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Development of an Active Suspension System Model Based on Dynamic Performance

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Abstract— The purpose of suspension system isto minimizethe vibration that is being transmitted to the passenger compartment of vehicle and thereby reinforce rider comfort. The traditional suspension system has fixed criteria for spring and damping. The performance of the suspension systemcan be improved by dynamically varying the stiffness and damping coefficient of the suspension system elements which can be achieved by introducing active suspension system. In this study, the performance of passive and active suspension system for a quarter-car model are analysed using MATLAB SIMULINK package.A Proportional Integral Derivative (PID) control, Fuzzy tunedPID control and Particle Swarm Optimization (PSO)tunedfuzzy control techniques are used to control the dynamic characteristics of the active suspension system. The characteristics of PSO rules areframed to reduce the sprung mass acceleration. The results showthat PSO tuned fuzzy controlapproach issignificantly improvingthe overall performance of the active suspension system.

Keywords — Particle swarm optimization, Fuzzy logic control, Active suspension system and Passive system

1. INTRODUCTION

A car suspension is a physical mechanism that separates the car body and wheels apart in a car. The performance of the control systems of automobiles have been greatly increased due to development of technologies. The suspension system consists of shock absorbers, springsand links that connect a car body to its wheels. The most important function of an automotive suspension system is to minimize the vertical acceleration transmitted to the passenger which directly provides ride comfort. A passive suspension can store energy via a spring and dissipate it through a damper but its parameters are generally fixed. Whereas an active suspension system has the ability to store and dissipate energy as a system. Its parameters can be varied depending upon operating conditions at that instance of a vehicle dynamic conditions. The active suspension system is more efficient compared to the passive suspension system and semi-active suspension systems.

Various control methods likeProportional Integral Derivative (PID) as a feedback loop controller[1,2,3],Particle Swarm optimization [4, 5, 6], Fuzzy controller[7, 8], skyhook model and Ground hook model[9]are reported to regulate the active suspension system.Xing et al. [10]used the adaptive fuzzy fault-tolerant controlapproach to analyse the performance of active suspension system.

Implementation of a Fuzzy Logic Controller (FLC) with heuristic rules will improve the performance of suspension system. The parameters of a fuzzy control system are tuned by means of atrial and error technique.The performance of the passive suspension system and active suspension system with Fuzzy Logic Controller, Fuzzy-PID Controller, PID Controllerare discussedby Swethamarai et al [8] and Rajendiran et al.[11].Shen etal. [12] applied the Power-By-Wire system to control the active suspension system and a Fuzzy PID controller is used for optimizing controlparameters.Mohammadjavadet al.[13]modeled the suspension system as a quarter-car model and used Magneto rheological (MR) damper and fuzzy PID controller to control the semi-active suspension system.

The PSO model generates high-quality solutions with increased convergence characteristics and lower calculation time than alternative random strategies. Rajeswari et al.[14]used PSO approach to tune the Adaptive Neuro-Fuzzy Control for the active suspension system and result shows good performance in ride comfort and road holding ability.Srinivasa Rao et al. [6]proposed a particle swarm optimization based PID control forsuspension system and the studies are carried out for various road conditions.Qin et al.[15] proposed a probabilistic neural network approach to study the performance of a semi-active suspension system. The results are validated with the skyhook controlstrategy.

Jeongwooet al. [16] proposed a new active suspension system with linear motor and the study shows that linearmotor-based control systemprovides better result compared to the hydraulic active suspensionsystem.Vineet Kumar et al. [17] analysed the performance of active suspension system with robust fractional orderFPDcontrollerfor better ride comfort and the controller is tuned using GA technique. Priyandoko et al. [18] studied the performance of active suspension with adaptiveneuroactiveforcecontroland results are compared with PID and passive suspension systems.

Numerous studies have been carried out to improve the performance of active suspension system by considering the either PSO or FLC method. This paperpresents the performance of the active suspension system with PSO tuned FL control. The behaviour of active suspension system with PSO tuned FL control is compared with that of the passive suspension system and active suspension system with PID control, Fuzzy -PID control. The suspension system of a quarter-car model is analysed using SIMULINK package by considering control techniques such as PID, FLC and PSO based FLC.

