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A 3 Degree of Freedom Quarter Car Active Suspension System Model Design Approach using PID, Fuzzy Logic and Fuzzy Tuned PID

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Abstract—The primary objective of any suspension system in automobiles is to isolate the road disturbances experienced by the tires frombeing transmitted to the passengers due to road profile. ***The passive suspension system can hardly improve the ride quality and handling performance at the same time. The aim of suspension system is to improve ride comfort, road handling and stability of vehicles.In this paper the study is extended to a quarter car (3-DOF) seat-suspension model instead of 2 DOF suspension systems. Three different active controllers are designed to compare the performance of three controllers with the passive suspension system. The three controllers designed are PID controller,Fuzzy logic controller and fuzzy tuned PID controller. In this work, MATLAB/SIMULINK software is used for simulation purpose and simulation result demonstrates that active suspension system shows better result in comparison to passive suspension system.*

Keywords—suspension system,3-DOF,2 DOF,passive suspension system,PID,Fuzzy logic, fuzzy tuned PID,MATLAB/SIMULINK,ride quality.

I. INTRODUCTION

A suspension system is of three types: passive, semi-active and active suspension system. Passive suspension system is the simplest and consists of springs and dampers. In semi active suspension system consists of a variable damper that can adapt to actual demands. The active suspension system contains separate actuator to exert extra force on the suspension system.Researchers have already investigated active suspension system using models like 1/4 car model, 1/2 car model, full car model etc.Previously various works have been done on 2 degree of freedom quarter car model. Mat Hussin Ab. Talib and Intan Z. Mat Darus[1] investigated the performance of PID controller for ½ car model and PID parameters are tuned using heuristic method, Ziegler Nichols method and iterative method. In paper [2], Fuzzy logic has been studied and successfully implemented on a 2-DOF quarter car model.Muhamadetal.[3] proposed composite nonlinear feedback control for a linear 2-DOFquarter car model and was compared with LQR controller. In [4] the research work investigates the design of observer for 2 DOF model using sliding mode control methodology. In [5], LQR, optimised LQR and H infinity control was discussed and implemented in quarter car model and it was found that optimised LQR control scheme give the best result compared to other control methods. When the degree of freedom of the system increases, complexity of the system also increases along with the difficulty level to control the system. A 3-DOF system is designed using a fuzzy logic controller for the suspension system and analyzed to comparewith that of passive suspension system [6].In [7], two optimal controllers PID and LQR are designed for2 DOF model. The Fuzzy PID control scheme was proposed in previous research work in many systems. In fuzzy PID control scheme, Kp, Ki and Kd parameters are automatically tuned using fuzzy rules. Fuzzy PID control technique was successfully applied in 2 DOF quarter car model based active suspension system [8].

In this paper,3 DOF quarter car model is modeled and three different control methods namely

PID,fuzzy and fuzzy tuned PID are successfully designed and verified in simulation. The response of the control methods are compared with that of passive suspension system. The overall system is designed using MATLAB's Fuzzy Logic Toolbox and SIMULINK toolbox.

Section II gives description modeling of 3-DOF quarter car model for active and passive suspension system. Section III gives the formulation and design of the proposed controllers. Section IV gives description of simulation result and comparison of control schemes. Section V gives the conclusion.

II. MODELLING OF ACTIVE AND PASSIVE SUSPENSION

The 3 DOF quarter car model used is a simplified version of the full car model. It consists of passenger mass(m_p), sprung mass (m_s) and unsprung mass(m_{us}). Spring ($k_{p)}$ and damper (c_p) represents the seat. The sprung mass is known as mass of the car body and it is supported on spring ($k_{s)}$ and damper (c_s)of suspension system. Unsprung mass represents mass of car wheel. Tyre of the car is replaced by using spring (k_t). Fig. 1 represents the 3 DOF quarter car model for active suspension system.

