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Research paper



Effect of Fuzzy Logic Based-Skyhook Policy with Particle Swarm Optimization for Semi-Active Ride Comfort

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Abstract

This paper presents the effect of the fuzzy logic based-skyhook policy tuned using particle swarm optimization (FLSP-PSO) for semi-active ride comfort of quarter vehicle model. Spencer model was used to represent the magnetorheological damper model and its behavior was investigated in the form of force-displacement and force-velocity characteristics. The fuzzy logic control adopted with the skyhook policy based on Sugeno-type fuzzy was used to enhance the ride performance. An intelligent evolutionary algorithm known as the particle swarm optimization was also adapted in the proposed controller to compute the fuzzy gain scaling. The performance of the FLSP-PSO controller is compared to other controller responses. The effect of the PSO techniques to optimize the FLPS parameters gives a better performance and able to improve the vehicle ride comfort than its counterparts.

Keywords: *Fuzzy logic, Particle swarm optimization, Ride comfort, Semi-active suspension, Skyhook*

1. Introduction

Most modern car today relies on a number of electronic control systems. They are many types of controllers including self-contained, stand-alone controllers fulfilling a particular function while other is co-ordinate by a higher level supervisory logic. These controllers are already can be found on breaking control, suspension control and etc. The purpose of the system is to enhance the driving experience involving handling, safety and driving comfort. A vehicle's suspension system is one of the decisive factor in determining the quality of ride. Apart from the car's tires and seats, the suspension is the prime mechanism that separates the bump from the road. In most basic form, the suspension consists of two components which are spring and shock absorber. Under a normal condition, the spring support the body of the car evenly by compressing and expending with every up-and-down movement after hit the bump. However, the movement give unpleasant experience to the passenger and the effect is reduced by the shock absorber[1].

Current research on the suspension system mainly focuses on the controller strategy design and its corresponding structure. Several control strategies have been investigated previously like skyhook controller[2], fuzzy logic control [3]-[4], neural network [5]-[6] and optimal control [7]. Some of them have been also focused on the hybrid controllers in order to improve the system[8]-[9]. Among of them, the conventional skyhook as introduced by Karnop [10] is the familiar approach that could be investigated further. However, the skyhook is mainly utilized to suppress body movement. Thus, the combination of other controllers with the skyhook control is one of the solutions that could be addressed in order to improve the controller performance. Previously, Ubaidillah and his team [11] presents the combination of the fuzzy logic based on skyhook controller and its performance has proven better than the conventional skyhook. However, in their research, no fuzzy gain scaling is considered since it is one of the important parts need to be considered due to be as a sort of context information[12]. Thus, in order to optimize the gain parameters, an intelligent optimization techniques based on evolutionary algorithm is used since it is very powerful and able to compute the controller with high performance level. Recently, nature-inspired evolutionary algorithms are the interesting approach that have mostly investigated due to the powerful performance and efficiently in solving any types of complex problems. Several algorithms such as the firefly algorithm [19] and the artificial bee colony [20] are among of the approaches that have been widely presented. Similarly, the particle swarm optimization (PSO) is among them that able to give a better performance, very efficient and easy to be used. [21]

The intent of this study is to investigate the effect of the fuzzy logic based skyhook policy (FLPS) controller tuned using the evolutionary algorithm based of the PSO technique in order to improve the vehicle ride comfort of the system. The Spencer model is used to represent the MR damper system and its behavior is identified based on force, velocity and displacement behaviours. In addition, an inner loop controller is simulated by checking the accuracy of the MR damper system to track the desired input force. The semi-active control algorithms, namely skyhook, FLSP and FLSP-PSO controllers are investigated and evaluated in time domain simulation using sinusoidal road profile input.

This paper is organized as follows; the first section covers on introduction of the semi-active suspension system with the MR damper and review on the previous works on the related field. Section two explains the modelling of the semi-active suspension system and the MR damper system, the third section describes the controller approach used in this study including the explanation and strategy

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of the optimization technique. Section 4 describes the implementation of the proposed controllers to the semi-active suspension system. Analysis and discussion is presented under section five and the conclusion is presented lastly.

