Quarter Car Active Suspension System Control Using PID Controller tuned by PSO

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Abstract *(The objective of this paper is to design an efficient control scheme for car suspension system. The purpose of suspension system in vehicles is to get more comfortable riding and good handling with road vibrations. A nonlinear hydraulic actuator is connected to passive suspension system in parallel with damper. The Particles Swarm Optimization is used to tune a PID controller for active suspension system. The designed controller is applied for quarter car suspension system and result is compared with passive suspension system model and input road profile. Simulation results show good performance for the designed controller*

Index Terms— Active suspension, PSO, PID controller, quarter car

I. Introduction

Suspensions systems can be classified into three types are (passive, simi active and active). Figs. 1, 2 and 3 below shows the three types of Quarter car suspension system and hydraulic actuator position in each type.[1]

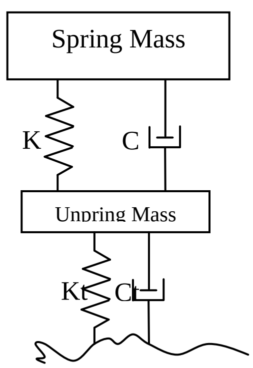

Fig. 1 Passive Quarter Car Model

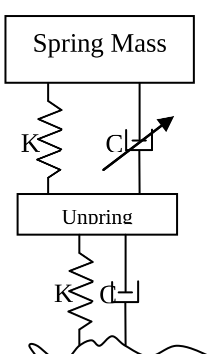

Fig. 2 Simi-Active Quarter Car Model

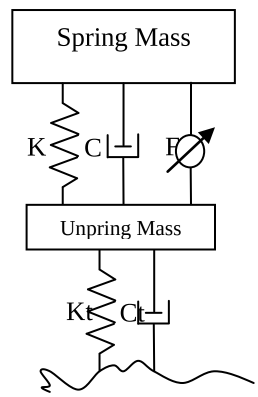

Fig. 3 Active Quarter Car Model

In passive suspension systems the main parts are springs and hydraulic dumpers. The main job of these dumpers is to decrease the road profile and vibration effects into driver and passenger's cabin. In active suspension system there are three parts under spring mass (body of car), spring, dumper and hydraulic actuator are connected in parallel. In this paper an additional parts is added to passive suspension system in parallel with springs and dumpers called a hydraulic actuator to get an active suspension system. This hydraulic actuator is a nonlinear part and it is controlled by spool valve. The mechanism of this actuator is to decrease the road profile and vibration from passive suspension system to get more comfortable riding. By using PID controller trained by Particle Swarm Optimization (PSO) to find optimal values of proportional, divertive and integral gains. MATLAB/Simulink will be use to simulate a quarter car model and auto tuning PID parameters by PSO algorithm. Quarter car active suspension system can be represented by state space form by mathematical analysis then simulate it into MATLAB. Also, optimal values of PID parameters can be get from comparison between passive response and active response in POS algorithm.

