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"Simulation And Analysis Of Passive And Active Suspension System Using Quarter Car Model For Non Uniform Road Profile"

Abdolvahab Agharkakli*Chavan U. S. Dr. Phvithran S.
Address for Correspondence
Department of Mechanical Engineering, University of Pune (Vishwakarma Institute of Technology), Pune, Maharashtra, India

Abstract

The objectives of this study are to obtain a mathematical model for the passive and active suspensions systems for quarter car model and construct an active suspension control for a quarter car model subject to excitation from a road profile using LQR controller. Current automobile suspension systems using passive components only by utilizing spring and damping coefficient with fixed rates. Vehicle suspensions systems typically rated by its ability to provide good road handling and improve passenger comfort. Passive suspensions only offer compromise between these two conflicting criteria. Active suspension poses 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 synthesized based on the Linear Quadratic Regulator (LQR) control technique for a quarter car model. Comparison between passive and active suspensions system are performed by using road profile. The performance of the controller is compared with the LQR controller and the passive suspension system. The performance of this controller will be determined by performing computer simulations using the MATLAB and SIMULINK toolbox.

Keywords: Quarter Car Model, Active Suspension System, LQR Control Design, Road Profile

1. INTRODUCTION

A car suspension system is the mechanism that physically separates the car body from the wheels of the car. The purpose of suspension system is to improve the ride comfort, road handling and stability of vehicles. Apple yard and Well stead (1995) have proposed several 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. Current automobile suspension systems using passive components can only offer a compromise between these two conflicting criteria by providing spring and damping coefficients with fixed rates. A good suspension system should provide good vibration isolation, i.e. small acceleration of the body mass, and a small "rattle space", which is the maximal allowable relative displacement between the vehicle body and various suspension components. A passive suspension has the ability to store energy via a spring and to dissipate it via a damper. Its parameters are generally fixed, being chosen to achieve a certain level of compromise between road handling, load carrying and ride comfort. An active suspension system has the ability to store, dissipate and to introduce energy to the system. It may vary its parameters depending upon operating conditions. Generally, the vehicle suspension models are divided into three types namely quarter car, half car and full car models. 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 fix and cannot be adjusted by any mechanical part. The problem of passive suspension is if it designs heavily damped or too hard suspension it will transfer a lot of road input or throwing the car on unevenness of the road. Then, if it lightly damped or soft suspension it will give reduce the stability of vehicle in turns or Change lane or it will swing the car. 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. Therefore, an active suspension system shown is Figure1 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 by using LQR controller and passive suspension only.

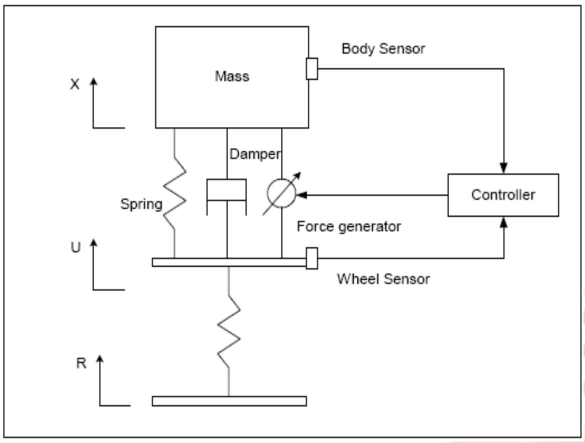

Figure1: Active Suspension System

2. MATHEMATICAL MODELLING OF ACTIVE SUSPENSION FOR QUARTER CAR MODEL

Quarter-car model in Figure 2 is often used for suspension analysis; because it simple and can capture important characteristics of full model. The equation for the model motions are found by adding vertical forces on the sprung and unsparing masses. Most of the quarter-car model suspension will represent the M as the sprung mass, while tire and axles are illustrated by the unsparing mass m. The spring, shock absorber and a variable force-generating element placed between the sprung and unsparing masses constitutes suspension. From the quarter car model, the design can be expend into full car model

