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A NOVEL APPLICATION OF PARTICLE SWARM OPTIMIZATION TECHNIQUE IN SEMI-ACTIVE SUSPENSION SYSTEM CONTROL

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ABSTRACT

This paper is based on the quarter car semi-active suspension system. Semi-active suspension system proves to be a better choice in comparison with the passive and active systems keeping in view the inherent benefits of better performance, light weight and cost effective design. The semi-active system is driven by a fuzzy logic controller that is based on the feedback of relative displacement of the suspension with respect to the road disturbance and relative velocity across the damper. Fuzzy logic control can cope with the non-linearities of system using heuristic rules. Three gains are incorporated in the system corresponding to the inputs and output of the controller. Particle swarm optimization method is utilized for its better convergence and precision. The technique results in evaluation of appropriate gains that result in superior performance of the designed system. The models are compared on the basis of suspension displacement and tire displacement for ascertaining ride comfort and road handling attributes respectively.

KEY WORDS: *semi-active suspension, fuzzy logic controller, particle swarm optimization, convergence.*

1. INTRODUCTION

Suspension system performs the shock absorption in automobiles. It supports weight of the vehicle and damps out the vibrations experienced by the vehicle in relation to various road disturbances[1]. Designing a suspension system needs compromising between the goals of ride comfort and road handling. The active suspension systems are complex, bulky and expensive and therefore, they are not commonly used in commercial vehicles. Issues related to the design and control aspects in active suspension systems appear to be the real challenges. An excessive power is required that results in heavy loads on the engine[2]. Semi-active suspension is a better choice than active suspension at the cost of ride comfort and road handling but there is not a significant degradation of the performance. Semi-active suspensions need a damper and few sensors for adequate performance. The damping force can easily be varied instantaneously with the introduction of magnetorheological (MR) fluid dampers[3].

Fuzzy logic controllers have been widely used to control the suspension systems keeping in view their better performance for non-linear systems and uncertain disturbances[4,5,6]. However, it is always difficult to control the parameters of the fuzzy logic control system. Therefore, bio-inspired optimization method has been utilized in the tuning of important scaling parameters. Particle swarm optimization (PSO) method gives better results both in terms of convergence and computation time in comparison with genetic algorithms. PSO is a mathematical model that represents a flock of birds in search of food. Every bird is considered a particle and it keeps record of its best position and velocity. The best position and velocity of the complete flock is also recorded and in this way a bird keeps on orienting towards the best path based on its own experience as well as that of the group. This technique has been widely used in engineering problems[7].

The modeling of systems is based on quarter car suspension system. The gain factors in semi-active model are evaluated by performing off-line tuning method using PSO. Based on the optimized parameters, the performances of the two models are compared for a sinusoidal road profile. The PSO helps in determining maximum damping coefficient to be used in the semi-active suspension system. Section 2 presents modeling of the systems along with the implementation of PSO technique. Section 3 discusses the simulation results while Section 4 comprises the conclusion.

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2. MODELING OF SYSTEMS

This section describes the modeling of systems in detail. The proposed semi-active system based on the fuzzy logic control and optimized by PSO technique is described in Figure 1. A semi-active suspension system is modeled in Simulink. A fuzzy logic controller is designed in Fuzzy Logic Toolbox that is described in detail in following section. Two scaling factors namely A and B are incorporated before the inputs of the controller while scaling factor C is connected with the output of controller. The normalization of the inputs and output makes it easier to get the optimized values of the mentioned scaling factors. Otherwise, there would be requirement of manually adjusting the ranges of the fuzzy membership functions of the inputs and output. Relative displacement of the sprung mass with respect to the road disturbance is fed into the scaling factor A while the relative velocity across the sprung and unsprung masses is fed to the scaling factor B. Scaling factor C indicates the optimized value of the maximum damping coefficient of variable damper. The PSO algorithm gets the value of objective function at each iteration and evaluates corresponding values of scaling factors.

