Vibration Control of Bus Suspension System using PI and PID Controller

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Abstract—**This paper presents the application of PI and PID controller to control the vibration occurred in the bus suspension system. When the suspension system is designed, a ¼ model of bus is used to simplify the problem to a one dimensional mass-spring-damper system. Its open-loop performance on the basis of time response is observed which depicts that the bus suspension has oscillations with large settling time. To overcome this problem, closed-loop system is used. Despite continuous advancement in control theory, Proportional –Integral (PI) and Proportional-Integral-Derivative (PID) Controllers are the popular technique to control any process. In this paper, Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers are used to control the vibrations to give smooth response of the bus suspension system and carry-out their comparison on the basis of time and frequency using Matlab environment. The simulation and implementation of the controller is done using MATLAB/SIMULINK.**

Keywords- Bus suspension system, dynamic modeling, Proportional-Integral controller and Proportional-Integral-Derivative controller.

I. INTRODUCTION

Increasing progress in automobile industry demands for better riding capabilities and passenger comfort, to produce highly developed model. The aim of the advanced bus suspension system is to provide smooth ride and maintain the control of the vehicle over cracks, uneven pavement of the road. Moreover, suspension system modeling has an important role for realistic control design of suspension [1-3].

In passive suspension system, spring and diminishing element is placed between the wheel and the bus body. They allow the forward compensation between the suspension stroke deviation and the driving comfort. According to the bus structural feature, suspension stroke is limited for some specified values. Riding comfort reduces as suspension deviation reached these limited specified values. In active suspension system, a hydraulic system which is controlled by feedback controller is placed between the wheel and the bus body. Controlled suspension system allows forward compensation between the performance criteria of suspension deviation and the riding comfort [4-7].

Nowadays, different types of controllers are used to control the bus suspension system such as adaptive control, LQG, nonlinear control, H infinity, P, PI and PID [8-10]. In this paper, PI and PID controllers are designed to control the vibration occurred in bus suspension system using SIMULINK/MATLAB [11-13].

This paper is organized as follows: Section 2 devoted to the bus suspension system. The simulation implementation of open loop system and modeling is also presented in this section. Section 3 gives the introduction of PI and PID Controllers. Section 4 applies the PI and PID Controllers to the bus suspension system. Section 5 covers the comparison of the open-loop bus suspension system with PI and PID Controllers. Section 6 gives the conclusion and results.

II. THE BUS SUSPENSION SYSTEM

Bus Suspension is the system of springs, shock absorbers and linkages that connects a bus to its wheels and allows relative motion between the two. Suspension system serves a dual purpose- contributing to the vehicle's road holding/handling and braking for safety purpose and pleasure driving, and keeping vehicle occupants comfortable and isolated from road noise, bumps, and vibrations, etc.

A. Modeling and System Analysis

In the present paper, a ¼ model of the bus (one of four wheels) is used to design a simple bus suspension system which is taken as a plant. The Bus Suspension System is illustrated in Figure 1.

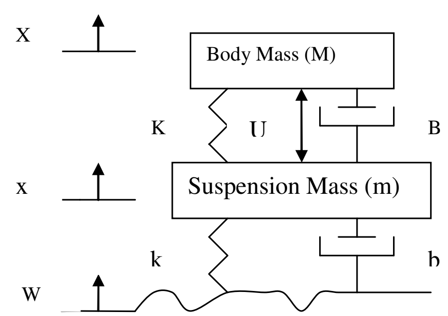

Figure 1. Bus Suspension System model of ¼ Bus

From the bus suspension system model, we can directly get the dynamic equation by using the Newton's law.

$$M\ddot{X} + B(\dot{X} - \dot{x}) + K(X - x) = U \quad (1)$$

$$m\ddot{x} = B(\dot{X} - \dot{x}) + K(X - x) + b(\dot{W} - \dot{x}) + k(W - x) - U \quad (2)$$

where M is the mass of body, m is the mass of suspension system, K is the spring constant of suspension system, k is the spring constant of wheel and tyre, B is the damping constant of suspension system, b is the damping constant of wheel and tyre, U is the force from the controller which is to be controlled [14].

