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Research Article

An Effective Fractional-Order PID Controller to Improve a Quarter Car Active Suspension: Comparative Study

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ABSTRACT

In this study, a two-degree-of-freedom active suspension control system for a quarter automobile model is presented. Cars with active suspension are safer and more comfortable to ride in, and they handle better. Two controllers are utilised in this work to lessen the impact of road roughness that tires send to the vehicle body : (1) The standard PID (2) the manual method for the fractional-order PID (FOPID). To effectively manage uncertainties, meta heuristic techniques Genetic Algorithms (GA) and Particle Swarm Optimisation (PSO) are used to estimate the unknown PID and FOPID parameters. According to simulation studies, the PSO-optimized FOPID is excellent at reducing body vibrations and demonstrates superior performance and durability characteristics for a variety of challenging road conditions, such as uneven or dug roadways.

Keywords: Quarter car model, Active suspension, Ziegler-Nichols-PID, FOPID controller, Genetic Algorithms, Particle swarm optimization (PSO).

INTRODUCTION

Although there has been a lot of progress in recent years in making adjustments and improvements to vehicle design and technology, the most significant challenge in recent years has been the development of advanced suspension systems to achieve higher speeds over bumpy roads with high comfort quality [1]. Since suspension systems affect the car's handling and ride quality, they are currently of great interest to both industry and academia [2]. The main functions of suspension systems are to transmit all forces between the vehicle body and the road, which primarily ensures ride comfort, road holding, and safety.

The dynamic behaviour of the suspension systems greatly affects the vehicle's capabilities; enhancements in performance can avoid physical weariness and have a favourable impact on the driver's and passengers' comfort [3][4]. Active suspension, semi-active suspension, and passive suspension are the three different kinds of suspension systems [5]. The characteristics of the springs and dampers in a passive suspension system fixed, whereas semi-active and active suspension systems typically use components with variable parameters that adjusted by intelligent controllers to increase vehicle security and lessen the impact of road distortions and disturbances. [6].

Numerous studies addressing the contemporary control of suspension systems may be found in the literature. In [7], D. ROSHEILA AND Y.M. SAM enhanced the car's handling by applying the Linear Quadratic Regulator (LQR) to a quarter-car model. The disadvantage of this suggested approach is that it cannot guarantee strong performance in the event of adverse road disruptions. G. Wang et al. employed a useful terminal sliding mode control for a quarter-vehicle model in [8]. A theoretical study of riding behaviour employing FLC and LQR to integrate an effective active suspension was of interest to H. Elbab et al. in [9]. In order to ensure global stability for the closed loop system, A. Aela et al. proposed an active suspension control system for a quarter vehicle that modified by a neural network.

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As shown in [11]-[12]-[13], many studies used the developed PID, such as Fractional-order PID (FOPID), which demonstrated its efficacy in adjusting the active suspension and the vehicle's stability. It also makes driving easier and the passenger more comfortable. Recently, Z. A. Karam and O. A. Awad tuned a fraction-al-order PID controller to stabilise a quarter car suspension system using a novel optimisation algorithm known as Whale's Optimisation. The step input is the only kind of road that the authors attempted to test their suggested method on in this final report. The active suspension for a quarter automobile model with two degrees of freedom is the main topic of this research. We used both classical and clever ways to tune two types of controllers (PID and FOPID controllers). Keep in mind that particle swarm optimisation and genetic algorithms used to adjust both. This study demonstrates how the suggested FOPID optimised with PSO improves handling and comfort during a car journey.

The rest of this paper is organized as follows: in Section I mathematical modeling of an active suspension system of a quarter car is discussed. Section II presents the theoretical formulation of the implemented controllers, design and algo-rithms. Section III is devoted to the experimental simulations and interpretations where we illustrate the performance of the proposed controller. Finally, section IV describes the con-clusion of the work

MODELING OF QUARTER CAR DYNAMIC

Active car suspension system can be represented through a dynamic model as it is shown in Fig 1 [15]-[16]-[17]. The model consists of a damper placed between the sprung and unsprang masses. Unlike passive suspension system, in active suspensions we have to add a force element F (Force actuator) having as a task the application of a desired force between the vehicle and its wheel. The purpose of this paper is to propose a contribution for designing a controller for this force.

