Optimal Control based Intelligent Controller for Active Suspension System

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Abstract: Suspension systems play a vital role in providing comfortable and safe vehicle ride. This paper proposes a controller that is developed by combining optimal control and intelligent control techniques to minimize the vehicle's body vertical displacement. The actuator control force is also reduced through this integration. The numerical simulation results have been provided for the non-linear quarter vehicle suspension system using MATLAB/SIMULINK. The comparison between uncontrolled suspension systems, Linear Quadratic Regulator Controller based active suspension system, and active suspension system using Optimal Control based Intelligent Controller are presented and thoroughly explained.
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Key-words: Active Suspension System, Linear Quadratic Regulator (LQR) Controller, Optimal Control based Intelligent Controller, MATLAB/SIMULINK (Licensed Version)

1. Introduction

All automobiles have specific suspension system for avoiding the vehicle's road disturbances and providing comfortable ride (Darus & Sam, 2005**)**. Suspension system is designed for getting dual benefits including contributing to vehicle's handling, road holding and also keeping vehicle tenants agreeable from road commotion, knocks and vibrations and so forth (Jazar, 2013). Traditional suspension system is mainly designed by using two parallel components named spring and damper. But suspension system designers faced a major issue of figuring out spring and damper suspension coefficients (Sakman et. al., 2005).As in traditional passive suspension system, two important factors like spring properties and resulting damping were at compromise (Sahraie et. al., 2011). Passive suspension system with soft spring supports comfortable ride resulting in high damping movements due to weak road holding and with hard spring resulting in hard moves due to road roughness and unevenness (Sakman et. al., 2005; Sahraie et. al., 2011; Gysen, 2008).

In order to improve passenger's comfort, vibrations must be minimized. This is possible by using semi-active (Al-Holou et. al., 1993) or active suspension system (Yagiz et. al., 2008) rather than passive one. Active suspension system has closed loop control system that can provide better root mean squared vertical accelerations of vehicle body (Baumal et. al., 1998) than semi-active or passive suspension system (Agharkakli et. al., 2012). Active suspension system works without compromise between road handling, load carrying and comfortable ride because of its characteristic additional power usage that provides response-dependent damper (Sireteanu & Stoia, 2003; Sun et. al., 2007, Jamil et. al., 2009). Force actuator (linear motor, hydraulic cylinder, etc.) (Pekgokgoz et. al., 2010) is a mechanical part incorporated in active suspension system design that is controlled by a controller developed on the basis of optimal control theory (Meditch, 1993) and is a reason of improved performance of active suspension system (Agharkakli et.al., 2012; Sam et. al., 2004).Suspension system dynamics are accurately represented as linear model for the controller design (Yoshimura et. al., 1999). Nevertheless, non-linearity and uncertainties are generally included in real vehicle suspension system dynamics (Yoshimura et. al., 1999; Yung & Cole, 2006).

Active vehicle suspension system can be modeled in three types named as quarter vehicle, half vehicle and full vehicle models (William & Hadad, 1997). Active suspension system needs an appropriate control technique for vehicle vibration. There are many types of controllers developed for making active suspension system more appropriate e.g. LQR Optimal Controller. LQR Optimal Controller is used to improve passenger ride comfort by minimizing the effect of road irregularities, cornering and braking. This is accomplished through application of vertical forces actively (Creed, 2012***)***.

The paper aims to propose a novel controller design strategy for suspension system developed through the combination of optimal control with intelligent control for optimizing the performance of a tire-vehicle (quarter vehicle) suspension system. LQR controller is also designed separately first in Simulink using state space function. Two controllers are combined afterwards and variations in body displacement, velocity, acceleration and force of designed active suspension system are evaluated.

2. Quarter Vehicle Suspension System Modeling:

Suspension system designing is a challenging control task. Designing of a suspension system (quarter model) is simply a one dimensional multiple spring-damper system, shown in Figure (1). Actuator included in active suspension system is key element able to generate control force that plays important role in comfort and controlled motion of body. System parameters required for simple passenger's quarter vehicle model are described in Table (1).