2. Semi-active and MR damper system

An intelligent variable damper in the semi-active system has a fail-safe structure that give an advantages to the system [13]. The semi-active equation can be described as follows:

$$m_s\ddot{x}_s + F_d - k_s(x_u - x_s) = 0 \quad (1)$$

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

where m_s and m_u are the sprung and unsprung masses, respectively. The x_r is define as a road profile, x_u and x_s are the tire and body displacements, respectively. k_s is spring stiffness, k_t is tire stiffness, and F_d is damper force. The parameter model of the semi-active system is shown in Table 1. The structure model of semi-active system and Spencer model is shown in Figs. 1 and 2, respectively.

Table 1: Parameter of the system [14]

Parameter	Value
Sprung mass, m_s	338.5 kg
Unsprung mass, m_t	59 kg
Spring stiffness, k_s	15000 N/m
Tire stiffness, k_t	190000 N/m

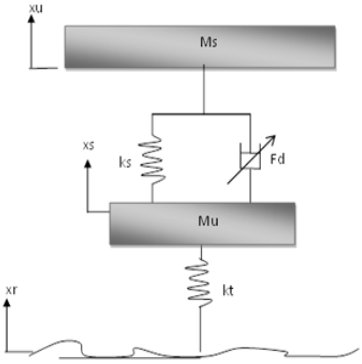


Fig. 1: Semi-active suspension model

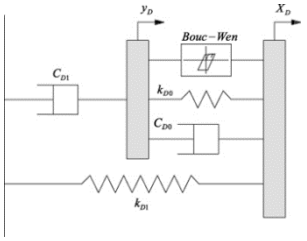


Fig. 2: MR damper with Spencer model

A ride comfort constitutes of important factors including the frequency at which a system resonances or known as the natural frequencies. The natural frequency of a body depends on the mass of the system. For example, if the system has a lower mass, the natural frequency of the system is high, or vice-versa. Thus, it is very important to determine the natural frequency mode of sprung and unsprung masses. It can be determined by using a standard control engineering technique in MATLAB simulation environment. The first natural frequency occurs at the vehicle sprung mass with 1.09 Hz and the other natural frequency occurs at the vehicle unsprung mass with 9.5 Hz It can be stated that, in the bode mode as shown in Fig. 3, two peak values occurs at the vehicle sprung natural frequency and unsprung natural frequency.

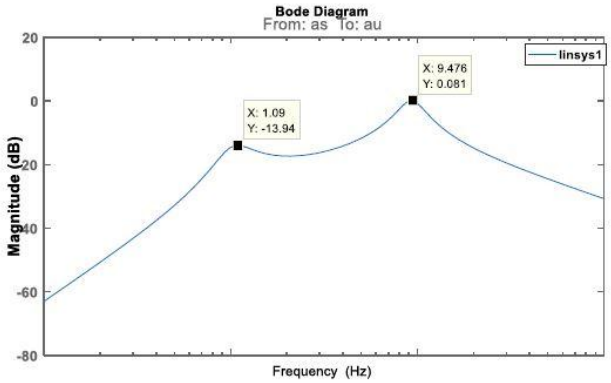


Fig. 3: Natural frequencies of the system

The force of the damper can be generated according to the following equations:

$$F_d = C_{D1}\dot{y} + k_{D1}(x_D - x_0) \quad (3)$$

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

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

where y_D is define as the displacement of internal piston and x_0 is the damper refraction. The relationship equation from (3) to (5) is also dependent on the current driver of the model as given by:

$$\alpha = \alpha_a + \alpha_b u \quad (6)$$

$$c_0 = c_a + c_{0b}u \quad (7)$$

$$c_1 = c_a + c_{1b}u \quad (8)$$

where u represents output of the first order filter given as follows:

$$\dot{u} = -\mu(u - v) \quad (9)$$

The developed model reflected to the Equations 3-9 must be validated to ensure the model give the nonlinear characteristic of the actual MR damper. The parameter of MR damper is obtained from reliable resource which are previous researches that give promising result [15]. Then, the velocity input is applied to the model to obtain the behaviour of the model. The input applied to the model is sinusoidal form at 2.5 Hz. The result obtained is compared to the actual Spencer's results. The related parameter used for Spencer model in this study are show in Table 2. The behaviour of the MR damper are also depicted in Figs 4 and 5. According to these figures, it can be observed that as the voltage is increased, the force required shows an increasing values and its behaviour is likely proving as predicted in the previous research, done by Spencer *et al.*, in 1997 [16].

