Development of Fuzzy Logic Controller by Particle Swarm Optimization Algorithm for Semi-active Suspension System using Magneto-rheological Damper

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Abstract: -The performance of fuzzy logic (FLC) and PID controllers optimized by particle swarm optimization (PSO) for semi-active suspension system using magneto-rheological (MR) damper are investigated. MR damper is an intelligent damper filled with particle magnetic polarizable and suspended into a liquid form. The Bouc-Wen model of MR damper is used to determine the required damping force based on force-displacement and force-velocity characteristics. During this research, the scaling factors of FLC and the gain parameters of PID controller will be optimized using the intelligent PSO technique to achieve the lowest Mean Square Error (MSE) of the system response. The performance of the proposed controllers based on intelligent PSO technique will be compared with the performance of passive suspension system for the body displacement, body acceleration, tire displacement and tire acceleration. Two different disturbances namely bump and hole, and random signals is implemented into the system. The simulation results demonstrates that the PSO tuned FLC exhibits an improvement to the ride comfort and has the smallest MSE as compared to the performance of PSO tuned PID and passive suspension system.

Key-Words: -suspension system, semi-active, fuzzy logic controller (FLC), PID controller, particle swarm optimization (PSO)

1 Introduction

Suspension system is one of the critical components in the present of vehicle system. Recently, the improvements of vehicle body system always have a critical thinking by many researchers to ensure the system always improved ride comfort and good road handling. Three types of system namely passive, semi-active and active suspension system have been widely investigated by many researchers with a different technique and algorithm for respective conditions [1], [2], [3]. Passive suspension system proved lack of performance of vehicle stability in recent findings as compared with semi-active and active suspension system. The fixed damper and spring component of passive system has not well enough for energy absorption to sustain the load or road disturbance acted into the vehicle system.

Semi-active suspension system has a most attractive research currently. This system contains a spring and a variable damper. Unlike passive system, variable damper of semi-active system can be controlled effectively in term of damper stiffness based on required values on a particular situation. MR damper is an intelligent damper which has been investigated by many researchers previously. This type of intelligent damper has a significant attention due to fast time response, low power requirement, mechanical simplicity and high dynamic range [4]. Many researchers gave a significant attention for their research findings in term of intelligent controller such as neural network [5], PID Neural network [6], Fuzzy Neural Network [7] and Fuzzy PID [8]. In other hand, MR damper also has been investigated by other researchers in term of design [9], model properties [10] and fluid performance [11]. MR damper system is very attractive chosen of controlling suspension for vehicle body improvement.

To implement the MR damper into the simulation study, the mathematical model of MR damper namely Bouc Wen model will be used as a significant attention to determine the actual damping force through to the system. The parameter of Bouc Wen model is very important to determine the optimum value of the required damping force for the system. Basically, the intelligent method or experimental study can be used for determining the required value of hysteresis Bouc Wen model. In 2007, Faycal et al. [10] have been studied about dynamic properties of the Bouc Wen model. In their research, a set of input and output data was collected from black-box approach. Thus, the parameters of Bouc Wen model can be adjusted so that the output of the model matches with the experimental data. Various control strategy have been implemented into the system. In this paper, PSO technique will be used for tuning scaling factor of FLC. Particle swarm optimization technique initially introduced by Eberhart and Kennedy[12]. In 2010, PSO optimized Fuzzy Logic Controller for active system has been introduced by Rajeswari et al. [13]. The performance of this technique proved that the body amplitude shows much better in comparison with Genetic Algorithm tuning. However, using active system as a significant attention, it has lead several disadvantages in comparison with semi-active system such as complex structure, need high energy consumption and expensive hardware[14].

The main objectives of this paper are to develop intelligent Fuzzy Logic controller tuned by PSO and to investigate the comparative assessment between FLC-PSO and PID-PSO for semi-active system using MR damper.

This paper will be organized as follows. Section 2 presents semi-active quarter car model. In section 3, modeling and control suspension system will be developed including Fuzzy Rules with PSO algorithm. Section 4 shows the analysis and discussion and in section 5, the conclusion is shown.

2 Semi – Active Quarter Car Model

The different between passive and semi-active system is damping mechanism system in which the damper system of semi-active can changes the damping force in real time depending of the dynamics of the controlled masses [15]. Based on the quarter car model, the mathematical equation of semi- active including car’s body and wheel can be represented based on Fig. 1.