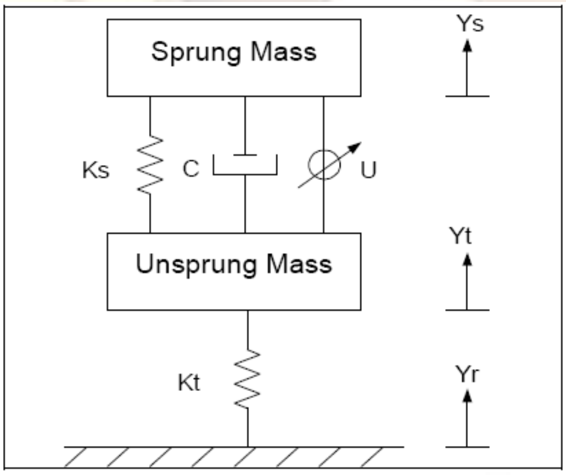

Figure2: Quarter Car Model

The main focus is to provide background for mathematical model of a quarter car model. The dynamic model, which can describes the relationship between the input and output, enables ones to understand the behaviour of the system. The purpose of mathematical modelling is to obtain a state space representation of the quarter car model. Suspension system is modelled as a linear suspension system. The state variable can be represented as a vertical movement of the car body and a vertical movement of the wheels.

Figure3 shows a basic two-degree-of freedom system representing the model of a quarter-car. The model consists of the sprung mass M2 and the unsprung mass M1. The tire is modelled as a linear spring with stiffness Kt. The suspension system consists of a passive spring Ka and a damper Ca in parallel with an active control force u. 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.

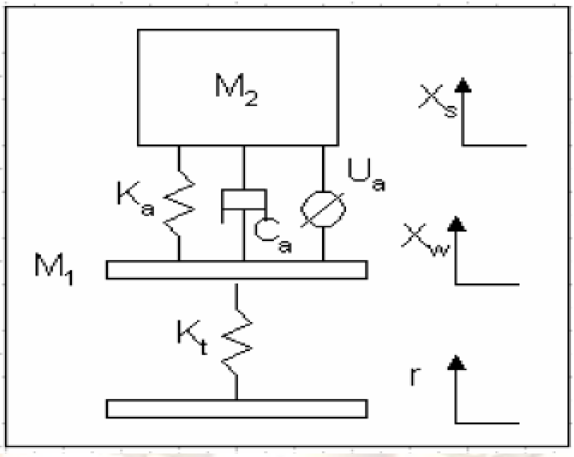

Figure3: Active Suspension for Quarter car Model

From the Figure 3 and Newton's law, we can obtain the dynamic equations as the following:

For M_1,
$F = Ma$
$K_t(X_w - r) - Ka(X_s - X_w) - Ca(\dot{X}_s - \dot{X}_w) - Ua = M_1\ddot{X}_w$

$$\ddot{X}_w = \frac{K_t(X_w - r) - Ka(X_s - X_w) - Ca(\dot{X}_s - \dot{X}_w) - Ua}{M_1} \quad (1)$$

For M_2,
$F = Ma$
$-Ka(X_s - X_w) - Ca(\dot{X}_s - \dot{X}_w) + Ua = M_2\ddot{X}_s$

$$\ddot{X}_s = \frac{-Ka(X_s - X_w) - Ca(\dot{X}_s - \dot{X}_w) + Ua}{M_2} \quad (2)$$

Let the state variables are;

$$\begin{aligned} X_1 &= X_s - X_w \\ X_2 &= \dot{X}_s \\ X_3 &= X_w - r \\ X_4 &= \dot{X}_w \end{aligned} \quad (3)$$

Where,
$X_s - X_w$ = Suspension travel
$\dot{X}_s$ = Car Body Velocity
$\ddot{X}s$ = Car Body Acceleration
$X_w - r$ = Wheel Deflection
$\dot{X}_w$ = Wheel Velocity