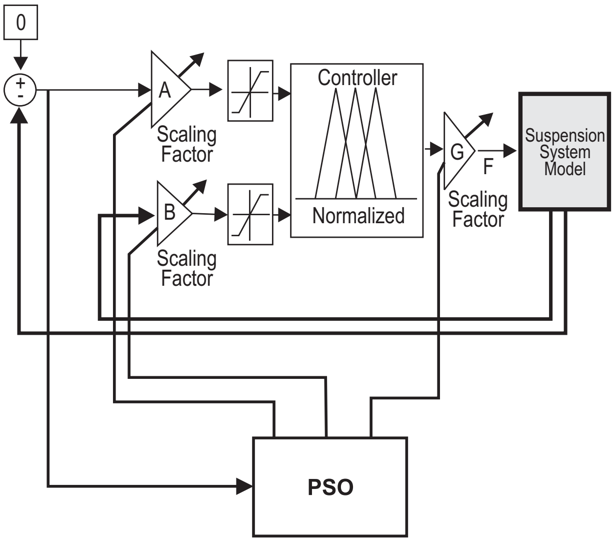

Figure 1: Block diagram of PSO tuned fuzzy logic control system

2.1 QUARTER CAR MODEL

The quarter car model of a passive suspension system is shown in Figure 2. This model has two degrees of freedom. Quarter car parameters have been tabulated in Table 1[8]. z_s and z_u represent the displacements of sprung and unsprung masses respectively, z_r represents road disturbance and c_s denotes fixed damping coefficient. In case of a semi-active suspension system, a passive damper has also been considered for providing standby arrangement in case of an emergency besides a variable damper having damping coefficient c_a. Equations (1) and (2) represent mathematical modeling of passive suspension system while Equations. (3) and (4) represent mathematical modeling of semi-active suspension system.

$$m_s \ddot{z}_s = -c_s(\dot{z}_s - \dot{z}_u) - k_s(z_s - z_u) \tag{1}$$

$$m_u \ddot{z}_u = c_s(\dot{z}_s - \dot{z}_u) + k_s(z_s - z_u) - k_t(z_u - z_r) \tag{2}$$

$$m_s \ddot{z}_s = -c_s(\dot{z}_s - \dot{z}_u) - k_s(z_s - z_u) - c_a(\dot{z}_s - \dot{z}_u) \tag{3}$$

$$m_u \ddot{z}_u = (c_s + c_a)(\dot{z}_s - \dot{z}_u) + k_s(z_s - z_u) - k_t(z_u - z_r) \tag{4}$$

Table 1: Quarter car parameters

Parameter	Symbol	Value	Units
Suspension Mass	m_s	300	Kg
Tire Mass	m_u	36	Kg
Suspension Damping Coefficient	c_s	1000	N s/m
Tire Damping Coefficient	c_u	0	N s/m
Suspension Stiffness	k_s	16000	N/m
Tire Stiffness	k_t	160000	N/m

The step profile considered in the research is depicted in Figure 3.

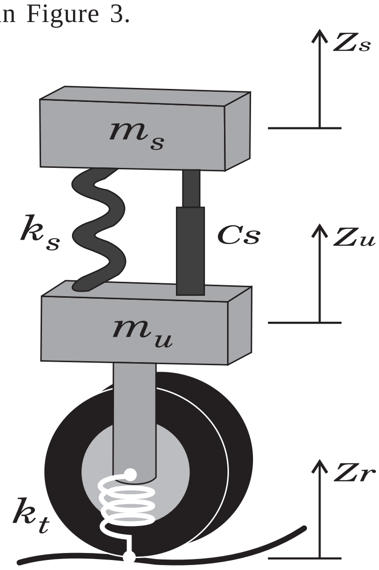

Figure 2: Quarter car passive suspension system[9]