Using Newton’s second law, the mathematical equation can be described as follows:

$$m_s\ddot{x}_s + F_{mr} - k_s(x_u - x_s) = 0 \qquad (1)$$

$$m_u\ddot{x}_u - F_{mr} + k_s(x_u - x_s) - k_t(x_r - x_u) = 0 \qquad (2)$$

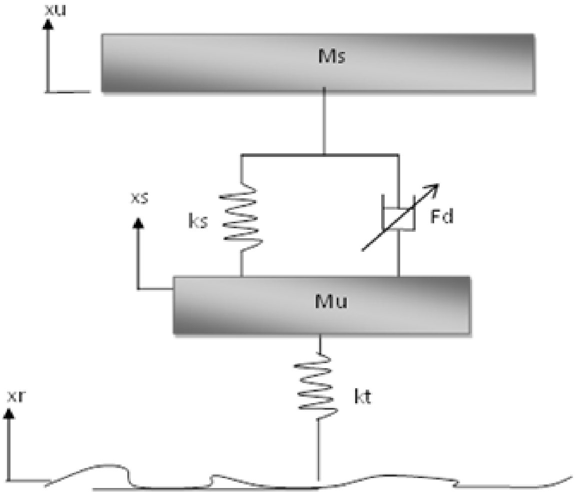


Fig.1: Semi-active suspension model

where m_s is sprung mass, m_u is unsprung mass, $x_r$ia a road profile, x_u is unsprung mass displacement, x_s is sprung mass displacement, k_s is a spring stiffness and F_d is a damper force. The parameter model of semi-active system is shown in Table 1.

Table 1. Parameter value for Quarter Car model

Parameter	**Value**
m_s= Sprung mass	*325 kg*
m_t = Unsprung mass	*55 kg*
k_s= Spring stiffness	*45.0 N/mm*
k_t = Tire stiffness	*150.0 N/mm*

To implement the damper into a variable condition, the Bouc Wen model is used to develop semi-active control for MR damper. Basically, the characteristic of MR damper need to investigate in order to validate the performance of damper to the system.

The characteristic using a proposed model has been introduced by Bouc 1967 and later modified by Wen 1976. This type of model has successful proved that hysteresis behaviour of (MR) dampers has emerged as a potential technology to implement semi-active control in structures [16]. The Bouc Wen model is shown in Fig. 2.

The damper force based on this model can be predicted using the equations described as:

$$F_{mr} = C_{D1}\dot{y} + k_{D1}(x_D - x_0) \qquad (3)$$

$$\dot{y} = \frac{1}{c_0 + c_{D1}}[\alpha z + c_0\dot{x} + k_{D0}(x_D - y_D)] \qquad (4)$$

$$\dot{z} = -\gamma\,|\,\dot{x}_D - \dot{y}_D\,|\,z\,|\,z\,|^{n-1} - \beta(\dot{x}_D - \dot{y}_D)\,|\,z\,|^{n} + A(\dot{x}_D - \dot{y}_D) \qquad (5)$$

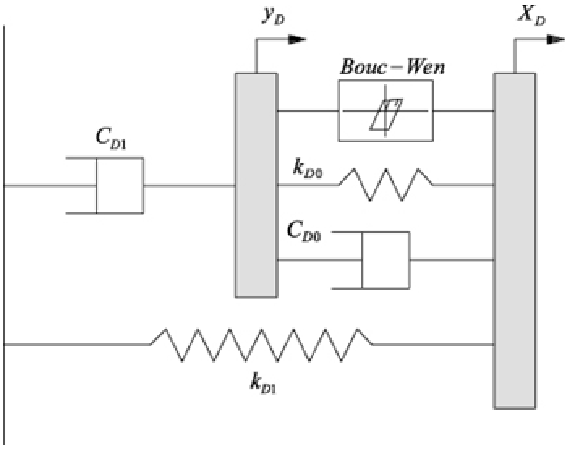


Fig. 2:Bouc Wen model of MR damper [17]

wherey_D is internal displacement, x_D is a damper displacement, x_0 is the initial condition of damper deflection and z is a variable response from historical. The voltage applied is depending on current driver from parameter model as follow:

$$\alpha = \alpha_a + \alpha_b u \tag{6}$$

$$c_0 = c_{0a} + c_{0b} u \tag{7}$$

$$c_1 = c_{1a} + c_{1b} u \tag{8}$$

where$u$ represent for output of the first order filter given as follow:

$$\dot{u} = -\eta(u - \upsilon) \tag{9}$$

Based on equation 9, η is filter time constant and υ is a voltage input of the first filter. All parameter model including k_{D0}, k_{D1}, c_{0a}, c_{0b}, c_{1a}, c_{1b}, α_a, α_b, x_0, γ, β, n and A need to be defined in order to characterize the MR damper. All parameter values are taken from previous work and shown in Table 2.