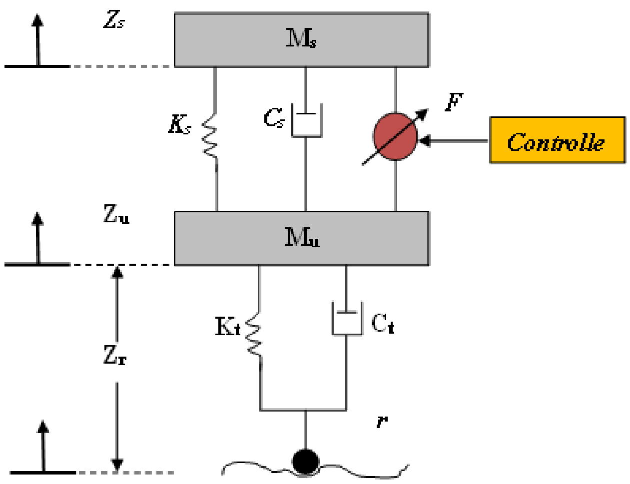

Fig. 1. The active Dynamic Model of Quarter Car Suspension [17]

The dynamic equations for the quarter car model shown as:

$$\begin{cases} M_s\ddot{Z}_s = -K_s(Z_s - Z_u) - C_s(\dot{Z}_s - \dot{Z}_u) + F \\ M_u\ddot{Z}_u = K_s(Z_s - Z_u) + C_s(\dot{Z}_s - \dot{Z}_u) - K_t(Z_u - Z_r) - C_t(\dot{Z}_u - \dot{Z}_r) - F \end{cases} \quad (1)$$

Equation (1)'s matching variables and parameters are shown in Table 1:

Table 1. Quarter car properties

Heading level	Example	Font size and style
Ms	Body Mass	Kg
Mu	Unspring Mass	Kg
Ks	suspension system Spring	N/m
Kt	wheel and tire Spring	N/m

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Cs	suspension system Damping	N.s/m
Ct	wheel and tire Damping	N.s/m
F	Actuator Force	N
Zs	Body Position	m
Zu	Wheel Position	m
Zr	Vertical vector of the road profile	m/s
r	Road Profil Testing	m

The state space representation of dynamic (1) of the quarter car model defined as in [18] as:

$$\begin{cases} \dot{Z} = AZ + BF + GZ_r \\ y = CZ + DF + EZ_r \end{cases} \tag{2}$$

Which gives the following state space form:

$$\begin{cases} Z_1 = \dot{Z}_s \\ Z_2 = Z_s \\ Z_3 = \dot{Z}_u \\ Z_4 = Z_u \end{cases}$$

$$\Downarrow$$

$$\begin{cases} \dot{Z}_1 = -\frac{C_s}{M_s} Z_1 - \frac{K_s}{M_s} Z_2 + \frac{C_s}{M_s} Z_3 + \frac{K_s}{M_s} Z_4 + \frac{1}{M_s} F \\ \dot{Z}_2 = Z_1 \\ \dot{Z}_3 = \frac{C_s}{M_u} Z_1 + \frac{K_s}{M_u} Z_2 - \frac{(C_s+C_t)}{M_u} Z_3 - \frac{(K_s+K_t)}{M_u} Z_4 + \frac{K_t}{M_u} Z_r + \frac{C_t}{M_u} \dot{Z}_r - \frac{1}{M_u} F \\ \dot{Z}_4 = Z_3 \end{cases} \tag{3}$$

Assuming that the vertical velocity caused by the road profile $\dot{Z}_r$ r is negligible, the state equation with respect to variable $\dot{Z}_3$ is as follows:

$$\dot{Z}_3 = \frac{C_s}{M_u} Z_1 + \frac{K_s}{M_u} Z_2 - \frac{(C_s+C_t)}{M_u} Z_3 - \frac{(K_s+K_t)}{M_u} Z_4 + \frac{K_t}{M_u} Z_r - \frac{1}{M_u} F \tag{4}$$

Consequently, the state and output equation will be given by:

$$\underbrace{\begin{bmatrix} \dot{Z}_1 \\ \dot{Z}_2 \\ \dot{Z}_3 \\ \dot{Z}_4 \end{bmatrix}}_{\dot{Z}} = \underbrace{\begin{bmatrix} -\frac{C_s}{M_s} & -\frac{K_s}{M_s} & \frac{C_s}{M_s} & \frac{K_s}{M_s} \\ 1 & 0 & 0 & 0 \\ \frac{C_s}{M_u} & \frac{K_s}{M_u} & \frac{(C_s+C_t)}{M_u} & \frac{(K_s+K_t)}{M_u} \\ 0 & 0 & 1 & 0 \end{bmatrix}}_{A} \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{1}{M_s} \\ 0 \\ -\frac{1}{M_u} \\ 0 \end{bmatrix}}_{B} F + \underbrace{\begin{bmatrix} 0 \\ 0 \\ \frac{K_t}{M_u} \\ 0 \end{bmatrix}}_{G} Z_r \tag{5}$$

PID AND FRACTIONAL ORDER SYSTEMS

The objective of control design in this investigation is to give the required dynamic behavior to the car under road variations by using a fractional order PID controller.