Table 2: Parameters of Spencer model

Parameter	Value
α_a	462000 N/m
α_b	41200 N/V.m
c_{0a}	110000 N.s/m
c_{0b}	114300 N.s/V.m
c_{1a}	8359200 N.s/m
c_{1b}	7482900 N.s/V.m
x_0	0
k_{D0}	2 N/m
k_{D1}	9.7 N/m
A	1107.2 m^{-1}
β	164 m^{-1}
γ	164 m^{-2}

η	100
n	2

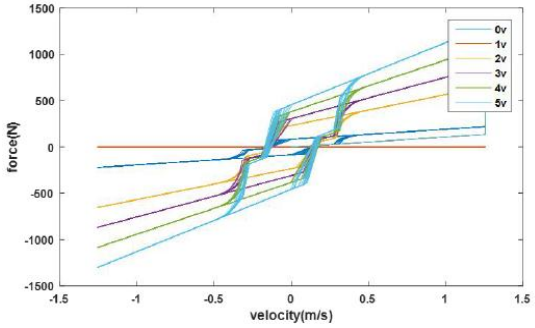


Fig. 4: MR damper behavior for force-velocity characteristic

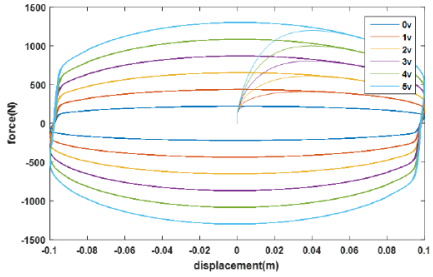


Fig. 5: MR damper behavior for force-displacement characteristic

3. Control design and optimization

3.1. Fuzzy logic based skyhook policy (FLSP)

Since the conventional skyhook controller is unable to consider the movement between sprung and unsprung masses, the use of the FL is a good approach to solve this problem. The FL is good to handle such a need due to fact that it is able to be identified by considering the deflection diasplacment between sprung and unsprung masses [17]. The FL control output may exist anywhere between the high and low states. The FL control in this study focuses on integration of the body and relative velocities as the inputs and damping coefficient as the output of the said controller. The sensitivity analysis is conducted in order to identify the best type among of them and the Trapezoidal membership function is the best choice to be used and it is shown in Fig. 6.

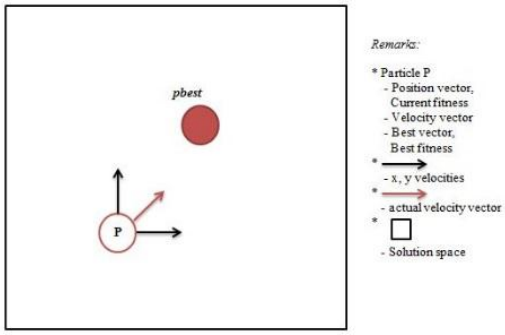


Fig. 6: The trapezoidal membership function

Based on IF-THEN rules, the generic form of the fuzzy rule is defining as:

If $\dot{\boldsymbol{z}}_{\boldsymbol{s}}$ is (A) and $\dot{\boldsymbol{z}}_{\boldsymbol{rel}}$ is (B) then $\boldsymbol{C_d}$ is (C)

where A, B and C are defining as the linguistic values for the body velocity, the relative velocity and the damping coefficient, respectively. The FL control output is shown in Table 3. The linguistic variables fuzzy output is shown as:

$$\boldsymbol{V} = (\boldsymbol{C_{min}}, \boldsymbol{C_{d1}}, \boldsymbol{C_{d2}}, \boldsymbol{C_{d3}}, \boldsymbol{C_{d4}}, \boldsymbol{C_{max}}) \quad (10)$$

where C_{min} is the minimum damping coefficient, C_{d1}, C_{d2}, C_{d3} and C_{d4}, are the damping values in between low and high damping coefficient and C_{max} is the maximum damping values. The rules of the system is also be developed. The fuzzy logic controller rule-base for this system is shown in Table 4. To generate the desired damping force, F_d, the damping coefficient, C_d, should muliply with the velocity, $\dot{\boldsymbol{z}}_{rel}$ and the equations as follow:

$$\boldsymbol{F_d} = \boldsymbol{C_d}\dot{\boldsymbol{z}}_{\boldsymbol{rel}} \quad (11)$$

