Fuzzy Logic Control of Hydraulic Actuated Active Suspension System

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***Abstract*— Fuzzy logic technique has been proposed to control the hydraulic actuator operated active suspension system. The quarter car model has been used to simulate the mathematical model of active suspension system. The dynamic nature of suspension system and complex nonlinear characteristics of actuating system has increased the difficulty of creating mathematical model for active suspension system. In real time, the controller designed based on analytical method will not give better result due to its complex mathematical model. The fuzzy logic technique has able to give better performance for active suspension system irrespective of the complex nature of mathematical model of suspension system. This paper describes mathematical model of suspension system with hydraulic actuator and fuzzy controller in order to obtain vehicle response for range of road input. The simulation and experiment conducted on real time control platform will confirm the performance of fuzzy logic controller for active suspension system.**

***Index Term*— Fuzzy logic, Intelligent Control, Active suspension, Hydraulic actuator dynamics.**

I. INTRODUCTION

The handling and ride quality of car depends on suspension system. Ride quality and handling performance are two important function of suspension system. Ride quality represent the amount of vibration isolated by vehicle body from irregular road surface. Handling Performance maintain proper contact between tire and road. The conventional passive suspension consist of spring and damper only. The vehicle and road connected by suspension which act as link. Soft suspension support ride quality by offering a better isolation to disturbance from road whereas hard suspension support handling performance by offering a better support to maintain the stability of vehicle. Hence there is a tradeoff needed in suspension system to satisfy the need of both ride quality and handling performance. In that case, active suspension [1] able to provide better suspension by compromising on soft and hard suspension. In recent times, active suspension control attracted the attention of many researcher because it can provide more handling capacity and ride quality than other suspension system.

An active suspension system is more elastic and efficient than passive or semi active suspension system. Many solution for active suspension [2-5] have been recommended to reduce suspension travel and acceleration of car body. Model based controller for active suspension is difficult to design because of the complexity and nonlinear characteristics [6] of hydraulic actuator. In recent years, fuzzy logic control has been employed successfully in control engineering research. Fuzzy logic has feature to develop controller without the need of mathematical model of a system. Hence fuzzy logic controller [7-8] can be used effectively to control dynamic characteristics of suspension system.

An ideal suspension should reduce body displacement and acceleration so as to provide satisfactory suspension deflection. Fuzzy controller based on fuzzy sets, are designed without system models for the development of the controllers and have been extensively employed in active suspension system. A fuzzy logic controller [9] can easily handle environmental deviation during operation of suspension system, so that it has been used in active suspension system.

Fuzzy logic controller for quarter car active suspension [10] proposed with inputs as suspension deflection and its change and the output as the change of the control signal. Fuzzy approach also used to solve the ride/rattle space tradeoff [11] for active suspensions to reduce vertical movement of vehicle body. An active suspension system proposed for a half-car model where the active control is the sum of two kinds of control. Fuzzy logic algorithm [12-14] for quarter car model was developed for better ride comfort using hybrid intelligent algorithm. Expert’s knowledge and experience plays an important role in creating fuzzy rules for conventional fuzzy logic controller. So, there is no proper guideline for selecting rules and parameter for fuzzy controller.

The hydraulic actuator reveals nonlinear characteristic [15] due to the effect of back pressure and dynamics of servo valve. Hence a force tracking controller will be used to create an actuator force which is equal to target force. A few works on force tracking control can be found on [16]. The complex nonlinear mathematical model of hydraulic actuator has been included in this study in order to measure the performance of active suspension. Electro hydraulic operated direction control vale has been used for control of hydraulic actuator.

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The rest of this paper is organized as follows: The mathematical model of quarter car model with hydraulic actuator is described in section 2. The fuzzy controller design is presented in Section 3. The simulation and experimental work has been carried out in Section 4 and 5 respectively. Finally the conclusion is presented in Section 6.