Equations of Motion of quarter-bus model, given in equations (1) and (2) has been transformed in state-space model, shown in equations (3) and (4) including variable vector, disturbance vector and the input vector by applying some algebraic operations on them.

$$\begin{bmatrix} \dot{X} \\ \ddot{X} \\ \dot{Y} \\ \ddot{Y} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{Bb}{Mm} & 0 & \left(\frac{B}{M}\left(\frac{b}{M}+\frac{B}{m}+\frac{b}{m}\right)-\frac{K}{M}\right) & -\frac{B}{M} \\ \frac{b}{m} & 0 & -\left(\frac{B}{M}+\frac{B}{m}+\frac{b}{m}\right) & 1 \\ \frac{k}{m} & 0 & -\left(\frac{k}{M}+\frac{K}{m}+\frac{k}{m}\right) & 0 \end{bmatrix} \begin{bmatrix} X \\ \dot{X} \\ Y \\ \dot{Y} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{B}{M} & -\frac{Bb}{Mm} \\ 0 & -\frac{b}{m} \\ \left(\frac{1}{M}+\frac{1}{m}\right) & -\frac{k}{m} \end{bmatrix} \begin{bmatrix} U \\ W \end{bmatrix} \quad (3)$$

$$Y = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} X \\ \dot{X} \\ Y \\ y \end{bmatrix} + \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} U \\ W \end{bmatrix} \quad (4)$$

In this paper, the distance $\mathbf{X_1}$-$\mathbf{X_2}$ instead of $\mathbf{X_1}$-$\mathbf{W}$ is used as output as the distance $\mathbf{X_1}$-$\mathbf{W}$ is very difficult to measure and the deformation of tyre ($\mathbf{X_2}$-$\mathbf{W}$) is negligible.

B. Controllability and Obsrvability

Open loop system using state space representation can be described by state equation and output equation [15] given as

$$\dot{X} = AX + BU \qquad \text{State equation} \qquad (5)$$

$$Y = CX + DU \qquad \text{Output equation} \qquad (6)$$

where X is state vector of the system, U is control signal, Y is output signal, A is n×n state matrix (n is the number of states or order of system), B is n×1 input matrix, C is 1×n output matrix, D is direct transmission matrix (scalar).

1) Controllability

A system is said to be controllable if it is possible by means of input vector U(t), to take a system from any initial state $X(t_i)$ to any final state $X(t_o)$ in a finite time $(t_0 - t_i)$ where $t_i \leq t \leq t_0$. For a completely controllable system every state must be controllable [16].

Based on controllability matrix Ct, a system given by equations (5) and (6) is said to be completely controllable if and only if the rank of controllability matrix Ct is equals to the order of system [15, 17].

$$Ct = [B \vdots AB \vdots \cdots \ldots\ldots\ldots A^{n-1}B] \qquad (7)$$

A system is said to be stabilizable if matrices A and B are controllable. In the present paper, the rank of controllability matrix is 4, the order of the system, and hence system is completely state controllable.

2) Observability

An unforced system (input vector U(t) = 0) is said to be completely observable if any initial state $X(t_i)$ can be determined by the observation of output Y(t) over a finite interval $t_i \leq t \leq t_1$. Sometimes all state variables are not accessible for direct measurement, in such situations the concept of observability is very useful to reconstruct immeasurable state variables form the measurable variables in a very short period of time [18].

Based upon observability matrix O_t, a system described by state space equations (3) and (4) is said to be completely observable if and only if the rank of observability test matrix O_t is equals to the order of system.

$$O_t = [C^T \vdots A^T C^T \vdots (A^T)^2 C^T \vdots \cdots \ldots\ldots (A^T)^{n-1} C^T] \qquad (8)$$

A system is detectable if matrices A and C are observable. For the system given, the rank of observability matrix is 4 which is equal to the order of system hence from the observability test theorem the system is completely observable.