Table 3: Fuzzy coefficient

C_{min}	C_{d1}	C_{d2}	C_{d3}	C_{d4}	C_{max}
700	3000	6000	9000	12000	15000

Table 4: Fuzzy rule

Sprung Velocity (SV)	Relative Velocity (RV)			
	N	Z	P	
N	C_{max}	C_{d3}	C_{min}	
Z	C_{d4}	C_{d2}	C_{d1}	
P	C_{min}	C_{d2}	C_{max}	

The scaling inputs (gain sprung velocity, GSV and gain relative velocity, GRV) and output (gain coefficient, GC) for the FL control are very critical in order to obtain the the highest performance. Thus, to compute the said gain values, the intelligent PSO technique is integrated and a detail information of the PSO is discussed in the next section.

3.2. Particle swarm optimization (PSO)

The PSO is one of the method approach that could be used due to a familiar and popular choice among of the researchers. The particle and smarm of PSO are represents as a number of potential and each of a potential solution which hold a positon and velocity. The PSO is mainly needs find the potential particle's position according to the fitness function. Elements of PSO's particle can be shown in Figure 7.

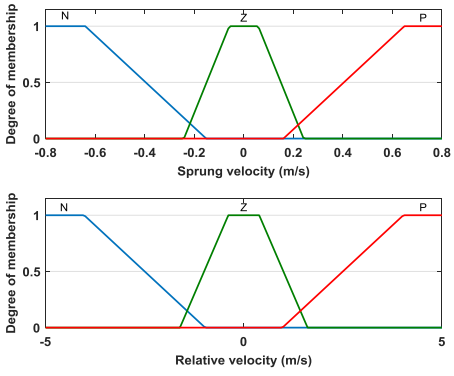


Fig. 7: The main element of PSO

The first step is by initialize the swarm, x_{id} (current particle's position), v_{id} (current particle's velocity), p_{id} (*pbest*) and p_{gd} (*gbest*), d is the particle's dimension, $1 < d < D$ and i is i^{th} particle, $1 < i < S$. D is swarm size and S is the problem specific. Based on the D-dimensional search space, all the elements are defining as:

For i^{th} particle $\rightarrow x_i = [x_{i1}, x_{i2}, \ldots, x_{iD}]$ (12)

For *pbest* $\rightarrow p_i = [p_{i1}, p_{i2}, \ldots., p_{iD}]$ (13)

For *gbest* $\rightarrow p_g = [p_{g1}, p_{g2}, \ldots., p_{gD}]$ (14)

For velocity vector $\rightarrow v_i = [v_{i1}, v_{i2}, \ldots., v_{iD}]$ (15)

After evaluation, the *pbest* and *gbest* need to be updated as:

$$p_{id}(t+1) = \begin{cases} p_{id}(t) & \text{if} \quad f(x_{id}(t+1)) \geq f(p_{id}(t)) \\ x_{id}(t+1) & \text{if} \quad f(x_{id}(t+1)) < f(p_{id}(t)) \end{cases} \quad (16)$$

$$p_{gd}(t) \in \{p_{1d}, p_{2d}, \ldots., p_{sd}\} = \min\{f(p_{id}(t)), f(p_{2d}(t)), \ldots, f(p_{sd}(t))\} \quad (17)$$

The main element of the PSO strategy should be depends on the velocity and particle's equations and it is given by:

$$v_{id}(t+1) = wv_{id}(t) + c_1 r_1(t)(p_{id}(t) - x_{id}(t)) + c_2 r_2(t)\left(p_{gd}(t) - x_{id}(t)\right) \quad (18)$$

and

$$x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \quad (19)$$

where, inertia weight is defining as w, random numbers as r_1&r_2 and acceleration constants as c_1&c_2 [18]. The steps of the PSO strategy is illustrated as in Figure 8.

