Passenger Seat Vibration Control in Active Quarter Car Model Using Bat Algorithm Based PID Controller

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Abstract: Present paper is related to improving the passenger ride comfort and safety in an active quarter car model. For this purpose, a quarter car model with passenger seat is considered to capture the dynamic behaviour of a real car system. To achieve the desired target, PID controller is applied in main suspenson of active quarter car model. The parameters of PID controller in first case are manually selected while in second case, optimized parameters of PID controller are used based on bat algorithm technique. The simulation results of active quarter car model are compared with passive one taking random road excitation. The parameters for comparison purpose are passenger seat acceleration and displacement response. Simulation results show the succesful application and desired performance provided by PID controller tuned by bat algorithm compared to manually tuned PID controller and passive one.

Keywords— Active quarter car model, PID controller, Bat algorithm, Passenger ride comfort.

I. INTRODUCTION

Vehicle vibration control performance is dependent on the type of integrated suspension system. Passive suspension provide limited performance considering ride comfort and road holding ability of vehicles due to fixed spring stiffness and damper damping coefficient [1-2]. Therefore, the area of suspension system design and development using semi-active and active suspension system technology is main concern for automotive manufacturers to enhance the vehicle performance in terms of ride comfort and road holding ability. Active suspension systems are most successful in improving the vehicle performance over a wide range of frequency. Active suspension systems are integrated with actuators and sensors for achieving desired characteristics of vehicle movement related to displacement and acceleration response. An active suspension system is supplied with external variable actuating force to control the intensity of road induced vibrations in vehicle body. These suspension systems can achieve high performance in the resonance frequency region of the vehicle. These favourable characteristics in active suspension system are main reasons for their choice and developments in automotive industry [3-4].

The performance of an active suspension is dependent on the selected and integrated controller in it. In last few decades, various studies have been conducted using designed control systems in active quarter car model. The various controllers include linear parameter-varying control [5], a neural network based sliding mode control [6], self-tuning fuzzy logic control[7], linear quadratic optimal control theory using conventional method (CM) and acceleration dependent method (ADM) [8], finite-frequency method [9], a neural network based PID controller [10], Neural Network (NN) control [11], a combination of fuzzy and PID controller with coupled rules (HFPIDCR) [12], etc.

Present study is related to improvement in ride comfort of passengers in active quarter car model. Thus, PID controller is designed for application in main/ primary suspension of active quarter car model. The proposed quarter car model is having three degrees of freedom. The PID controller is tuned with bat algorithm. The simulation work under random road profile is done. Finally, simulation results are compared.

II. ACTIVE QUARTER CAR MODEL

The proposed active quarter car model is the simplest model for study purpose. Fig. 1 shows the model having three degrees of freedom. Here, m_1, m_2, and m_3 are mass parameters; c_1, c_2, k_1, and k_2 are damping and spring stiffness parameters; k_t represents tyre stiffness. F_a represents the supplied control force in main suspension; z_1, z_2, and z_3 are displacements of the respective masses while z_r is the road input.

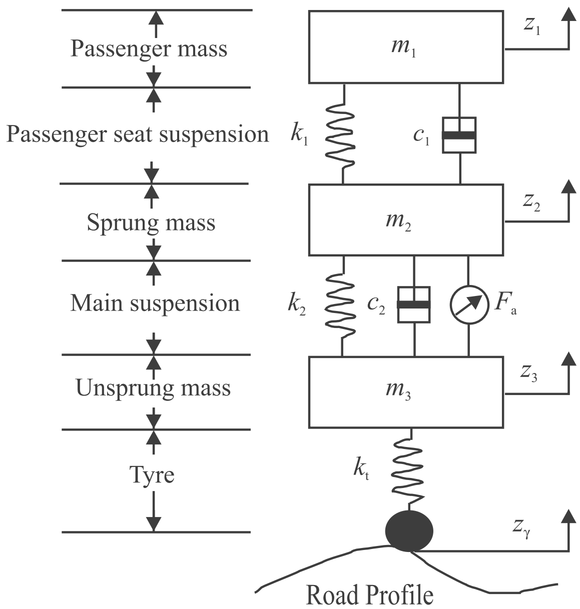

Fig. 1. Active quarter car suspension system

The mathematical equations for this model are as follows:

$$m_1\ddot{z}_1 + c_1(\dot{z}_1 - \dot{z}_2) + k_1(z_1 - z_2) = 0 \quad (1)$$

$$m_2\ddot{z}_2 - c_1(\dot{z}_1 - \dot{z}_2) - k_1(z_1 - z_2) + c_2(\dot{z}_2 - \dot{z}_3) + k_2(z_2 - z_3) + F_a = 0 \quad (2)$$

$$m_3\ddot{z}_3 - c_2(\dot{z}_2 - \dot{z}_3) - k_2(z_2 - z_3) + k_t(z_3 - z_\gamma) - F_a = 0 \quad (3)$$

III. OBJECTIVE FUNCTION

To optimize the parameters of PID controller, an objective function is formulated. The parameters of PID controller are optimizes taking minimization of sum of integral of absolute error (IAE), integral of time multiple of absolute error (ITAE), integral of squared of absolute error (ISE) and integral of time multiple of squared error (ITSE). The main purpose is to achieve reduced level of passenger seat acceleration and displacement response. Bat algorithm is used to minimize the value of objective function given by:

Objective function

$$= \min(\mathrm{IAE} + \mathrm{ITAE} + \mathrm{ISE} + \mathrm{ITSE}) \quad (4)$$

where,

$$\mathrm{IAE} = \int_0^{tsim} |e(t)|\, dt \quad (5)$$

$$\mathrm{ITAE} = \int_0^{tsim} t|e(t)|\, dt \quad (6)$$

$$\mathrm{ISE} = \int_0^{tsim} e(t)^2\, dt \quad (7)$$

$$\mathrm{ITSE} = \int_0^{tsim} t\,(e(t))^2\, dt \quad (8)$$

Here, tsim represents total simulation time. In present study the simulation time is taken as 4 seconds.

IV. PID CONTROLLER

A PID controller is the combination of three parameters namely proportional, integral and derivative parts. It is also known as three-term controller and works based on the input reference signal. It is one the simplest and highly successful controller useful in industrial applications. Due to its design simplicity and effectiveness in controlling, it can be used in control system work and vibration control of suspension system as shown in Fig. 2.

The error signal and the output signal supplied by the considered PID controller is generally denoted by:

$$\mathrm{e}(t) = y_{ref} - y \quad (9)$$

$$\mathrm{U}_{PID}(t) = K_p e(t) + Ki \sum_{i=0}^{t} e(t) + K_d\, \dot{e}(t) \quad (10)$$

where, y_{ref} is the reference position and y is the current position of the sprung mass while K_p, K_i, and K_d are respective gains of PID controller.

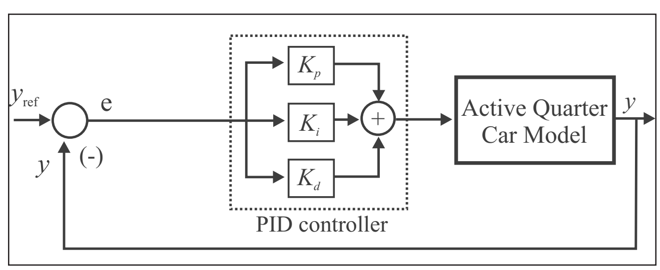

Fig. 2. PID controller in active quarter car model

V. BAT ALGORITHM

Bat algorithm was developed by Yang recently and was added in the category of meta-heuristic optimization technique [13]. Bats search for food/prey using echolocation technique. The mechanism of echolocation is helpful in knowing the location and distance of food/ prey for the bats. Bats fly randomly in space with some velocity v_i at certain location x_i having certain minimum frequency value f_{min} as well as with loudness value L_i and pulse emission rate γ_i . The parameters selected for bat algorithm in present work are given in Table 1. The optimization process of PID parameters i.e., and is carried out as per the arrangement presented in Fig. 3.