II. MODELING OF ACTIVE SUSPENSION SYSTEM

A. *Mathematical Modelling*

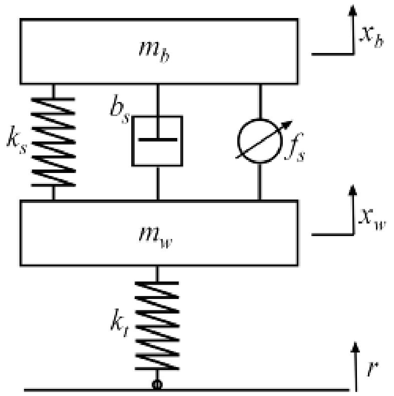

Fig. 1. Quarter car suspension Model

A two degree of freedom of quarter car model is represented in Fig.1. The model consist of one quarter of vehicle mass, wheel and active suspension system. Sprung mass m_b represent one quarter of vehicle mass. Unsprung mass m_w indicates mass of wheel. Hydraulic actuator is installed between sprung and unsprung mass along with suspension system. The tire is modelled as linear spring of stiffness k_t. The damping coefficient and stiffness coefficient of suspension system are b_s, z_s respectively. The actuator force f_s created by hydraulic actuator placed between sprung and unsprung mass. This study consider only the vertical movement of suspension by assuming tyre always in contact with road on travel. The state variables x_b and x_w are the vertical displacements of the sprung and unsprung masses, respectively. r is the vertical road profile.

B. *System Description*

Four-way valve-piston system is used for modelling of hydraulic actuator [17] is as shown in Fig. 2. The actuator force is calculated using $f_a=A_aP_L$ where Aa is piston area and P_L is the pressure drop in cylinder.

The time derivative of P_L can be expressed as in equation (1).

$$\frac{V_t}{4\beta_e}\dot{P}_L = C_{tp}P_L - A_a\left(\dot{x}_b - \dot{x}_w\right) + Q \qquad (1)$$

In the above equation, *Vt* is the total actuator volume, *PL* is the pressure drop, β*e* is the effective bulk modulus, *Ctp* is the total leakage coefficient of the piston, and Q is the hydraulic load flow which can be calculated using Equation (2).

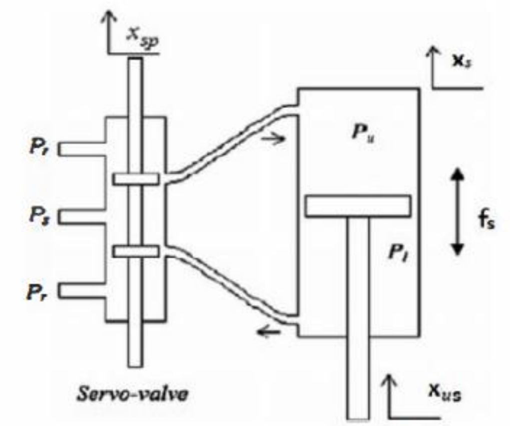

Fig. 2. Electro hydraulic actuator Model

$$Q = C_d w x_v \sqrt{\frac{1}{\rho}\left[P_s - \operatorname{sgn}\left(x_v\right)P_L\right]} \qquad (2)$$

Where C_d is the discharge coefficient, x_v is the spool valve displacement, *w* is the spool valve area slope, P_s is the source pressure and ρ is the hydraulic fluid density. The dynamics for the suspension system with actuator dynamics is described by the nonlinear equation (3), (4) and (5).

$$m_b\ddot{x}_b + b_s(\dot{x}_b - \dot{x}_w) + k_s(x_b - x_w) = f_s \qquad (3)$$

$$m_w\ddot{x}_w + b_s(\dot{x}_w - \dot{x}_b) + k_s\left(x_w - x_b\right) + k_t\left(x_w - r\right) = -f_s \qquad (4)$$

$$\dot{f}_s = -\beta f_s - \alpha A_a^2\left(\dot{x}_b - \dot{x}_w\right) + A_a x_v\sqrt{P_s - \frac{\operatorname{sgn}\left(x_v\right)f_s}{A_a}} \qquad (5)$$