C. Simulink Implementation of Bus Suspension System

The bus suspension shown in Figure 1 has been implemented in SIMULINK as shown in Figure 2 [19]. The MATLAB/SIMULINK is used to display how the original open-loop system performs without any feedback control.

The response of the system to a unit step actuated force input and unit step disturbance input is observed. The road disturbance in this problem will be simulated by a step input. This step could represent the bus coming out of a pothole.

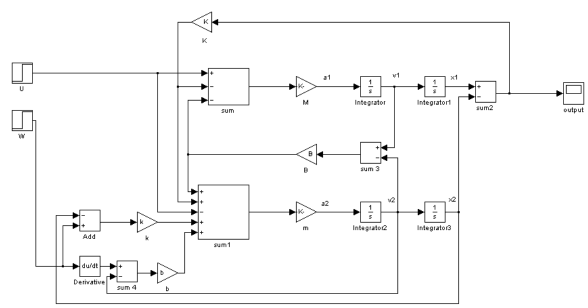

Figure 2. Simulink Model of Bus Suspension System

In this paper, uneven pavement and cracks are considered as disturbance that creates vibration in the bus. The aim of this work is to reduce vibration in the Bus for the comfort of the passenger.

When consider the control input **U(s)** only, set **W(s)** = 0. Thus, observe an Open-Loop response of step actuated force as shown in figure 3.

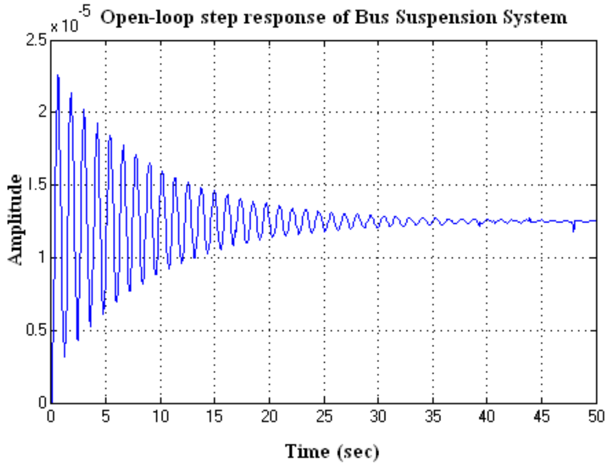

Figure 3. Open-loop step response of Bus Suspension System

When consider the disturbance input W(s) only, set **U(s)** = 0. Thus, observe an Open-Loop response of unit step disturbance force as shown in figure 4.

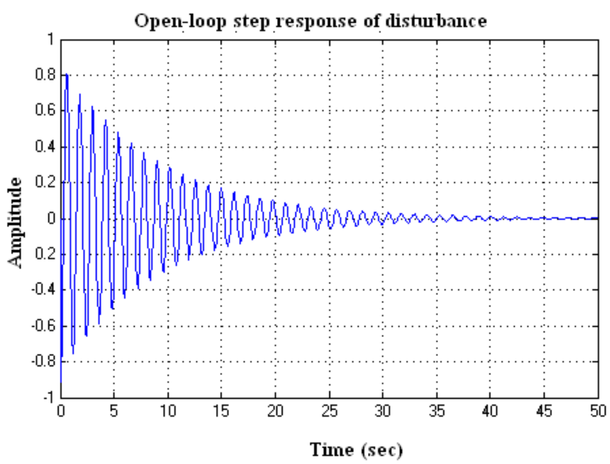

Figure 4. Open-loop step response of disturbance

It is observed from the open-loop response that for a unit step actuated force; the system is under-damped. The overshoot is about 0.81 and settling time is 38sec. People sitting in the bus will feel very small amount of oscillation but it takes an unacceptably long time to reach the steady state (the settling time is very large). The solution to this problem is to add a controller into the system to improve the performance.