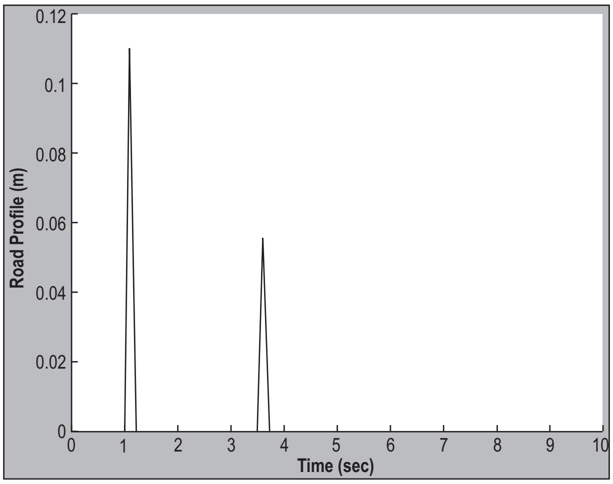

Figure 3: Sinusoidal road profile

2.2 FUZZY LOGIC CONTROLLER

In current research, the proposed fuzzy logic controller comprises two inputs namely relative displacement (suspension body and disturbance) and relative velocity (suspension body and unsprung mass) while damping coefficient is the output of the controller. Each of the inputs has three membership functions namely N (triangular), Z (singleton) and P (triangular) as shown in Figure 4 while the output comprises three membership functions namely S (triangular), M (Gaussian) and L (triangular) as shown in Figure 5. In case of each input variable, singleton shape is selected for the Z membership function as the value of the damping force is insignificant corresponding to the relative velocity being zero. The shapes of the membership functions for input and output variables are selected on the basis of best results obtained through a number of combinations. Based on three membership functions for each input, there is requirement of formulating nine rules. The formulated rules are depicted in Table 2.

All the input and output variables have been normalized, therefore, the universe of discourse for each input is [-1,1] while for the output, the range is [0,1]. Mamdani inference system is selected based on the minimum function for 'and' operator and centroid defuzzification method[10].

2.3 PARTICLE SWARM OPTIMIZATION (PSO)

PSO is a bio-inspired technique based on the behavior of swarms of birds. The algorithm searches the optimized solution of a problem governed by the

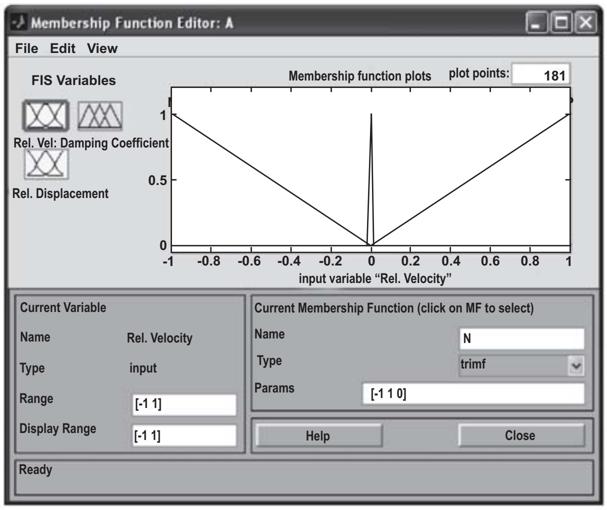

Figure 4: Membership function properties of relative velocity

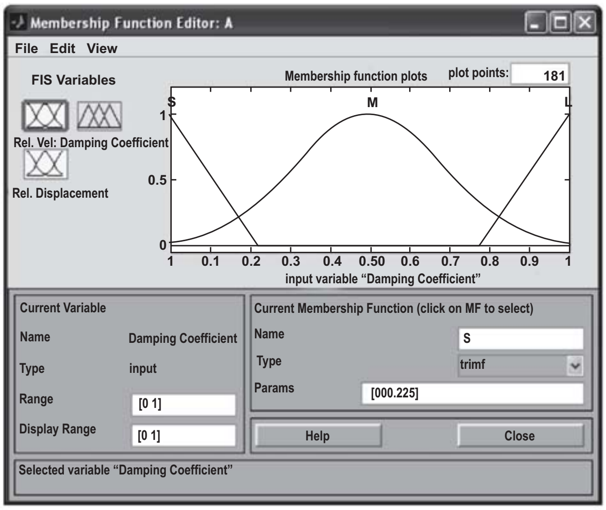

Figure 5: Membership function properties of damping coefficient

objective function. The technique is simple and achieves the result in short time without being trapped by local minima[11]. There are fixed number of birds in a swarm representing the number of iterations. These birds interact with each other in order to evaluate the optimized solution.