Where α = 4βe/Vt, β = αCtp, Γ = *α cd w* $\sqrt{\frac{1}{\rho}}$ and $x_v = k_cU$ kc is the conversion gain, and u represent servo valve voltage [18]. The values of parameters used in active suspension system [19] listed in Table 1. The state variables x_1 and x_3 are the vertical displacements of the sprung and unsprung masses, respectively and z_r is the vertical road profile. In actuator dynamics, x_5 and x_6 to be the actuator force (f_a) and spool valve displacement respectively. The governing equation of hydraulic actuated active suspension system by neglecting the effect actuator fiction can be described as

$$\dot{x}_1 = x_2 \qquad (6)$$

$$\dot{x}_2 = \frac{1}{m_s}\left[k_s\left(x_3 - x_1\right) + c_s\left(x_4 - x_2\right) + x_5\right] \qquad (7)$$

$$\dot{x}_3 = x_4 \qquad (8)$$

$$\dot{x}_4 = \frac{1}{m_{us}}\left[k_s\left(x_1 - x_3\right) + c_s\left(x_2 - x_4\right) + k_t\left(z_r - x_3\right) - x_5\right] \qquad (9)$$

$$\dot{x}_5 = -\beta x_5 - \alpha A_a{}^2 \left(x_2 - x_4\right) + \Gamma A_a x_v \sqrt{P_s - \frac{\operatorname{sgn}\left(x_v\right) x_5}{A_a}} \quad (10)$$

III. INTELLIGENT CONTROLLER DESIGN

A. *Control Problem*

The control objective is to maximize the passenger comfort, while preserving performance of suspension system, under road disturbances. The comfort is determined by vertical acceleration of car body experienced by the passenger.

The road input indicated in equation (11) & (12) is used as input to quarter car model suspension [20-21] in order to measure the performance of developed controller in active suspension.

$$Z_{r1} = \begin{cases} -0.1 & 0 \le t \le 10 \\ 0 & otherwise \end{cases}$$

(11)

TABLE I

PARAMETER VALUES OF ACTIVE SUSPENSION SYSTEM

Symbol	Quantity	Value
m_w	Mass of wheel	60 kg
m_b	Mass of body	300 kg
k_s	Stiffness coefficient of suspension	16000 N/m
k_t	Stiffness coefficient of tire	19000 N/m
b_s	Damping coefficient of suspension	1000 Ns/m
P_s	Hydraulic pressure	10,342,500 Pa
A_a	Actuator ram area	$3.35*10^{-4}$ m^2
k_c	Conversion gain	0.001 m/V
α	α	$4.515x\ 10^{13}$ N/m^5
Β	Β	1 s^{-1}
Γ	Γ	$1.545x\ 10^9$ $N/m^{5/2}kg^{1/2}$

$$Z_{r2} = \begin{cases} 0.1\left(1-\cos\left(2\pi t\right)\right) & 1 \le t \le 2 \\ 0.4\left(1-\cos\left(2\pi t\right)\right) & 2 \le t \le 4 \\ 0 & otherwise \end{cases} \quad (12)$$

B. *Fuzzy Controller*

The traditional controller performance fully depends on the accuracy of known dynamic model. The complex unpredictable characteristics of hydraulically actuated suspension system increased the difficulty of identifying mathematical model for traditional controller. Apart from that, road disturbance introduces random noise to the controller and the suspension control disturbs the tire deformation continuously. These uncertain effects cannot be measured. Hence, a model free intelligent controller is introduced to solve this kind of problem by using fuzzy theory. The fuzzy controller has ability to handle complexity, non-linearity and unpredictable situation so that it will control the behavior of suspension system very well.

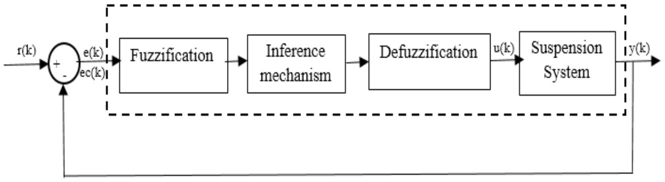

Fig. 3. Outline of Fuzzy controller for active suspension

The outline of fuzzy controller for active suspension is shown in Fig. 3. The entire concept of fuzzy logic depends on fuzzy rules and membership function. The major components of Fuzzy controller are fuzzy rules, inference engine and defuzzification. The knowledge of expert converted into control signal with the help of fuzzy rules. The entire performance of fuzzy controller depends on antecedent and consequent part of fuzzy rules. The fuzzification stage converts the error e(k) and error change ec(k) of suspension deflection into fuzzy values with help of membership function. The fuzzy rules which are designed based on expert knowledge has been applied in inference mechanism. The defuzzification process converts fuzzy values into control voltage so that it will drive actuator.

