot elements. The aim is to study linear spring-dashpot road vehicle suspension system with respect to ride comfort.

The suspension of a two-degree-of-freedom (2-DOF) vehicle traveling on a road surface is studied and is simulated with respect to test rig design. In the proposed work, a 2-DOF linear quarter car is modeled to carry out computer simulations. During simulations, a vehicle is assumed to run at a certain speed while it hits a step or a pothole or a bump or a random road profile defined by PSD (Power Spectral Density).[4] Vehicle response corresponding to above mentioned road disturbances is obtained for ride quality and comfort. Quarter Car suspension system is modeled and simulated for above mentioned road disturbances to analyze performance.

The work involves –

- Study of suspension systems.
- Modeling of a vehicle suspension system – A linear quarter car model.
- Deriving the equations for the quarter car model and formulation of Transfer Function and State Space equations for vehicle suspension system.
- Mathematical modeling for the actuator system.
- Simulation of suspension system using road surface disturbances as input at the tire to analyze the vehicle performance.
- Repeating the simulations over wide range of road surfaces and vehicle speeds and analyzing the performance of the vehicle in terms of Body Displacement, Body Vertical acceleration, Suspension working Space or Rattle Space, Controller Force, etc
- Mechanical Design and Development of a Quarter Car Test Rig.
- Simulation of a Quarter Car Test Rig.
- Design, Implementation and Simulation of Suspension System on a Quarter Car Test Rig.
- Validation of simulation and Quarter Car Test Rig results.

4. Simulation and Analysis

4.1. Simulation

The McPherson strut to be tested first was planned to be simulated analytically on MatLab software to form a reference readings or results with which the experimental results will need to be compared. For this the basic mathematical model of strut was needed. The different literature reviewed in study helped to develop model. The model for strut is given in below discussion.

The main parameter to find out in the study is the sprung mass acceleration which will be again recorded in experimentation also.

The paper titled Design optimization of vehicle suspensions with a quarter car model [3] gave the sprung mass acceleration, as,

$$\ddot{z}_2 = \left\{ \pi R V \left[\frac{K_t C}{2 m_2^{3/2} K^{1/2}} + \left(\frac{(m_1 + m_2) K^2}{2 C m_2^2} \right) \right] \right\}^{1/2}$$

Where,

$\ddot{z}$ = sprung mass acceleration (m/s^2),
V = Vehicle speed (m/s),
K_t = tire stiffness (N/m),
C = damping coefficient (N/m/s),
m_2 = sprung mass (kg),
m_1= unsprung mass (kg),
K = suspension stiffness (N/m),

And $R = n_0^2 G_q (n_0)(n/n_0)^{-w}$

Where,

R=RMS of the sprung mass acceleration.
G_q = power spectral density, a measure to express the road profile elevation,
n = spatial frequency,
$n = 2\pi/\lambda$ (rad/sec),
λ= wavelength (m),
n_0 = reference spatial frequency,

Generally n0 = 1.0 (rad/m),
And w = Vn
w = spatial frequency of road excitation,

When the mathematical model is given to MatLab 10, it gives out the results as sprung mass acceleration. The input data given during the simulation was different which was used in experimental tests.[3]

The input data is as follows,

- m_2 = 260 kg
- m_1 = 80 kg
- C = 1000 N/m/s
- K = 16182 N/m
- Kt = 190000 N/m

The simulation was carried at different vehicle speeds like 10 km/hr, 20 km/hr, 30 km/hr, 40 km/hr, 50 km/hr and 60 km/hr. The simulation needed the road input to be given. The simplified quarter car model is shown in figure 4-1. The simulation program was done in Matlab. The results are obtained and plotted for various parameters like road profile, body travel, body acceleration, suspension deflection. The plotted results are shown in figure 4-2(a) and 4-2(b).