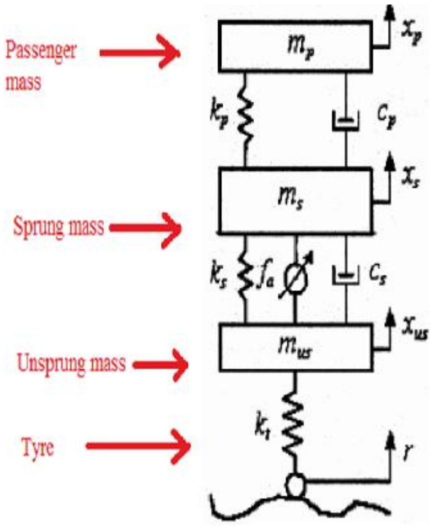


Fig.1. 3 DOF quarter car model of active suspension system.

A. Equations

Newton's second law of motion is applied to the seat, sprung mass and unsprung mass and the differential equations obtained are as follows:

$$m_p\ddot{x}_p + k_p\left(x_p - x_s\right) + c_p\left(\dot{x}_p - \dot{x}_s\right) = 0 \qquad (1)$$

$$m_s\ddot{x}_s - k_p\left(x_p - x_s\right) - c_p\left(\dot{x}_p - \dot{x}_s\right) + k_s(x_s - x_u\ ) + c_s(\dot{x}_s - \dot{x}_u\ ) = f_u \qquad (2)$$

$$m_u\ \ddot{x_u}\ - k_s(x_s - x_u\ ) - c_s(\dot{x}_s - \dot{x}_u\ ) + k_t(x_u\ - r) = -f_u \qquad (3)$$

Here,$x_1 = x_p, x_2 = \dot{x}_p, x_3 = x_s, x_4 = \dot{x}_s, x_5 = x_u\ , x_6 = \dot{x}_u$, the equations can be written in terms of state variable $x_1, x_2, x_3, x_4, x_5, x_6$as follows

$$\dot{x} = A\ \ + B\ \ + G \qquad (4)$$

Where X=state input matrix, U=control input matrix W=road input matrix.

$$\dot{x_1} = x_2 \qquad (5)$$

$$\dot{x_2} = -1/m_p[k_p(x_1 - x_3) + c_p(x_2 - x_4)] \qquad (6)$$

$$\dot{x}_3 = x_4 \qquad (7)$$

$$\dot{x_4} = {}^{-1}\!\Big/_{m_s}\begin{bmatrix} k_p(x_3 - x_1) + c_p(x_4 - x_2) + k_s(x_3 - x_5) + \\ c_s(x_4 - x_6) \end{bmatrix} + f_u/m_s \qquad (8)$$

$$\dot{x_5} = x_6 \qquad (9)$$

$$\dot{x_6} = {}^{-1}\!\Big/_{m_u}\left[k_s(x_5 - x_3) + c_s(x_6 - x_4) + k_t(x_5 - r)\right] - {}^{f_u}\!/_{m_u} \qquad (10)$$

For passive suspension system f_a=0.Table I shows value of all the system parameters used in the model [6].

TABLE I. SYSTEM PARAMETER VALUES FOR QUARTER CAR MODEL

Parameter		
Parameter	***Value***	***Unit***
Passenger mass, m_p	100	Kg
Sprung mass, m_s	2050	Kg
Unsprung mass, m_{us}	100	Kg
Stiffness of the seat, k_p	100000	N/m
Seat Damping coefficien, c_p	6000	Ns/m
Stiffness of suspension system, k_s	400000	N/m
Damping coeffcient of suspension system, c_s	5000	Ns/m
Stiffness of the tyre, k_t	2000000	N/m

III. CONTROLLERS DESIGN

Auto tuned PID, Fuzzy logic controller and fuzzy tuned PID are proposed to control the vehicle dynamic model. A step input of 10 cm or 0.1 m is used as disturbance to test the system performance.

A. PID controller

PID controller is a commonly used control scheme in many industrial control systems. In this work, PID controller is auto tuned using MATLAB Simulink's auto tune box designed.

