Fuzzy Control of Vehicle Active Suspension System

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***Abstract*—Suspension in a vehicle is provided primarily to improve the passenger comfort and road handling to different road conditions. An active suspension is proved to be better than a passive suspension system. Ride comfort can be measured by observing the body acceleration in the vertical direction and vehicle handling performance can be observed by suspension deflection. In this paper, the suspension dynamics are modeled by using 2- degree of freedom linear time invariant quarter car model. The purpose of this paper is to investigate the performance of active suspension system using fuzzy logic controller and linear quadratic regulator controllers in comparison with passive suspension system. The simulation of vehicle performance on road is studied by using MATLAB/SIMULINK. The results shows that both LQR and FLC can effectively control the vibration of the vehicle as compared to passive suspension system. Moreover FLC control method is more effective in reducing the acceleration of sprung mass as compared to LQR control.**

***Index Terms*—Vehicle Active Suspension System (VASS), Fuzzy Logic Controller (FLC), Linear Quadratic Regulator (LQR)**

I. INTRODUCTION

Suspension is a property which is common to all automobiles. It isolates the vehicle body from road disturbance for comfortable ride. Performance of suspension system is determined by ride comfort and road handling. Ride comfort can be measured by observing the body acceleration and road handling can be observed by suspension deflection. Suspension system can be classified into three categories such as passive, semi active and active suspensions. Passive suspension has the ability to store energy via a spring and dissipate it via a damper. Passive suspensions can only achieve good ride comfort or good road handling since these two criteria conflict each other and involve different spring and damper characteristics. Semi-active suspensions with their variable damping characteristics and low power consumption, offers a considerable improvement. A significant improvement can be achieved by using an active suspension system. The active suspension system is able to inject energy into the vehicle dynamic system via actuator. The force actuator is able to add and dissipate energy from the system. This force may be function of several variables, which can be measured or sensed by sensors, so the flexibility can be greatly improved.

A lot has been reported in the literature on the control strategies of the active suspension system. Linear quadratic regulator and fuzzy logic controllers are the popular controller used to improve the ride comfort and road handling. A comparison between passive and active suspension system was performed by using different types of road profiles for quarter car model, in which LQR control is found to be better in suppressing the vibrations, than passive system [1]-[3]. Fuzzy control is found to be better in suppressing the vibrations than PID control [4]. Better results are even obtained in suppressing the vibrations with FLC than LQR control method [5]. Fuzzy control using two loops with FLC in the outer loop for a quarter car is also found to be better than FLC using alone [6]-[8]. An active suspension system for half car model using FLC and LQR controller has been made, in which performance of LQR control method is found to be better than FLC at the expense of control force [9]. Robust control has shown to have better settling time among H_∞, fuzzy and LQR controllers for quarter car model [10].

The aim of the paper is to present a fuzzy logic algorithm to improve the passenger ride comfort and road handling for quarter car model. A comparison of body displacement, body acceleration and suspension deflection using FLC and LQR control methods with passive suspension has been made.

II. MATHEMATICALMODELING

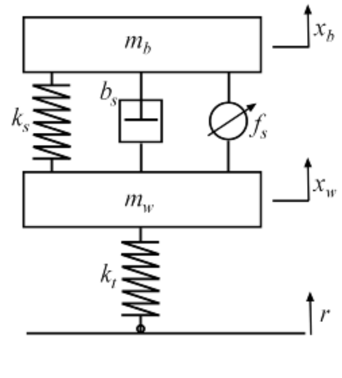

Figure 1. Quarter vehicle model of active suspension system.

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Fig. 1 shows the quarter vehicle model for active suspension system. The sprung mass m_b represents the mass of the vehicle body, frame and internal components that are supported by the suspension. The unsprung mass is mass of the assembly of the axle and wheel. k_S and b_S are respectively the spring and damper coefficients of the passive components. Tyre compressibility is K_t. The control force generated by the actuator is f_S. Where r denotes the road disturbance input acting on the unsprung mass.

The vertical displacements of the sprung and unsprung masses are denoted as x_b and x_w respectively. The parameters of quarter active suspension system have been shown in the Table I.