4.2. Linear State Space Equations

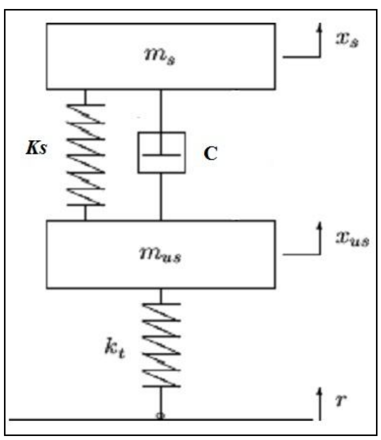


Figure 4.1: Quarter car model

The sprung mass m_s represent the car chassis, while the unsprung mass m_{us} represent the wheel assembly. The spring, *ks*, and damper, *C*, represent a passive spring and shock absorber that are placed between the car body and the wheel assembly, while the spring k_t

serves to model the compressibility of the pneumatic tire. The variables x_s , x_{us}, and r are the car body travel, the wheel travel, and the road disturbance, respectively.

- **Defining**
- x_1= sprung mass displacement,
- x_2=sprung mass velocity,
- x_3= unsprung mass displacement,
- x_4=unsprung mass velocity,
- r= road disturbance.
- Hence,

$x_1 = x_s$, $x_2 := \dot{x}_s$, $x_3 = x_{us}$, and $x_4 = \dot{x}_{us}$,
the following is the state-space description of the quarter car dynamics.

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\frac{1}{m_s}[k_s(x_1 - x_3) + c(x_2 - x_4)]$$
$$\dot{x}_3 = x_4$$
$$\dot{x}_1 = \frac{1}{m_s}[k_s(x_1 - x_3) + c\,(x_2 - x_4) - k_t(x_3 - r)]$$

4.2.1. Matlab Simulation Results
The simulation was carried on class C road. The road classes are actually classified as A (very good), B (good), C (average), D (poor) and E (very poor) in the international conventions and standards. The class of road changes from like F1 race track to the conventional transport track. For simplification and actual road conditions class 3 roads are selected in simulation. The detailed road classification can be studied in various references published internationally.
The response of the suspension system at vehicle speed of 10 kmph is plotted. In this the parameters road profile i.e. road distance (m), body travel (m), body acceleration (m/s^2), suspension deflection (m), are plotted against the time (sec).

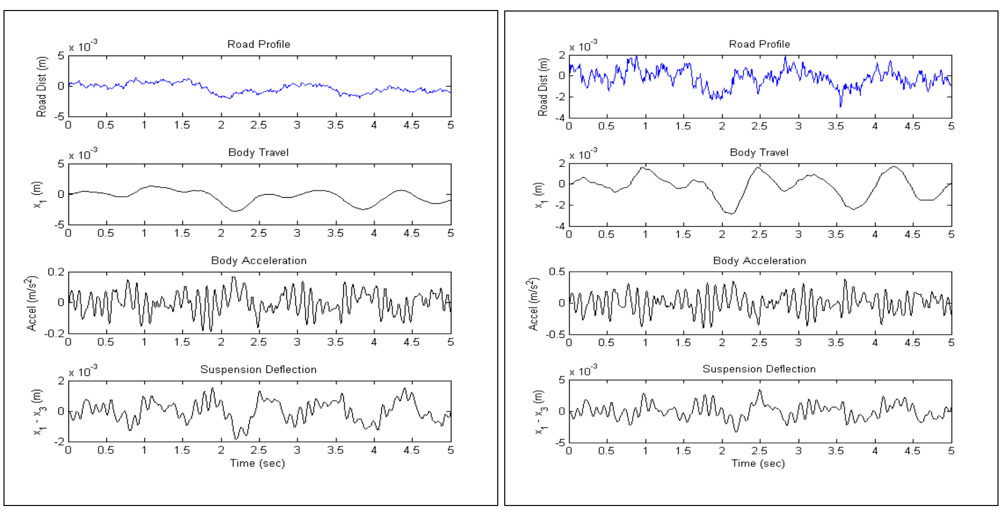


Figure 4.2(a): Suspension response at 10 kmph Speed
Figure 4.2(b): Suspension response at 60 kmph Speed

These plots show the variations in the interested parameters such as the body acceleration and suspension deflection significantly varying according to the vehicle speed. As the speed is increasing body travel is varying with higher amplitudes. Also the frequency of body acceleration is increasing significantly with increasing vehicle speed. The amplitude of suspension deflection is also increased with the speed along with the little randomness of increased frequency.

