OPTIMUM PID CONTROLLER DESIGN USING PSO FOR VEHICLE ACTIVE SUSPENSION SYSTEM CONSIDERING MATLAB SIMULINK MODELING BASED ROAD PROFILES

Srinivasa Rao GAMPA, Siva Kumar M
Department of Electrical and Electronics Engineering, Gudlavalleru Engineering College, Andhra Pradesh, India
Email: gsr_gsrinu@yahoo.co.in, Tel: +91 7702427286
D. DAS
Department of Electrical Engineering, Indian Institute of Technology, Kharagpur, India
Email: ddas@ee.iitkgp.ernet.in, Tel:: +91 3222 283042

Abstract: *The vehicle active suspension system is mainly used in the automobile industry to improve ride comfort, road handling ability under different road disturbance conditions. In the present paper particle swarm optimization (PSO) based Proportional-Integral-Derivative (P-I-D) controller is proposed considering the objective of minimizing the sprung mass acceleration when the vehicle is subjected to various road conditions. Matlab Simulink based quarter vehicle and road bump disturbance models are developed for the dynamic analysis of the vehicle suspension system. Simulation results are demonstrated to show the advantage of the proposed PSO based P-I-D controller in terms of improving the dynamic performance of the active suspension system regarding body acceleration, velocity, position and providing good tire-road contact compared to Ziegler-Nichols tuning method and passive suspension system.*

Key words: *Particle swarm optimization Quarter vehicle model, Suspension system, Suspension deflection, Road profiles*

1. Introduction

Modern trends in technology have been drastically changed the automobile industries. Suspension system plays a critical role in improving ride comfort and road-handling ability. The main function of suspension system is to minimize the vertical acceleration of the vehicle body that is transmitted to the occupants in order to achieve ride comfort and also keep the tires in contact with road during disturbance conditions of the vehicle. Vehicle suspension system can be controlled by using three basic approaches which are classified as passive, semi-active and active suspension systems. Active suspension system employs actuators to provide desired control action between the vehicle sprung body and wheel axle to minimize the impact of road disturbances on the passengers and hence they are more efficient compared to passive suspension system and semi-active suspension systems [1-14].

Researchers have proposed many techniques based on conventional and artificial intelligence based techniques for vehicle suspension system. Gordon [1] proposed dynamic optimization technique for the semi-active suspension quarter vehicle model to minimize body acceleration and suspension deflections. Hayakawa et al. [2] have proposed H_∞ output feed control for automobile suspension system based on kanes dynamics in order to reduce controller complexity. Yang et al. [3] have designed two-degree-of-freedom controller in order to minimize disturbances caused by the vehicle engine body system. Lu Sun [4] has developed an optimum design methodology based on stochastic process theory to minimize the impact of tire load by the vehicles on the road pavement. Al-Holou et al. [5] have proposed adaptive fuzzy based controller to determine the designer objective such that it provides robust and adaptive control of desired parameters of vehicle suspension system. Baumal et al. [6] proposed genetic algorithm based optimization technique for minimizing the passenengers seat acceleration for active suspension system control under road disturbance conditions. Kuo and Hseng [7] have developed fuzzy PI/PD controller based on genetic algorithm in order to provide optimal decision-making rules for different road conditions. Al-Holou et al.[8] have developed a robust intelligent nonlinear controller based on the combination of sliding mode, neural network and fuzzy logic techniques to handle complex uncertainties in active suspension system. Rattasiri and Halgamuge [9] have presented a new type of hierarchical fuzzy classifying control system in order to avoid repetitive defuzzification process in conventional fuzzy systems and to minimize the computational time for active suspension system control. Precup et al. [10] proposed combination of Takagi Sugeno and interpolative fuzzy controllers for tire slip control in anti lock braking systems.

Tung et al.[11] have proposed a new exponential stabilization methodology for active suspension system control based on particle swarm optimization (PSO) algorithm for twin-shaft vehicle model with three-degree-of-freedom with bounded uncertainties. Ghafouri et al. [12] have developed a PI controller for quarter car model of active suspension system in which the gains are tuned by using PSO to optimize body acceleration and tire deflection. Soleymani et al. [13] have proposed a multi-objective adaptive fuzzy controller and parameters are tuned for various traffic conditions via a multi-objective genetic algorithm based optimization approach. Huerel et al. [14] proposed a PSO based fuzzy PD controller considering the objective of minimizing sprung mass acceleration for active suspension system.