TABLE I. PARAMETERS OF QUARTER VEHICLE MODEL

Model parameters	symbol	Values
Vehicle body mass	m_b	300kg
Wheel assembly mass	m_w	60kg
Suspension stiffness	k_s	1600N/m
Suspension damping	b_s	1000N-s/m
Tyre stiffness	k_t	190000N/m

To develop the state space model of the system, the state variable are defined as $x_1 = x_b$, $x_2 = x_w$, $x_3 = \dot{x}_b$,

$$x_4 = \dot{x}_w$$

Equation of motion of the system for sprung and unsprung masses are as follow

$$m_b\,\ddot{x}_b = k_s\left(x_w - x_b\right) + b_s\left(\dot{x}_w - \dot{x}_b\right) + f_s \quad (1)$$

$$m_w\,\ddot{x}_w = k_t\left(r - x_w\right) - k_s\left(x_w - x_b\right) - b_s\left(\dot{x}_w - \dot{x}_b\right) - f_s \quad (2)$$

Dynamics of the system is described by the following state space model.

State space representation is given by

$$\dot{X} = AX + Bf_S + Fr \quad (3)$$

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ -\frac{k_s}{m_b} & \frac{k_s}{m_b} & -\frac{b_s}{m_b} & \frac{b_s}{m_b}\\ \frac{k_s}{m_w} & -\frac{(k_s+k_t)}{m_w} & \frac{b_s}{m_w} & -\frac{b_s}{m_w}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 0\\ \frac{k_t}{m_w}\end{bmatrix} r + \begin{bmatrix}0\\ 0\\ \frac{1}{m_w}\\ -\frac{1}{m_w}\end{bmatrix} f_s$$

III. CONTROLLER DESIGN

In this paper, two types of controller are studied for active suspension system. These are linear quadratic regulator (LQR) and fuzzy logic controller.

A. Linear Quadratic Regulator (LQR) Controller

The statement of optimal control is to find an optimal control vector $u^*(t)$ that minimizes a quadratic cost function consists of state vector and control vector. The cost function is denoted as

$$J = \int_0^\infty \left[X^{'}QX + U^{'}RU \right] dt \quad (4)$$

where X is state vector and u is control vector.

A positive semi definite solution exist under certain conditions yielding a control vector u (t) given by

$$u^*(t) = KX(t) \quad (5)$$

where K is the feedback gain matrix defined by

$$K = -R^{-1}B^T PX \quad (6)$$

where P is solution of Riccati equation

$$PA + A^T P - PBR^{-1}B^T P + Q = 0 \quad (7)$$

The state variable feedback configuration is as shown in the Fig. 2.

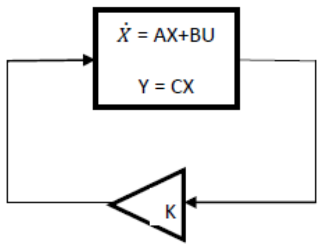

Figure 2. State variable feedback configuration.

The main problem of linear optimal control is how to select the matrices Q and R to meet the demand of satisfying response of control system. Closed loop response will change depends on the choice of Q and R matrices. Generally speaking selecting Q large means that, to keep J small, the state x(t) must be small, on the other hand , selecting R large means that, the control input u(t) must be small, to keep J small. If we want fast response, Q should be large and R small. For a slow response, Q should be low and R high. One should select Q to be positive semi definite and R to be positive definite.

The feedback gain matrix (K) is determined using control system toolbox and is given by

K= [0.2846; -20.4494; 0.9726; -0.8260]

The Simulink model for LQR controller based control system is as shown in the Fig. 3.

B. Fuzzy Logic Controller

The fuzzy logic controller used in the active suspension system has two input; body velocity and body acceleration and one output; desired actuator force f_s. The control system consists of three stages, fuzzification, fuzzy inference engine and defuzzification. The fuzzification stage converts crispinput into fuzzy values, while fuzzy inference engine processes the input data and computes the controller output according to rule base. These outputs are then converted into real numbers by defuzzification.

The membership function for the three mentioned variables of active suspension system are represented by fuzzy sets. The membership function for the body velocity, body acceleration and actuator force are shown in the Fig. 4(a), Fig. 4(b) and Fig. 4(c).Triangular membership function has been defined for each variable. Five membership function has been assigned to each variable and linguistic terms assigned to membership functions are positive large (PL), positive small (PS), zero (ZE), negative small (NS) and negative large (NL). The range of universe of discourse for body velocity is [-2, 2], for body acceleration is [-3, 3] and for actuator force is [-10, 10].