The content of the paper is organized as follows: Section II presents the governing equations of asuspension system for a quarter-car model. Section III offers an implementation of PID, FLC and PSO based FL control strategiesto the suspension system of a quarter-car model. Simulation results and its justification are discussed in section IV. The conclusion is presented in section V.

2. MATHEMATICAL MODELING

The passive and active suspension system of a quarter-car model are considered in this study. A quarter car model with two degrees of freedom is examined instead of a full car model. It simplifies the analysis phase and also represents most of the features of the full car model.

A. Passive Suspension System

Aquarter-car model with two degrees of freedom used for analyzing the performance of passive suspension system is shown in figure 1. The equations of motion for the passive suspension system can be written as,

For sprung mass M_S,
$M_S \ddot{X}_S + C_S (\dot{X}_S - \dot{X}_U) + K_S (X_S - X_U) = 0$ (1)
For un-sprung mass M_U,
$M_U \ddot{X}_U - C_S (\dot{X}_S - \dot{X}_U) - K_S (X_S - X_U) + K_t (X_U - X_r) = 0$
(2)
Where, M_s-sprung mass,
M_u- un-sprung mass,
C_S-Damping coefficient of suspension system, K_S-suspension stiffness,
K_t- tire stiffness,
X_S- displacement of sprung mass,
X_u- displacement of un-sprung mass.

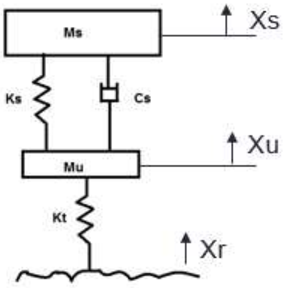

Fig. 1. Quarter-car model of a passive suspension system

B.Active Suspension System

Figure 2 represents the quarter-car model with two-degrees-of-freedom active suspension system considered in this study. In active suspension systems hydraulic actuators are added to the passive components. The advantage of this system is that even if the active hydraulic actuator or the control system fails, the passive components continue to operate.

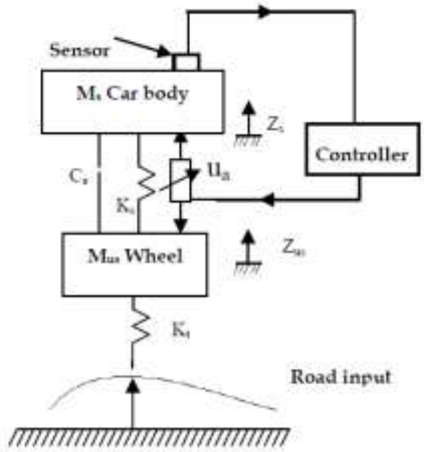

Fig. 2.Quarter-car model of an active suspension system

The suspension system consists of sprung mass M_S, un-sprung mass M_U and anactuator. The motion of the sprung and un-sprung mass is represented by Z_S, and Z_u, while the excitation due to road disturbance is Z_r. The governing equations of motion of a quarter-car model, considering U_a as the control input, is given in equations (3) and (4).
For sprung mass M_S,
$M_S \ddot{X}_S + C_S (\dot{X}_S - \dot{X}_U) + K_S (X_S - X_U) - U_a = 0$ (3)

For un-sprung mass M_U,
$M_U \ddot{X}_S – C_S(\dot{X}_S - \dot{X}_U) – K_S(X_S – X_U) + K_t(X_U – X_r) + U_a = 0$(4)

3. PROPOSED CONTROLLER STRUCTURE

The Fuzzy PID Controlused in this study is shown in figure 3. FLC is employed for disturbance rejection management to control the motion of sprung mass of the vehicle. Suspension deflection is taken as the input variable and actuator force is the output of the controller. A, B, and C are the scaling factors considered in the PSO-based FLC method. The peak overshoot value of the body acceleration, displacement and suspension travel is taken as the performance criteria.

A. Fuzzy Logic Controller

The parameters of the PID controller is tuned with help of Fuzzy logic. Fuzzy rule-based system is widely known as Fuzzy Inference System (FIS) and it is the key unit of FLC. The desired membership function is chosen for the fuzzy set. The decision-making unit performs the operation on rules with both the input and output sets. Fuzzification converts the crisp quantities of input variables into fuzzy quantities and defuzzification changes the fuzzy quantities into crisp quantities.