Therefore in state space equation, the state variables are established in equation (3). Therefore, equations (1) and (2) can be written as below

$$\dot{X}(t) = AX(t) + Bu(t) + f(t) \quad (4)$$

Where,

$$\begin{aligned} \dot{X}_1 &= \dot{X}_s - \dot{X}_w \approx X_2 - X_4 \\ \dot{X}_2 &= \ddot{X}_s \\ \dot{X}_3 &= \dot{X}_w - \dot{r} \approx X_4 - \dot{r} \\ \dot{X}_4 &= \ddot{X}_w \end{aligned} \quad (5)$$

Rewrite equation (4) into the matrix form yield

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & -1 \\ \frac{-Ka}{M_2} & \frac{-Ca}{M_2} & 0 & \frac{Ca}{M_2} \\ 0 & 0 & 0 & 1 \\ \frac{-Ka}{M_1} & \frac{Ca}{M_1} & \frac{-K_t}{M_1} & \frac{-Ca}{M_1} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{M_2} \\ 0 \\ \frac{1}{M_1} \end{bmatrix} Ua + \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix} \dot{r} \quad (6)$$

Parameters of Quarter Car Model for Simple Passenger Car;

M_1=59kg
M_2=290kg
Ka=16812(N/m)
K_t=190000(N/m)
Ca=1000(Ns/m)

Table1: Parameter for Quarter Car Model

3. CONTROLLER DESIGN USING LINEAR QUADRATIC REGULATOR (LQR)

The main objective of this section is to design LQR controller for the active suspension system. In optimal control, the attempts to find controller that can provide the best possible performance. The LQR approach of vehicle suspension control is widely used in background of many studies in vehicle suspension control. . The strength of LQR approach is that in using it the factors of the performance index can be weighted according to the designer's desires or other constraints. In this study, the LQR method is used to improve the road handling and the ride comfort for a quarter car model. LQR control approach in controlling a linear active suspension system.

We have system like $\dot{X}(t) = AX(t) + Bu(t) + f(t)$ Consider a state variable feedback regulator for the system as $u(t) = -Kx(t)$ K is the state feedback gain matrix (controller). Then, we make new system like this $\dot{X}(t) = (A - BK)X(t) + f(t)$.

The optimization procedure consists of determining the control input U, which minimizes the performance index. The performance index J represents the performance characteristic requirement as well as the controller input limitation. The optimal controller of given system is defined as controller design which minimizes the following performance index.

$$J = \int_0^{\infty} (x(t)^T Qx(t) + u(t)^T Ru(t))\, dt \quad (7)$$

Where u is state input, and Q and R are positive definite weighting matrices.

The matrix gain K (controller) is represented by:

$$K = R^{-1}B^T P \quad (8)$$

where the matrix P is evaluated being the solution of the Algebric Riccati Equation (ARE). Look like

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \quad (9)$$

This is a knwon as a Algebric Riccati Equation (ARE). By substituting gain matrix K in $\dot{X}(t) = AX(t) + Bu(t) + f(t)$ we get the controlled states in the form, $\dot{X}(t) = (A - BK)X(t) + f(t)$ So, I have big equation look where is take my system A matrix, my system B matrix, a takes the weating matrix Q, a take the weating matrix R and there exist matrix p. So, this solotion P will exist and solve this (ARE) and solution it can speed out A, B, Q, R and P matrix. Then, once you solve for the P, then, use R and B and solve for k and we do that. then, this matrix $(A - BK)$ has eigenvalue there are stable. These eigenvalue we should to find these value by tuning valus of Q and R. This is give you stablizing controlable and its going to be controler the minimazing that Performance index (cost function). So, for the propuse of this method you just to need to know how solve this (ARE) for P and you can do numerically but MATLAB has tools help related to Algebric Riccati Equation (ARE) and it has tools related to LQR method. So, can do help in matlab for Algebric Riccati Equation (ARE) and for LQR.

Then the feedback regulator U

$$\begin{aligned} u(t) &= -R^{-1}B^T Px(t) \\ &= -K\,x(t) \end{aligned} \quad (10)$$

The design procedure for finding the LQR feedback K is:

• Select design parameter matrices Q and R
• Solve the algebraic Riccati equation for P
• Find the SVFB using $K = R^{-1}B^T P$

Limitations;

We take $(x(t)^T Qx(t) \geq 0)$ and $(u(t)^T Ru(t) > 0)$ Because we want the penelize all state in $(x(t)^T Qx(t))$ and all input $(u(t)^T Ru(t))$ and if we don't penelize all of state in input, then the controller is diffecult.