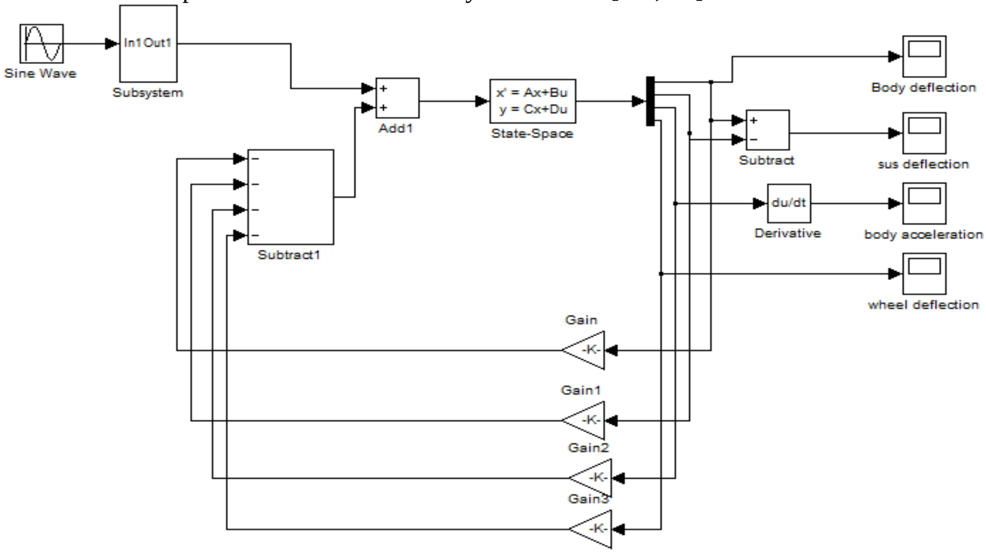

Figure 3. The LQR controller based active suspension system

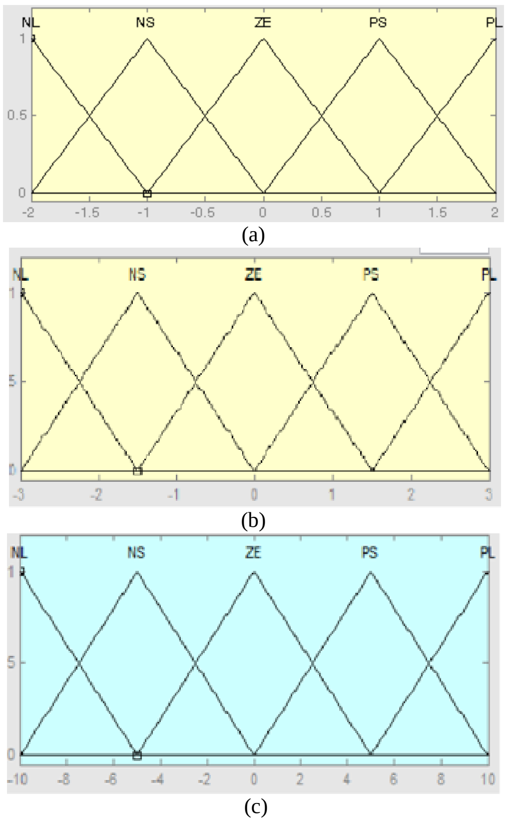

Figure 4. Membership function of Body Velocity, (b) Membership function of Body acceleration, (c) Membership function of actuator force.

The rule base used in the active suspension system is shown in the Table II.

TABLE II. FUZZY RULE BASE

Error rate/ Error	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

The Simulink model for the fuzzy controller based active suspension system is as shown in the Fig. 5.

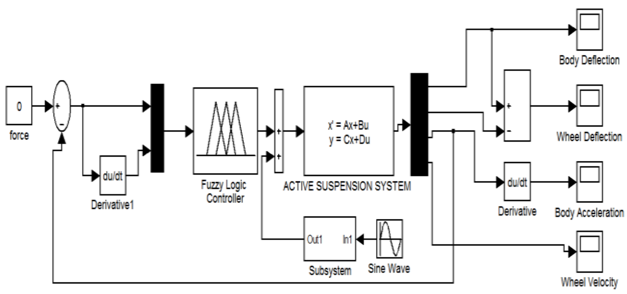

Figure 5. The fuzzy controller based active suspension system.

IV. Simulation and Results

To investigate the suspension performance, a perfect road surface model is necessary to design the active suspension. In this study, the sine function is used to simulate the road disturbance. The road input is described by equation (8) and is as shown in the Fig. 6.

$$r(t) = \begin{cases} a(1-\cos 8\pi t), & 0.5 \leq t \leq 0.75 \\ 0\ , & \text{otherwise} \end{cases} \tag{8}$$

where a=0.05(road bump height 10cm)

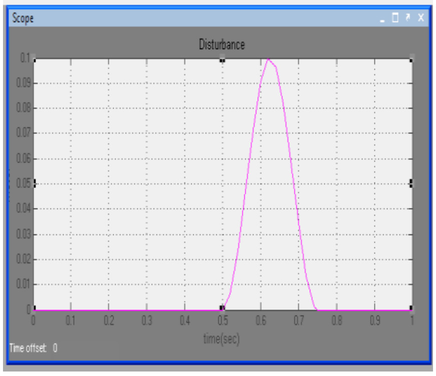

Figure 6. Road disturbance.