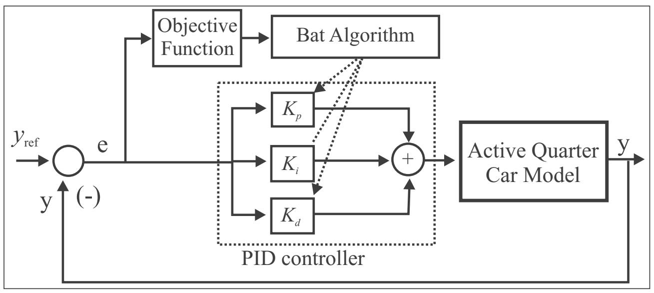

Fig. 3. Bat algorithm optimized PID control in active quarter car model

The working of bat algorithm is based on the following equations [14]:

$$f_i = f_{min} + (f_{min} - f_{min})\,\beta \qquad (11)$$

$$v_i^t = v_i^{t-1} + (x_i^t - x_*)\, f_i \qquad (12)$$

$$x_i^t = x_i^{t-1} + v_i^t \qquad (13)$$

where, $\beta \in [0,1]$ represents a random vector while x_* is the recent global best mathematical value (location) which is selected after comparing the complete values/ solutions from all the *n* bats in the population after every iteration.

Further, the process of local search is used for getting the new solutions taking local random walk criterion into consideration using eqn. (14). The magnitude of ε is chosen from the range [-1, 1] having the average loudness vale L^t at any time t.

$$x_{new} = x_{old} + \varepsilon L^t \qquad (14)$$

On further continuation of the iterations, two parameters namely loudness and pulse emission rate are further updated using following equations:

$$L_i^t = x_{old} + \alpha L_i^{t-1} \qquad (15)$$

$$\gamma_i^t = \gamma_i^0 \,[1 - e^{\gamma t}] \qquad (16)$$

where, the symbols α and γ denotes the constant mathematical values which lies in the range of $\leq \alpha \leq 1$ and $0 < \gamma$.

Table 1. Parameters selected for BA algorithm

Parameter	Values
Population size: *n*	15
Emission rate: γ_i	0.5
Loudness value: L_i	0.5
Frequency (minimum): f_{min}	0
Frequency (maximum): f_{max}	2
Number of iterations	30

VI. SIMULATION WORK & RESULTS

6.1 *Optimal set of PID controller parameters*

To obtain the optimal values, the problem is formulated in simulation environment of MATLAB software and simulation work for the same was done. The fitness values convergence curve using bat algorithm with 30 iterations is shown in Fig. 4. The changes in parameters of PID controller is presented in