4. SYSTEM MODELING

Designing an automatic suspension system for a car turns out to be an interesting control problem. When the suspension system is designed, a 1/4 car model (one of the four wheels) is used to simplify the problem to a one dimensional spring-damper system.

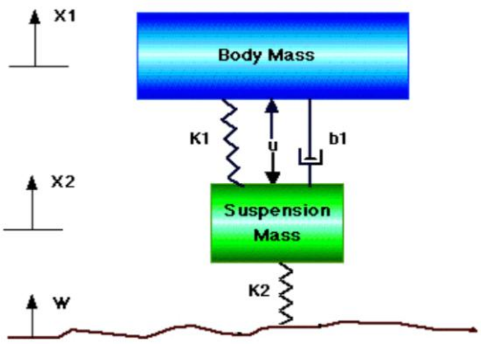

Figure4: active suspension system

Where:
* Body mass (M1) = 290 kg,
* Suspension mass (M2) = 59 kg,
* spring constant of Suspension system (K1) = 16182 N/m,
* spring constant of wheel and tire (K2) = 190000 N/m,
* damping constant of suspension system (b1) = 1000 Ns/m.
* Control force (u) = force from the controller we are going to design.

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. We want to design a feedback controller so that the output (**X1-X2**) has an overshoot less than 5% and a settling time shorter than 5 seconds. For example, when the car runs onto a 10 cm high step, the car body will oscillate within a range of +/- 5 mm and return to a smooth ride within 5 and 8 seconds.

Equations of motion: From the picture above and Newton's law, we can obtain the dynamic equations as the following:

$$\begin{aligned} M\ddot{X}1 &= -b1(\dot{X}1-\dot{X}2) - K1(X1-X2) + U \\ M\ddot{X}2 &= b1(\dot{X}1-\dot{X}2) + K1(X1-X2) \\ &\quad + K2(W-X2) - U \end{aligned} \tag{11}$$

Quarter car simulation model:

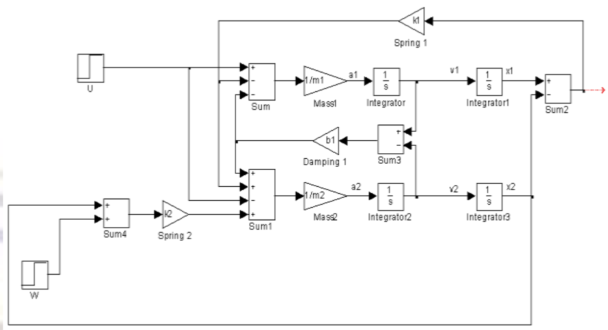

Figure 5: simulation modelling for Quarter car model

5. RESULT AND DISCUSSION

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 suspension travel, wheel deflection and the car body acceleration for quarter car. The aim is to achieve small amplitude value for suspension travel, wheel deflection and the car body acceleration. The steady state for each part also should be fast.

One type of road disturbance is assumed as the input for the system. The road profile is assumed have 3 bumps as below where a denotes the bump amplitude. The sinusoidal bump with frequency of 4 HZ, 2 HZ and 4 HZ has been characterized by,

The road profile is

$$r(t) = \begin{cases} a(1-\cos 8\pi t)/2, & (0.5 \le t \le 0.75, \\ & 3 \le t \le 3.25 \\ & 5 \le t \le 5.25\,) \\ 0, & \text{otherwisw} \end{cases} \tag{12}$$

Where, a= 0.05 (road bump hieght 5, -2.5 cm and 5 cm).