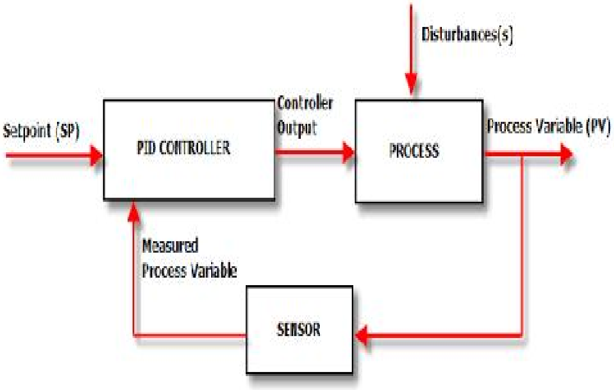


Fig.2.PID controller block digram for vehicle system.

The PID controller is represented by:

$$u(t) = Kp \times e(t) + Ki \int_0^t e(\tau)d\tau + Kd\frac{d}{d} \quad (11)$$

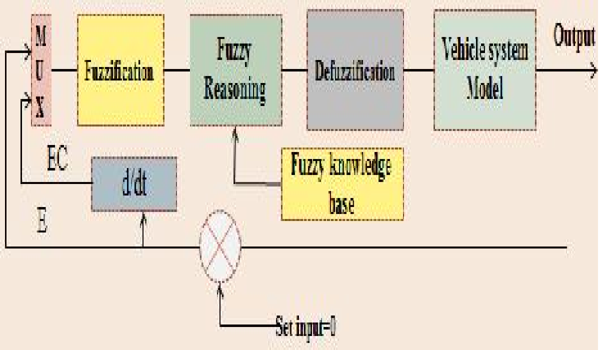
Where Kp is the proportional gain, Ki is the integral gain and Kd is derivative gain, e is the positional error.

B. FUZZY logic controller

Figure 3 represents the block diagram of fuzzy logic controller.

The steps in designing fuzzy logic controller are as follows:

- Trapezoidal membership functions are used and Linguistic variables assigned to these fuzzy sets are, NB, NM, NS, ZE, PS, PM and PB. Total 49 rules are made.



.Fig.3. Fuzzy logic controller block.

- .Mamdani type inference method and centroid defuzzification method are used. Output of fuzzy controller is actuator and inputs are the sprung mass displacement error(E) and the rate of change of velocity(EC) of the suspension system.

Fuzzy control rules are shown in table II.

TABLE II. FUZZY CONTROL RULES

		E						
		PB	**PM**	**PS**	**ZE**	**NS**	**NM**	**NB**
EC	**PB**	PB	PM	PM	PB	PM	PS	ZE
	PM	PM	PM	PM	PM	PS	ZE	NS
	PS	PM	PM	PM	PS	ZE	NS	NM
	ZE	PM	PM	PS	ZE	NS	NM	NM
	NS	PM	PS	ZE	NS	NM	NM	NM
	NM	PS	ZE	NS	NM	NM	NM	NM
	NB	ZE	NS	NM	NM	NM	NM	NM

C. FUZZY tuned PID controller

Fuzzy self-adjusting PID controller is the combination of PID controller with adjustable parameters and fuzzy controller. Figure 4 represents the schematic block diagram of fuzzy tuned PID controller for vehicle suspension system.

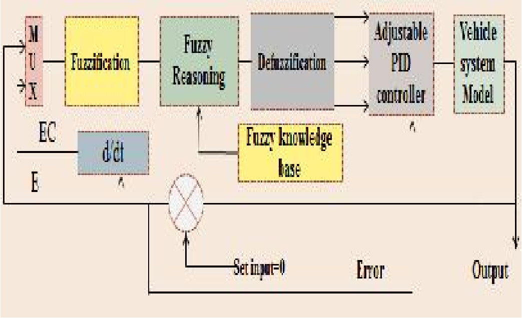


Fig.4. Fuzzy tuned pid controller block.