Precup et al. [15] proposed an adaptive gravitational search algorithm for optimal tuning of fuzzy controlled servo systems considering the objective of minimizing process gain variations and sensitivity. Rmirez et al.[16] proposed a novel optimization technique based on Bayes theory considering the objective of minimum error rate threshold for removing binary artifacts from hand written and printed documents. Ragab et al. [17] proposed a fuzzy based multiobjective algorithm for reactive power management problem considering both technical and economical aspects. Hongyi et al. [18] have designed output-feedback and state-feedback based sampled-data controllers based on lyapunov stability theory via Takagi-Sugeno fuzzy control approach. Khmelev et al.[19] proposed a hybrid metaheuristic optimization technique for optimum split delivery vehicle routing combining neighborhood decent and stochastic tabu search methods.Brezas et al. [20] developed an algorithm based on Hamilton Jacobi Bellaman for obtaining simultaneously optimizing ride and road handling behaviuor of semi active suspension system. Lin et al. [21] have proposed adaptive sliding mode technique for electro magnetic suspension system with linear switched reluctance actuator to compensate suspension system nonlinearities and external road disturbances.

In this paper particle swarm optimization based optimum Proportional-Integral-Derivative controller is proposed for minimizing vertical body acceleration and to provide better road handling ability for vehicle active suspension system considering MATLAB simulink modeling based road disturbances.

2. State Space Modeling of Active Suspension System for Quarter Vehicle Model

Suspension System can be modeled as two degree freedom system, approximating as a dual spring-mass-damper with controlled actuator to represent the quarter-vehicle active suspension system model as shown in **Fig. 1**. The system consists of a spring, damper and actuators, which provide the desired control force in the suspension system, connecting the, vehicle body to ground via the wheel tire spring.

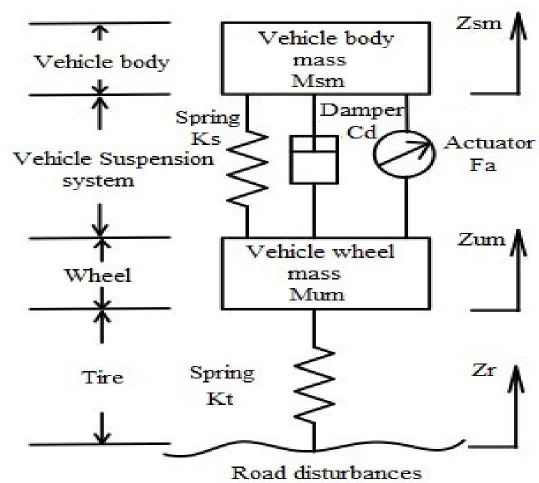

Fig.1 Quarter vehicle active suspension system

The dynamics of the sprung mass and unsprung mass of the quarter-vehicle suspension model can be derived using Newton's second law, and are given by the following equations.

$$M_{SM}\ddot{Z}_{SM}+K_S(Z_{SM}-Z_{UM})+C_a(\dot{Z}_{SM}-\dot{Z}_{UM})-F_a=0 \quad (1)$$

$$M_{UM}\ddot{Z}_{UM}+K_S(Z_{UM}-Z_{SM})+C_a(\dot{Z}_{UM}-\dot{Z}_{SM})+K_t(Z_{UM}-Z_r)+F_a=0 \quad (2)$$

Where,

M_{SM}: Sprung mass
M_{UM}: UnSprung mass
Z_{SM}: Displacement of sprung mass
Z_{UM}: Displacement of unsprung mass
K_S: Spring stiffness constant Suspension
C_d: Damping coefficient
K_t: Spring stiffness Constant of Tire

F_a: Actuator Control force
Z_r: Displacement of tire

The active suspension system parameters [14] are given in **Table-A** in the **Appendix A**.

In the present work a proportional integral derivative controller proposed for improving the vehicle dynamics.

The P-I-D control law can be written as follows

$$F_a = K_p e(t) + K_i \int e(t)dt + K_d \frac{d(e(t))}{dt} \qquad (3)$$

Where K_p, K_i and K_d are proportional, integral and derivative gain constants of the P-I-D controller. Here the sprung mass acceleration is taken as feed back and hence the error input for the P-I-D controller can be defined as follows:

$$e(t) = R_{ref} - \ddot{Z}_{SM} \qquad (4)$$

The state variables for active suspension system are chosen as follows:

$X_1 = Z_{SM}$, $X_2 = Z_{UM}$, $X_3 = \dot{Z}_{SM}$, $X_4 = \dot{Z}_{UM}$,
$X_5 = \ddot{Z}_{SM}$ and $X_6 = K_i \int e(t)dt$

The state space model can be described by the following state equation,

$$\dot{X} = PX + \Gamma R \qquad (5)$$

Where X and R are state and input vectors respectively and P and Γ are constant matrices of active suspension system with the P-I-D controller.

$$X' = [X_1, X_2, X_3, X_4, X_5, X_6]$$
(6)

$$R' = [R_{ref} \;\; R_d \;] \qquad (7)$$

In the Eq.(7) R_{ref} and R_d are reference input and road disturbance of the active suspension system. The X' and R' are transpose matrices of X and R. The matrices P and Γ are given in **Appendix-B**.