4. Semi-active controller design and modelling

Since, the implementation of the proposed optimization strategies has the parameters need to be defined, the sensitivity study is used to identify the proper selection of the proposed optimizer parameters and to study the effect of varying those parameters. Sensitivity analysis study is conducted in order to identify the optimum values

inertia weight and correction factor as it is shown in Figure 9. All related result of the proposed optimizer parameters is also shown in Table 5

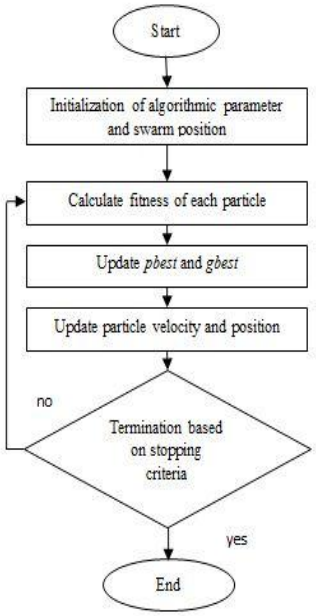


Fig. 8. The procedure

Table 5: The PSO parameters

Parameter name	Value
Iteration, *k*	100
Inertia weight, *w*	1
Correction factor, c_1 & c_2	2
Swarm size, *n*	30

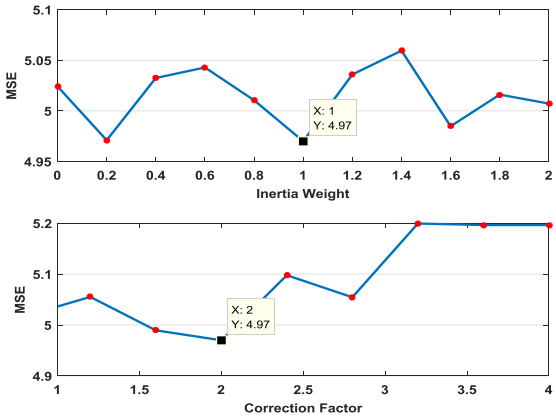


Fig. 9: Sensitivity study analysis for PSO parameters

Overview structure of control design can be depicted in Figure 10. The minimization of the mean square error (MSE) of acceleration is evaluated by the evolutionary algorithm strategies in order to satisfy the control performance specifications. The performances of the PSO in optimizing the FLSP parameter is depicted graphically in Figure 11.

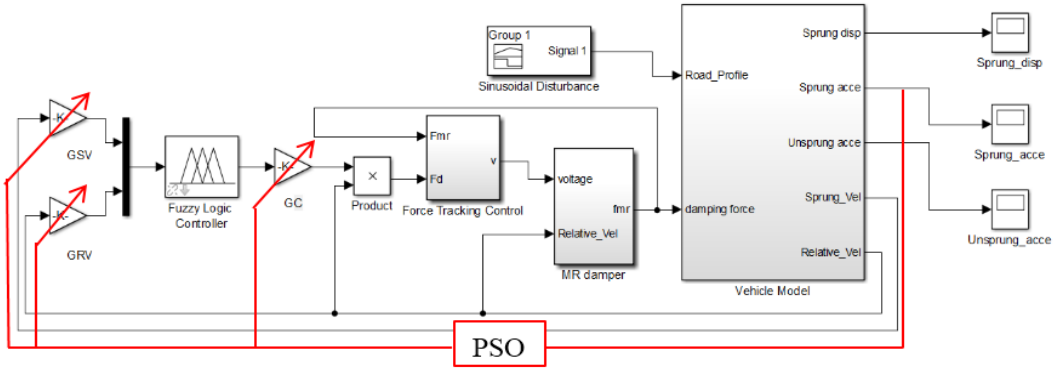


Fig. 10: Structure design of FLSP-PSO into semi-active suspension system

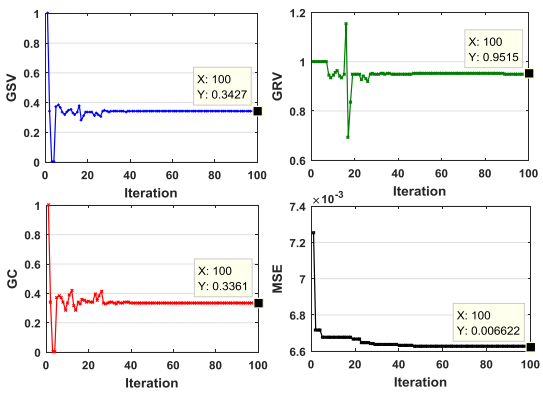


Fig. 11: Performance of FLSP gain scaling tuned using PSO algorithm under sinusoidal input