Each bird tries to improve its performance that corresponds to its cognitive ability while the social component of the swarm is responsible for providing the overall best values for the entire swarm. The algorithm has been illustrated in Figure 6. The objective function used in the current research is minimization of the suspension displacement with respect to the disturbance. Each particle optimizes a set of three variables that are A, B and C.

Table 2: Rule base

Rule No	Description
1	If (Rel. Velocity is N) and (Rel. Displacement is N) then (Damping Coefficient is M) (1)
2	If (Rel. Velocity is N) and (Rel. Displacement is Z) then (Damping Coefficient is L) (1)
3	If (Rel. Velocity is N) and (Rel. Displacement is P) then (Damping Coefficient is L) (1)
4	If (Rel. Velocity is Z) and (Rel. Displacement is N) then (Damping Coefficient is S) (1)
5	If (Rel. Velocity is Z) and (Rel. Displacement is Z) then (Damping Coefficient is S) (1)
6	If (Rel. Velocity is Z) and (Rel. Displacement is P) then (Damping Coefficient is S) (1)
7	If (Rel. Velocity is P) and (Rel. Displacement is N) then (Damping Coefficient is L) (1)
8	If (Rel. Velocity is P) and (Rel. Displacement is Z) then (Damping Coefficient is L) (1)
9	If (Rel. Velocity is P) and (Rel. Displacement is P) then (Damping Coefficient is M) (1)

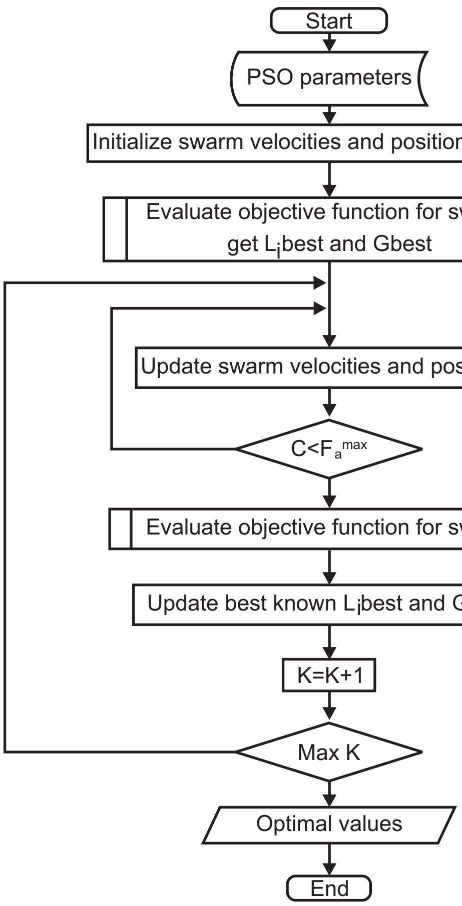

Figure 6: Flow chart of PSO algorithm[12]

$L_i best$ indicates the best known position for each particle while *Gbest* denotes the best known position for the complete swarm. The position (p_i) and velocity (v_i) of each particle are given by Eqns. (5) and (6).

$$v_i(k+1) = w \times v_i(k) + c_1 \times r_1(k) \times (L_i best - p_i(k)) + c_2 \times r_2(k) \times (Gbest - p_i(k)) \quad (5)$$

$$p_i(k+1) = p_i(k) + v_i(k) \quad (6)$$

where c_1 and c_2 denote cognitive and social factors for the individual and swarm best positions respectively, w denotes inertial weight constant and $r_1(k)$ *and* $r_2(k)$ represent random numbers generated in the uniform distribution domain of [0,1].