S. H. Hashemipour, M. Rezaei lasboei and M. Khaliji [1] a PID linear controller and two nonlinear controllers were designed using the sliding mode and Lyapunov way for a vehicle active suspension system. Because of the linear behavior of the PID controller, it was a failure to control this system. Though it had a relatively good tracking behavior, its control signal could not be applied and the system was highly dependent on parameters and did not prove to be robust at all. In Lyapunov method, by choosing the vertical acceleration square as the candidate Lyapunov function, the controller was designed in a way that the chosen function would be a real Lyapunov function. This controller did not control the effective factors of a vehicle's handling and stability and excessive reduction of acceleration led to increased suspension displacement close to the set boundaries. Also, Lyapunov controller did not have a good robustness against parameter variation. Ian Fialho and Gary J. Balas, Member [2] are discuss same suspension system model but they used Linear Parameters Varying gain scheduling have presented a workspace for designing road adaptive suspension controllers. Linear parameter varying techniques were used in formulation with nonlinear retreat to achieve the wanted nonlinear response of the car suspension. Also, Dr. Shibly Ahmed Al-Samarraie, Dr. Muhsin N.Hamza & Yasir Khudhair Abbas [3] used robust control to improve their quarter car active suspension system response to get more comfortable riding in passengers' cabin. Dr. Marialena Vagia [10] work with PID controller to improve comfortable riding with quarter car active suspension system. A quarter car vehicle models with two-degrees-of-freedom have been modeled. Hydraulic dynamics is also considered while simulated. Ziegler-Nichols tuning rules are used to determine proportional critical gain, reset rate and critical period time of PID controllers. The system is developed for bumpy way and random road inputs. The simulated results prove that, active suspension system with PID control improves good handling and ride comfort. At the same time, it needs only less clank space. However, there is no significant improvement in road holding ability observed especially for random road natural. Because of simplicity in design and the obtainable of well known standard hardware, the viability of PID controller as good effective tool in developing active suspension system has been proved. M. D. Donahue and J. K. Hedrick [11] improve the hydraulic actuators are managed by mechatronic servo valves and are connected in parallel to the suspension springs, enfeeble for the generation of forces between the sprung and unsprung masses. Here we can denote that this mechatronic is used with quarter, half and full active suspension systems. Goegoes Dwi Nusantoro and Gigih Priyandoko [12] presents control of hydraulic actuator to be used for an active suspension system. Proportional and integrator gains PI controller was used for force tracked control of the hydraulic actuator. The results of their study show that the hydraulic actuator can be get the actual force near to the aim force with acceptable force tracking error. A PID state feedback controller was used to reduce the effects of road profile and vibrations to the car chassis performance. From the simulation results, it can be seen that the limited state feedback controller shows momentous experiment in reducing the magnitude and settling time of the body acceleration, body vertical speed and suspension vertical displacement. In term of the wheel displacement, it is noted that even though the magnitude of the wheel vertical displacement for the active suspension system is slightly worse signal form than passive system, the settling time of tire vibrate for the active system is less than passive system.

III. MODELING OF ACTIVE SUSPENSION SYSTEM OF QUARTER CAR MODEL

The quarter car model shown below in Fig. 4, is used for active suspension system with the marked elements

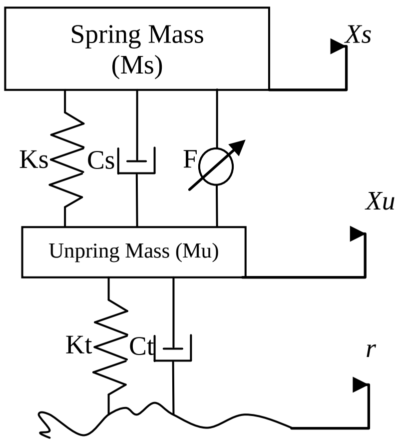

Fig. 4 Quarter Car Model

Ms: car chassis mass.
Mu: wheel mass.
Ks: Spring Stiffness.
Kt: Tire Stiffness corresponded to spring.
Cs: Dumper force.
Ct: Tire force corresponded to dumber
F: Actuator force.
Xs: Body displacement.
Xu: Wheel displacement.
r: Road profile.
From Newton's laws can be write quarter car model active suspension system as below [1], [2], [3] equations:

Spring mass part

$$Ms\ddot{X}s + Ks(Xs - Xu) + Cs(\dot{X}s - \dot{X}u) - F = 0 \quad \text{..... (1)}$$

Unspring mass part

$$Mu\ddot{X}u + Kt(Xu - r) + Ct(\dot{X}u - \dot{r}) - Ks(Xs - Xu) - Cs(\dot{X}s - \dot{X}u) + F = 0 \quad \text{..... (2)}$$

A three land four-way spool valve is based on the hydraulic actuator in this design [4], [8], [9].

$$\dot{P}l = -\beta Pl - \sigma Ap(\dot{X}s - \dot{X}u) + \gamma Xv\sqrt{(Ps - Pl\,Sgn(Xv)} \quad \text{..... (3)}$$

Where:
Ps: Supply pressure.
Xv: Spool displacement of servo valve.

$$\dot{X}v = \frac{1}{\tau}(Um - Xv) \quad \text{..... (4)}$$

Xv: Valve displacement.
Um: Control signal to Spool.

$$F = Pl\,Ap \quad \text{.....(5)}$$

Ap: Cross section area of actuator piston [4].