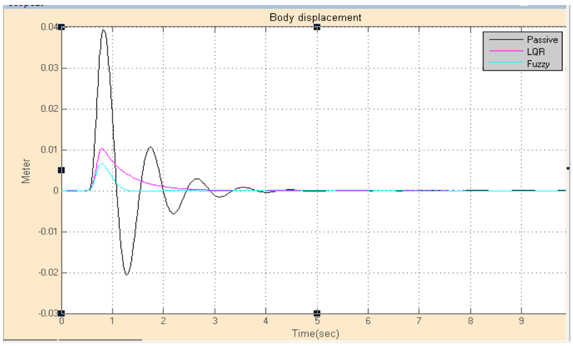

Figure 7. Body deflection.

The simulation results are shown in the Fig. 7, Fig. 8 and Fig. 9. It shows the comparison between passive, LQR and FLC controlled systems for body deflection, suspension deflection and body acceleration with road disturbance. It shows that there is improvement in the ride comfort performance and suppression of vibrations with fuzzy control as compared to passive and LQR based systems.

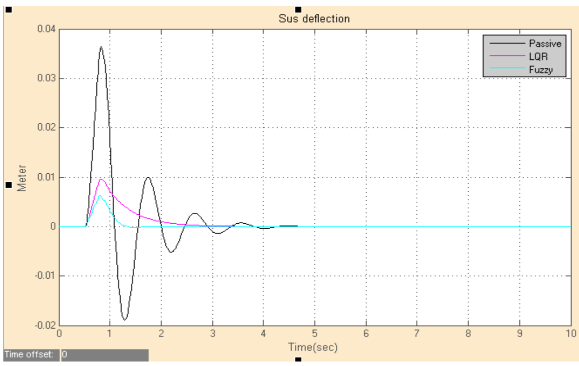

Figure 8. Suspension deflection.

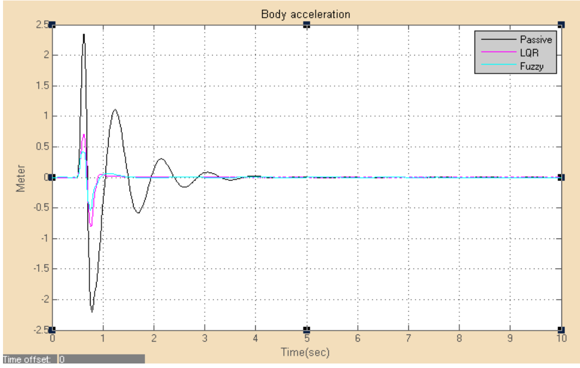

Figure 9. Body acceleration.

Table III, Table IV and Table V shows the comparison between passive, LQR and FLC based suspension systems in terms of settling time and percentage overshoot in body deflection, suspension deflection and body acceleration.

In comparison with LQR controller, the fuzzy controller gives percentage reduction in settling time and % overshoot in body displacement are 50% and 40% respectively, as shown in the Table III. The percentage reduction in settling time and % overshoot in suspension deflection are 50% and 40% respectively, as shown in the Table IV. The percentage reduction in settling time and %overshoot in body acceleration are 10% and 42.8% respectively, as shown in the Table V. In comparison with passive suspension system, the percentage reduction in settling time and % overshoot in body displacement are 68% and 85% respectively. In suspension deflection, the percentage reduction in settling time and % overshoot are 68% and 83.3% respectively. The percentage reduction in settling time and % overshoot in body acceleration are 97% and 83.3% respectively.

TABLE III. Comparison of Body Displacement

Controller	Settling time (sec)	%Overshot
Passive	4.0	40
LQR	2.5	10
Fuzzy	1.25	6

TABLE IV. Comparison of Suspension Deflection

Controller	Settling time (sec)	%Overshot
Passive	4.0	36
LQR	2.5	10
Fuzzy	1.25	6

TABLE V. Comparison of Body Acceleration

Controller	Settling time (sec)	%Overshot
Passive	4.0	24
LQR	1.0	7
Fuzzy	0.9	4

V. Conclusion

In this paper, Fuzzy logic controller and linear quadratic regulator controllers are successfully designed using MATLAB for quarter car active suspension system. Both controllers are capable of stabilizing the suspension system very effectively as compared to passive suspension system, but the suppression of vibration is more effective with fuzzy logic controller as compared to LQR controller and passive suspension systems.

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