The triangular membership function with five linguistic variable represented in in Fig 4 to 6. These membership function converts the real input data into fuzzy values in order to reduce the complexity and processing time of fuzzy controller. A classic interpretation of Mamdani [22] was used as rule basis. The range of input variable and output variable were determined by the simulation results in different conditions. The rules table for fuzzy logic control is shown in table II. The fuzzy controller has 25 control rules. Singleton method and centre of gravity method were selected for fuzzification and defuzzification, respectively. Minimizing the vertical displacement of the automobile body is the basis of constructing the fuzzy control rules.

Hydraulic actuated suspension system can be controlled by electro hydraulic servo valve. Hence the control structure has inner loop control as well as outer loop control. The inner loop control act as disturbance reducer in order to reduce unwanted vehicle motion. The outer loop control has suspension travel as input and target force as output.

TABLE II

FUZZY RULES TABLE

Symbol	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NM	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

The abbreviations used correspond to: NB: Negative Big; NS: Negative Small; ZE: Zero; PS: Positive Small; PB: Positive Big; e (k): Error; ec(k): change in error.

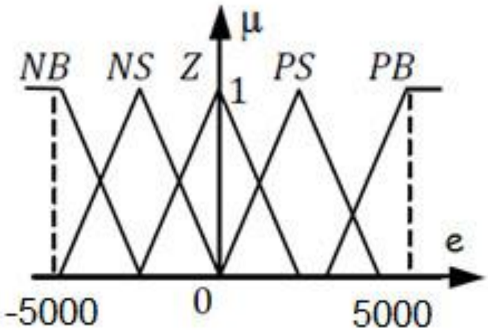

Fig. 4. Membership function for error

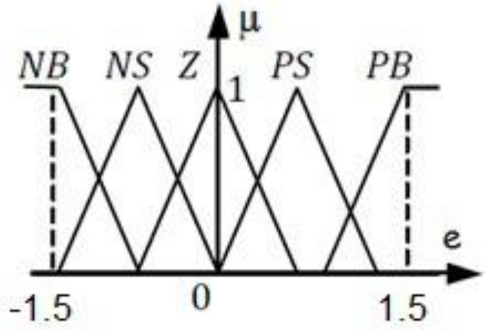

Fig. 5. Membership function for error

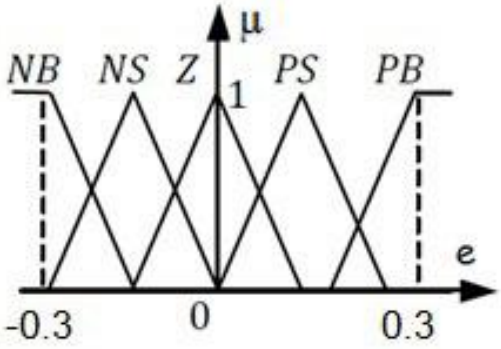

Fig. 6. Membership function for control voltage

Defuzzification process converts the fuzzy values obtained membership function into real output data as control voltage which drives servo valve. Among the many defuzzification methods, centroid method is simple and easy to use for control application [23-25]. The only limitation of this method is that it is computationally difficult for complex membership functions [26].The centroid defuzzification technique can be expressed as

$$Z_{COG} = \frac{\int_{Z} \mu_A(Z) Z dz}{\int_{Z} \mu_A(Z) dz} \tag{13}$$

Where Z_{COG} is the crisp output, $\mu_A(z)$ is the aggregated membership function and z is the output variable.

IV. SIMULATION

The performance of the proposed fuzzy control scheme is illustrated in this section through a series of simulations. Simulation results are carried out with different road profile Zr1, Zr2 and Zr3 as shown in Fig. 7-9. For comparison purposes, the numerical results of the vehicle model with PID controller are also presented. PID control is perhaps the most widely used control method. It can provide fast response, well system stability and small steady state errors with known parameters.