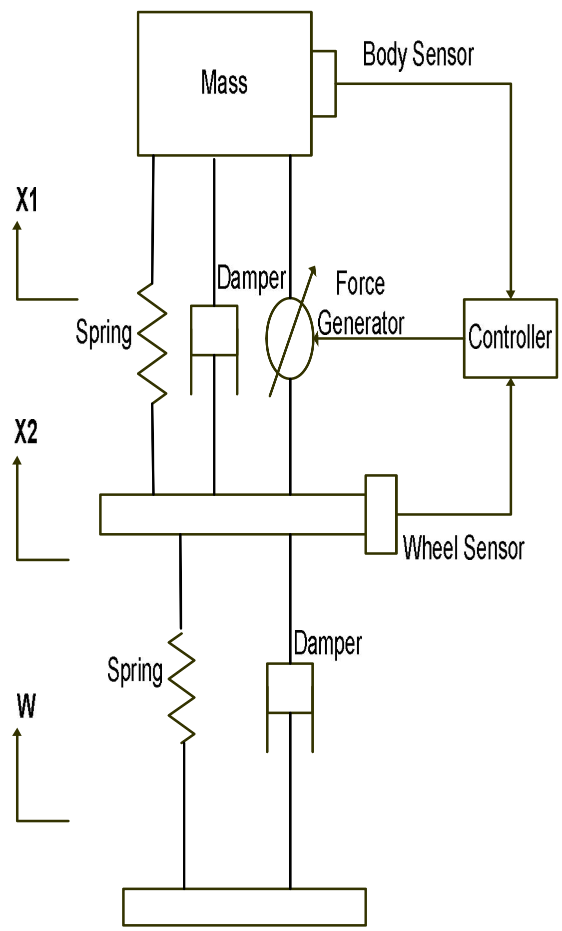

Figure (1): Active Suspension using Quarter Vehicle Model

Table (1): Parameters of the model

Property	Value
Quarter Body Mass(M_1)	2500.00kg
Quarter Suspension Mass(M_2)	320.00kg
Quarter Suspension Spring CoefficientK_1)	80,000.00N/m
Quarter Wheel Spring Coefficient(K_2)	500,000.00N/m
Quarter Suspension Damping CoefficientC_1)	350.00N.s/m
Quarter Wheel Damping Coefficient(C_2)	15,020.00N.s/m
Control force of Actuator(U)	has to measure

3. System Transfer Functions

Dynamic equations of quarter vehicle model motion can be converted into transfer functions by using Laplace transformation method. Derived transfer functions $G_1(S)$ and $G_2(S)$ from motion equations 1and 2 by considering U and W factor as input and X_1-X_2 as output;

$$G_1(S) = \frac{(X_1 - X_2)}{U(S)} = \frac{[(M_1+M_2)S^2+C_2S+K_2]}{\Delta} \quad (1)$$

Where; U(S) = Control input and W(S) = 0

$$G_2(S) = \frac{(X_1 - X_2)}{W(S)} = \frac{[-M_1C_2S^3 - M_1K_2S^2]}{\Delta} \quad (2)$$

Where; W(S) = Disturbance input and U(S) = 0

The value of Δ is given in equation 3.

$$\Delta = det\begin{bmatrix}(M_1S^2 + C_1S + K_1) & -(C_1S + K_1) \\ -(C_1S + K_1) & (M_2S^2 + (C_1 + C_2)S + (K_1 + K_2))\end{bmatrix} \quad (3)$$

5. Active Suspension System with Linear Quadratic Regulator Controller:

LQR Controller is used for improving road handling and comfort ride of quarter vehicle suspension system model. LQR approach is helpful in weighing factor of performance index in accordance with designer's desires and constraints. For state space LQR controller design, equations of active suspension system and state variables are established in equations 4 and 5.State space equation in matrix form is represented in equation 6 and 7.