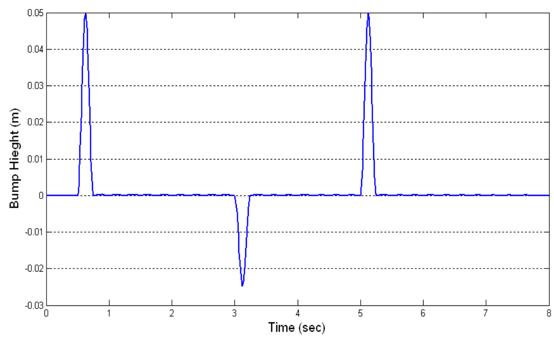

Figure6: Road Profile

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 LQR controller, the waiting matrix Q and waiting matrix R is set to be as below. First we can choose any Q and R. and then, if we getting more control input then we increase the R, if we want faster performance then we need more control so, Q should be more and R is less. If we want slow performance then Q should be less and R high.

$$Q = \begin{bmatrix} 50 & 0 & 0 & 0 \\ 0 & 50 & 0 & 0 \\ 0 & 0 & 200 & 0 \\ 0 & 0 & 0 & 250 \end{bmatrix} \quad (13)$$

And (14)

$R = 0.01$

Therefore, the value of gain k

$$K = [949630 \quad 66830 \quad -764050 \quad 1230] \quad (15)$$

Effect of the Suspension Performance on Various road Profiles:

In this section, the performance of the quarter car active suspension system is evaluated under Road profile between the passive and LQR controller. It shows the LQR with disturbance observer and the proposed observer is robustness to overcome and performance better than passive one. Figures (7-13) shows the performance for road profile. Excitation Force and Generate Force by the actuator shown in Figure7, the Excitation Force gets cancelled by the Generated Force. This indicates the efficiency of the LQR controller.