3. Modeling of Road Profiles

In order to investigate the suspension dynamics with respect to ride comfort and handling capability of the vehicle different models of the road profiles are taken into consideration. Generally the road disturbances which appear relatively for very short duration and with high impact will seriously effect passengers ride comfort and may lose holding capability of the road surface. In general many of the road disturbances are of bump roads. For dynamic response analysis of the vehicle suspension system on rough road, the road disturbances are modeled with simple sinusoidal functions. In the present analysis road disturbances with one bump and two bumps are considered for the performance analysis of the vehicle suspension system.

3.1 Road disturbance with one bump (R_{d1})

The road disturbance with one bump can be modeled by the following equation.

$$R_{d1}(t) = \begin{cases} \frac{A}{2}\left(1-\cos\left(2\pi\left(\frac{t}{T_{b1}}\right)\right)\right), & \text{for } T_{b1} \le t \le 2T_{b1} \\ 0 & \textit{Otherwise} \end{cases} \qquad (8)$$

In the Eq.(8), A is the height of the bump and T_{b1} is the duration of the bump. The magnitude of the duration of the bump is defined as the ratio of bump length (L) to the velocity of the vehicle (V). In the present work it is considered that the road bump disturbance is generated between the time T_{b1} and $2T_{b1}$ seconds and for the remaining period plain road profile is assumed.

3.2 Road disturbance with two bumps (R_{d2})

The road disturbance with two bumps of different magnitudes is modeled using the following Eq.(9).

$$R_{d2}(t) = \begin{cases} \frac{A}{2}\left(1-\cos\left(2\pi\left(\frac{t}{T_{b1}}\right)\right)\right), & \text{for } T_{b1} \le t \le 2T_{b1} \\ \frac{B}{2}\left(1-\cos\left(2\pi\left(\frac{t}{T_{b2}}\right)\right)\right), & \text{for } 8T_{b2} \le t \le 9T_{b2} \\ 0 & \textit{Otherwise} \end{cases} \qquad (9)$$

In the Eq.(9) it is considered that the height of the initial road bump disturbance is A during the first disturbance time interval between T_{b1} and $2T_{b1}$ seconds and the second bump disturbance of height B is considered during the time interval between $8T_{b2}$ and $9T_{b2}$ seconds.

4. Simulink Modeling of Active Suspension System for Quarter Vehicle Model

In order to perform dynamic performance analysis of the active suspension system subject to road disturbances in the present work Matlab simulink models are developed for quarter car model and road disturbances from the equations developed in the previous two sections for the active suspension system.

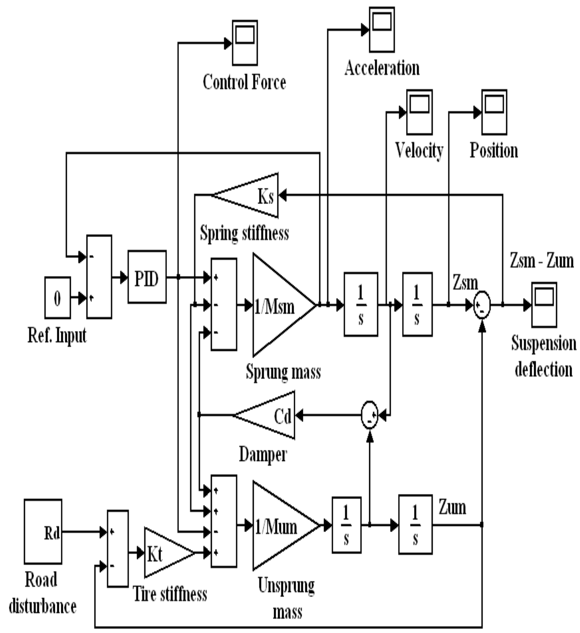

Fig. 2. Simulink model of quarter vehicle active suspension system.

In the present analysis minimization of vehicle body acceleration using PSO based PID controller is considered and it is incorporated in the simulink model. Matlab simulink models are developed for road disturbances for analyzing the performance of active suspension system. In the present work simulink models are developed for the two types of road disturbances considered one with single bump and the other with two bumps as described by Eq.(8) and Eq.(9) in the previous section.