III. CONTROLLER

A controller is a device, may be in the form of analogue circuit, chip or computer that monitors and physically alters the operating conditions of a given dynamical system.

From the past decades, the importance of the control system has been increased due to the increment in complexity of the system under control and to achieve optimum performance of the system. The block diagram of closed-loop Bus Suspension System is shown in Figure 5.

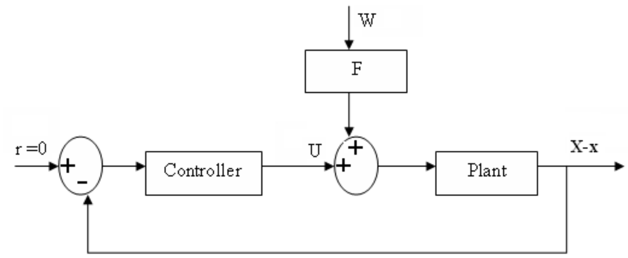

Figure 5. Open-loop step response of Bus Suspension System

In this paper, two controllers, Proportional-Integral (PI) Controller and Proportional-Integral-Derivative (PID) Controller are used to improve the response of the system.

A. *Proportional-Integral Controller*

The combination of proportional and integral terms is important to increase the speed of the response and also to eliminate the steady state error. $C(s)$ the transfer function of PI controller has the form of

$$C(s) = K_P + \frac{K_I}{s} = \frac{K_p s + K_I}{s} \tag{9}$$

The PID controller block is reduced to P and I blocks only as shown in figure 6.

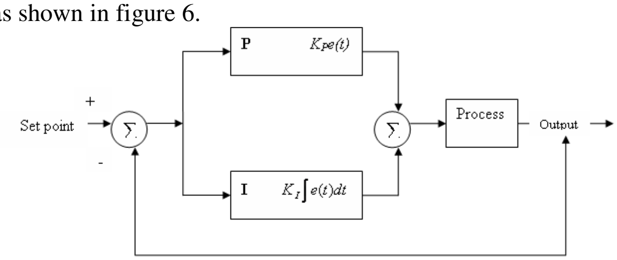

Figure 6. Block Diagram of PI controller

Where, K_P is proportional gain and K_I is an Integral gain. The proportional term (sometimes called gain) makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant Kp, called the proportional gain.

The contribution from the integral term sometimes called reset is proportional to both the magnitude of the error and the duration of the error. Summing the instantaneous error over time gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain and added to the controller output [20].

A. *Proportional-Integral-Derivative Controller*

A proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism widely used in industrial control systems - a PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs [20].

In this section, the method to obtain the controller for the bus suspension system is described when a PID scheme is used to perform control actions and $C(s)$ the transfer function of PID controller has a form

$$C(s) = K_P + \frac{K_I}{s} + K_D s = \frac{K_D s^2 + K_p s + K_I}{s} \quad (10)$$

The block diagram of the PID controller is shown in Figure 7.

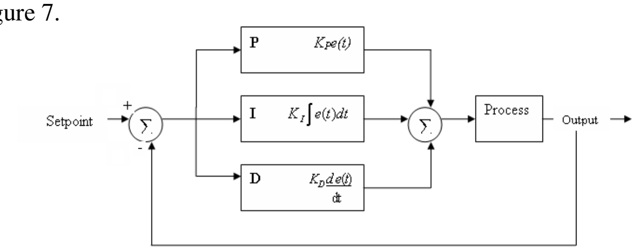

Figure 7. Block Diagram of PID controller

The PID controller calculation involves three separate parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. The proportional value determines the reaction to the current error, the integral value determines the reaction based on the sum of recent errors, and the derivative value determines the reaction based on the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the disturbances of a bus suspension system.

IV. Design of PI and PID Controllers

In this section, PI and PID Controllers are applied to the Bus Suspension System. To design a PI and PID Controller MATLAB/SIMULINK is used.