$$\dot{x} = Ax + Bu \quad (4)$$

$$y = Cx + Du \quad (5)$$

$$\begin{bmatrix}\dot{X}_1\\ \ddot{X}_1\\ \dot{X}_1-\dot{X}_2\\ \ddot{X}_1-\ddot{X}_2\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0\\ \frac{-b_1b_2}{M_1M_2} & 0 & \left[\frac{b_1}{M_1}\left(\frac{b_1}{M_1}+\frac{b_1}{M_2}+\frac{b_2}{M_2}\right)\right] & \frac{-b_1}{M_1}\\ \frac{b_2}{M_2} & 0 & -\left(\frac{b_1}{M_1}+\frac{b_1}{M_2}+\frac{b_2}{M_2}\right) & 1\\ \frac{K_2}{M_2} & 0 & -\left(\frac{K_1}{M_1}+\frac{K_1}{M_2}+\frac{K_2}{M_2}\right) & 0\end{bmatrix}\begin{bmatrix}X_1\\ \dot{X}_1\\ X_1-X_2\\ \dot{X}_1-\dot{X}_2\end{bmatrix}+\begin{bmatrix}0 & 0\\ \frac{1}{M_1} & \frac{b_1b_2}{M_1M_2}\\ 0 & \frac{-b_2}{M_2}\\ \left(\frac{1}{M_2}+\frac{1}{M_2}\right) & -\frac{K_2}{M_2}\end{bmatrix}\begin{bmatrix}U\\ W\end{bmatrix} \quad (6)$$

$$X_1-X_2=\begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}X_1\\ \dot{X}_1\\ X_1-X_2\\ \dot{X}_1-\dot{X}_2\end{bmatrix}+\begin{bmatrix}0 & 0\end{bmatrix}\begin{bmatrix}U\\ W\end{bmatrix} \quad (7)$$

The equation for cost function is defined by the Quadratic performance index, represented by equation 8. From which the required LQR gain matrix is obtained.

$$J=\frac{1}{2}\int_{\infty}^{0}(x^TQx+u^TRu)dt \quad (8)$$

Matrix Q and R represents symmetric positive semi-definite and positive symmetric definite value respectively. These both matrices are weight matrices such as;

$$R=R^T>0 \; and \; Q=Q^T\geq 0$$

Generally matrix Q and R are represented by equations 9 and 10.

$$R=BB^T \quad (9)$$

$$Q=C^TC \quad (10)$$

Linear feedback of controller is governed through equation 11.

$$u=-Kx \quad (11)$$

Where matrix K is represented using equation 12.

$$K=R^{-1}B^TP \quad (12)$$

State feedback gain is denoted by K. The matrix P is determined by the help of Algebraic Riccati Equation and MATLAB command used for obtaining suitable LQR controller Simulink design is given below (shown in Figure (2)).

K=lqr(A,B,Q,R)

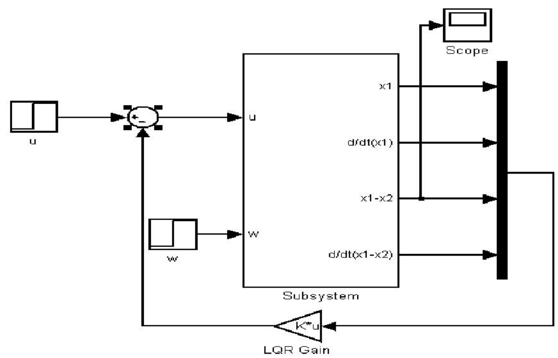

Figure (2): LQR Controller model using SIMULINK

6. Active Suspension System with Optimal Control based Intelligent Controller:

The general layout for the controller using Optimal Control based Intelligent Controller is shown in Figure (3) and active suspension system model using this novel technique in MATLAB/SIMULINK is shown in Figure (4).The controller comprises of two indigenous controllers: Optimal (LQR) Controller and Intelligent Controller combined together in such a manner that both controllers receive road disturbance signal (unit step) simultaneously, and then perform their respective operations in parallel. The main focus while designing this new technique was on the optimization of vehicle's body vertical displacement and actuator control force for ensuring comfortable ride. The vehicle's body vertical displacement is optimized by implementing closed-loop feedback mechanism in the model as represented in equation 13.