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PID is the most used controller in industrial applications due to its simple structure [20][21][22][23]. Its tuning can be guar-anteed by using Ziegler-Nichols method or by metaheuristic techniques. Mathematically a PID control law given by:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t) \quad (6)$$

Where $K_p$is the proportional gain, $K_i = K_p/T_i$is the integral gain with $T_i$the integral time and $K_d = K_p T_d$represents the derivative gain with T_d derivative time.

Usually, Industrial processes controlled by PID are tuned by the Ziegler-Nichols method [24][25][26]. This tuning can also be carried out by more modern optimization approaches, as will be proposed in this paper.

Alin Oustaloup was credited with developing the CRONE controller [27] [28], and Podlubny came up with the concept of the controller, which uses Laplace transforms to solve the following fractional-order differential equation [29] [30]:$L[\alpha D_t^q f(t)] = s^q F(s) - \sum_{i=0}^{m} [D^{q-i-1} f(t)]_{t=0}$ (7)

Where α and t are the bounds of the fractional differential; $f(t)$ is a real function defined from $R \to R$; q is the fractional order, which may be a complex integer; and $F(s)$ is the Laplace transforms of $f(t)$.

The fundamental operator aD_t^q can be generalised from the differential and integral operators as follows:

$$aD_t^q = \begin{cases} \frac{d^q}{dt^q} & q > 0 \\ 1 & q = 0 \\ \int_a^t (d\tau)^{-q} & q < 0 \end{cases} \quad (8)$$

Fractional integral defined as:

$$I^\alpha f(t) = \frac{1}{\Gamma(\alpha)} \int_0^t (t-\tau)^{\alpha-1} f(\tau)d\tau, t > 0 \; \alpha \in \mathcal{R}^+ \quad (9)$$

Fractional derivative defined as

$$D^\alpha f(t) = \frac{d^\alpha f(t)}{dt^\alpha} = \frac{1}{\Gamma(\alpha-1)} \int_0^t \frac{f^n(\tau)}{(t-\tau)^{\alpha+1-n}} d\tau, (n-1) < \alpha < n \quad (10)$$

With $\Gamma(n) = (n-1)(n-2) \ldots \ldots (2)(1)!$

Similar to Grunwald-Lenikover's definition (see [30][31]), there are numerous other definitions:

$$aD_t^q f(t) = \frac{d^q f(t)}{d(t-a)^q} = \lim_{N\to\infty} \left[\frac{t-a}{N}\right]^{-q} \sum_{j=0}^{N-1} (-1)^j \binom{q}{j} f(t - j\left[\frac{t-a}{N}\right]) \quad (11)$$

Nonetheless, the most widely used definition of Riemann-Liouville is provided by:

$$aD_t^q f(t) = \frac{d^q f(t)}{d(t-a)^q} = \frac{1}{\Gamma(n-q)} \frac{d^n}{dt^n} \int_0^t (t-\tau)^{n-q-1} f(\tau)d\tau \quad (12)$$

With $\Gamma(z) = \int_0^\infty t^{z-1-t} e^{-t} dt$ (13)

Where $\Gamma(z)$ is the Euler's Gamma function.

The fractional-order PID framework is similar to the conventional PID except for the fractional integral and derivative orders. The performance of this controller can surpass that of the conventional one by using fractional calculus to provide order flexibility [32] [33, 34].

The following is the form of the $PI^\lambda D^\mu$ controller's transfer function:

$$g_c(s) = K_p + K_i \frac{1}{s^\lambda} e(s) + K_d s^\mu e \quad (14)$$

The controller transfer function is denoted by $g_c(t)$ the integrator term is $\frac{1}{s^\lambda}$ the derivation term is s^μ, and the non-integer orders of