Now, by the following assumptions can be get state space form as below:
Let:

$X_1 = Xs - Xu$
$X_2 = \dot{X}s$
$X_3 = Xu - r$
$X_4 = \dot{X}u$
$X_5 = Pl$
$X_6 = Xv$

Yield

$$\dot{X}_1 = X_2 - X_4 \quad \text{.....(6)}$$

$$\dot{X}_2 = -\frac{Ks}{Ms}X_1 - \frac{Cs}{Ms}X_2 + \frac{Cs}{Ms}X_2 + \frac{Ap}{Ms}X_5 \quad \text{.....(7)}$$

$$\dot{X}_3 = X_4 - \dot{r} \quad \text{.....(8)}$$

$$\dot{X}_4 = -\frac{Kt}{Mu}X_3 - \frac{Ct}{Mu}X_4 + \frac{Ks}{Mu}X_1 + \frac{Cs}{Mu}X_2 - \frac{Cs}{Mu}X_4 - \frac{Ap}{Mu}X_5 \quad \text{.....(9)}$$

$$\dot{X}_5 = -\beta X_5 - \sigma ApX_2 + \sigma ApX_4 + \gamma X_6\sqrt{(Ps - X_5 Sgn(X_6)} \quad \text{.....(10)}$$

$$\dot{X}_6 = \frac{1}{\tau}(Um - X_6) \quad \text{.....(11)}$$

State space form for the system can be written as

$$\dot{X} = AX + B\dot{r} + CUm$$

Where:

$$A = \begin{bmatrix} 0 & 1 & 0 & -1 & 0 & 0 \\ -\frac{Ks}{Ms} & -\frac{Cs}{Ms} & 0 & \frac{Cs}{Ms} & \frac{Ap}{Ms} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \frac{Ks}{Mu} & -\frac{Cs}{Mu} & -\frac{Kt}{Mu} & -\frac{Cs+Ct}{Mu} & \frac{Ap}{Mu} & 0 \\ 0 & -\sigma Ap & 0 & \sigma Ap & \beta & \gamma\sqrt{Ps - X_5 Sgn(X_6)} \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\tau} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{\frac{Ct}{Mu}} \\ 0 \\ 0 \end{bmatrix} \quad \& \quad C = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{\tau} \end{bmatrix}$$

IV. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) Put forward by Dr.Eberhart and Dr. Kennedy in 1995 [13], they took over from the bird predation behavior as a simulation, by tracking two "extreme" to upgrade their position and velocity by starting with initial value of random population where each particle in the population shows a potential solution to solve the problem. Each one of the iteration has its right position and speed for every particle.

To finding the optimal solution should be chosen every individual extreme value respectively. The local positions are generated through iterations and themselves lead us to the global position. Each individual particle i has the following details. A current position in problem surrounding, x_{id}, a current velocity, p_{id}, and a best position in problem surrounding, p_{id}. The best position, p_{id}, corresponds to the position in problem surrounding where the smallest error is referred as particle i as defined by function. The lowest error among the particles value is the global best position p_{gd}.[13]

When it finds the best extreme value by the formula (12), (13) it will automatically upgrade position and speed.

$$V^{i+1} = w.V^{i} + c1.rand.\left(Pbest^{i} - X^{i}\right) + c2.rand.\left(gbest^{i} - X^{i}\right) \quad \text{.....(12)}$$

$$X^{i+1} = X^{i} + V^{i+1} \quad \text{.....(13)}$$

Steps in PSO algorithm can be listed as below:

a) start this work by assuming a random position to each particle in the swarm.
b) Calculating the fitness function (mean square error in this paper) for each particle.
c) Comparing each particle's fitness with its $p_{best,}$ we can get result of the better current value to assign it as the $p_{best.}$
d) The result of the best fitness value refers as guest and its position as p_{gd}.
e) Upgrading values of the velocities and positions of all the particles using (a) and (b).
f) Back to steps b–e until maximum number of iteration stops for a sufficiently right fitness value. [14].