A. Design of PI Controller

The test presented in this section is related to the PI Controller performance for the bus suspension system. The main purpose of this implementation is to get the desired response of the system. The Simulink model of the Bus Suspension system using PI Controller is shown in Figure 8.

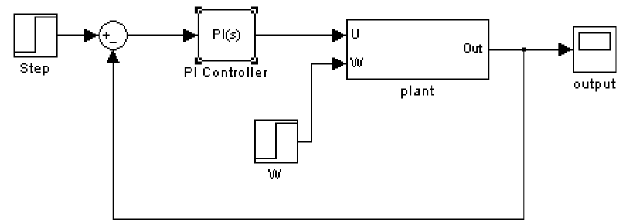

Figure 8. Simulink Model of Bus Suspension System using PI Controller

The Simulink Model of PI Controller is shown in Figure 9.

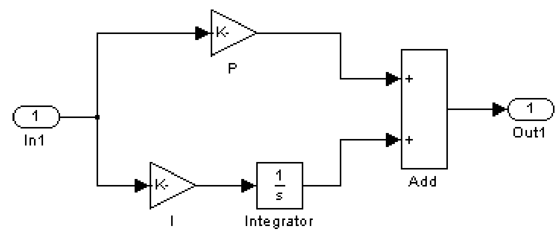

Figure 9. Simulink Model of PI Controller

The values of K_P and K_I are 832100 and 624075 respectively are taken. The response of the Bus Suspension System using PI Controller is shown in Figure 10.

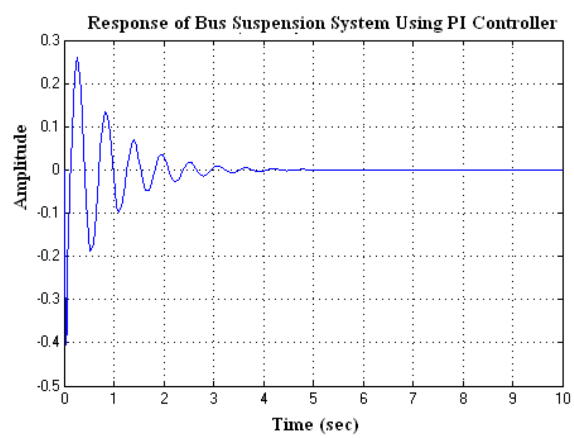

Figure 10. Response of Bus Suspension System using PI Controller

Figure 10 depicts that the people sitting in bus feels small amount of oscillations for 5 seconds. Without derivative action, a PI-controlled system is less responsive to real and relatively fast alterations in state and so the system will be slower to reach set-point and slower to respond to perturbations than a well-tuned PID system.

B. Design of PID Controller

The test presented in this section is related to the PID Controller performance for the bus suspension system. The main purpose of this implementation is to get the desired response of the system. The Simulink model of the Bus Suspension system using PID Controller is shown in Figure 11.

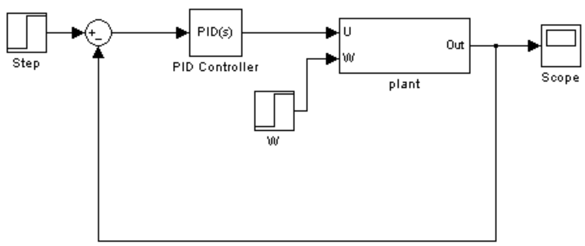

Figure 11. Simulink Model of Bus Suspension System using PID Controller

The Simulink Model of PID Controller is shown in Figure 12.

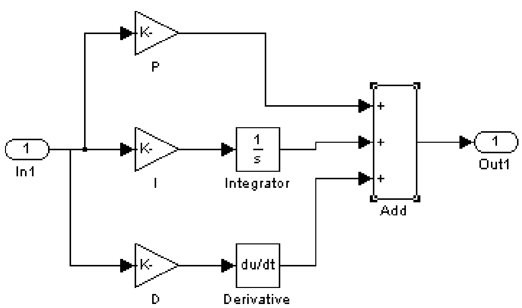

Figure 12. Simulink Model of PID Controller

The values of K_P, K_I and K_D are 832100, 624075 and 208025 respectively. The response of the Bus Suspension System using PID controller is shown in Figure 13.