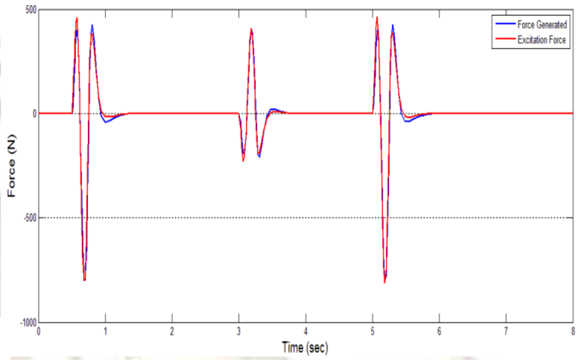

Figure7: Excitation Force and Force Generated

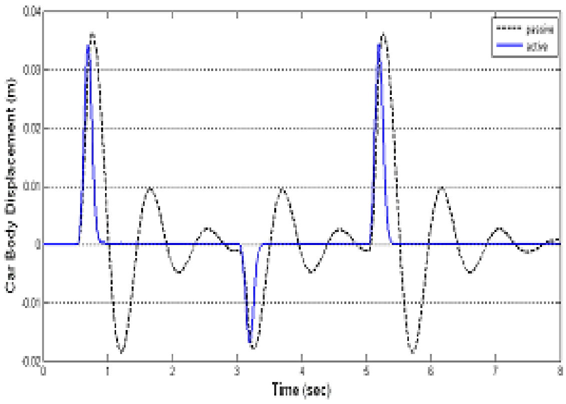

Figure8: Body Displacement

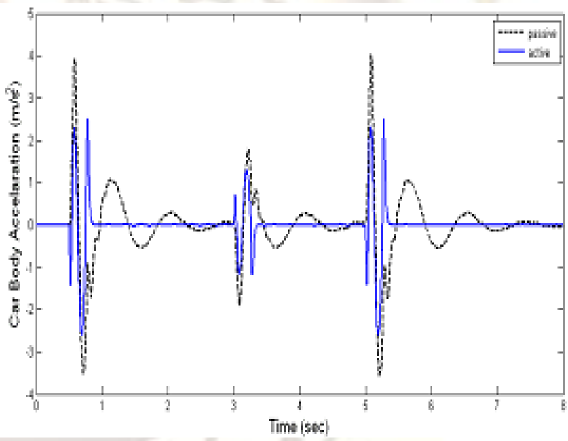

Figure9: Body Acceleration

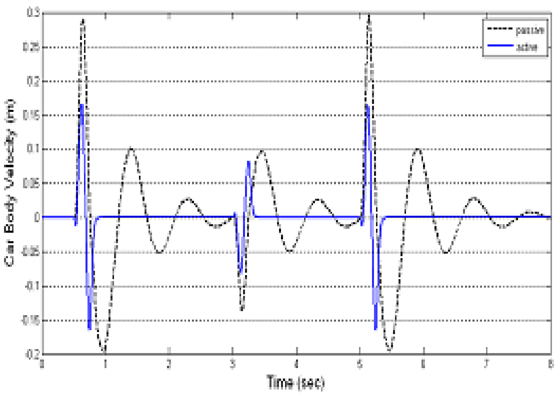

Figure10: Body Velocity

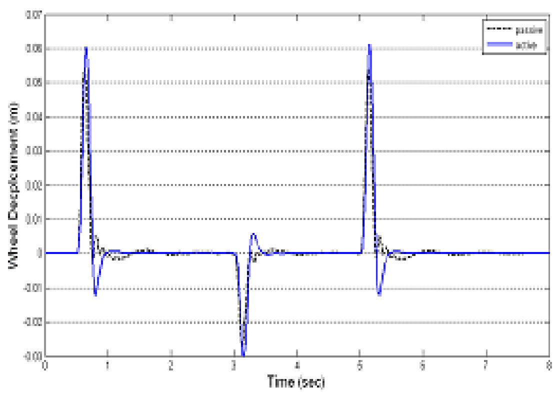

Figure11: Wheel Displacement

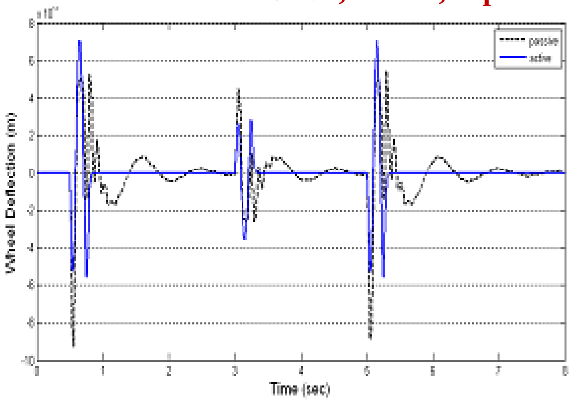

Figure12: Wheel Deflection

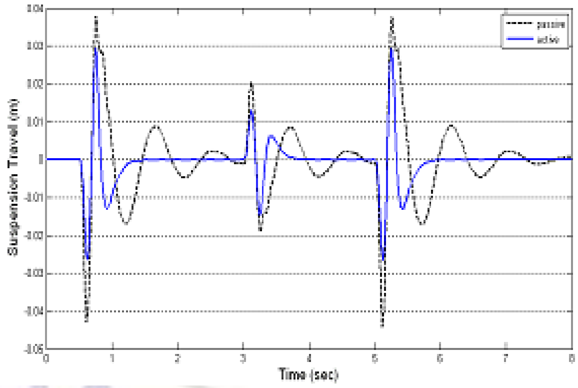

Figure13: Suspension Travel

By comparing the performance of the passive and active suspension system using LQR control technique it is clearly shows that active suspension can give lower amplitude and faster settling time. Suspension Travel can reduce the amplitude and settling time compare to passive suspension system. Body Displacement also improve even the amplitude is slightly higher compare with passive suspension system but the settling time is very fast. Body Displacement is used to represent ride quality.

LQR controller design approach has been examined for the active system. Suspension travel in active case has been found reduced to more than half of their value in passive system. By including an active element in the suspension, it is possible to reach a better compromise than is possible using purely passive elements. The potential for improved ride comfort and better road handling using LQR controller design is examined. MATLAB software programs have been developed to handle the control design and simulation for passive and active systems.

6. CONCLUSIONS

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 modelling has been performed using a two degree-of-freedom model of the 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. LQR controller design approach has been examined for the active system. Suspension travel in active case has been found reduced to more than half of their value in passive system. By including an active element in the suspension, it is possible to reach a better compromise than is possible using purely passive elements. The potential for improved ride comfort and better road handling using LQR controller design is examined.