3. SIMULATION AND ANALYSIS

Matlab Fuzzy Tool Box has been used in designing the controller. The PSO algorithm is programmed in Matlab and executed to determine the three optimized gain factors. The Simulink model illustrating semi-active suspension system along with the fuzzy logic controller is illustrated in Figure 7. The objective function used in the model is difference between the displacement of sprung mass and road disturbance profile. The algorithm optimizes the values of scaling factors keeping the mentioned error at minimum value. Parameters used for PSO algorithm are described in Table 3.

The optimization of the scaling factors yields values of A = 19.0129, B = 12.3983, and C = 3802.3.

The simulation results of suspension displacement, and tire load for the two systems are depicted in Figures 8 and 9 respectively.

Values of important performance parameters of semi-active and passive suspension systems have been tabulated in Table 4 in relation to sinusoidal road profile.

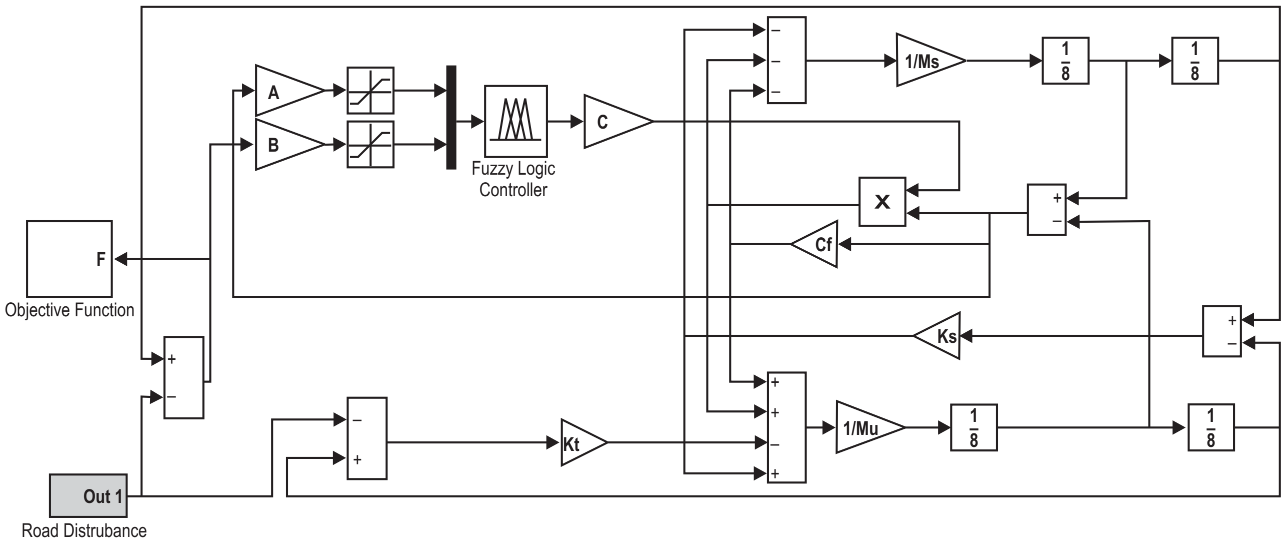

Figure 7: Simulink model of semi-active suspension system including fuzzy logic controller

Table 3: PSO algorithm parameters

Parameter	Value
Swarm Size	30
Number of Iterations	30
Unknown Variables	3
Cognitive Acceleration	1.2
Social Acceleration	1.6
Inertial Weight	0.4