4.3. Analysis of Test Rig Reaction Frame
The figure 4-3 shows the reaction or load frame placed on base frame. The material and the channels selected were ISLC 125 C channels, and moreover the 'I' beam structure was developed for frame manufacture; obviously it was much stronger and rigid to bear

the loads of heavy duty suspensions such as leaf springs in trucks. This was done intentionally keeping in the mind the future scope of research expansion and flexibility of testing.

Still as a part of design it was necessary to analyze the frame structure for its safe limits of strength. Again as the vibration was the working phenomenon it was crucial to check the first frequency of the structure so that it would not interfere with the test results and affect the reliability of test rig.

Treating the frame as beam element the analysis was carried out. In analysis applying the load on frame was crucial. As the load on the reaction frame was not of a conventional type load i.e. directly acting on it, but the loading was occurring on the bearing rods through the sliding bearing pipes. And it was of lateral type. But for avoiding the complexity of loading the load was assumed to be equal to the corner weight of vehicle, which was much higher than actual load and acting transversely along the length of vertical beams at rod supports. This was done on an account of the extreme case condition and also the simplicity involved.

In some extreme situations like cornering and braking, the corner weight goes up to half the weight of vehicle. So the transverse load acting at bearing rod supports was taken about 350 kgf. Now as per the rigidity of frame it was safe under this load. And also by performing the analysis the structure proved itself safe.

Figure 4.3: Reaction frame on base frame

5. Experimentation

The experimentation is the most critical and important aspect of the study as the project was dealt with the development of it, only the experimental validation can lead us to the successful completion of the work.

The experimentation was carried on the first Nano suspension to check the analytical and experimental validity of project. In subsequent topics the whole proceeding is discussed.

- **Setting Up The Rig**
  Before the experimental tests it was needed to have set up all the required equipments, resources, methodology, procedure etc.
- **Compressor**
  The actuation needed the high pressure pneumatic supply. This was fulfilled by the air compressor of capacity 12 bar. The compressor was two stages reciprocating with intercooler. Though it has the capacity 12 bar, the delivery pressure we intended was only between 5 to 6 bars. It was kept running during whole testing to assure constant pressure air supply. The reducer at the delivery end was used as per the tubing size available for a connection to solenoid valve. The compressor unit used is shown in following figure.

Figure 5: Air compressor unit

- **Solenoid valve**

  The high pressure air was carried through the standard tubing up to the solenoid valve with proper connections. The solenoid valve used is from SPAC industries.

  The valve is single coil 5/2 way, pneumatic function valve. The valve is receiving the compressed air from compressor unit and by 2 out coming connections it is sent to the actuating cylinder in controlled manner via timing relay circuit. Out of 3 incoming connections one is for compressor unit and two are opened to atmosphere via silencer. The connections are shown in below figure.

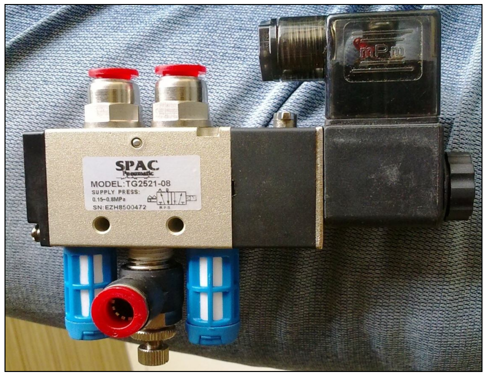


Figure 6: Solenoid valve

- **Controller (Timing relay unit)**

  For controlled signals to be sent to solenoid valve the timing relay circuit was used. The unit is consisting of two parts; one is timing circuit and other relay circuit. But the unit we used is inclusive of both the units. The unit is shown in figure 5-3.

  The timer relay circuit has two control knobs to set the timing of on and off strokes manually. Using these we can control the speed of ON/OFF solenoid positions, intern the stroke frequency. It has the input from the conventional single phase electric supply and gives out the control signals to solenoid valve.