4.1 *Simulink model of road disturbance with one bump*

Simulink model of road disturbance with single bump is developed from Eq.(8) is shown is **Fig.3**.

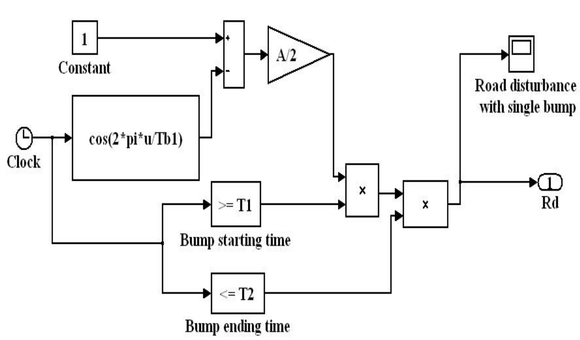

Fig. 3. Simulink model road disturbance with one bump.

In the **Fig.3** the values of T_1 and T_2 are considered equal to bump starting time T_{b1} and bump ending time $2T_{b1}$ as described in Eq.(8) respectively.

4.2 *Simulink model of road disturbance with two bumps*

Matlab Simulink model of road disturbance with two bumps is developed from Eq.(9) and is shown is **Fig.4**.

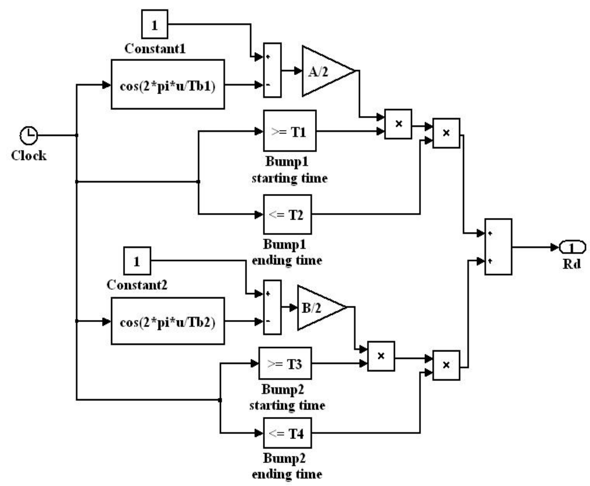

Fig. 4. Simulink model road disturbance with two bumps.

In the Fig.4 the values of T_1 and T_2 are considered equal to bump starting time T_{b1} and bump ending time $2T_{b1}$ during the first road disturbance interval as described in Eq.(9) respectively. The values of T_3 and T_4 are considered equal to $8T_{b2}$ and $9T_{b2}$ respectively during second road disturbance interval with two bumps.

5. Optimum PID Gains for Vehicle Active Suspension System Using PSO

Particle Swarm Optimization (PSO) is a population-based search algorithm proposed by Kennedy and Eberhant and is motivated by simulation of social behavior of bird flocking, fish schooling and swarming theory [22]. In PSO each particle is associated with two set of factors the velocity and position. The velocity factor is updated based on particles own experience and social experience within the swarm and position of the particle is updated using velocity of the particle. The particles move in the multi-dimensional search space collectively based on the objective to be optimized to find the global best in total swarm in the given search space.

The velocity and position of the particles are updated using the following equations.

$$V_i^{k+1} = W_i^k V_i^k + c_1 r_1 (Pbest_i^k - S_i^k) + c_2 r_2 (Gbest_i^k - S_i^k) \quad (10)$$

$$S_i^{k+1} = V_i^k + S_i^k \quad (11)$$

The values of C_1 and C_2 are in the Eq.(10) are acceleration constants set to a constant value of 2. The values of r_1 and r_2 are randomly generated numbers inbetween 0 and 1. The velocity and position of i^th^ particle of (k+1)^th^ iteration V_i^{k+1} and S_i^{k+1} are updated using Eq.(10) and Eq.(11). The inertia weight (*W*) linearly decreases from 0.9 to 0.4 as the algorithm proceeds from one iteration to another iteration. The velocity is limited to predetermined minimum and maximum values. The $Pbest_i^k$, $Gbest_i^k$ are population best and global best of i^th^ particle and k^th^ iteration of PSO algorithm[22].