$$u_{opt\_intel}=k_1u_{optimal}-k_2u_{intelligent} \quad (13)$$

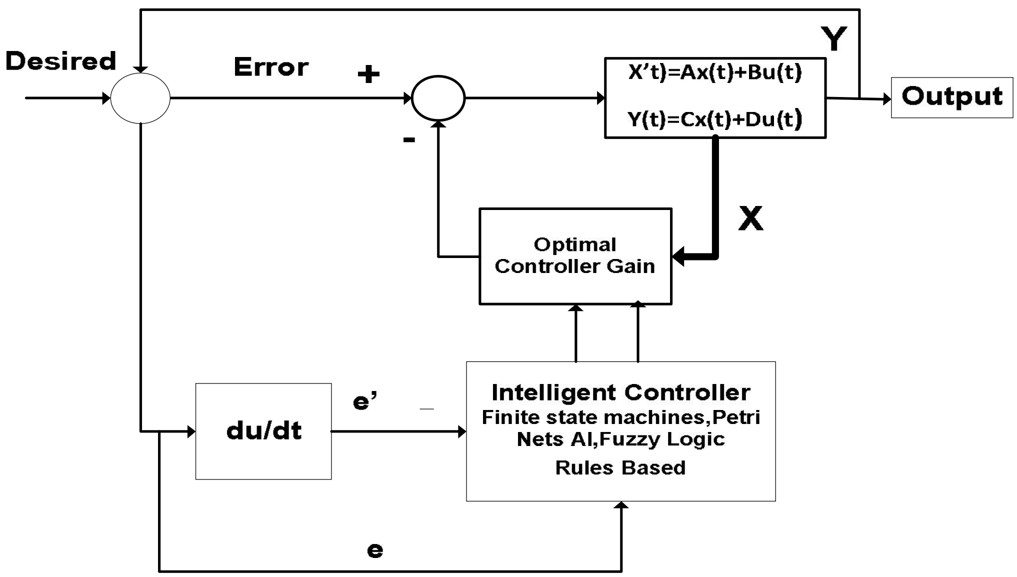

Figure (3): General Layout of Optimal Controller based Intelligent Controller

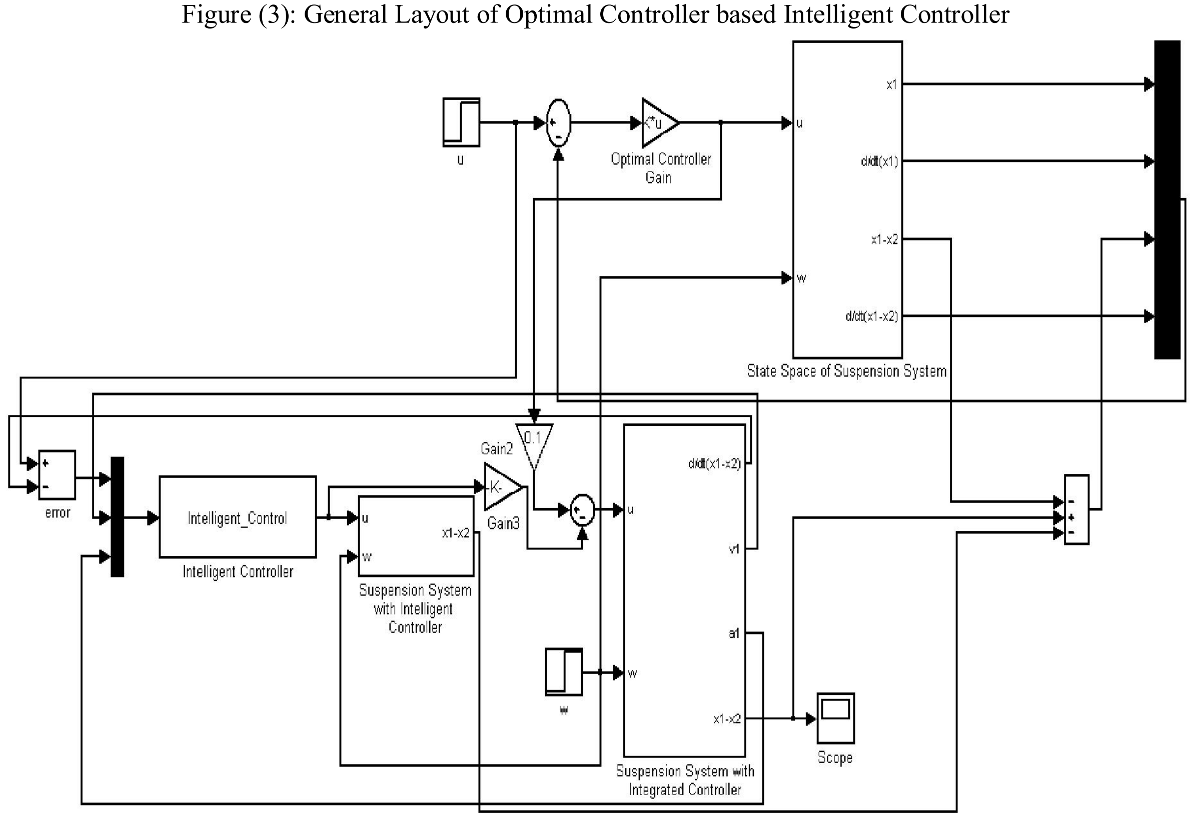

Figure (4): Active Suspension using Optimal Control based Intelligent Controller SIMULINK model