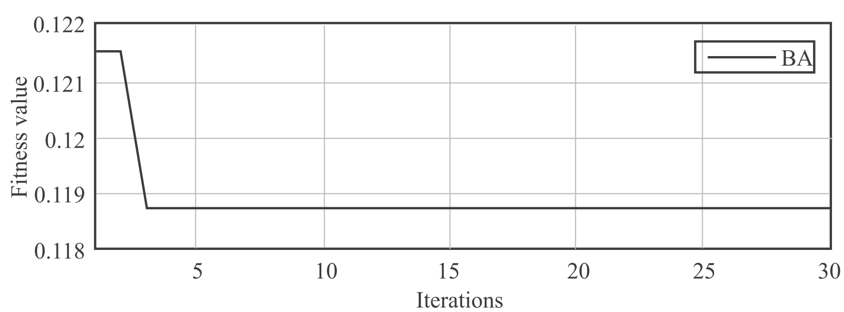

Fig. 4. Convergence curve for the fitness function

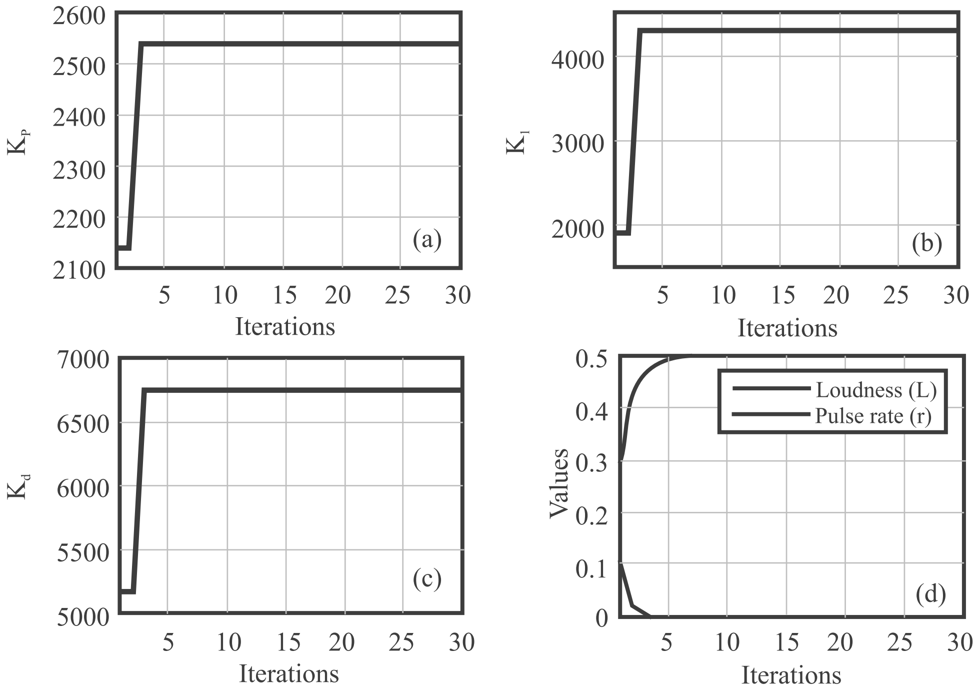

Fig. 5 (a) Plot of K_p with iterations (b) Plot of K_i with iterations (c) Plot of K_d with iterations (d) Variation of loudness and pulse rate with iterations

Fig. 5. The optimal values of PID parameters obtained after 30 iterations using the bat algorithm are presented in Table 2.

6.2 Response of Quarter Car Model

The selected random road profile for simulation work is shown in Fig. 6. The designed passive and active simulink models of quarter car system were run taking simulation time as 4 seconds having the vehicle velocity as 40 km/hr. The selected values in quarter car model are: m_1 = 70 k_g; m_2 = 300 *kg*; m_3 = 40 kg; c_1 = 800 *Ns*/*m*, c_2 = 2200 Ns/*m*, k_1 = 8000 *N*/*m*, k_2 = 25000 *N*/*m* respectively. The tyre stiffness k_t is having the value of 180,000 *N/m*. The values selected for PID controller using manual tuning method are: K_p = 1250, K_i = 800 and K_d = 2500 respective ly.

Table 2. Optimal values of PID controller with BA algorithm

Algorithm	Parameter	Values	Bounds		Computational time (sec)
			Lower	Upper	
BA	K_p	2539.97	100	3000	102.91
	K_i	4300.34	100	5000	
	K_d	6748.92	100	7000	