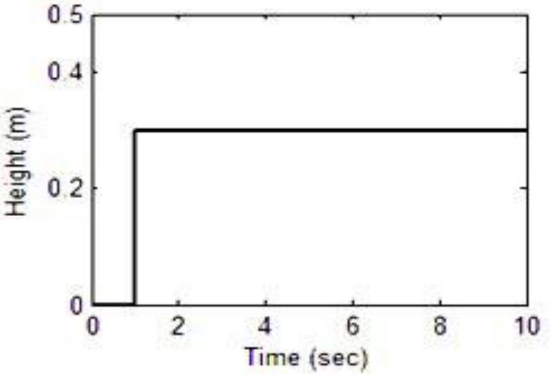

Fig. 7. Road input signal Zr_1 for simulation

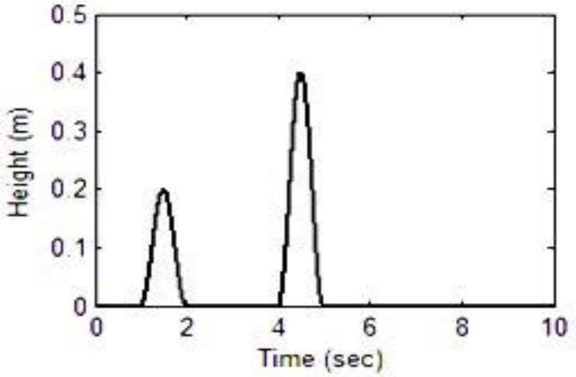

Fig. 8. Road input signal Zr_2 for simulation

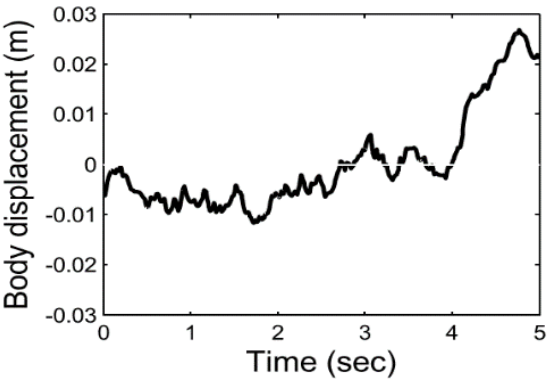

Fig. 9. Road input signal Zr_3 for simulation

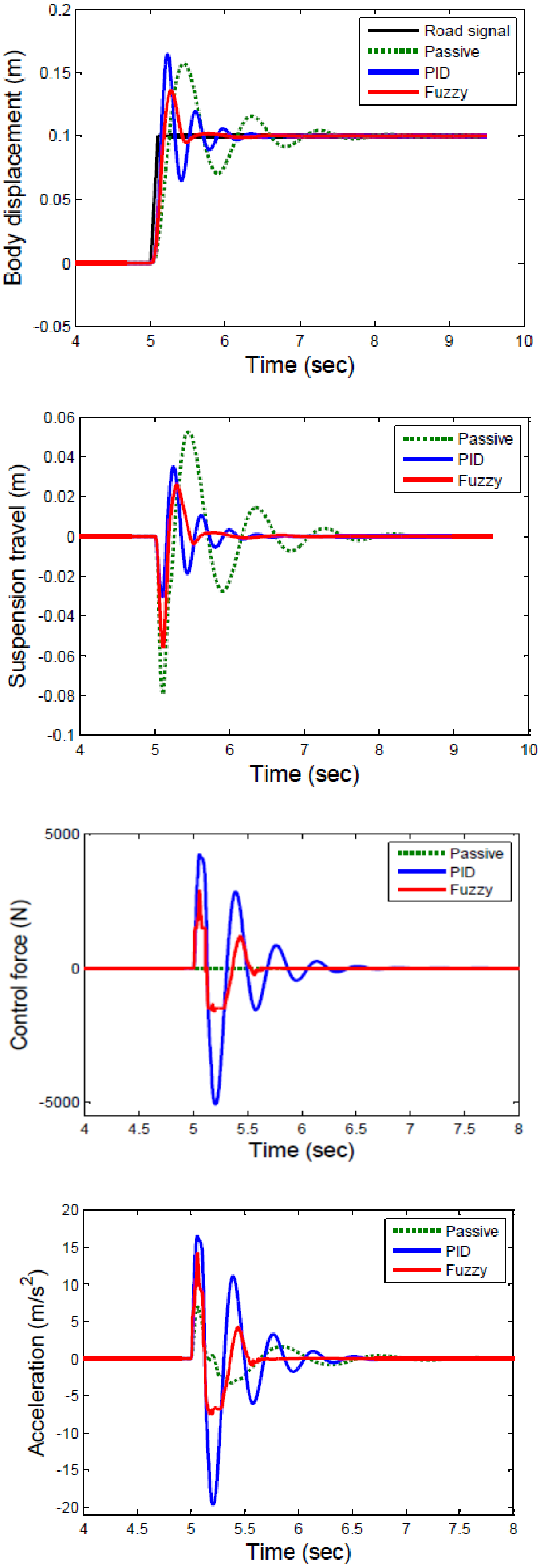

Fig. 10. Response of Road input signal Zr1

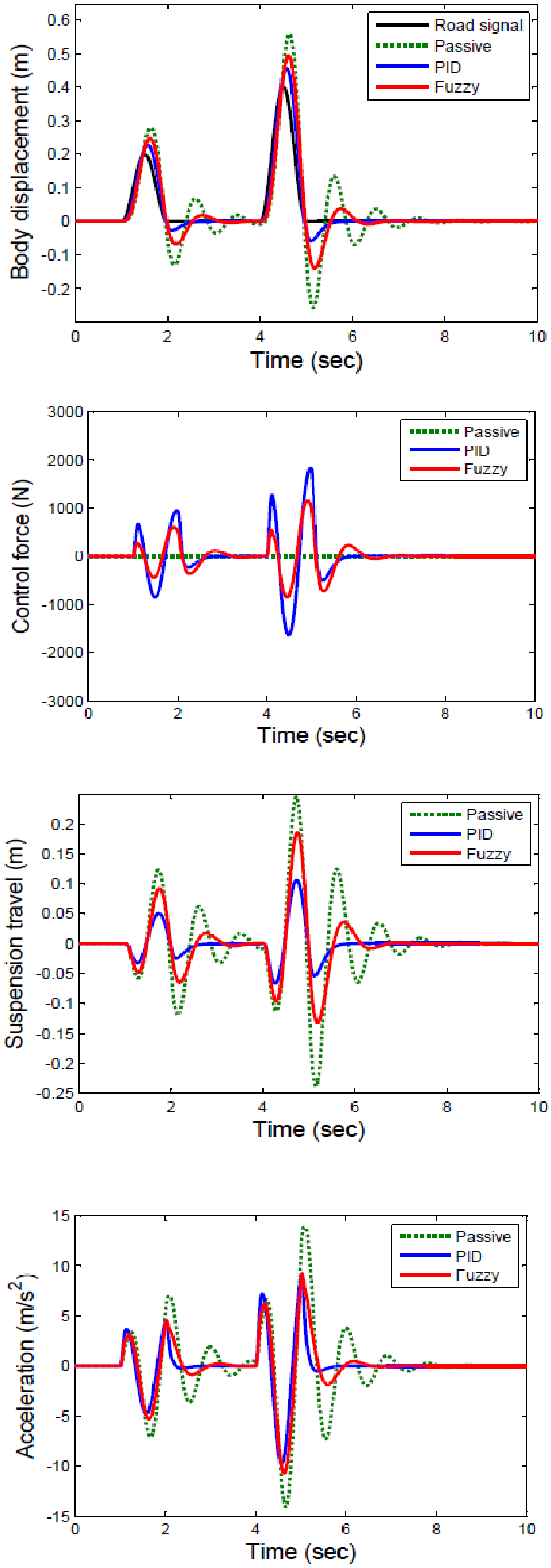

Fig. 11. Response of Road input signal Zr2

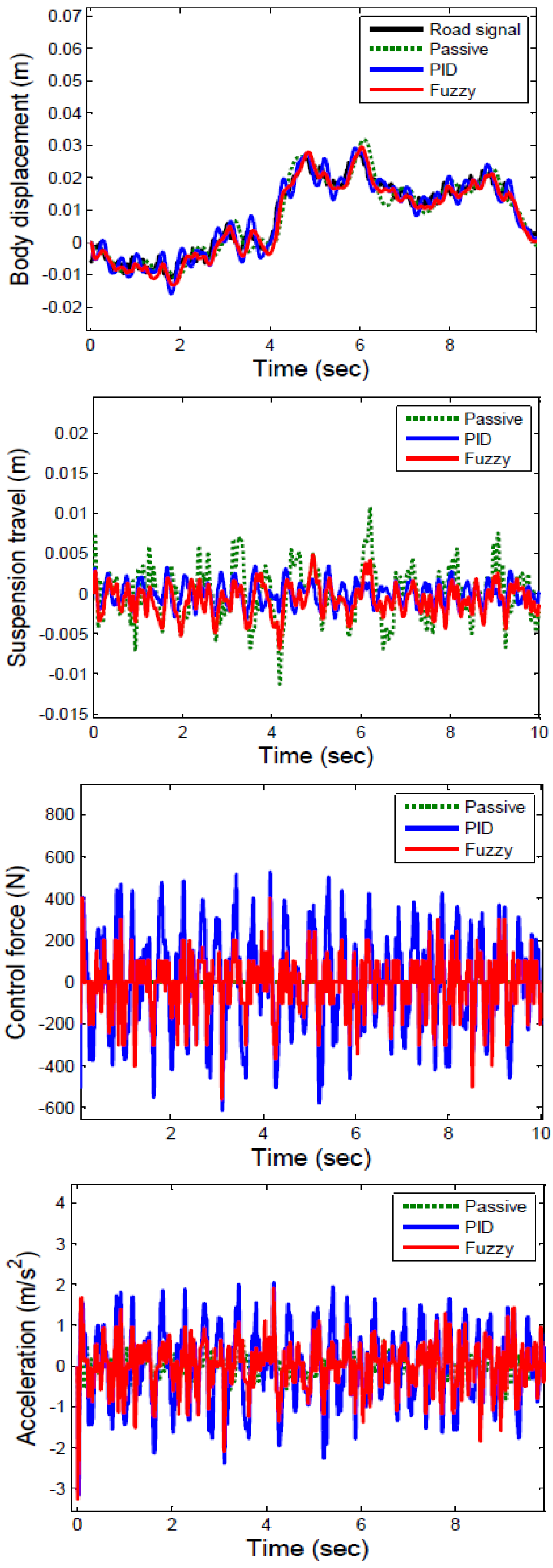

Fig. 12. Response of Road input signal Zr3

The result of the simulation of Fuzzy controller for road input Zr1 is shown Fig. 10. The four representative variables for controller evaluation are body displacement, suspension travel, Control force, body acceleration. The body displacement of passive suspension shows that long settling time and the overshoot is very big. The output has an overshoot more than 20% and settling time is long and unstable. Fuzzy controller reduces overshoot and short settling time in active suspension. The suspension travel has an overshoot of less than 20% and a settling time shorter than 1 sec. The fuzzy controller in active suspension reduces body acceleration which will improve the ride comfort of vehicle.