Relative displacement andrelative velocity are taken as error(E) and rate of change of error(EC) and using fuzzy logic rules given in table III Kp, Ki and Kd values are determined. Mamdani type inference method, centroid defuzzification method and Trapezoidal membership functions are used. Total of 27 rules are made and linguistic variables assigned are Low, Medium and High.Range of error, rate of error, Kp, Ki and Kd are estimated as:

E=[-0.13 0.07], EC=[-11 7],Kp=[0 1e+04], Ki=[0 1e+04],Kd=[1000 3e+03]

TABLE III. FUZZY CONTROL RULES FOR KP, KI AND KD

Kp		**E**		
		Low	**Medium**	**High**
EC	**Low**	P	P	ZE
	Medium	ZE	ZE	ZE
	High	N	N	ZE

Ki		**E**		
		Low	**Medium**	**High**
EC	**Low**	P	P	ZE
	Medium	ZE	ZE	ZE
	High	N	N	ZE

Kd		**E**		
		Low	**Medium**	**High**
EC	**Low**	N	N	ZE
	Medium	N	ZE	P
	High	ZE	P	P

IV. RESULT AND COMPARISON

A. Result

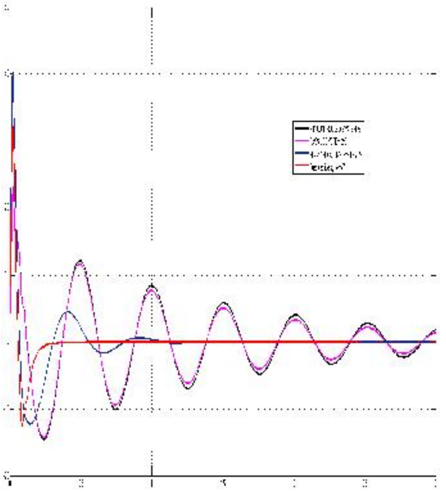


Fig.5. Passenger acceleration (m/sec^2) vs. time (sec).

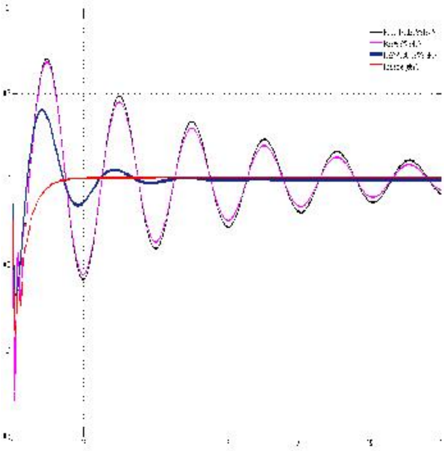


Fig.6. Suspension deflection (m) vs. time (sec).

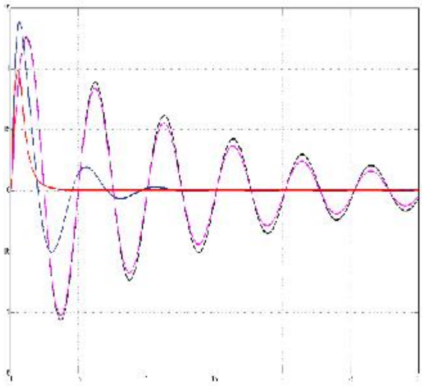


Fig7. Seat velocity (m/sec) vs. time (sec).

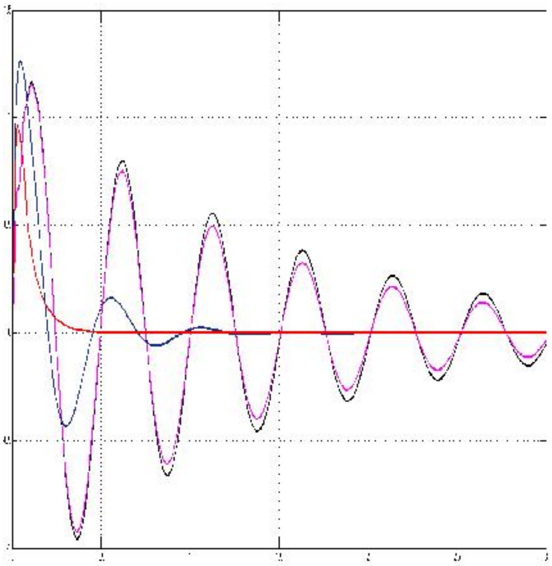


Fig.8. Sprung mass velocity (m/sec) vs. time(sec).