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 LQR.

REFERENCES

[1] Robert L.W. & Kent L.L., "Modeling and Simulation of Dynamic System", Second Edition, Prentice-Hall, 1997

[2] Sam Y.M., Osman H.S.O., Ghani M.R.A., "A Class of Proportional-Integral sliding Mode Control with Application to Active Suspension System" System and Control Letters. 2004. 51:217-223

[3] Kim C., Ro P.I, "An Accurate Full Car Ride Model Using Model Reducing Techniques," Journal of Mechanical Design. 2002. 124:697-705

[4] Sam Y.M., Ghani M.R.A and Ahmad, N. LQR Controller for Active Car Suspension. IEEE Control System 2000 I441-I444

[5] Hespanhna J.P., "Undergraduate Lecture Note on LQG/LGR controller Design", University of California Santa Barbara; 2007

[6] Wu S.J., Chiang H.H., Chen J.H., & Lee T.T., "Optimal Fuzzy Control Design for Half-Car Active Suspension Systems" IEEE Proceeding of the International Conference on Networking, Sensing and Control. March, Taipei, Taiwan: IEEE. 2004. 21-23

[7] Astrom K.J. & Wittenmark B., "Adaptive Control", Second Editon, Addison- Wesley Pub, 1995.

[8] Chen H.Y. & Huang S.J., "Adaptive Control for Active Suspension System" International Conference on Control and Automatic. June. Budapest, Hungary: 2005.

[9] Ikenaga S., Lewis F.L., Campos J., & Davis L., "Active Suspension Control of Ground Vehicle Based on a Full Car Model" Proceeding of America Control Conference. June. Chicago, Illinois: 2000.

[10] Shariati A., Taghirad H.D. & Fatehi A. "Decentralized Robust H-∞ Controller Design for a Full Car Active Suspension

System" Control. University of Bath, United Kingdom. 2004

[11] William D.L., Hadad W.M., "Active Suspension Control to Improve Vehicle Ride and Handling", *Vehicle System Dynamic*. 1997. 28: 1-24 70

[12] Sam Y.M. Proportional Integral Sliding Mode Control of an Active Suspension System, Malaysia University of Technology, PHD Dissertation, Malaysia University of Technology; 2004

[13] Hyvarinen J.P., "The Improvement of Full Vehicle Semi-Active Suspension through Kenimatical Model," Master Science Disertation. Oulu of University Findland; 2004

[14] Winfred K.N., Dion R.T., Scott C.J., Jon B., Dale G., George W.A., Ron R., Jixiang S., Scott G., Li C. "Development and Control of a Prototype Pneumatic Active Suspension System," IEEE Transaction on Education. 2002. Vol. 45; No.1; pp. 43-49

[15] Joo D.S. & Al-Holou N., "Development & Evamation of Fuzzy Logic Controller for Vehicle Suspension System," (1995) MI 48219; pp. 295-299

[16] Hung V.V. & Esfandiari S.R., "Dynamic Systems: Modeling and Analysis", Second Edition, McGraw-Hill, 1997

[17] Lowen J. Shearer & Kulakowski B.T., "Dynamic Modeling and Control of Engineering Systems" Second Edition, Macmillan Publishing, 1990

[18] Gallestey P., "Undergraduate Lecture Note on Applied Nonlinear Control Design", University of Califonia Santa Barbara; 2000

[19] Yoshimura T., Kume A., Kurimoto M., Hino J., "Construction of an Active Suspension System of a Quarter-Car Model Using the Concept of Sliding Mode Control," Journal of Sound and Vibration. 2000. 239:187-199.

[20] Hrovat, D. & Tseng, T., "Some Characteristics of Optimal Vehicle Suspensions Based on Quarter Car Model" IEEE Proceedings of the 29th Conferences on Decision and Control, December, Honolulu, Hawaii: IEEE. 1990. 2232-2237

[21] E. Esmailzadeh and H.D. Taghrirad "Active Vehicle Suspensions with Optimal State-Feedback Control", International Journal of Mechanical Science, pg 1- 18, 1996.