5. Result and discussion

Taking the 0.7 Hz frequency (below than body natural frequency) of sinusoidal input, all results are summarized in Table 6. Referring to that table, the semi-active with the proposed controllers have shown a good respond. It is proven that, the proposed FLSP control with gain scaling tuned using PSO strategy has improved the ride comfort of the system (reducing the amplitude of the body acceleration) with up to 43.8 % reduction. It could also be realised as in Figure 12, the pattern of the FLSP-PSO graph is more steady and stable as compared to other controller's performance. On the other hand, it can also be stated that the proposed FLSP-PSO has significantly improve the body amplitude with up to 56.7 % over the passive system. For unsprung acceleration analysis, there are no improvement can be made for all semi active control systems. Hence, the controller design has a right track since all the forces has been transferred to the sprung position in order to maintain the body amplitude. For controller's comparison, the FLSP-PSO has slightly improved the vehicle performance for both sprung acceleration and sprung displacement analyses as compared to the FLSP and skyhook controllers. Results for all semi-active controllers and passive system are depicted in Figures 12-14.

Table 6: MSE values and percentage improvement for parameter of interest

Index	*Passive	Skyhook	FLSP	FLSP-FA
Sprung acceleration (m/s2)	0.0117	0.0070 (40.2%)	0.0068 (41.8%)	0.0066 (43.6%)
Sprung displacement (m)	2.86 × 10-5	1.5 × 10-7 (48.6 %)	1.3 × 10-7 (56.3 %)	1.2 × 10-7 (56.7 %)
Unsprung acceleration (m/s2)	0.0104	0.0265 (-55 %)	0.0286 (-75 %)	0.0306 (-94 %)

*Passive as benchmark

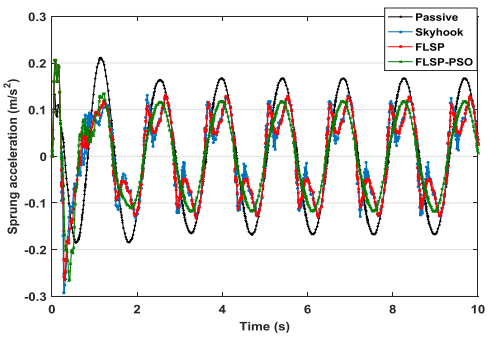


Fig. 12: Sprung acceleration time response

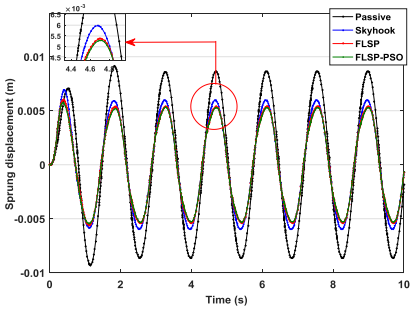


Fig. 13: Sprung displacement time response

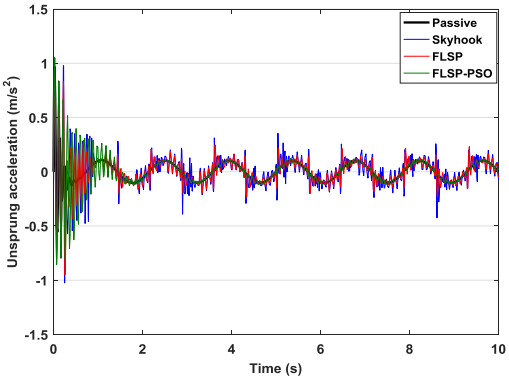


Fig. 14: Unsprung acceleration time response

6. Conclusion

The effectiveness of the proposed controller to improve the vehicle ride comfort has been presented. The system with MR damper based on Spencer model is also established. The parameter of interest known as the sprung acceleration, sprung displacement and unsprung acceleration are the main evaluation criteria that have been investigated. The proposed FLSP-PSO controller has been simulated compared with FLSP controller, skyhook controller and passive system. Results show that, the FLSP-PSO is able to reduce the body amplitude and shows a good improvement than its counterpart when the vehicle is hitting the 0.7 Hz sinusoidal road profile disturbance. The implementation of the FLSP-PSO managed to have a good vehicle ride comfort when amplitude is reduced with up to 43.6 %.

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