Figure 7: Timer relay circuit (controller)

- **Supply tubes, valves and connections**

  The tubes needed in the pneumatic supply needed to sustain the pressure of air up to 12 bar in extreme cases such as sudden valve closures. Hence the polyurethane tubes are used. They are of 8 mm size and flexible in bending or twist conditions making the operations easier. The tube connections made to cylinder, valve, and compressor had to be leak proof. So the sockets and joints used were of high quality and standard. The flow control valves were used at the compressor outlet connection so as to control the actuating force and speed. The flow control valves are also used on the cylinder connections at both ends. The Teflon tape is used at all the thread connections to seal the joints perfectly.

Figure 8: Flow control valve

6. Experimental Testing

The experimental testing was carried by keeping all the measures up to their ready level. The all connections are made proper with critical care, as any error will lead in the leakage of air and noticeable drop in supply pressure.

- The compressed air supply was set at constant value by keeping the delivery valve of compressor at fixed position. Also the compressor driving unit was kept running to maintain the constant delivery pressure.
- The timing relay unit was set to the frequency of on and off to desired level in such a way that the simulation data will resemble in comparative manner.
- Then the additional weights were added to the sprung mass frame so that the total sprung mass will be around 165 kg.
- The actuation cylinder and tire pan assembly was placed in proper position below wheel, to avoid any misalignment in forces which will lead to the turning couples to act on the wheel and the suspension setup.
- The both bearing rods and bearing pipes were properly lubricated with oil to ensure the smooth motion of moving frame.
- The tie rod was also fixed in its fixture to assure the wheel was parallel to the moving frame perfectly.

Figure 9: Sensor on sprung mass

- All the nuts and locking nuts were tightened to improve the damping of structure.
- The recording instruments were made on and placed in proper positions.
- The accelerometer sensors were attached to their relevant positions on parts.
- The delivery pressure of compressor unit was kept constant at 5 bar and the flow control valves were maintained at desired opening positions to have constant flow through air tube.
- Now by setting the timer relay unit at desired value the various sets of accelerometer readings on HMI were taken. During these each set of timer relay unit output, the flow control valve, the compressor delivery valve positions and delivery pressure were maintained constant.
- For every set of vehicle speed, only the timer relay unit output was changed and remaining procedure repeated successively.

Figure 10: Experimental testing

By the readings and observations made the results were tabulated and presented in succeeding chapter. Also they are compared and elaborately discussed emerging out in to conclusions made thereafter.
Due to the modular design of this new quarter-car test rig it is able to accommodate a multitude of different vehicle suspension designs. A photograph of the fully assembled test rig is shown in Figure 3-18 with the TATA Nano suspension installed. The design of the sprung mass to receive an additional masses rather than a single specific suspension keeps the rig from being purpose built for one suspension design and corresponding car mass. The configurability allotted by the base frame design and the single-piece design of the reaction load frame allow for a large window of placement of the tire relative to the sprung mass. The moving mass has provisions for adding mass which allows for vehicles of various weights to be replicated. Finally, provisions for additional functionality are designed into the rig making it useful for future studies.

Figure 11: Completed Test rig

7. Results
The results obtained were analytical and experimental in nature and were to be compared simultaneously for accuracy. The results are given in subsequent topics.

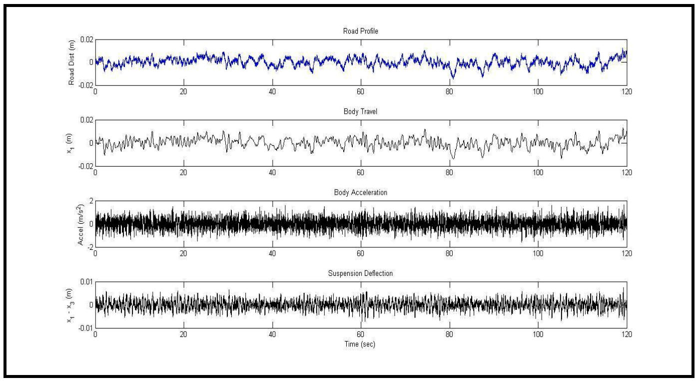
7.1. Simulation Results
After simulating the McPherson strut in MatLab, the results were obtained in graphical format. The results obtained were readable and self explanatory in nature. As shown in below figures, the results on MatLab simulation are given for various vehicle speeds. The simulation was done for 120 seconds cycle time. The input data for suspension was as follows,