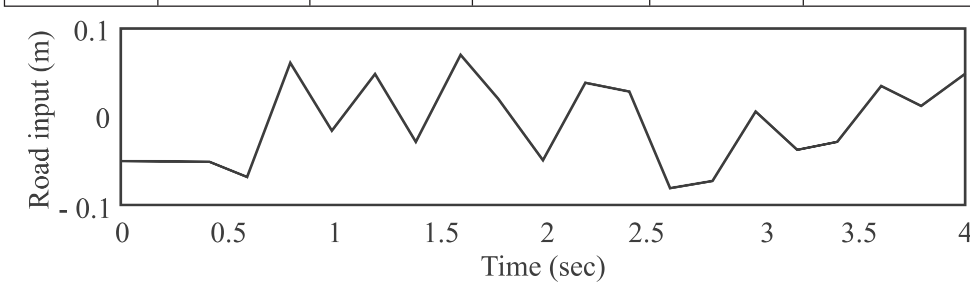

Fig. 6. Random road profile

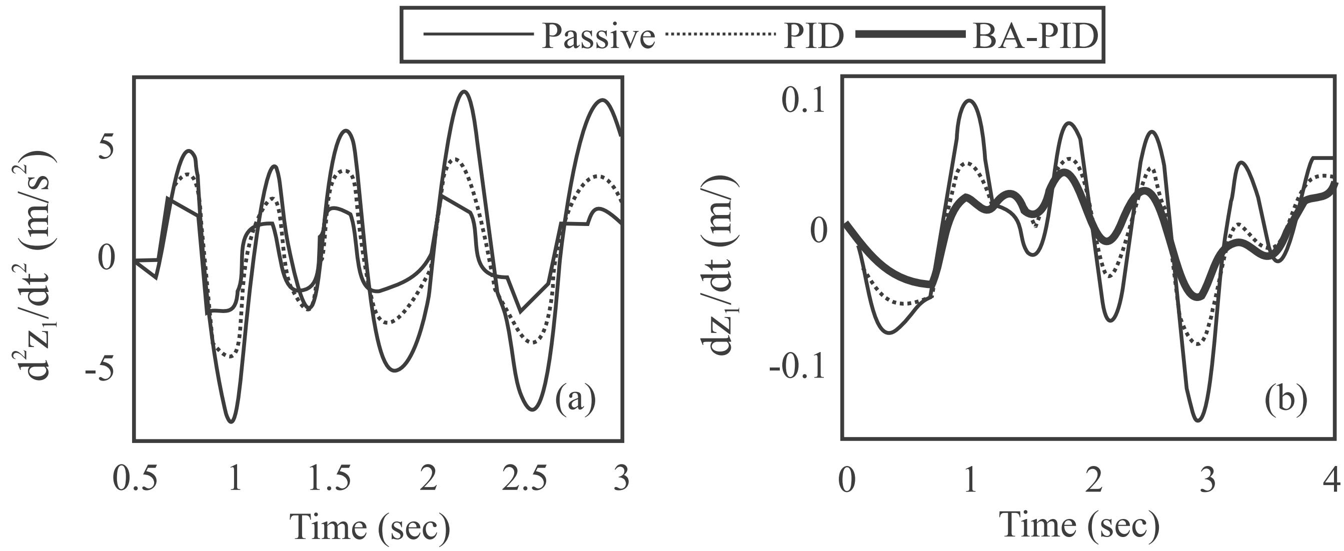

Fig. 7 (a) Passenger seat acceleration response (b) Passenger seat displacement response

The simulation results in terms of passenger seat acceleration and displacement response are shown in Fig. 7 while the mathematical results for the same is tabulated in Table 3. It can be seen from graphical and mathematical response that the passenger seat vibration suppression achieved by active suspension having PID-BA controller is best compared to suspension with passive mode and with PID controller.

The power spectral density (PSD) response plots in Fig. 8 for passenger seat acceleration and displacement response also shows the improved performance achieved by active suspension system assemble with PID controller having optimized values selected using bat algorithm compared to passive one and manually tuned PID controller. The damping force generated and power consumed by assembled controllers used in active quarter car model is also shown in Fig. 9.

Table 4 shows the performance of controllers in evaluating the four parameters namely IAE, ITAE, ISE and ITSE respectively. From the mathematical results, it can be concluded that best results are provided by controller having PID-BA parameters in terms of considered terms compared to other two cases.