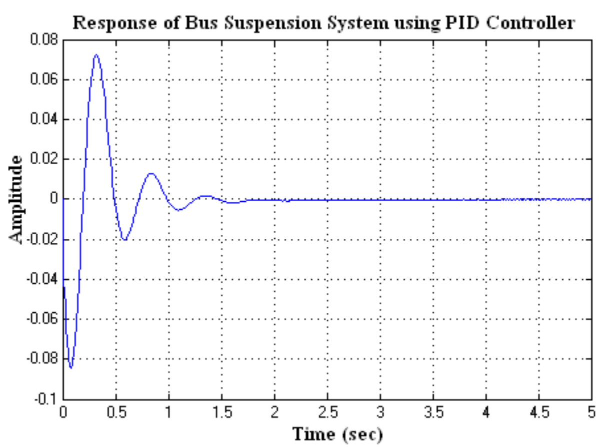

Figure 13. Response of Bus Suspension System using PID Controller

The Figure 13 depicts that the people sitting in Bus feels very small amount of oscillations in 2 seconds. By the use of PID Controller, the performance characteristics of bus suspension System are drastically improved.

V. Comparison of Open-Loop Bus Suspension System with PI and PID Controllers

The further analysis of Bus Suspension System is investigated by comparing it with the PI and PID Controllers.

Figure 14 shows the comparison response of the open-loop Bus Suspension System with PI and PID Controllers.

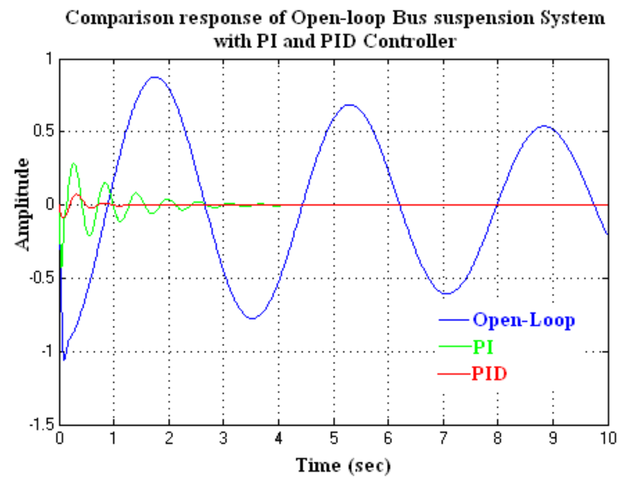

Figure 14. Comparison response of Open-loop Bus Suspension System using PI and PID Controller

It is observed from the comparison of the Open-loop Bus Suspension System using PI and PID controller is that the PID controller has less overshoot and has very small settling time i.e. 2 seconds as compare to others.

The analysis of figure 14 is tabulated in table 1 which shows the comparison of the Proportional Integral (PI), Proportional-Integral-derivative (PID) with Open Loop Response of the bus suspension system.

TABLE I
Comparison of Different controllers with Open-Loop

Properties	Open-loop	PI	PID
Settling time	38 sec	5 sec	2 sec
Rise time	0.255	0.249	0.09
Overshoot	0.81	0.0067	0.0048

VI. Conclusion

In this paper, PI and PID Controllers have been designed and employed for controlling a suspension system of a ¼ bus model. The control scheme has been implemented in SIMULINK and compared the response of open-loop, PI and PID controllers. The overshoot of open loop response is observed as 0.81 and settling time is 38sec which signifies that people sitting in the bus feel small amount of oscillation for unacceptably long time. When PI controller is used with this system, it is observed that the overshoot decreases to 0.0067 and settling time becomes too short about 5 sec which satisfies designed criteria up to some extend. For further improvement, PID controller is used and it has been observed that the overshoot decreases to 0.0048 and response is settled at 2 sec which is a desired response of the suspension system. The proposed model is aimed to developed and carry the response of system using PID controller up to a better level.