Equations (3)-(9) are used to simulate the model using Matlab SIMULINK environment. The model input and output of MR damper is voltage and damper force respectively. The MR damper model can be validated in order to make sure that the model can give desired nonlinear output. The parameter obtained previously can be proved to validate the model via force-displacement and force-velocity graph as shown in Figs. 3 and 4 respectively. It can be observed that as the voltage increase, the corresponding damping force increase as well.

Table 2. Parameter Value for MR damper RD-1005 [14]

Parameter	Value
α_a	12.44N/mm
α_b	38.43N/V.mm
c_{0a}	0.78N s/mm
c_{0b}	1.80N.s/V.mm
c_{1a}	14.64 N s/mm
c_{1b}	34.62 N.s/V.mm
x_0	0
k_{D0}	37.81N/mm
k_{D1}	0.62 N/mm
A	2.68m^{-1}
β	0.647 m^{-1}
γ	0.647 m^{-1}
η	90
n	10

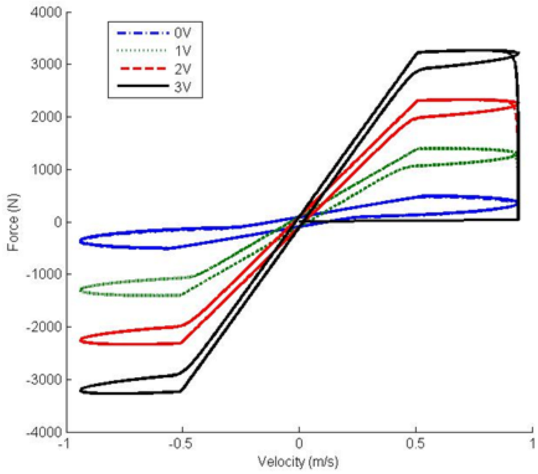


Fig. 3: Force-Displacement characteristic

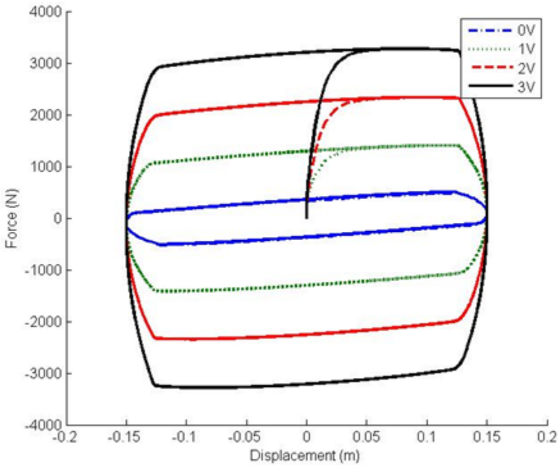


Fig. 4: Force-Veolocity characteristic

3 Controller Designand Modelling

3.1 Fuzzy Logic and PID controller design

The vehicle system is nonlinearity structure and the parameter system always changing due to vehicle rides and handling. Thus, FLC is used to reduce unwanted vehicle motion for disturbance rejection control. FLC consist of four important sections namely Fuzzification, Fuzzy Inference Engine, Fuzzy Rule Base and Defuzzification. Two input data from the system namely suspension displacement and velocity were trained by fuzzy logic system to produce the targeted voltage as an output variable. In this controller algorithm, scaling factor is considered as an important parameter for each variable input and output. GE, GV and GU are the scaling factor for displacement input, velocity input and variable voltage output respectively. The PSO strategy is used to determine the best value of the FLC scaling factors based on the mean square error (MSE) of the system. Triangular membership function is used in the controller design and seven regions for input variable namely Positive Large (PL), Positive Medium (PM), Positive Small (PS), Zero (ZE), Negative Small (NS), N egative Medium (NM) and Negative Large (NL) are used as linguistic variables. For output linguistic, five output variable is set as ZE, PS, PM and PL. A fuzzy controller rule for computing desired voltage output and membership function of input and output variables are set as shown in Table 3, Figs. 5, 6 and 7 respectively. The FIS-editor also shows in Fig. 8 using Mamdani-type inference.

Table 3.Fuzzy Rules for computing desired voltage output

		NL	NM	NS	ZE	PS	PM	PL
Displacement	NL	PL	PL	PL	PM	ZE	ZE	ZE
	NM	PL	PL	PL	PS	ZE	ZE	PS
	NS	PL	PL	PL	ZE	ZE	PS	PM
	ZE	PL	PL	PS	ZE	PS	PM	PL
	PS	PM	PM	ZE	ZE	PL	PL	PL
	PM	PS	ZE	ZE	PS	PL	PL	PL
	PL	ZE	ZE	ZE	PM	PL	PL	PL