Comparing with other evolutionary based algorithms particle swarm optimization algorithm is more popular because of it is simple in implementation and ablility to converge to a good solution with minimum number of iterations. In the present work the optimum gains of Proportional-Integral-Derivative (P-I-D) controller are obtained using PSO considering the objective of minimization of vehicle sprung body accelarion which is described by Eq.(12).

$$J = \int_0^t (\ddot{Z}_s(\mathrm{t}))^2 \, dt \qquad (12)$$

The PSO algorithm proceeds in the direction of maximization of fitness function and hence the fitness function J_F is considered described by the following Eq.(13) for obtaining the optimum solution.

$$J_F = \frac{K_1}{1 + K_2 J} \qquad (13)$$

The constants K_1 and K_2 are scaling factors and here both the values are set to a constant value of 100.

The flow diagram for obtaining optimum P-I-D gains using PSO for active suspension system is shown in the following **Fig.5**.

The step by step algorithm for PSO based optimization for vehicle suspension system is given below.

Step-1: Firstly the particles of the swarm are initialized by the randomly generated population for the P-I-D controller gains and set the velocity positions to a constant value.

Step-2: Set the iteration count to one.

Step-3: Calculate the fitness function values for each particle using Eq.(13).

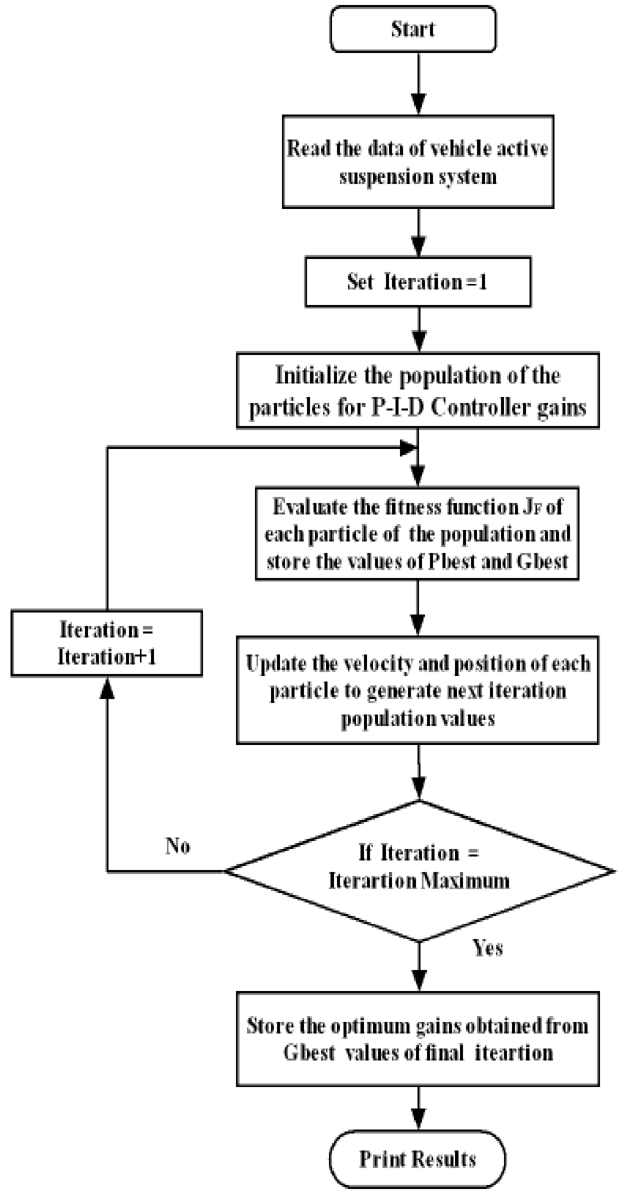

Fig. 5. Flow chart for obtaining optimum PID gains using PSO for active suspension system

Step-4: If the fitness value of the particle from current population is better than the corresponding previous population set the current value as Pbest.

Step-5: Set the best fitness value from the all previous iterations as Gbest.

Step-6: Determine velocity and position of each particle using Eq.(10) and Eq.(11) for next iteration.

Step-7: Increment the iteration count by one and if the iteration count is less than the maximum value Go To **Step-3**.

6. Results and Discussions

In the present work for improving the dynamic performance of the vehicle active suspension system PSO based P-I-D controller is proposed. The optimum gains are obtained considering the objective of minimizing vehicle body acceleration is considered. Matlab Simulink models are developed for road disturbances to facilitate the analysis using Simulink modeling. In the present analysis two types of road bumps disturbances are considered one with single bump and another with two bumps of different magnitude of height and time duration.

In the first case the road disturbance with single bump of height (A) 0.05m is considered. It is assumed that the length of the bump (L) is 5m and the vehicle is moving with a velocity (V) of magnitude 36km/h. The bump duration T_{b1} is calculated as (L/V) and is equals to 0.5 seconds, and it is considered that vehicle is crossing the bump inbetween the time interval 0.5 to 1.0 seconds. The road bump disturbance with single bump is shown in the following **Fig.6**.