7. Results and Discussions:

Vehicle Body Vertical Displacement Analysis

The simulation results for vehicle's body vertical displacement indicated that stability of suspension system without any controller takes very long time which results in the discomfort of the passengers and poor road handling capacity of the vehicle. The optimal LQR Controller was implemented to our system; it showed a decrease of 62.5% in the magnitude of the vertical displacement. The system When Optimal Control based Intelligent Controller was implemented; it showed 40% decrease in vertical displacement. The results of simulations for uncontrolled suspension, LQR controlled active suspension system, and active suspension systems with Optimal Control based Intelligent Control are compared (shown in Figure (5), Figure(6), and Figure(7) respectively).

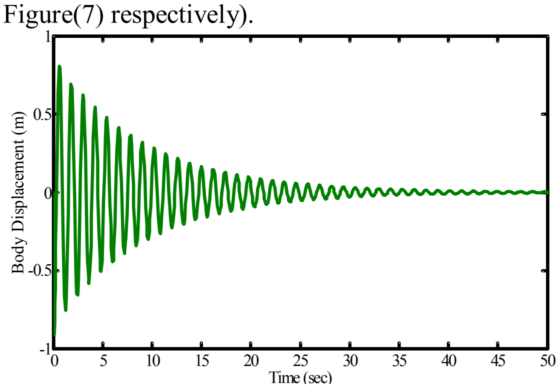

Figure (5): Body Displacement of Suspension System

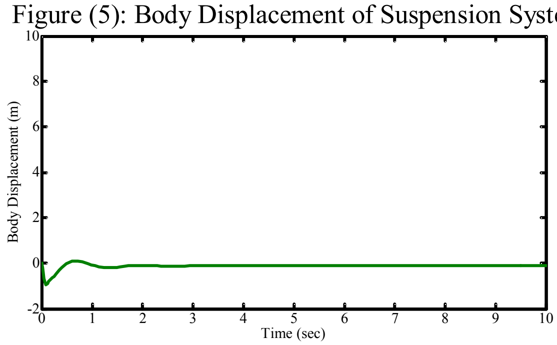

Figure (6): Body Displacement variations for LQR Controller

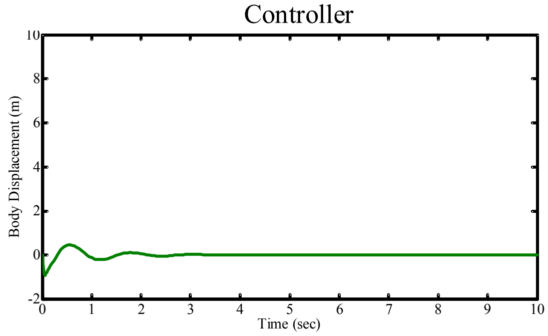

Figure (7): Body Displacement variations for Optimal Control Integration based Intelligent Controller

Actuator Control Force Analysis

The actuator control force generated by LQR Controller, and Optimal Control based Intelligent Controller are compared (shown in Figure (8), and Figure (9) respectively). When the system was incorporated with LQR Controller, it was observed that the actuator control force was generated in reverse direction reaching the maximum value of 40kN at negative peak and stabilizing at negative 10kN. It was also observed that actuator control force consumed 35% of the time span to achieve stabilization. In the case of Optimal Control based Intelligent Controller, the control force generated followed the curve similar to the curve generated by LQR Controller actuator control force, but the peak values that it attained was much less than the LQR Controller. At the positive peak, the actuator exerted the maximum force of 1.3kN while at negative peak; the force exerted by actuator was 31kN. The stabilization of force was achieved after 35% of time lapse with a decreased value of 300N. Thus at stabilization, in Optimal Control with Intelligent Controller, the actuator force has reduced by 22.5%.