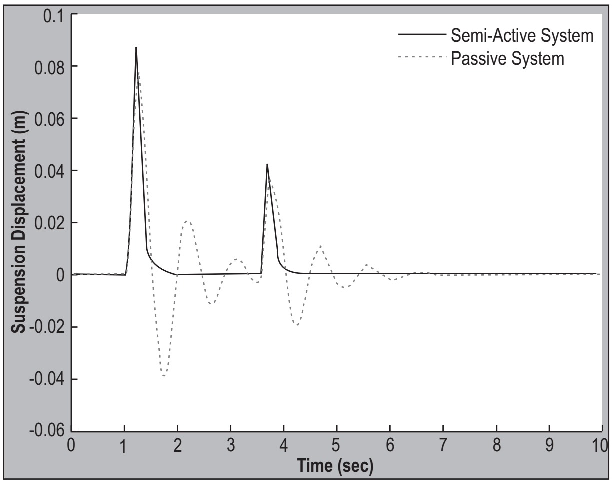

Figure 8: Suspension displacement of semi-active and passive systems

Top two values in each grid relate to the initial disturbance at t=1 sec while the bottom ones corre-

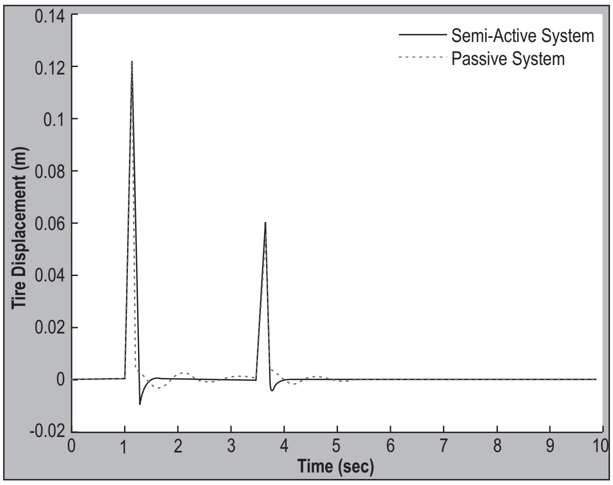

Figure 9: Tire displacement of semi-active and passive systems

spond to the second part of the disturbance at t=3.5 sec. Suspension displacement, suspension velocity and suspension acceleration are good indicators of ride comfort while tire load is a measure of road handling. In terms of suspension displacement, there is no overshoot for the semi-active system while for the passive system, overshoot is more pronounced. Furthermore, the optimized fuzzy system provides a very rapid stabilizing time in comparison with passive system. The passive system does not settle in case of first part of disturbance while for the second part, it stabilizes quite late.

Considering the tire load, fuzzy based system again exhibits rapid damping of the disturbance. Overall, the designed fuzzy based system is very efficient

Table 4: Performance comparison of PSO optimized semi-active and passive systems

Parameters	Control Systems			
	PSO Optimized Semi-Active		Passive	
	% Overshoot	Stabilizing Time (see)	% Overshoot	Stabilizing Time (see)
Suspension Displacement	0	2	-4.1	- -
	0	4.4	-2	7.5
Tire Displace-ment	-1	1.6	1	- -
	-0.05	4	0.05	5.4

in terms of passenger comfort and road handling. For the suspension displacement, there is an improvement of 100 percent in the percentage overshoot of semi-active suspension system in comparison with the passive system for both the disturbance parts. In the first part, the disturbance does not damp out at all for passive system while there is an improvement of 41.33 percent in the stabilizing time for semi-active system in second phase of disturbance. Considering the tire displacement, the percent overshoot values remain same for both the disturbance phases. As far as stabilizing time is concerned, in the first part of disturbance, the passive system does not damp out while in the second part of disturbance, the semi-active systems shows improvement of 25.92 percent in the stabilizing time in comparison with passive system.

4. CONCLUSION

The paper has demonstrated successful application of particle swarm optimization in the offline tuning of gain factors of semi-active quarter car suspension model. The PSO objective function was selected in order to minimize the off-set from road disturbance. The output of the algorithm also helps in finalizing the damping limit of the damper. The fuzzy system input and output membership functions have been normalized because of the incorporation of scaling factors. The performance of fuzzy logic controlled system is much better in comparison with the passive system both in terms of road handling and ride comfort. The PSO algorithm indicates better performance in terms of convergence and computation speed.

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