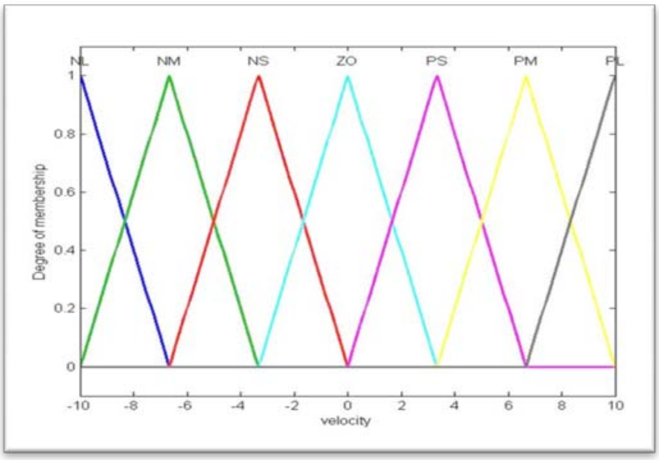


Fig. 5:Membership function for displacement input

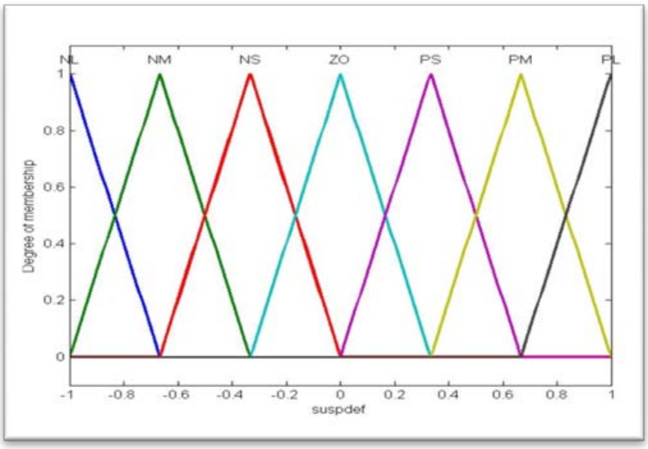


Fig. 6:Membership function for velocity input

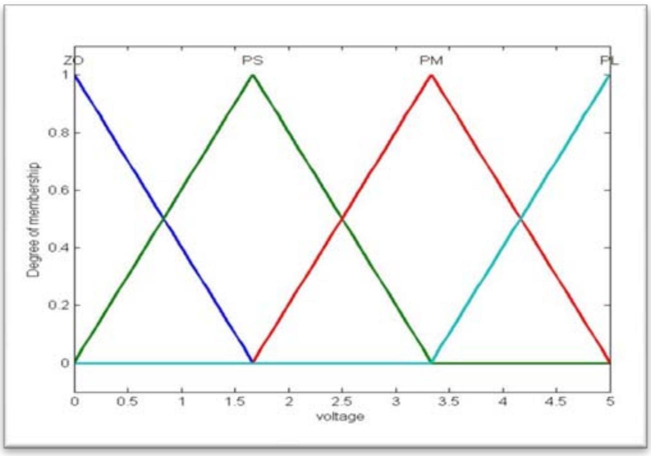
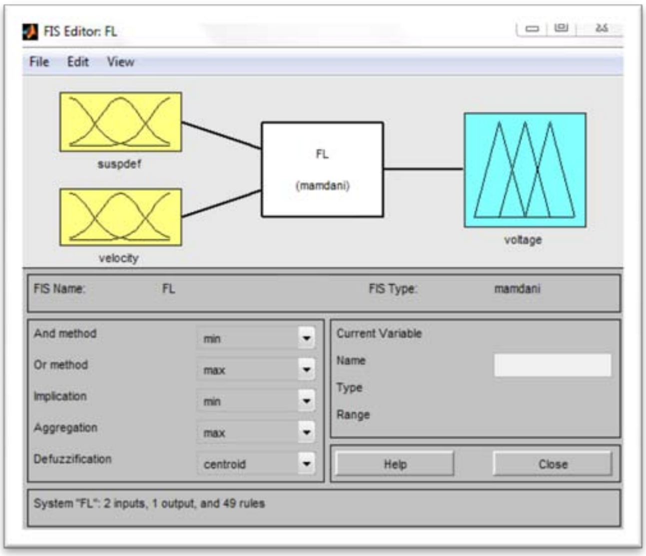


Fig.7:Membership function for desired voltage output



FIS Name: FL
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
System "FL": 2 inputs, 1 output, and 49 rules

Fig. 8.FIS-editor using Mamdani-type inference

Next, Proportional Integral and Derivative-PID controller also proposed in this study. The simplicity and acceptability of the controller always have an imperative role in control system. The PSO algorithm is used to determine the best parameter value of K_P, K_I and K_D.