- m_2 = 165 kg
- m_1 = 30 kg
- C = 1000 N/m/s
- K = 16182 N/m
- Kt = 190000 N/m

Where,
m_2 = sprung mass or body mass;
m_1 = unsprung mass;
C = suspension damper damping coefficient;
K = suspension spring stiffness;

And Kt = Tyre stiffness.

The simulation was carried at different vehicle speeds like 10 km/hr, 20 km/hr, 30 km/hr, 40 km/hr, 50 km/hr and 60 km/hr.



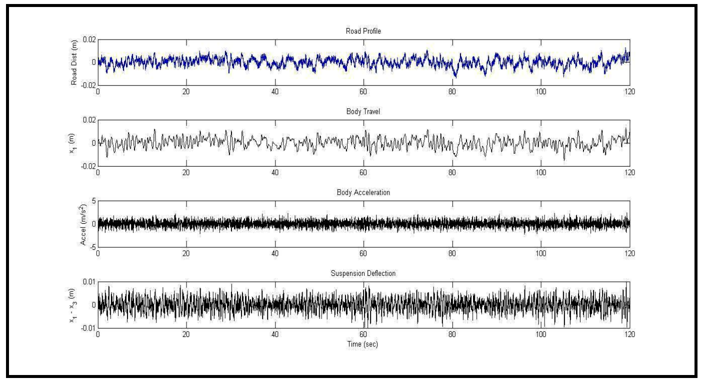
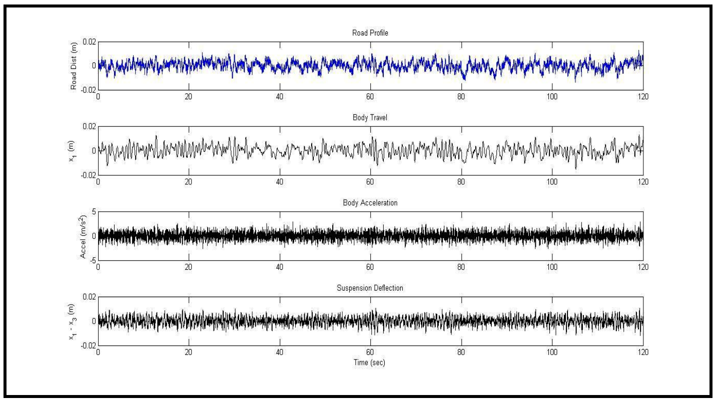


Figure 12: Suspension response at 10 kmph Speed
Figure 13: Suspension response at 20 kmph Speed



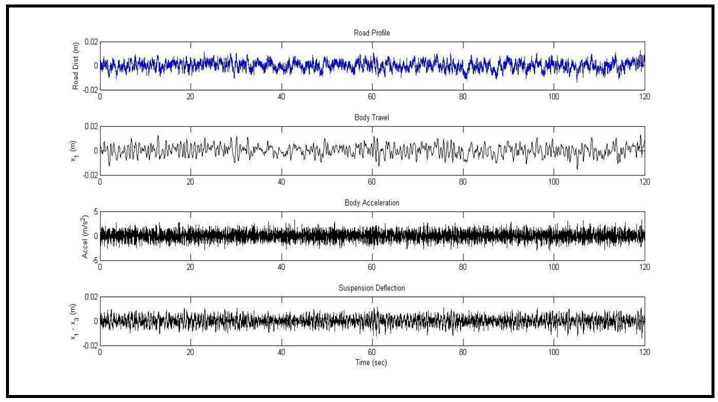
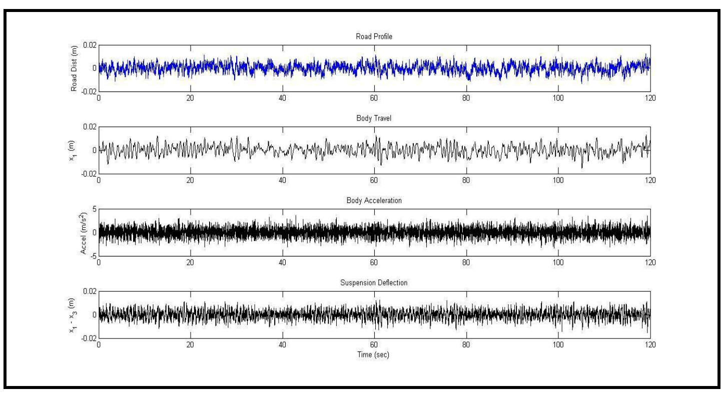