The results are shown in Fig. 11 for the case with the road profile Zr2. Here, the overshoot and settling time are not acceptable for passive suspension. The system has the suspension travel with overshoot more than 50% and a settling time longer than 3 sec. The fuzzy controlled system has less overshoot and settling time less than 1 sec which indicates the efficiency of the proposed controller. The decrease in body acceleration magnitudes guarantees improved ride comfort as appeared in body acceleration. There is no offset in suspension deflection which indicates that the fuzzy controller is a suitable for active suspension.

The response of active suspension for real road profile is shown Fig. 12. This result indicates that fuzzy controller reduces suspension travel and vertical acceleration amplitude of suspension significantly compare to passive and PID suspension. Table 3-5 lists parameter values obtained for profile Zr1, Zr2 and Zr3. It indicates that the ride comfort of the passengers is improved greatly by using the proposed FL controller.

TABLE IV

ROOT MEAN SQUARE VALUES OF ROAD PROFILE Z_{R2}

Parameter	Passive	PID	Fuzzy
Body displacement (m)	0.6	0.45	0.4
Suspension Travel (m)	0.25	0.03	0.1
Control force (KN)	0	3	2.5
Body Acceleration (m/s^2)	14	11	10

TABLE V

ROOT MEAN SQUARE VALUES OF ROAD PROFILE Z_{R3}

Parameter	Passive	PID	Fuzzy
Body displacement (m)	.008	0.009	0.008
Suspension Travel (m)	0.03	0.02	0.01
Control force (KN)	0	0.4	0.2
Body Acceleration (m/s^2)	.31	0.10	0.06

TABLE III

ROOT MEAN SQUARE VALUES OF ROAD PROFILE Z_{R1}

Parameter	Passive	PID	Fuzzy
Body displacement (m)	0.16	0.161	0.13
Suspension Travel (m)	0.05	0.04	0.03
Control force (KN)	0	4	3
Body Acceleration (m/s^2)	15	14	12

V. EXPERIMENTATION

The main motive of experiment is to verify how a fuzzy logic controller will give better performance for two degree of freedom quarter car test rig. The real time control of quarter car prototype used in this paper is shown in Fig. 13. The experiment was conducted by assuming that tire has always in contact [27] with road on travel.