3.2 Particle Swarm Optimization

Particle Swarm Optimization introduced in 1995 by Eberhart and Kennedy and inspired by the behavior of bird flocking and fish flock movement behavior. With this inspiration, swarm represents a number of potential solutions to the problem and the individual in PSO algorithm is called particle which means each individual in search space can be adjusted dynamically based on the movement of position and velocity. Position and velocity of particle represents for the candidate solution to the problem and flying direction of the particle respectively. With a given fitness function, the particle's position can be find with the best evaluation. To evaluate the best particle's position, two 'best' values namely *pbest*ang*gbest* are updated. Thus, based on these two 'best' values, the position of particle can be adjusted by changing its velocity dynamically toward the global optimum. The basic formula for velocity updated and position updated for each particle can be calculated as shown in equations 10 and 11.

$$v_i^{k+1} = w * v_i^k + c_1 * rand_1 * (pbest_i - x_i) + c2 * rand_2 * (gbest_i - x_i) \quad (10)$$

$$x_i^{k+1} = xi^k + v_i^{k+1} \quad (11)$$

where w is inertia weight parameter, c_1,c_1 is weight factors, v_i^k is velocity of particle *i* in k^{th} iteration, x_i^k is position of particle *i* in k^{th} iteration and, $rand^1$,$rand^2$ are random number between 0 and 1. The PSO algorithm parameter and the main procedure are shown in Table 4 and Fig.9 respectively.

Table 4. Parameters of PSO algorithm

No. of Iterations	5
Inertia weight, w	1
Correction factor, c1&c2	2
Swarm size	27

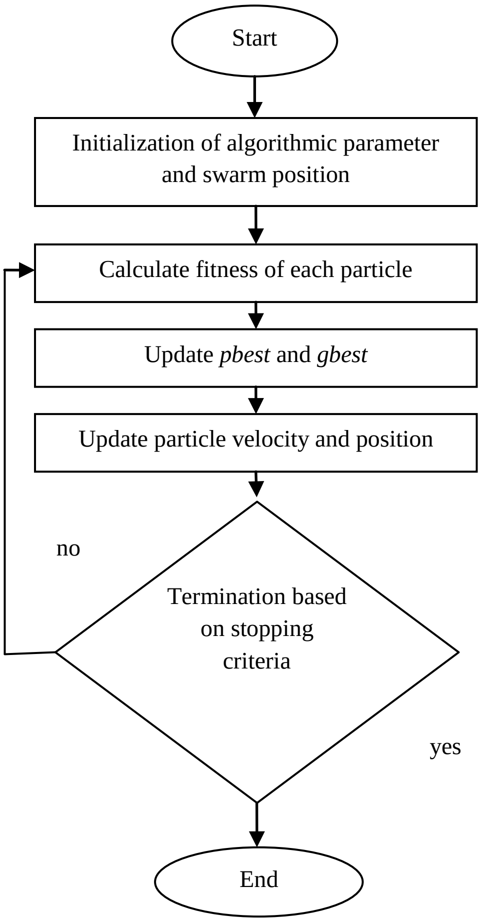


Fig.9: Steps in PSO algorithm

Block diagram of semi-active system with PID and FLC based PSO tuning algorithm are shown in Figs.10 and 11 respectively.