V. OPTIMAL PID USING PSO

A famous controller that used in industry is the PID controller. There are a lot of nonlinear systems can be controlled by this type of controller. Therefore, PID controller preferred as practical and experimental design to control quarter car model suspension system. The vertical speed is selected as PID feedback error with a reference point.

Fig. 5 below represent an active suspension system for quarter car model with PID controller

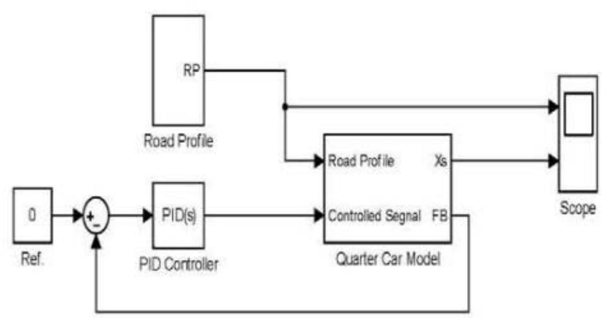

Fig. 5 Quarter car Active Suspension System with PID controller

The road profile is selected as shown below in fig. 6. This profile is proposed, may have multiple peaks but all these peak values within 0.08 m amplitude.

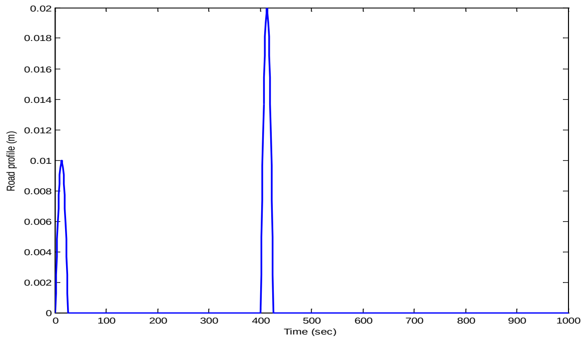

Fig. 6 Input road profile

Before applying the PID controller [2] [12] can be showing output response for passive suspension system (no actuator effect) and fig. 7 represents the passive suspension system response.

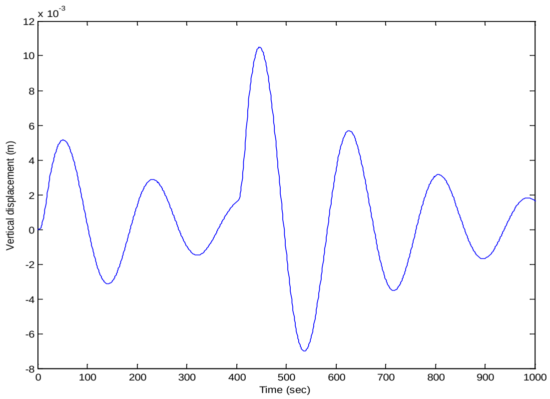

Fig. 7 Passive system Response

Now by using PSO algorithm to find values of Kp, Ki and Kd of PID controller to get an optimum output response as shown in fig. 8 below.

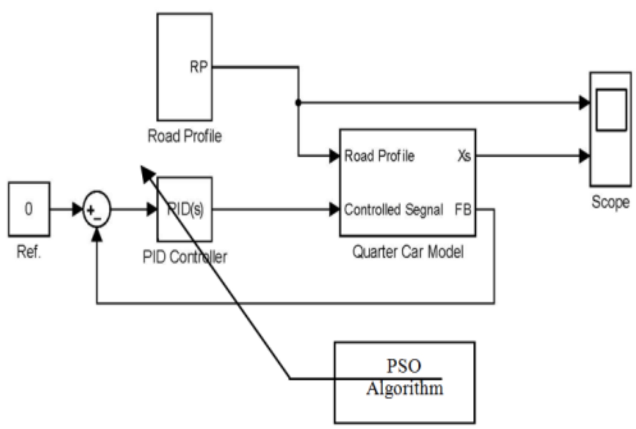

Fig. 8 Quarter Car model with PID controller and PSO Algorithm

The PSO algorithm flow chart is shown in fig. 11 [5] and it depends on assuming random position and velocity and then applied to PID in Simulink of MATLAB to get response the calculating the fitness function to see what error recorded and the fitness function based on this paper is mean square error. Parameters used in the simulation are listed in table 1 [4].