Figure 3 represents the block diagram for implementing the Fuzzy-PID controller in MATLAB.The FLC is designed with two-input, error and derivative of the error, and single output terms. The defuzzified output from the fuzzy controller is the desired control force given to quarter-car model. Appropriate scaling factors for input and output variables are chosen. The range for the input error and derivative of error is -1 to 1. The heuristic 49 fuzzy rule base for this problem is implemented in the MATLAB environment adopted by Hurel and Mandow [19].

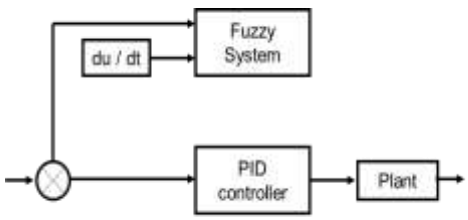

Fig. 3 Fuzzy PID Controller

The Fuzzy rule implemented in MATLAB FIS editor having two input variable namely error, change in error and one output variable namely control output are shown in figures4, 5, 6 and 7.The rule basis works based on the type "if X and Y then Z" based on error and change in error.

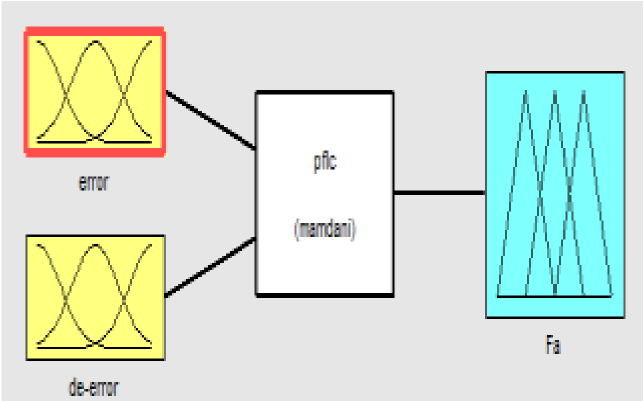

Fig. 4. MATLAB FIS editor

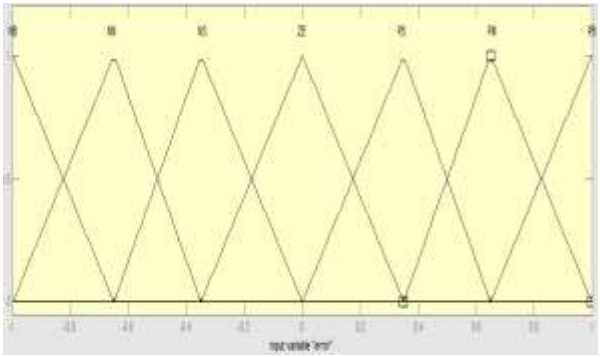

Fig. 5. Input variable – error

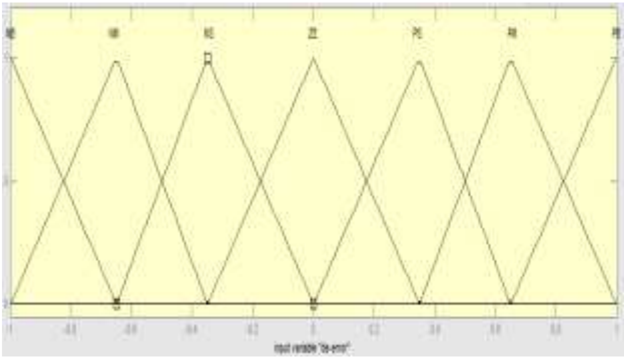

Fig. 6. Input variable change in error

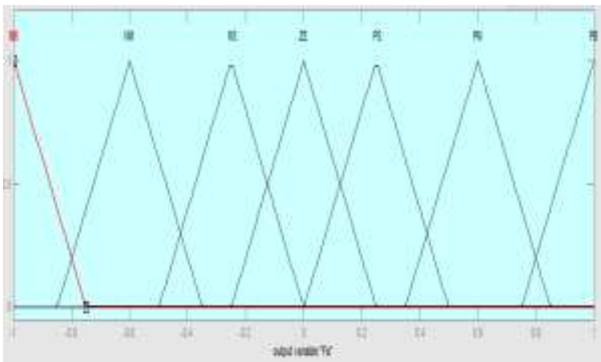

Fig. 7. Output variable -Force actuator

B. Particle Swarm Optimization

A Particle Swarm optimization is a population-basedsearch technique. The PSO algorithmic is changing into fashionable because of its simplicity in implementation and talent to quickly converge to a reasonably sensible resolution [20].