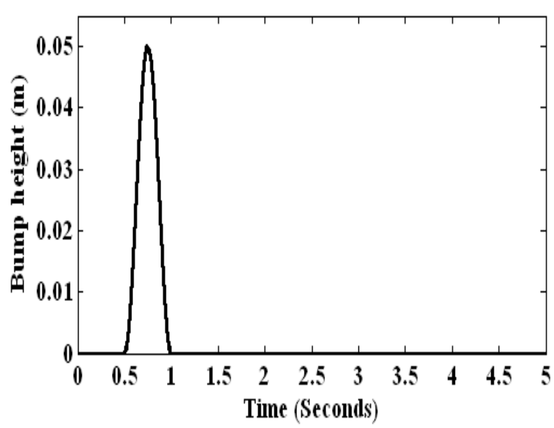

Fig. 6. Road disturbance with single bump.

The road disturbance with two bumps is shown in the following **Fig.7**.

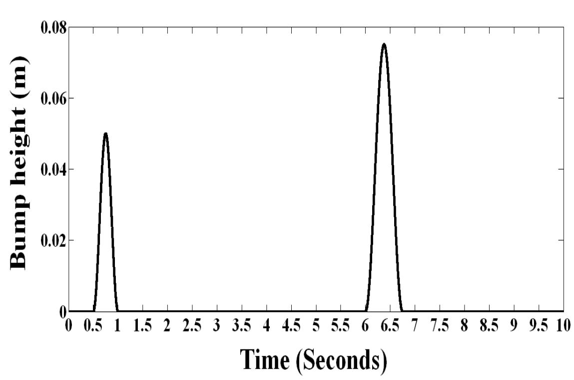

Fig. 7. Road disturbance with two bumps.

In the second case the road disturbance with two bumps of height (A) 0.05m and height (B) 0.075m is considered. It is assumed that the length of the first bump is 5m and second bump is 6m, and the vehicle is moving with a velocity (V) of magnitude 36km/h. The duration of first bump T_{b1} calculated as the ratio of bump length to velocity is to 0.5 seconds in the case of second bump is 0.75 seconds. The vehicle is crossing the first bump inbetween the time interval 0.5 to 1.0 seconds and inbetween the time interval 6.0 to 6.75 seconds.

The optimum gains of the P-I-D controller are obtained using PSO considering the objective of minimizing vehicle sprung body acceleration for single bump disturbance conditions and the P-I-D gains are Kp = 4912.38, Ki = 2935.90 and Kd = 22.61.

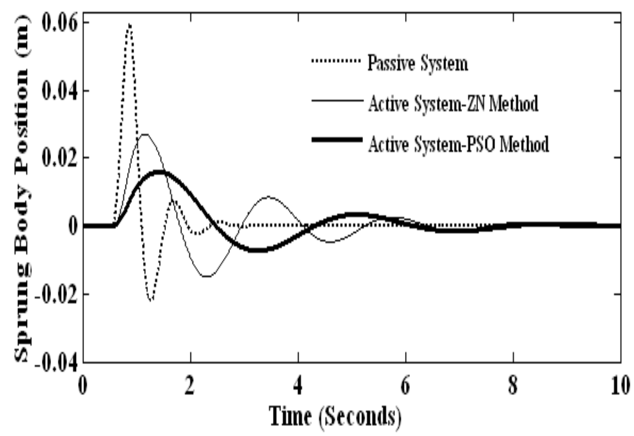

Fig.8 Sprung body position with single bump disturbance.

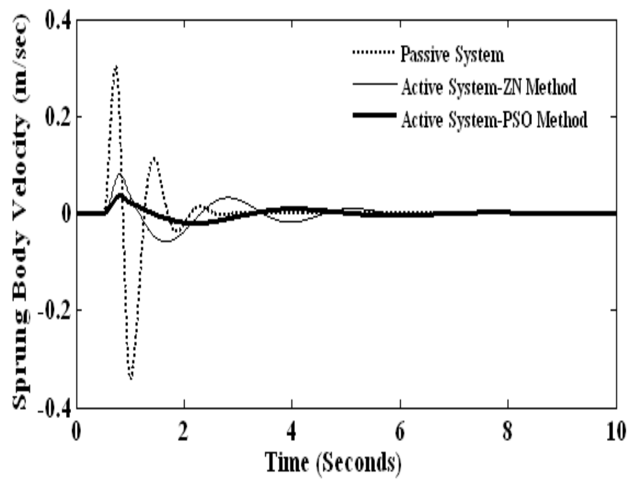

Fig.9. Sprung body velocity with single bump disturbance.