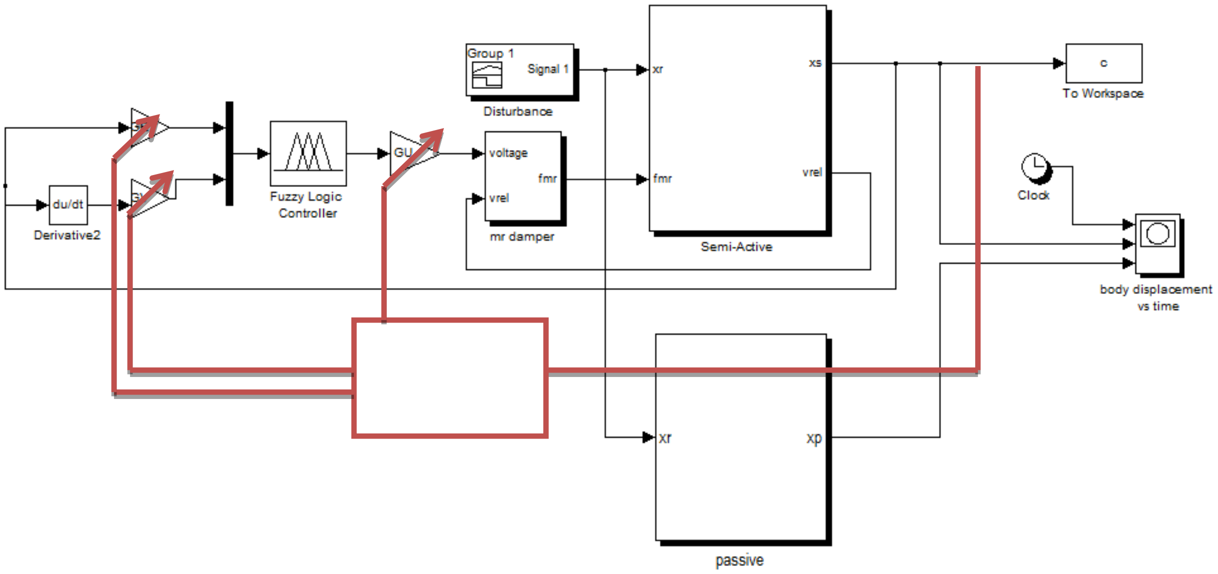


Fig.10:Block Diagram of FLC with PSO tuning algorithm

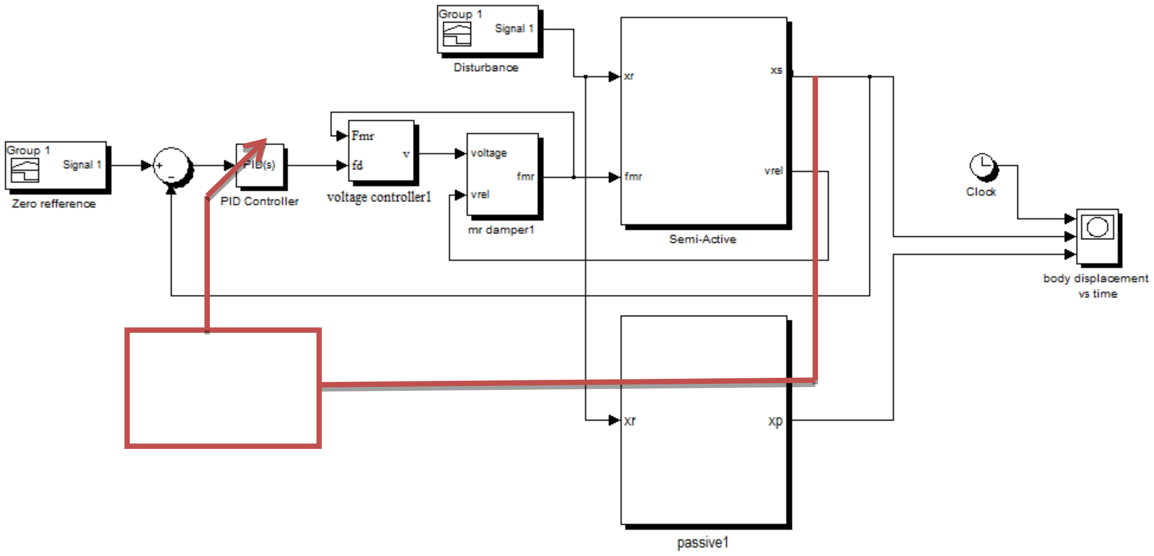


Fig.11:Block Diagram of PID Controller with PSO tuning algorithm

4 Simulation Resultsand Analysis

Two different disturbance introduced to excite the system namely bump and hole input and random input. 0.08m height and -0.08 width were set as a bump and hole amplitude respectively whereas the random input of disturbance were also set as 0.08m and -0.08m as a maximum and minimum amplitude respectively. Figs. 12and 13 shows disturbance of the system for bump and hole input and random input respectively.

Simulation study for tuning FLC scaling factor and parameter values of PID are perform using Matlab SIMULINK environment. The parameter tuning result for proposed controllers using PSO algorithm are shown in Table 5.

Table 5. Parameter results using PSO algorithm

Parameter’s name	**Values**
Fuzzy Logic Controller	
GE	0.1
GV	0.41
GU	6.21
PID controller	
K_P	520.7
K_I	2833
K_D	21230