The swarm comprises a fixed number of multiple solutions (particles). These particles are within the solution space in the swarm and develop a cooperative search for the optimal solution. Particles are termed as the cluster of scaling factors (A, B and C) over the FLC. A restriction is enclosed within the algorithmic program, to avoid C values that exceed the particular input limit F.The PSO algorithm parameters are chosen based on the population size, number of iterations, weight factors and the weight parameters. Optimized values generated for scaling factors A, B and C by the PSO algorithm for the fuzzy logic controllerare considered from the work carried out by Hurel and Mandow[19].

C. Modelling of Road Profile

In order to investigate the suspension dynamics with respect to ride comfort and handling capability of the vehicle, the road profilesare taken from the studies proposed by Siva Kumar and Das[6]and this profile is used as an input parameter to the suspension system.

The road disturbance with one bump can be modelled using equation(5) described below,

$$Z_r = \begin{cases} \frac{A}{2}\left(1-\cos(2\pi(t/T_{b1}))\right), & \text{for } T_{b1} \le t \le 2T_{b1} \\ 0 & \text{, otherwise} \end{cases} \quad (5)$$

'A' is the height of the bump and 'T_{b1}' is the duration of the bump.

4. RESULTS AND DISCUSSIONS

The dynamic performance analysis of the active suspension system is analysed using a quarter-car model and road disturbances are specified using equations (5). A MATLAB SIMULINKpackage is used to solve the equations. The parameters for the quarter-car model considered in this analysis are taken from the literature[21] are listed in Table. II.

A Road profile with single bump, used as an obstacle for the dynamic analysis of quarter-car model, is shown in figure 8. The block diagram of PSO based FLC system and Fuzzy PID controller design are shown in figures 9 and 10.

Table Ii. Parameters Included In Simulink Model[21]

Parameters	Description	Values
A	Height of the bump	0.05 m
T_b	Duration of the bump	0.5 sec to 1 sec
t	Bump created time	0.5 sec
M_S	Sprung mass	2500 kg
M_U	Un-Sprung mass	320 Kg
K_S	Suspension stiffness	80000 N/m
K_t	Tire stiffness	500000 N/m
C_S	Damper	350 N/m/sec

The quarter- car model developed using SIMULINK package and F-PID model are shown in figures 11 and 12.

The PSO based FLC, PID and Fuzzy-PID controller method is used study the performance of suspension system model. Simulation is carried out using MATLAB SIMULINK environment version R2014a.