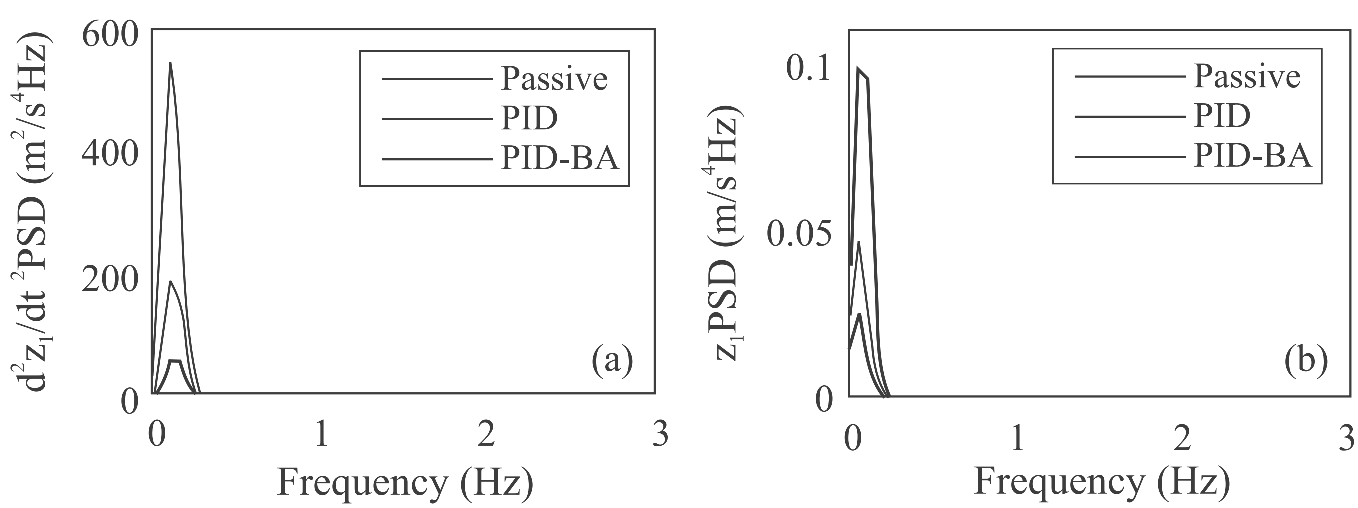

Fig. 8 (a) PSD response of passenger seat acceleration (b) PSD response of passenger seat displacement

Table 3. Simulation results of passenger seat response under random road profile

Controller	Peak Values		RMS Values	
	$\ddot{z}_1(ms^{-2})$	$z_1(m)$	$\ddot{z}_1(ms^{-2})$	$z_1(m)$
Passive	7.3861	0.0953	3.9439	0.0568
PID	4.3048	0.0512	2.4122	0.0369
Reduction (%)	41.7	46.3	38.8	34. 9
PID-BA	2.6159	0.0387	1.4674	0.0252
Reduction (%)	64.6	59.4	62.8	55.6