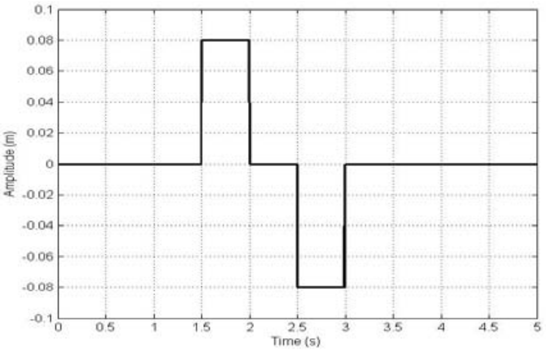


Fig. 12: Amplitude for bump and hole road profile

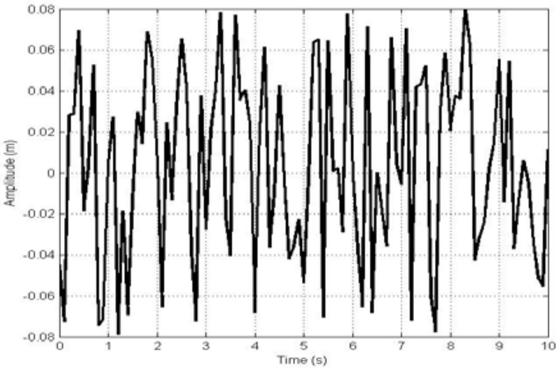


Fig. 13: Amplitude for random road profile

4.1 Bump and holeroad profile

Fig. 14 shows time responses of vertical amplitude for vehicle body. It clearly observed that FLC with PSO technique reduces the amplitude oscillation better than PID controller and passive system. Other than that, settling time of FLPSO also shows a significant improvement when the vehicle acted with the proposed disturbance. It can be mentioned that the passive condition lack of vehicle performance in term of overshot and settling time as compared with controlled systems. Similarly, the performance of FLPSO proved much better for body acceleration as compared with PIDPSO and passive system as shown in Fig. 15. The acceleration analysis is very important to determine the ride comfort and road handling of the vehicle. The passive system always shows lack of performance for vehicle stability when the oscillation of body acceleration still not reduced even the vehicle pass away after 3 seconds. Figs. 16 and 17 show the analysis of tire displacement and tire acceleration respectively. Based on these figures, it can be mentioned that FLPSO managed to reduce the amplitude oscillation when the system hitting the bump and hole at 1.5 seconds and 2.5 seconds respectively. In comparison, both figures show a better performance in term of ride comfort and road handling using FLPSO rather than PIDPSO and passive system. Without controller response, the magnetic field from MR damper cannot provide good enough energy to the system in order to maintain the body vehicle with the targeted level due to the proposed situation.

4.2 Random Road Profile

Random road profile is another disturbance acted into the system. Fig. 18 shows the analysis of body displacement of the system. It can be mentioned that FLPSO and PIDPSO managed to control the system better than passive system. However, the control system using PIDPSO do not have a good enough improvement for body acceleration analysis as shown in Fig. 19.Thus, passenger and driver's comfort in term of ride and handling might not as better as FLPSO strategy as presented.

Figs. 20 and 21 shows the output response with FLPSO and PIDPSO for tire displacement and tire acceleration respectively. It can be stated that the proposed controllers do not shows a significant improvement during tire analysis. This is because the controller's strategy managed to transfer the energy from the body vehicle to the tire through MR damper system. Overview results about Mean Square Error (MSE) and percentage improvement for the proposed controller's strategy are stated in Table 6.

Bump and hole disturbance		
	MSE	% Reduction
Passive	0.0042	
PIDPSO	0.0033	21.4
FLPSO	0.0015	64.2
Random disturbance		
Passive	0.0092	
PIDPSO	0.0056	39.1
FLPSO	0.0042	54.3

Table 6. MSE and improvement

5 Conclusions

The performance of FLC and PID controller with PSO tuning for semi active system were presented. Based on the simulation result, the ability of FLPSO to control the suspension system has been proven with 64.2 % and 54.3 % reduction bump and hole disturbance and random disturbance respectively. It can be also mentioned that the improvement of body vehicle for suspension system have a better than PIDPSO and passive system.