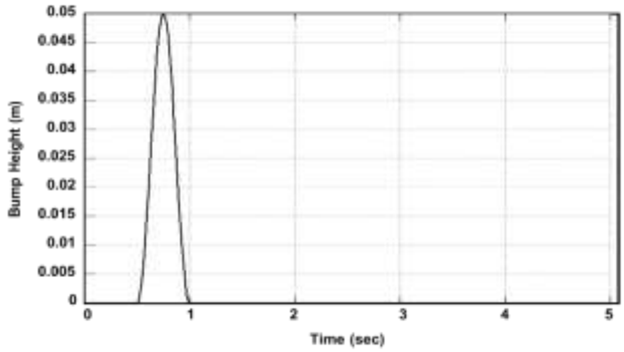

Fig. 8. Road profile with single bump

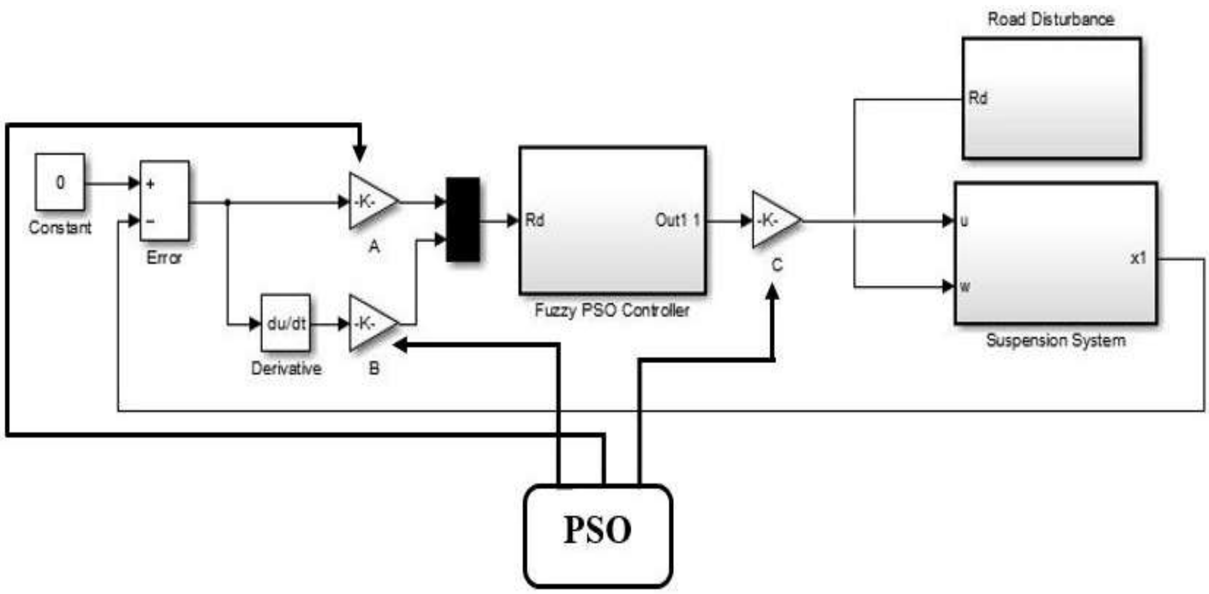

Fig. 9. Block diagram of PSO based FLC system

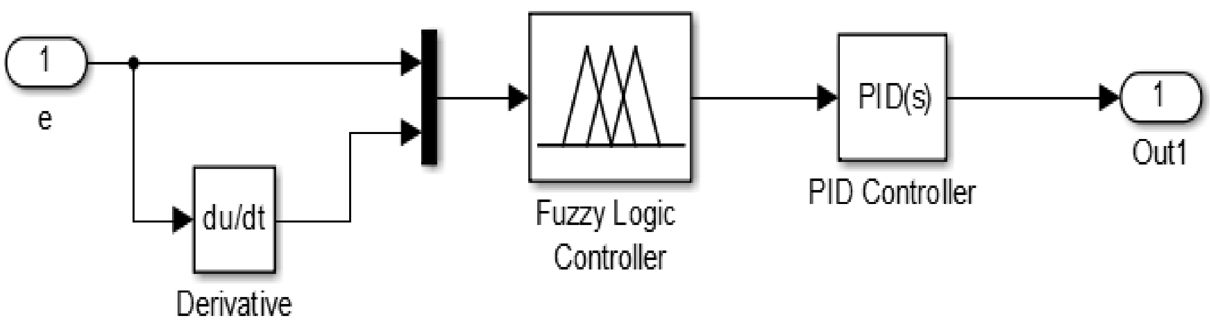

Fig. 10.Fuzzy-PID Controller Design

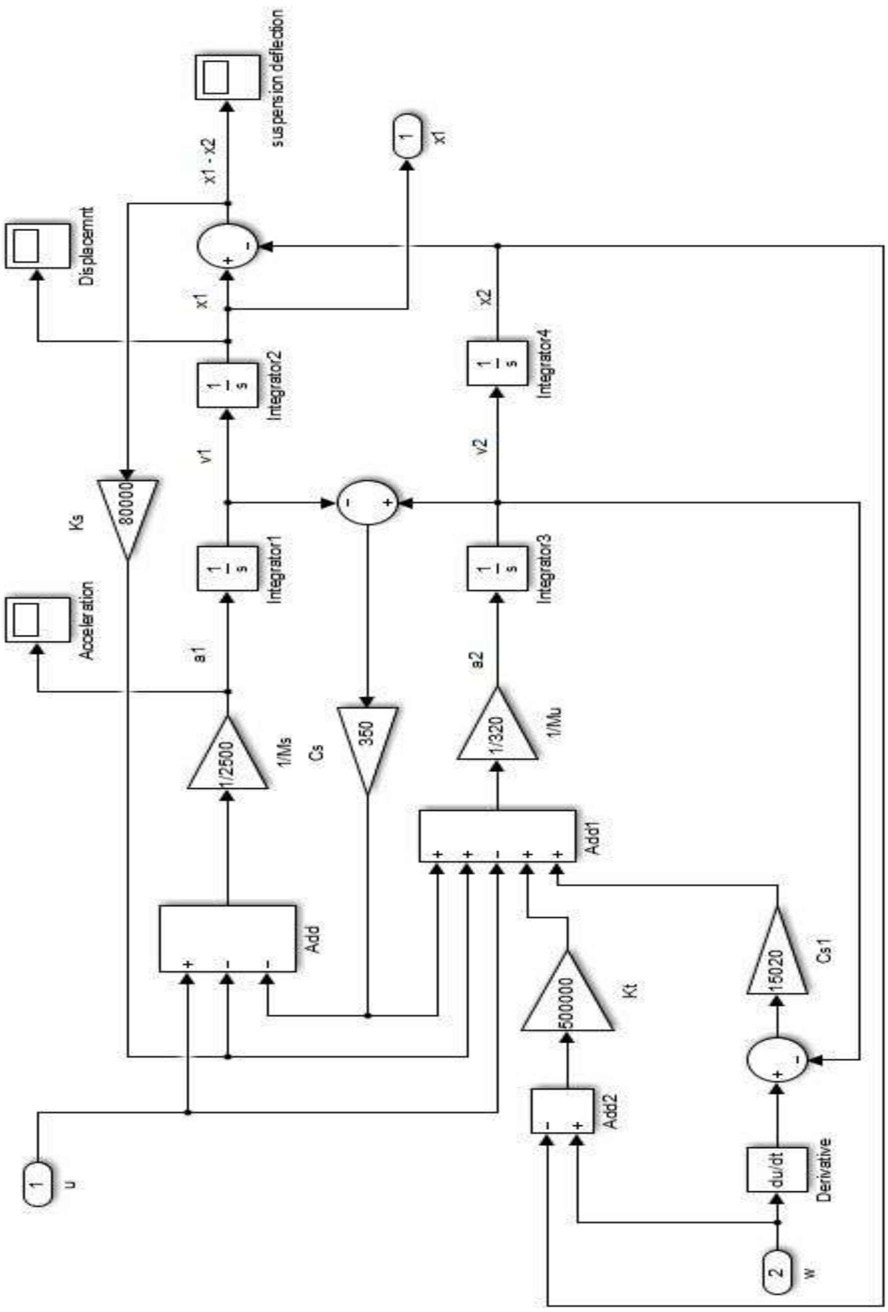

Fig. 11.SIMULINK model of a quarter-car model

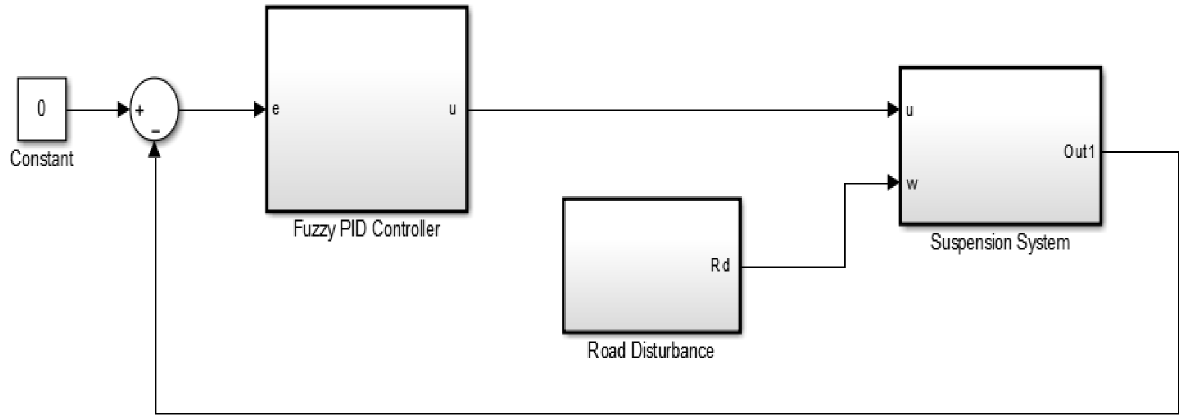

Fig. 12. F-PID SIMULINK Model

The displacementprofile of the passive suspension system, active suspension system with PID control and PSO tuned