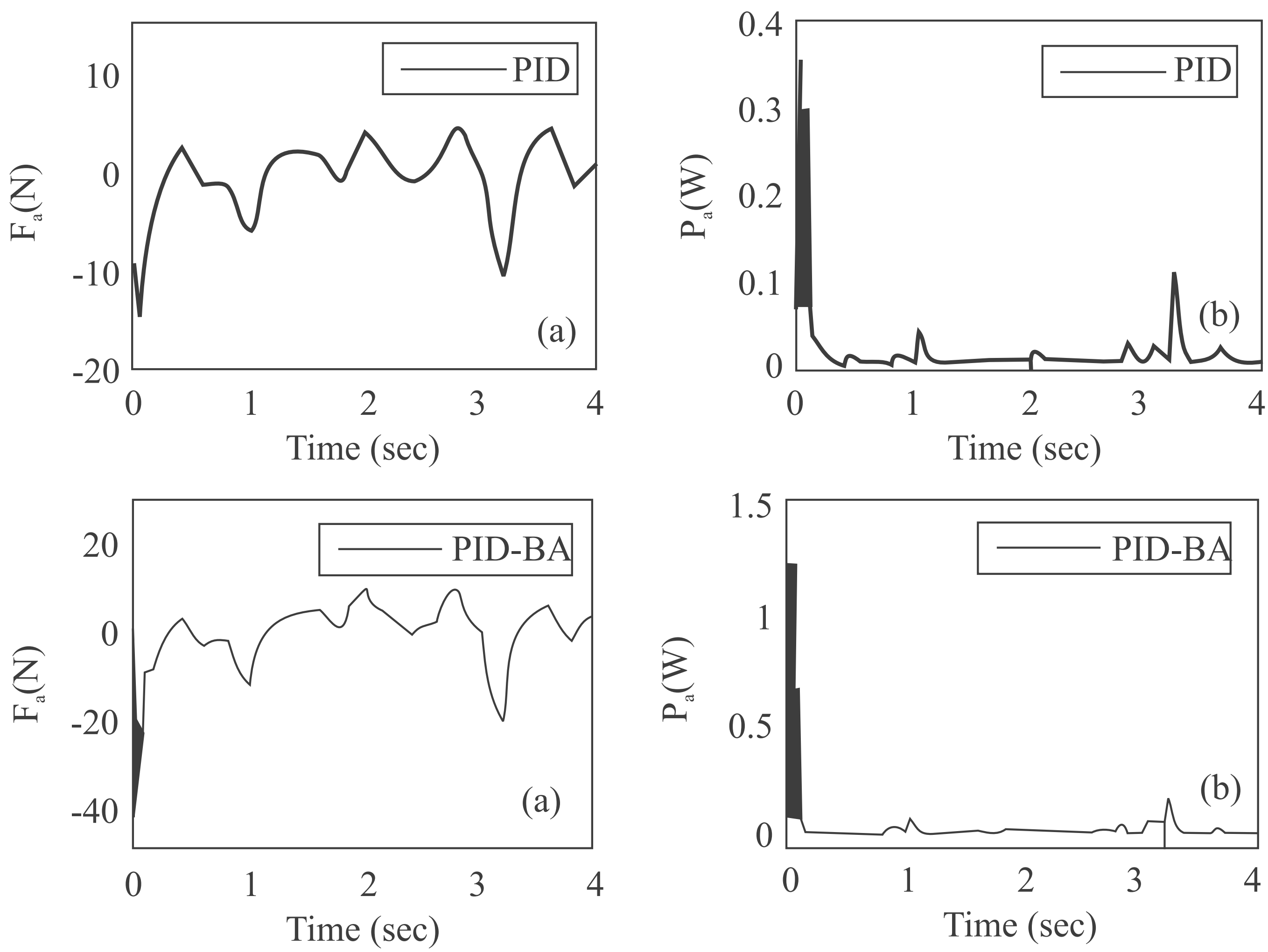

Fig. 9. Generated damping force and power absorber by applied controllers

Table 4. Comparison of controllers performance

Measurement Point	Controllers	Performance IAE	ITAE	ISE	ITSE
Passenger Seat	Passive	0.1231	0.2541	0.0056	0.0087
	PID	0.0882	0.1661	0.0029	0.0037
	PID-BA	0.0835	0.1633	0.0027	0.0035

Table 5 represents the results as per ISO 2631-1 criterion [15]. It is helpful in evaluating the performance of passenger ride comfort as per international standard. In this case, the two selected criterion for ride comfort evaluation are.

Table 5. Ride comfort comparison as per ISO 2631-1 standard

Controller	Passive	PID	PID-BA
RMS Aw (m/s^2)	2.0748	1.3562	0.8900
Reduction (%)	———	34.6	57.1
VDV (m/s$^{1.75}$)	15.4891	10.6545	7.5698
Reduction (%)	———	31.2	51.1

Weighted RMS acceleration (WRMS) and Vibration Dose Value (VDV) respectively. It can be finalized from the results of Table 5 that active quarter car system with PID-BA algorithm provide best ride comfort for passenger compared to other two strategies.

VII. CONCLUSION

In this research work, PID controller was designed in active quarter car model using bat algorithm. Simulation work demonstrated the successful application of PID controller with optimized values in suppressing the passenger seat vibrations during travelling period compared to other two cases. The designed PID-BA controller showed very good results for four different criterions such as IAE, ITAE, ISE and ITSE respectively. In conclusion, PID controller optimized using bat algorithm can be the option for controller design and suspension design engineers to obtain high ride comfort of travelling passengers.

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