REFERENCES

[1] K. Matsumoto, K. Yamashita and M. Suzuki, "Robust *H*∞ -output feedback control of decoupled automobile active suspension system", IEEE Transaction on Automatic Controller, vol. 44, pp.392-396, 1999.

[2] Elmadany, M., "Integral and state variable feedback controllers for improved Performance in automotive vehicles", Computer Structure., vol. 42, no. 2, pp. 237-244, 1992.

[3] Isobe, T. and O. Watanabe, "New semi-active suspension controller design using quasi-linearlization and frequency shaping", Control Eng. Pract., vol. 6, pp. 1183-1191, 1998.

[4] D'Amato, F.J. and D.E. Viassolo, "Fuzzy control for active suspension", Mechatronics, vol. 10, pp.897- 920, 2000.

[5] Kim H.J, H.S. Yaug and Y.P. Park, "Improving the vehicle performance with active suspension using road-sensing algorithm", Computers and Structure; vol. 80, pp. 1569-1577, 2002.

[6] Spentzas K. and A.K. Stratis "Design of a non-linear hybrid car suspension system using neural network", Mathematics and Computers in Simulation, vol. 60, pp. 369- 378, 2002.

[7] Yao, G. Z., F. F. Yap, G. Chen, W. H. Li and S. H. Yeo, "MR damper and its application for semi-active control of vehicle suspension system", Mechatronics, vol. 12, pp.963-973, 2002.

[8] Gordon, T. J., Marsh, C., and Milsted, M. G., "A Comparison of Adaptive LQG and Nonlinear Controllers for Vehicle Suspension Systems", Vehicle System Dynamics, pp. 321-340, 1991.

[9] Kuo Y. P. and T. H. S. Li, "GA-Based Fuzzy PI/PID Controller for Automotive Active Suspension System", IEEE Transactions on Industrial Electronics, vol. 46, pp. 1051–1056, December 1999.

[10] Zhuang, M. and D. P. Atherton, "Automatic tuning of optimum PID controllers," IEEE Proceeding Part D, vol. 140, pp. 216-224, 1993.

[11] Mathworks Matlab. [Online] Available: http://www.mathworks.com/products/matlab/

[12] Mathworks. Simulink.[Online].Available: http://www.mathworks.com/products/simulink/

[13] A. Tewari, "Modern Control Design with Matlab and Simulink", John Wiley & Sons, Ltd, 2002.

[14] Nurhan Gursel, Ismail Hakki Atlas and Levent Gumusel, " Fuzzy control of bus suspension system", proceedings of 5th International Symopsium on Intelligent Manufacturing Systems, Sakarya University, pp 1170-1177, May 29-31, 2006.

[15] S. Salapaka, A. Sebastian, J.P. Cleveland and M.V. Salapaka "High Bandwidth nanopositioner: A robust control approach" Review Scientific Instruments, vol. 73 no. 9, pp , 232-3241, 2002.

[16] Katsuhiko Ogata, Modern Control Engineering, fourth ed. Pearson education Inc. 2002.

[17] G. F Franklin, J.D. Powel and N.E. naeini, "Feedback Control of Dynamic System" Addison-Wesley M.A. 1986.

[18] CTMS Example: Bus suspension modeling in SIMULINK.

[19] Sheilza Aggarwal and Manisha Garg, "Design and Simulation of PID controller of nanopositioner for minimum integral of error", International Journal of Engineering Sciences (ISSN) online-2277-9698, pp. 127-132, 2012.

[20] Sharad Kumar Tiwari, "Analysis of fuzzy PID and Immune PID controller for three tank liquid level control", M.Tech Thesis, Thapar University, Punjab, 2011.