Table (1)
Quarter Car Parameters

Parameter	Value	Unit
Ks	19960	N/m
Kt	175500	N/m
Cs	1290	N. sec/m
Ct	14.6	N. sec/m
Ms	290	Kg
Mu	40	Kg
β	1	-
σ	$4.515*10^{13}$	-
γ	$1.545*10^{9}$	-
τ	1/30	sec

By using two hundred bird step and hundred birds in MATLAB, PID controller gains calculated as shown in table (2). Also, and 75% is reduction percent in output as below:

Table (2)
Optimal Values

Kp	Ki	Kd
3.0899	2.5892	0.2303

The execution time is depending on owner PC prosperities, where, this time will be shortest with high PC prosperities (processor and RAM).
Also, number of iterations, number of birds and problem variables have effect on execution time, additional to error tolerance in MATLAB.[5], [6]
Now, note the fig. 10 below and by increasing number of birds and number of iterations to (250, 300) respectively, the output vertical displacement is decreased more than case (200,100). In this point the aim of optimization is approached to the ideal case for no vibration and road ripple noise in passengers' cabin, as we note that in the fig. 10 below where the reduction in the output (passenger seats and cabin). Reduction ratio for this case reaches to 95.06% and error arrived to 10^{-7}. These results taken in 0.08 m maximum dump in the road. By using multi types of road profiles prove the robustness of this system, like uniform or random inputs as shown in the paper, and fig. 9 shows MSE curve with high numbers of iterations.

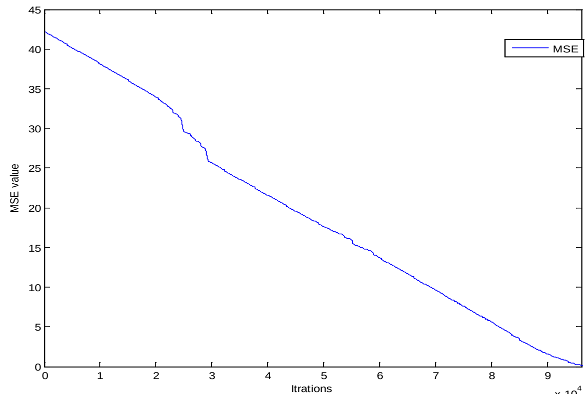

Fig. 9 MSE change during the iterations

Also, table 3 below shows PID gains results after (200,100) PSO iterations

Table (3)
Optimal Values

Kp	Ki	Kd
23.2023	1.5451	0.1091

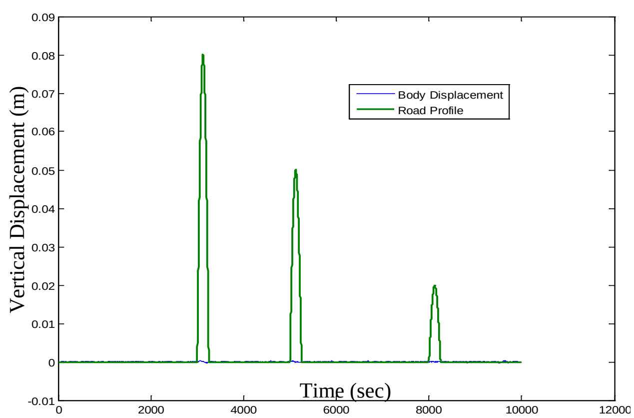

Fig. 10 Road profile and system response after high PSO iterations

Fig. 11 below is shown PSO algorithm specified to finding PID parameters (*Kp, Ki* and *Kd*) [13] [14]. Where this algorithm gets initial values for position and velocity, then it will be update these values by tracking to fitness error value.