FLC are shown in figures 13, 14, and 15. From the results of MATLAB simulation show that, the passive suspension system executes a few cycles of oscillations before the sprung mass comes to rest. In case of active suspension system with PID control and PSO tuned FLC, the sprung mass comes to rest within a short period of time also the amplitude of displacement is significantly reduced compared to the passive suspension system. The maximum amplitude of displacement obtained from the simulation is listed in Table III.

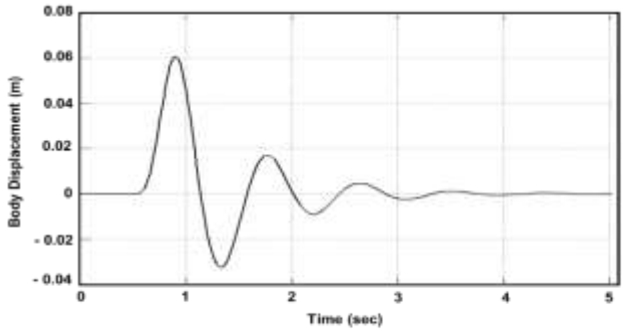

Fig. 13. Displacement profile of Passive suspension system

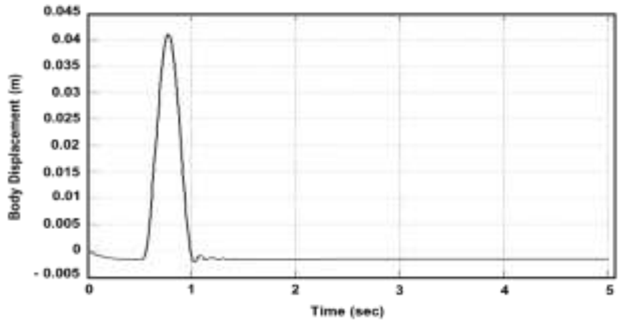

Fig. 14. Displacement profile of Active suspension system with PID

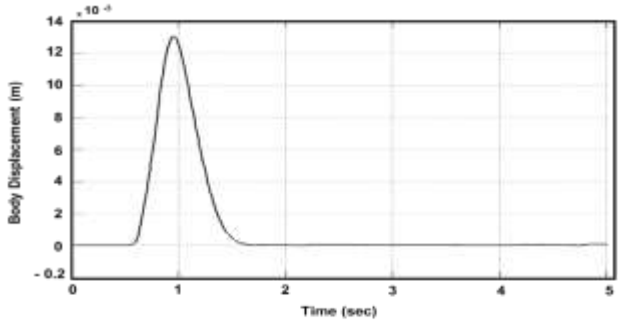

Fig. 15. Displacement profile of Active suspension system with PSO-FLC

Figure 16 shows the acceleration profile of the passive suspension system. Figures 17, 18 and 19 show acceleration profile active suspension system with PID control, F-PID control and PSO tuned FLC.