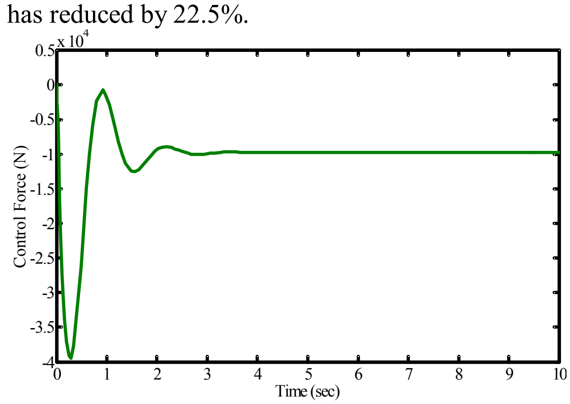

Figure (8): Control Force Outcomes of LQR Controller

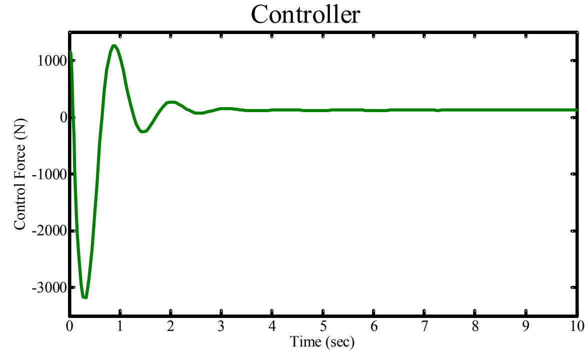

Figure (9): Control Force Outcomes of Optimal Control based Intelligent Controller

Vertical Velocity Analysis

The simulation results for vehicle's body vertical velocity are compared (shown in Figure (10), Figure (11), and Figure (12) respectively). The active suspension system with LQR Controller reduced the velocity magnitude by 40% and 80% at positive and negative peaks respectively with reduction in settling time by 92% in comparison to uncontrolled suspension system. 16% and 64% decrease in vertical velocity magnitude was observed respectively, when suspension system was controlled by using Optimal Control based Intelligent Controller. Settling time was reduced by 86% by the use of new proposed Controller.

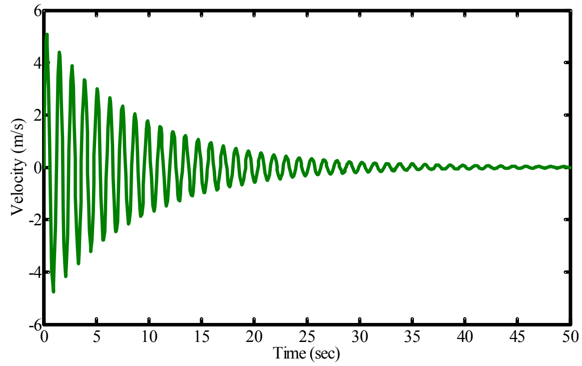

Figure (10): Velocity Variations of Suspension System

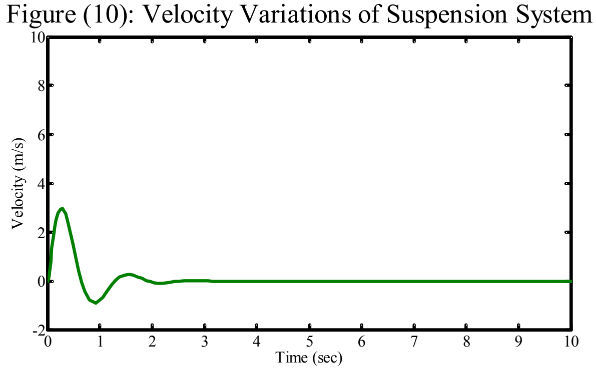

Figure (11): Velocity Variations for LQR Controller

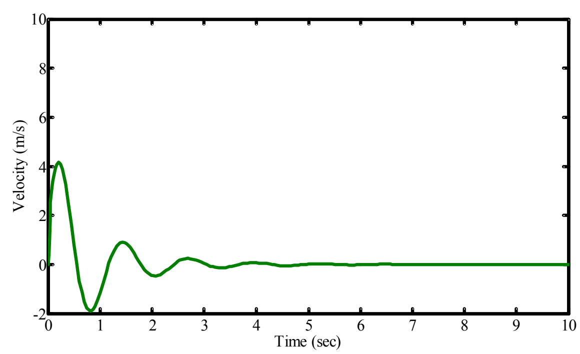

Figure (12): Velocity Variations for Optimal Control based Intelligent Controller