When this algorithm finished iterations number that are defined by researcher, finally these parameters goes to workspace of matlab automatically and applied to Simulink system, so these parameters represent the optimal values and the fitness reached to global minimum error and it is passed all local minimum error points.

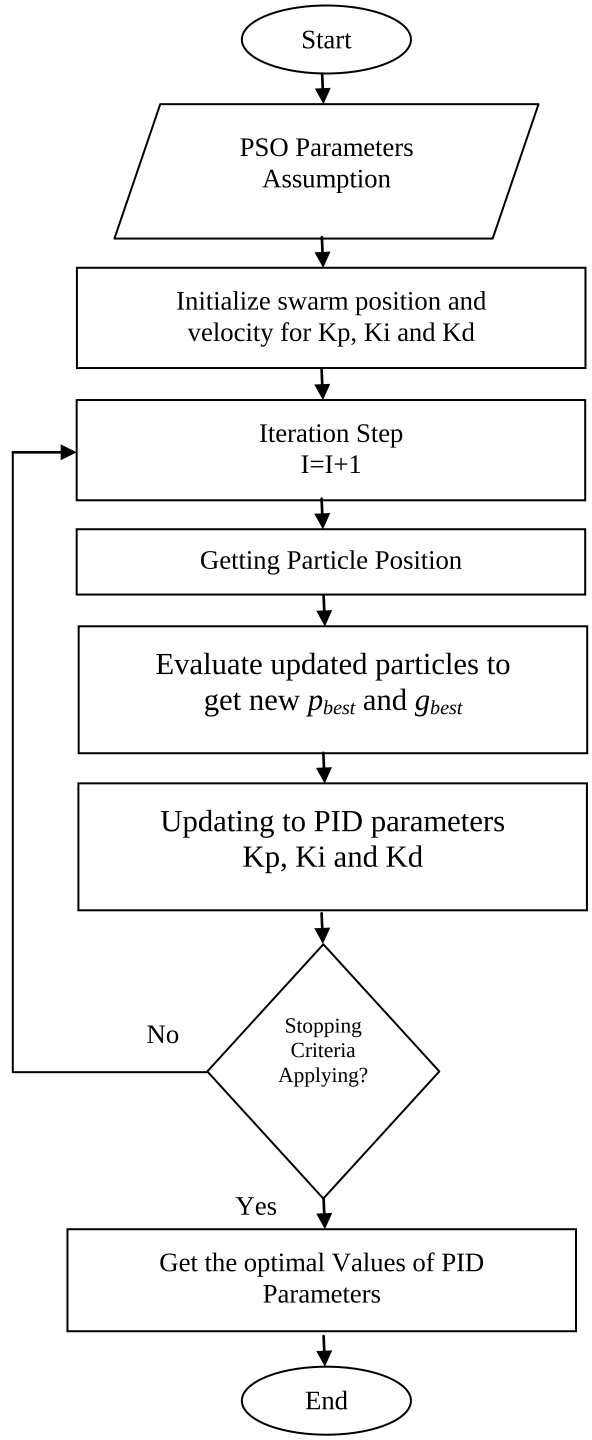

Fig. 11 PSO Flow Chart

It can be seen that the output response (vehicle body displacement) with input road profile in the fig. 12 below after applying PSO algorithm with 50 bird step and 30 numbers of birds output displacement or car's body traveling is reduced by 75.88% of input road profile. Fig. 12 represents 8 cm road bumps and body displacement. In other meaning if the number of iterations is high, the time to get global values should increase, then results should gives minimum error.

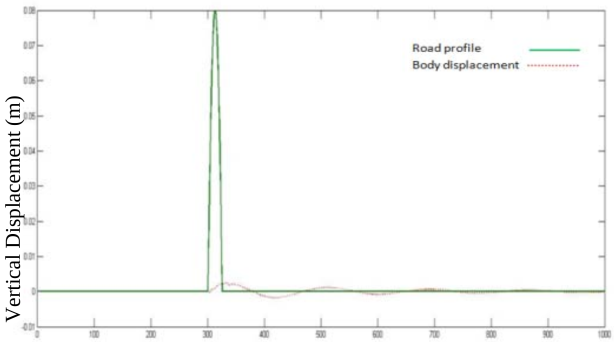

Fig. 12 Road profile and system response

Fig. 13 represent system response for another type of input road profile (random signal)