The low cost experimental setup consists of a HILINK microcontroller board manufactured by Zeltom Educational and Industrial Control System Company, a corresponding Simulink library for Matlab/Simulink, DC motor with encoder, and quarter car suspension test rig. The suspension system includes spring, sprung mass, unsprung mass and rack and pinion arrangement. A pneumatic system with compressor simulate the various road profile for suspension system. The relative distance between sprung and unsprung mass can be measured by rack and pinion arrangement to control the suspension travel of active suspension system.

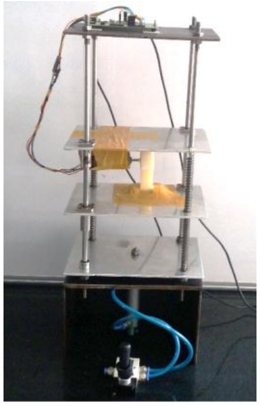

Fig. 13. Prototype of Quarter Car suspension Test Rig.

The HILINK microcontroller board [28-29] includes D/A card and an encoder card as shown in Fig. 14. The real-time control board is based on a dsPIC30F2012 digital signal controller. The board is interfaced to the main computer through a serial port. The HILINK platform offers a perfect interface between the physical plants and Simulink to implement hardware-in-the-loop simulation of real-time control systems. The platform achieves real-time operation with sampling rates up to 3.8 kHz. The board also contains two H-bridges with 5 A capability to drive external heavy loads. It is fully integrated with MATLAB and has a wide range of inputs and outputs. The displacement signal was send to the computer through HILINK board after it has been captured by the encoder. The captured signal was processed by Fuzzy controller in Simulink block to generate a current signal for HILINK output channel.

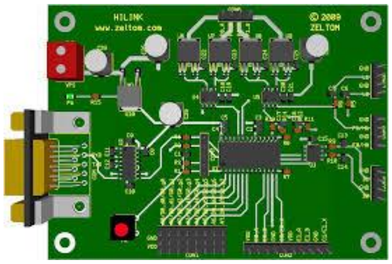

Fig. 14. Zeltom- Hilink Real Time Control Board

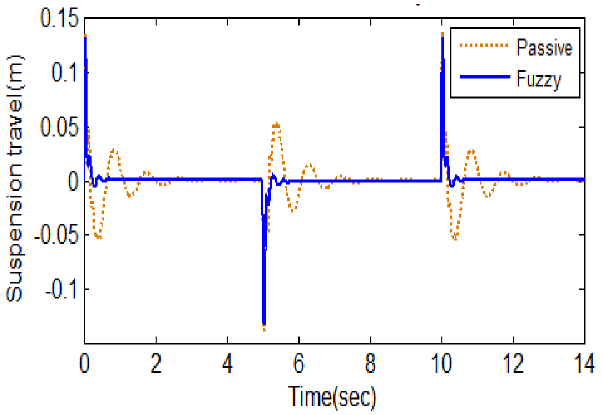

Fig. 14. Response of suspension travel

The signal from HILINK output channel goes to amplifier which generates necessary actuator force for active suspension. The experiment was performed under a disturbance of step input signal. The experiment is performed for final time of 14 seconds and the resulting response is shown in Fig. 15. The dash-dot line indicates passive suspension and the solid line indicates active suspension. It shows clearly that, the active suspension has better control in in reducing suspension travel in order to promote the road-holding capability of a car than with the passive suspension.

VI. CONCLUSION

The Two-degree-of-freedom quarter-car suspension has nonlinear characteristics as a result of its hydraulic components has increased the difficulty of creating mathematical model for active suspension system. In real time, the model based controller do not give better result due to its nonlinear behavior of hydraulic actuators used in active suspension system .The proposed fuzzy controller results have demonstrated that the magnitudes of the body displacement and acceleration are decreased as well as the resonance peak due to vehicle body is eliminated significantly compare to model based controller. The simulation and experiment conducted on real time control platform for active suspension system has confirmed improvement of the ride comfort in vehicles.

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