Vertical Acceleration Analysis

The simulation results for vertical acceleration of vehicle's body (shown in Figure (13), Figure (14), and Figure (15) respectively) are compared.LQR Controller reduced settling time by 92% with the reduction of magnitude by 23.33% and 60% at positive and negative peaks respectively. Optimal Control based with Intelligent Controller produced magnitude rise of 136.67% at positive peak and magnitude fall of 28% at negative peak. The settling time was reduced by 90% at zero magnitude by using Optimal Control Integration with Intelligent Control.

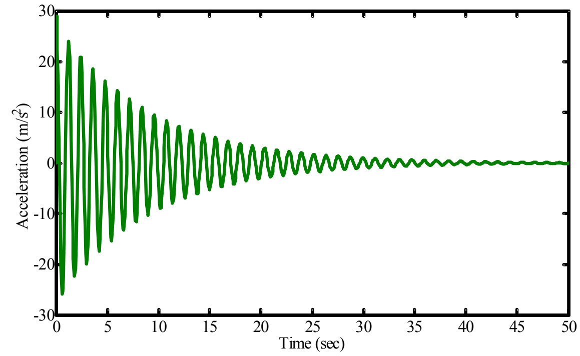

Figure (13): Acceleration Variations for Suspension System

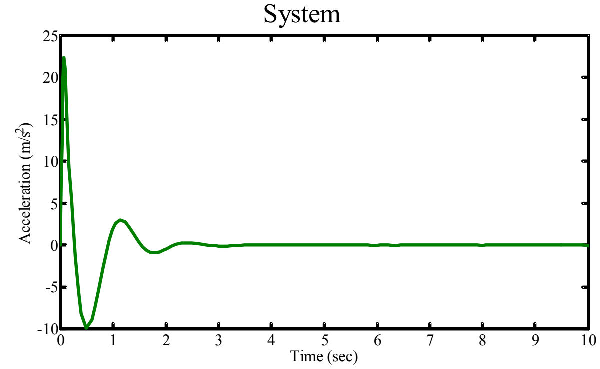

Figure (14): Acceleration Variations for LQR Controller

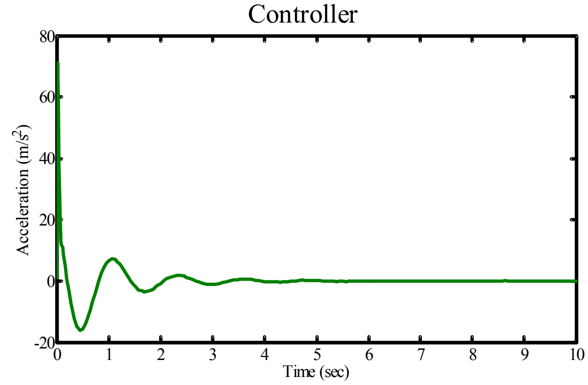

Figure (15): Acceleration Variations for Optimal Control based Intelligent Controller

8. Conclusion:

The active suspension system employing Optimal Control based Intelligent Controller has been proposed in this paper. The research was focused on minimizing vertical displacement of the vehicle's body and producing an optimized actuator control force. Though, the use of LQR Controller reduces the magnitude of vertical displacement to very small values by the use of very high forces in a short time span. But, such arrangements are not recommended to be used in real suspension systems due to the excessive loading of the actuator. In order to avoid such extreme loading conditions, Optimal Control based with Intelligent Controller has been proposed, that uses the characteristics of both Optimal & Intelligent controllers. The results of suspension system (controller less), LQR Controller based active suspension system, and active suspension system utilizing Optimal Control based Intelligent Controller has been compared and it was observed that the proposed technique using Optimal Control based Intelligent Controller displayed the high damping characteristics of LQR Controller while it produced the moderate peak and stabilized magnitudes of the actuator control force. These actuator control force characteristics make Optimal Control based Intelligent Controller; a better control methodology to be used in active suspension systems for the improved ride quality, road handling and passenger comfort.

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