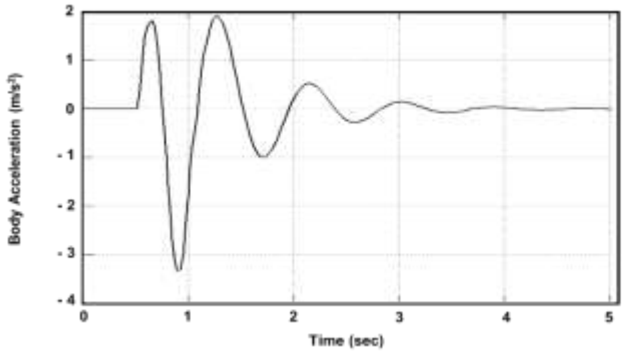

Fig. 16. Acceleration profile of Passive suspension system

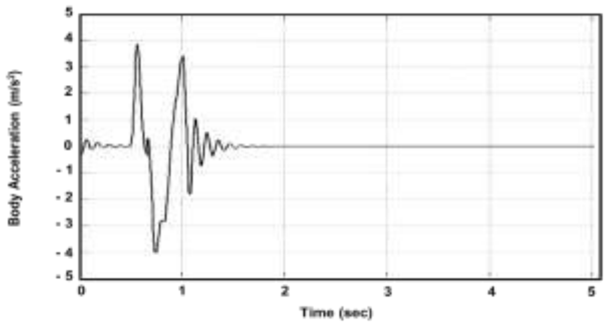

Fig. 17. Acceleration profile of Active suspension system with PID

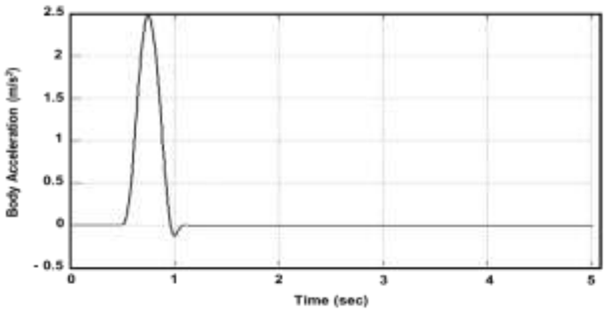

Fig. 18. Acceleration profile of Active suspension system with F-PID

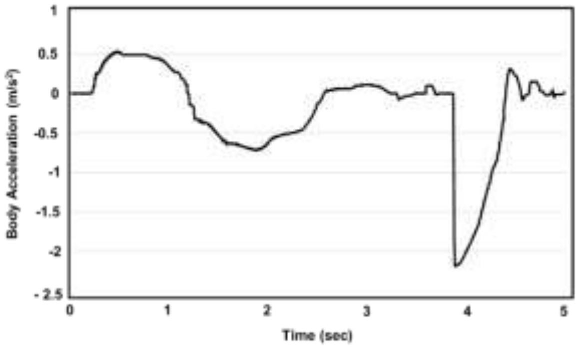

Fig. 19.Acceleration profile of Active suspensionsystem with PSO-FLC

The results obtained from the simulation of the quarter-car model suspension system having passive, Fuzzy-PID and PSO tuned fuzzy control show that, the acceleration of the car body significantly reduced while implementing PSO based fuzzy control to the active suspension system of a quarter-car model compared to the PID, F-PID controls. Also, it is observed that, the suspension travel profile is high in case of Fuzzy PID system and it requires fuzzy logic tuning to improve the stability. The maximum value of body acceleration, displacement and the suspension travel are listed in Table. III.

TABLE III. Peak overshoot values of the time responses

System	$\ddot{x}$ (m/s^2)	**Xs (m)**	**Xu (m)**
Passive	3.34	0.061	0.049
PID	3.88	0.054	0.032
F-PID	2.48	-	0.053
PSO -Fuzzy	2.19	0.013	0.050

Table IV compares the car body accelerationand the suspension travelobtained from the MATLAB SIMULINK simulation of a quarter-car model with the similar studies reported in the literature[21].

TABLE IV: Comparison of simulation and literature results

Controls	$\ddot{x}$ (m/s^2)		**Xu (m)**	
	SIMULINK results	**Literature results**	**SIMULINK results**	**Literature results**
Passive	3.34	1.57	0.049	0.018
F-PID	2.48	0.7048	0.053	0.01372
PSO-FLC	2.19	0.1761	0.050	0.01468

The results are validated by performing a comparative study with the results reported by Rajeswari and Lakshmi[5]. In the literature, the quarter-car model is analysed with different input parameters such as sprung mass, un-sprung mass, tire stiffness, suspension stiffness and damper. The results show that, the ride comfort and stability are improved inPSO based FLC compared to the Fuzzy PID controller.

5. CONCLUSIONS

In this paper, the suspension system of an automotive vehicle is analysedusing MATLAB SIMULINK package and the performance of an active suspension system withPID, PSO-based FLC and Fuzzy PID controller are compared with a passive suspension system.From the results obtained from the simulation, it is noticed that the PSO-based FLC suspension systemprovides betterride-comfort and road-holding ability then PID and Fuzzy -PID controls. It is also noticed that, the peak overshoot values of sprung mass displacement and body acceleration are also reduced in case of PSO based FLC active suspension compared to passive control system.

The evaluation of the controller with a physical suspension system and recommend a controller for the automotive suspension system can be considered for future studies.

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