Figure 14: Suspension response at 30 kmph Speed
Figure 15: Suspension response at 40 kmph Speed



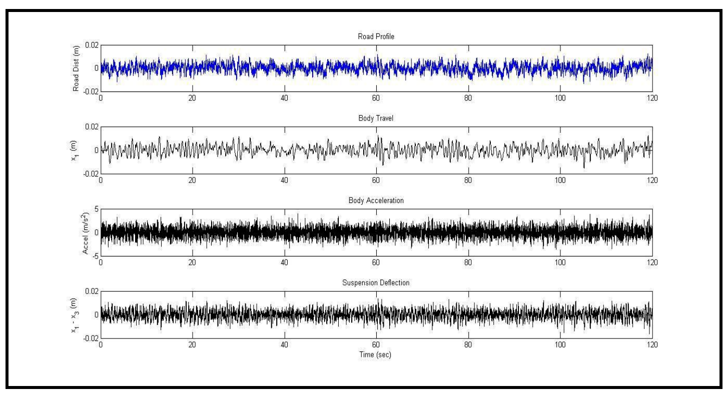


Figure 16: Suspension response at 50 kmph Speed
Figure 17: Suspension response at 60 kmph Speed

The plots above shows the graphical view of different parameters like road distance, body travel, body acceleration, suspension deflection against the time with the specified road input.

Vehicle Speed Parameters		10 kmph	20 kmph	30 kmph	40 kmph	50 kmph	60 kmph
Body Acceleration (m/s^2)	Maximum	1.623	2.3296	2.8453	3.2324	3.5174	3.7418
	Minimum	-1.4013	-1.8326	-2.0741	-2.311	-2.5427	-2.7358
Suspension Deflection (m)	Maximum	0.0075	0.0097	0.0107	0.0111	0.0112	0.0111
	Minimum	-0.0064	-0.0096	-0.0121	-0.014	-0.0153	-0.0163
Body travel (m)	Maximum	0.0128	0.0131	0.0131	0.013	0.0127	0.0124
	Minimum	-0.0059	-0.006	-0.0063	-0.0064	-0.0063	-0.0067
Road profile (m)	Maximum	0.0123	0.0129	0.013	0.0128	0.0125	0.0121
	Minimum	-0.0061	-0.0062	-0.0066	-0.007	-0.0073	-0.0075

Table 1: Simulation results (Experimental)

Vehicle Speed Parameters		10 kmph	20 kmph	30 kmph	40 kmph	50 kmph	60 kmph
Body Acceleration (m/s^2)	Maximum	1.5806	2.6344	2.7682	2.7729	2.9272	3.7533
	Minimum	-1.0374	-1.7290	-2.8287	-2.836	-1.9212	-1.8162
Suspension Deflection (m)	Maximum	0.0018	0.0090	0.0111	0.0120	0.0130	0.0173
	Minimum	-0.0039	-0.0083	-0.0131	-0.0103	-0.0154	-0.0163
Body travel (m)	Maximum	0.0100	0.0142	0.0149	0.0147	0.0123	0.0124
	Minimum	-0.0033	-0.0071	-0.0082	-0.0079	-0.0069	-0.0064
Road profile (m)	Maximum	0.0113	0.0132	0.0140	0.0122	0.0128	0.0129
	Minimum	-0.0053	-0.0056	-0.0073	-0.0068	-0.0093	-0.0096

Table 2: Simulation results (Analytical)

7.3. Interpretation of Results

Out of the four parameters viz. road distance, body travel, body acceleration and suspension deflection the body acceleration is the most important and considerable parameter to be observed and kept within the permissible limits.