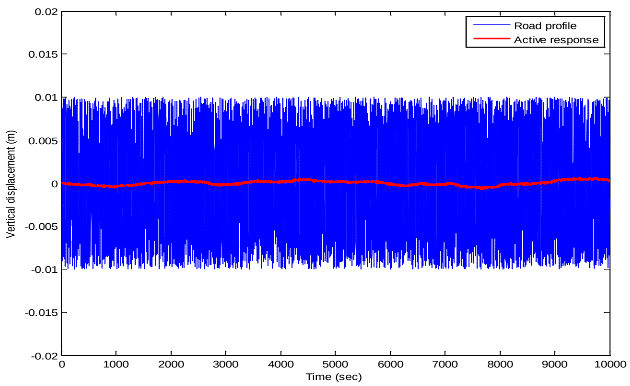

Fig. 13 system response with random road profile

Also, fig. 14 below shows sinusoidal form of road profile input

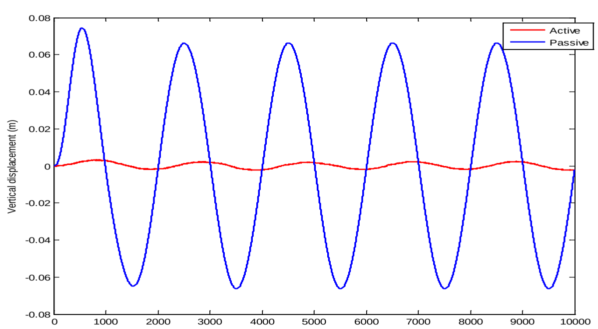

Fig. 14 system response with sinusoidal road profile

The difference between passive and active suspension system can be seen from figs. 15 and 16 for two different road profiles, where the second one have two bump road profile. By getting multi cases of road profiles (sinusoidal, random and different cases of bumpy road profile) prove the robustness for proposed control design. Where the body displacement is still within the minimum travel of vertical displacement.

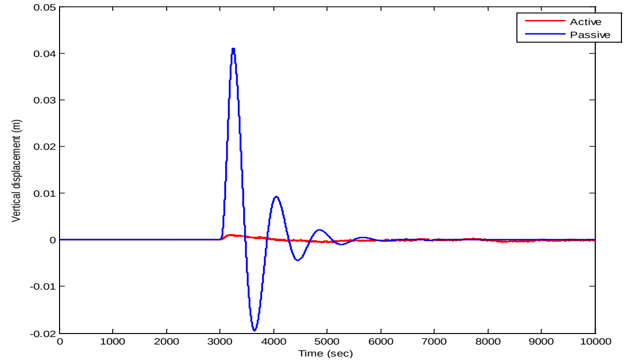

Fig. 15 Active and Passive Suspension Results

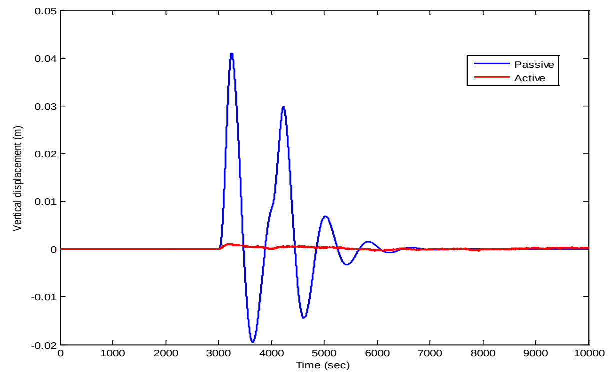

Fig. 16 Active and Passive Suspension Results with another road profile

V. Conclusion

PID controller is designed by PSO for quarter car active suspension system model to improve more comfortable ride comparison with passive model, by increasing iterations in PSO algorithm it has been noticed that the sprung mass displacement has been reduced by 75.88% which shows good improvement in ride comfort and sprung mass and 95.06% in the case of road bump 0.08 m.

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