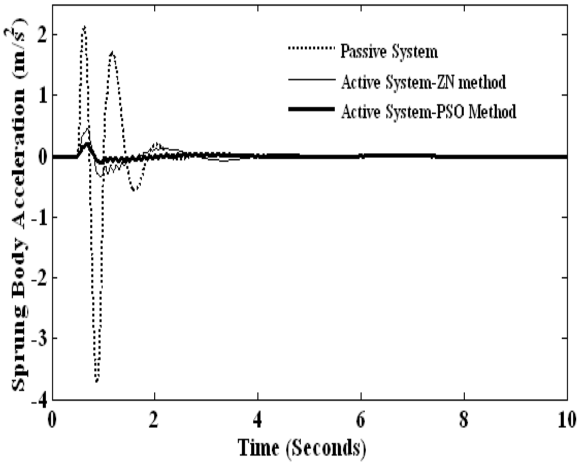

Fig.10. Sprung body acceleration with single bump disturbance.

The performance of the active suspension system with PSO based P-I-D controller is compared with conventional Ziegler-Nichols (ZN) tuning method. The dynamic performance improvement of proposed PSO based P-I-D controller is shown in **Fig.8**, **Fig.9** and **Fig.10** in the case of road disturbance with single bump.

From **Fig.8**, **Fig.9** and **Fig.10** it can be observed that the position, velocity and acceleration of vehicle sprung body subjected to single bump disturbance in the case of active suspension system with PSO based proposed P-I-D controller is much improved compared to passive suspension system and active suspension system with conventional Ziegler-Nichols method.

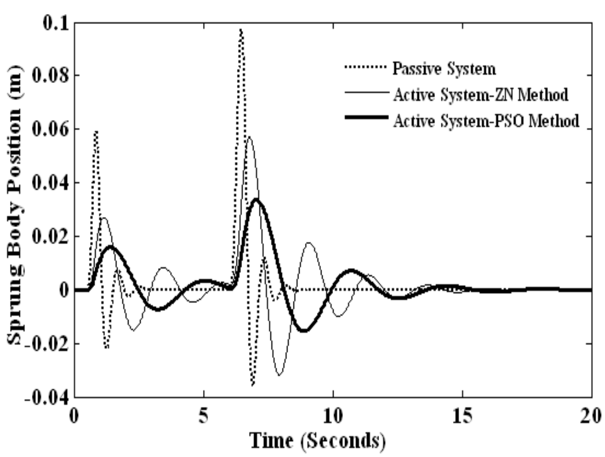

Fig.11. Sprung body position with two bump disturbances.

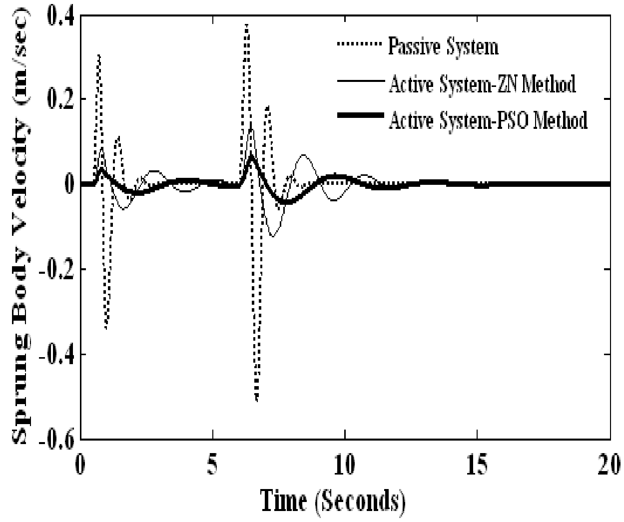

Fig.12. Sprung body velocity with two bump disturbances.

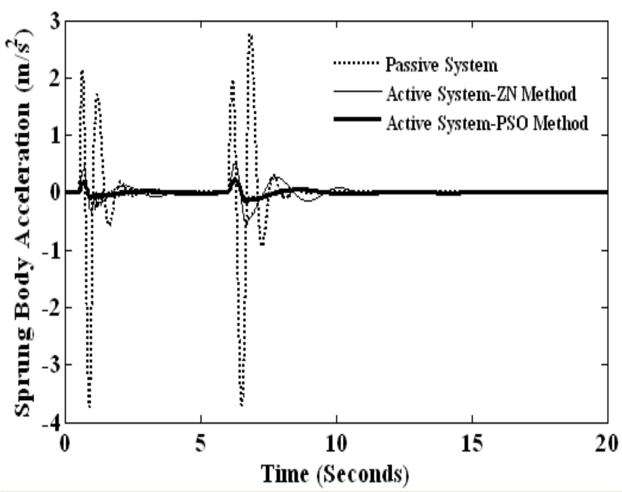

Fig.13. Sprung body acceleration with two bump disturbances.