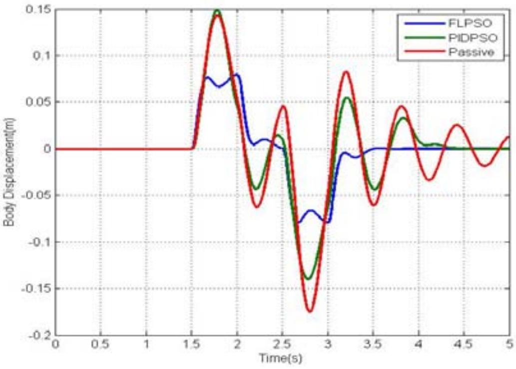


Fig. 14: Body displacement response for bump and hole disturbance

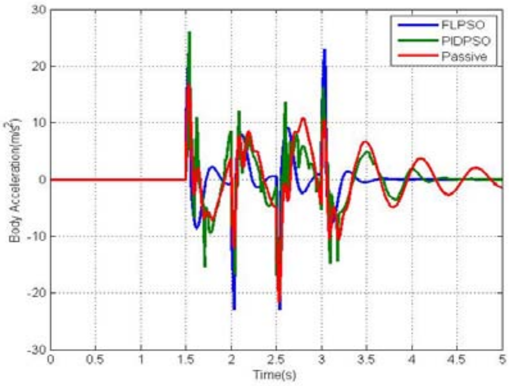


Fig. 15: Body acceleration response for bump and hole disturbance

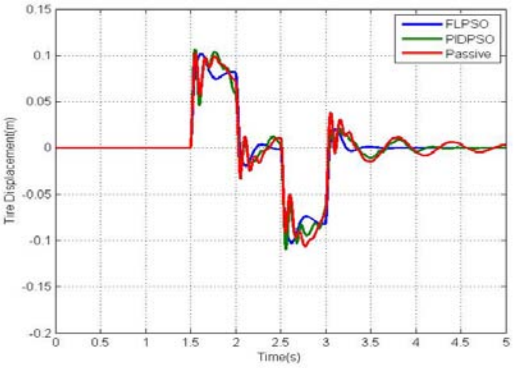


Fig. 16: Tire displacement response for bump and hole disturbance

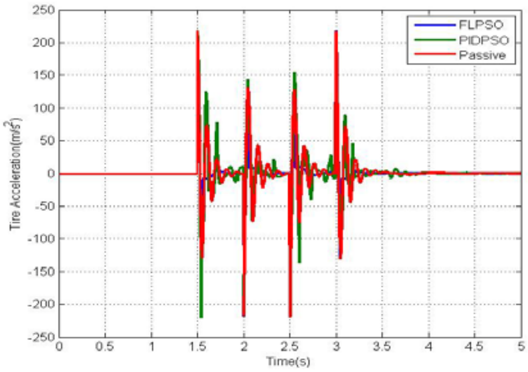


Fig. 17:Tire acceleration response for bump and hole disturbance

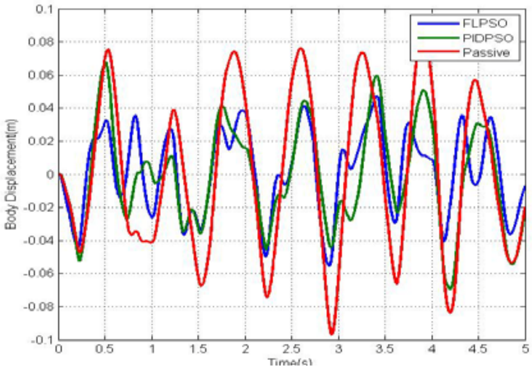


Fig. 18: Body displacement response for random disturbance

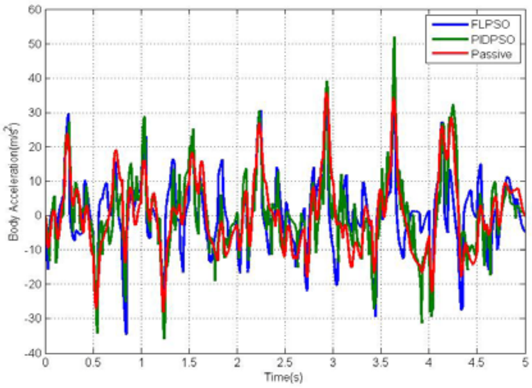


Fig. 19: Body acceleration response for random disturbance

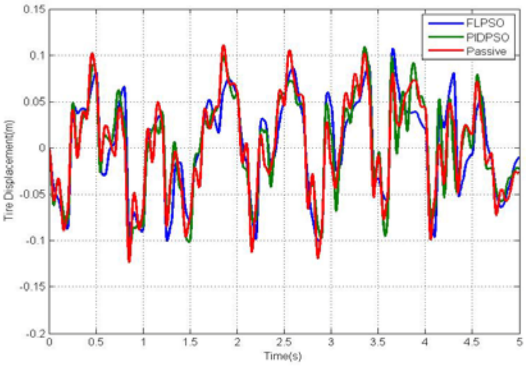


Fig. 20: Tire displacement response for random disturbance

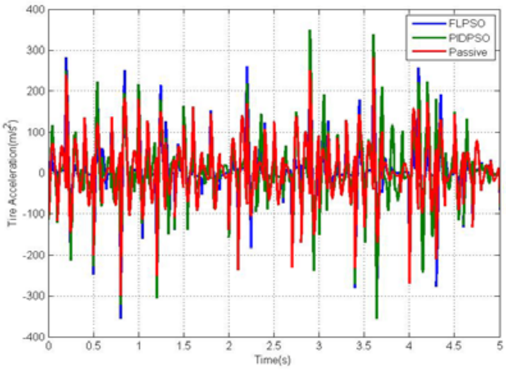


Fig. 21: Tire acceleration response for random disturbance

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