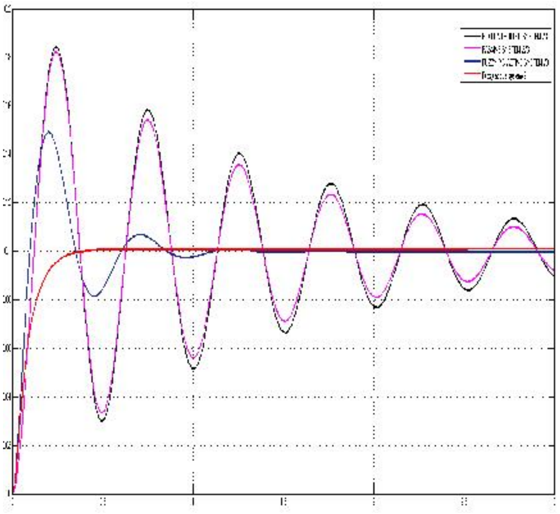


Fig.9. Sprung mass displacement (m) vs. time (sec).

In the figure black, blue, red and pink colors are used to denote Auto tuned PID, Fuzzy PID, Fuzzy and Passive Suspension system. Fig. 5,6,7,8,9 show the comparison between the PID, Fuzzy and Fuzzy tuned PID active suspension system and passive suspension system.

B. Comparison

Table IV, V, VI,VII and VIII show the comparison of the proposed controllers with passive suspension system.

TABLE IV. PERFORMANCE CHARACTERISTICS OF SUSPENSION DEFLECTION

	Suspension deflection			
	PID	***Fuzzy PID***	***FUZZY***	***PASSIVE***
Maximum peak value (m)	0.06	0.0405	0	0.0685
Settling time (sec.)	7	1.8	0.6	7.5
Steady state error (%)	0	0	0	0

TABLE V. PERFORMANCE CHARACTERISTICS OF SEAT ACCELERATION

	Seat acceleration			
	PID	***Fuzzy PID***	***FUZZY***	***PASSIVE***
Maximum peak value (m/sec^2)	23.609	41	32	23.7147
Settling time (sec.)	8	1.5	0.6	8.5
Steady state error (%)	0	0	0	0

TABLE VI. PERFORMANCE CHARACTERISTICS OF SEAT VELOCITY

	Seat velocity			
	PID	***Fuzzy PID***	***FUZZY***	***PASSIVE***
Maximum peak value (m/sec)	1.2	1.38	0.95	1.2525
Settling time (sec.)	8.5	1.5	0.8	9
Steady state error (%)	0	0	0	0

TABLE VII. PERFORMANCE CHARACTERISTICS OF SPRUNG MASS VELOCITY

	Sprung mass velocity			
	PID	***Fuzzy PID***	***FUZZY***	***PASSIVE***
Maximum peak value (m/sec)	0.9919	1.24	0.94	1.1545
Settling time (sec.)	2.1	1.5	0.9	9
Steady state error (%)	0	0	0	0

TABLE VIII. PERFORMANCE CHARACTERISTICS OF SPRUNG MASS DISPLACEMENT

	Sprung mass displacement			
	PID	***Fuzzy PID***	***FUZZY***	***PASSIVE***
Maximum peak value (m/sec)	0.18	0.13	0.1	0.1823
Settling time (sec.)	7.8	1.6	0.8	8
Steady state error (%)	0	0	0	0

V. CONCLUSIONS

Active suspension system has been successfully designed using the three controllers. The resulting closed-loop control systemcan be able to eliminate the effect of road disturbance to some extent. Auto tuned PID is designed using MATLAB Simulink's auto tune tool. Fuzzy tuned PID gives better result than Simulink's auto tuned PID model. In case of performance parameters like seat acceleration, suspension travel, sprung mass velocity, seat velocity, sprung mass displacement Fuzzy control scheme gives better result as compared to other control methods.

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