The P-I-D controller gains obtained with proposed PSO based methodology for single bump disturbance are used for analyzing the performance of the active suspension system in the case of road disturbance with two bumps to test the sensitivity of the P-I-D controller gains. From **Fig.11**, **Fig.12** and **Fig.13** it can be observed that the dynamic performance of the active suspension system is much better in the case of sprung mass position, velocity and acceleration compared to Ziegler Nichols based active suspension system method and passive suspension system without controller.

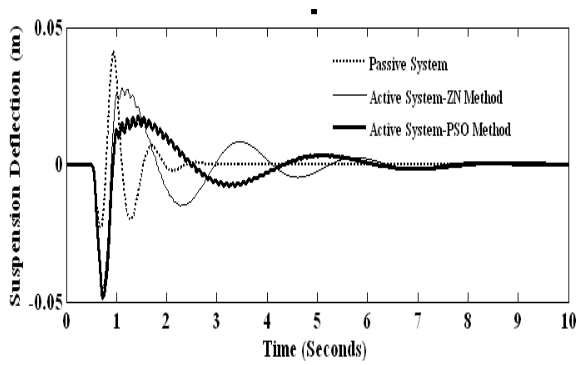

Fig.14. Suspension deflection with one bump disturbance.

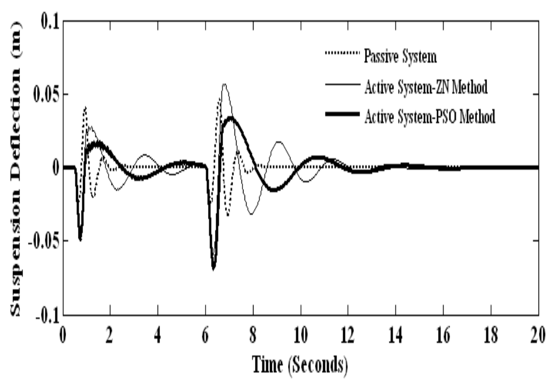

Fig.15. Suspension deflection with two bump disturbances.

From **Fig.14** and **Fig.15** it can be observed that during the bump disturbance intervals the negative deflection is more in the case of active suspension system with proposed controller The higher negative deflection indicates better road holding capacity and good tyre-road contact during the disturbance conditions.

7. Conclusions

In this paper PSO based optimum P-I-D controller is proposed for active suspension system for quarter vehicle model in order to achieve the objective of suspension system of better ride comfort and road handling ability during road disturbance conditions. In the present analysis two types of road disturbances, one with single bump and the other with two bumps are considered and Matlab Simulink models of single bump and two bump road disturbances are developed along with quarter vehicle model for facilitating the dynamic response analysis in Matlab Simulink environment. The optimum P-I-D gains are obtained using PSO and Matlab simulink models developed considering the objective of minimizing sprung mass acceleration. From the simulation results it can be observed that the performance of proposed PSO based P-I-D controller is much better in comparison with the passive system and active system based ZN-method in terms of position, velocity and acceleration and for providing good road-tyre contact during the bump road disturbance conditions.

Appendix-A

Table A: Parameters of Quarter Vehicle Model [14]

Sprung mass	Msm = 250Kg
Unsprung mass	Mum = 50Kg
Suspension damping	Cd=1500Ns/m
Suspension stiffness	Ks = 16000N/m
Tire stiffness	Kt = 160000N/m

Appendix-B

The constant matrices P and Γ corresponding to active suspension system state space model are given below.

$$P=\begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & \frac{-K_2}{M_{UM}} & 0 & 0 & \frac{-M_{SM}}{M_{UM}} & 0 \\ \frac{-K_1}{K_d} & \frac{K_1}{K_d} & \frac{-C_d}{K_d} & \frac{C_d}{K_d} & \frac{-K_p-M_{SM}}{K_d} & 1 \\ 0 & 0 & 0 & 0 & -K_i & 0 \end{bmatrix}$$

$$\Gamma = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{K_2}{M_{UM}} \\ \frac{K_p}{K_d} & 0 \\ K_i & 0 \end{bmatrix}$$

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