Hence in the present experimental tests as per the availability of instrumentation the main focus has been given to body acceleration.

The body acceleration was given in the form of tabulated data on HMI as an .xls file reading the acceleration values at particular time interval. The acceleration values were recorded at regular interval of 0.5 seconds. The tabulated data in the excel file was taken on the portable memory drive as the HMI facilitates the port for USB pen drive for data interaction. Finally the validation of analytical and experimental results was done from the data obtained as given in table.

8. References

1. Yahaya Md. Sam, Mohd. Ruddin Hj. Ab.Ghani, Nasarudin Ahmad "LQR Controller for Active Car Suspension", 2000 IEEE, 441-444.
2. Chuanyin Tang TiaoxiaZhang, "The research on control algorithms of vehicle active suspension system", 2005 IEEE, 320-325.
3. Seok-il Son' and Can Isik, "Fuzzy Control of an Automotive Active Suspension", 1996 IEEE, 377-381.
4. Andrew Barr and Dr. Jeffry Ray, "Control of an active suspension using fuzzy logic", 5.0001996 IEEE, 42-48.
5. Kateřina HYNIOVÁ and Antonín STŘÍBRSKÝ and Jaroslav HONCŮ, "FUZZY CONTROL OF MECHANICAL VIBRATING SYSTEMS", Department of Control Engineering, Faculty of Electrical Engineering, Czech Technical University Karlovo náměstí.
6. M. M. Elmadany, "Design of an Active Suspension for a Heavy Duty Truck using Optimal Control Theory", Computers and Structures Vol. 31. No. 3. pp. 38 M93, 1989.
7. Keum-Shik Hong, Dong-Seop Jeon, Hyun-Chul Sohn, "A New Modelling of the Macpherson Suspension System and its Optimal Pole-Placement Control" Proceedings of the 7th Mediterranean Conference on Control and Automation (MED99) Haifa, Israel - June 28-30, 1999.
8. Feng Tyan and Yu-Fen Hong, Shun-Hsu Tu and Wes S. Jeng, "Generation of Random Road Profiles."
9. Janusz KOWAL, Jacek SNAMINA, Tomasz WZOREK, "calculations for the project of the laboratory Stand for testing vehicle suspensions" Published in Mechanics and Control 2011 vol. 30 no. 1 s. 6–11
10. L.-J. ZHANG, C.-M. LEE and Y. S. WANG, "a study on nonstationary random vibration of a vehicle in time and frequency domains" International Journal of Automotive Technology, Vol. 3, No. 3, pp. 101−109 (2002).
11. Pananda N, Ferguson N S and Waters T P, ISVR, University of Southampton, "the effect of cubic damping in an automotive Vehicle suspension model."
12. Erik Ryan Andersen, "Multibody Dynamics Modelling and System Identification for a Quarter-Car Test Rig with McPherson Strut Suspension."
13. Peter Corke, "Analysis of the 2009 REV Race Car Suspension"

14. IS 2062, Bureau of Indian Standards, “Hot Rolled Low Medium and High Tensile Structural Steel” (Sixth Revision).
15. ‘Vibrations’ second edition by Balakumar Balachandran, Edward B. Magrab.
16. Justin D. Langdon ,“Design and Adaptive Control of a Lab-based, Tire-coupled, Quarter-car Suspension Test Rig for the Accurate Re-creation of Vehicle Response”
17. Quarter Car Suspension Model, a random source.
18. PSG Data Book, Design Data by Mahadevan.
19. CATIA workbench help.
20. AutoCAD workbench help.
21. ANSYS workbench tutorials