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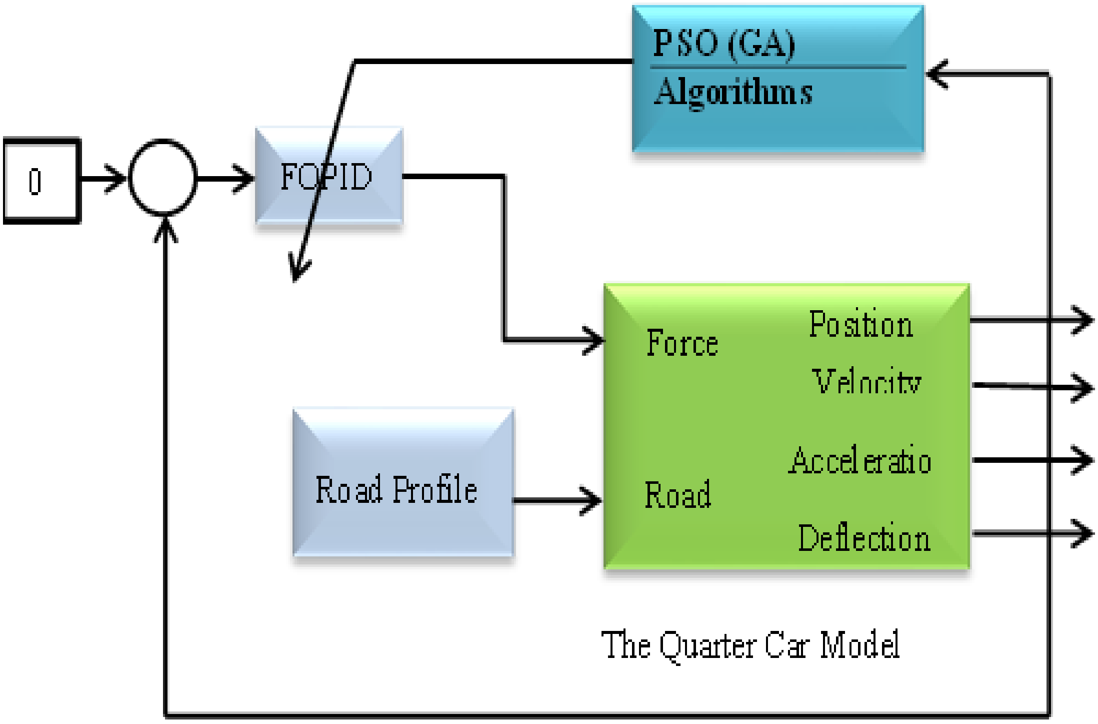
the integral and derivative terms are $\lambda, \mu \in \mathcal{R}^+$. In the time domain, the control action $u(t)$ can be written as [31]:

$$u(t) = K_p e(t) + K_i D^{\lambda} e(t) + K_d D^{\mu} e(t) \quad (15)$$

PARTICLE SWARM OPTIMISATION AND GENETIC ALGORITHMS FOR THE BEST FRACTIONAL-ORDER PID

The optimisation of Fractional Order PID (FOPID) controller parameters for active suspension systems (Fig. 2) is



covered in detail in this section. When compared to a conventional PID controller, the five parameters of FOPID significantly increase the search space, making tuning challenging. To achieve the best outcomes, heuristic optimisation techniques inspired by nature, such as genetic techniques (GA) and particle swarm optimisation (PSO), are employed. While PSO is inspired by the collective behaviour of fish schools and bird flocks, where particles interact with one another, GA mimics the process of natural evolution through selection, crossover, and mutation.

Fig. 2. Optimization Process Diagram Using Pso (Ga)

Adaptive techniques for search and optimisation issues are genetic algorithms. J. Holland was the first to propose the fundamental idea of GA in 1975 [35][36]. This evolutionary technique typically yields a large number of combinative issues with challenging mathematical formulations [37].

Reproduction, crossover, and mutation are the three basic operators that make up GA. The optimisation runs recursively with the three operators in a random manner after encoding parameters as binary models [38]. The fundamental search mechanism is provided by genetic operators, the most common of which are:

The fundamental operator of genetic algorithms is reproduction, which is carried over into the following generation based on the reproduction probabilityP_{ri}, which is stated in [39] as follows:

$$P_{ri} = F_i / \sum_{i=1}^{P_i} F_i \quad (16)$$

Where $P_i$the population's sizeand and F_i is is the chromosome's fitness.

SELECTION

Is the process of selecting specific genes from a population for subsequent breeding (with the aid of a crossover operator). Selecting the chromosomes with the finest traits for integration in the following generation is the primary objective.

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CROSSOVER AND MUTATION

The combining of two people's chromosomes is called crossover. They create new chromosomes and incorporate them into the population. Following the crossover phase is the mutation phase, which creates new individuals by utilising chromosome changes at random [40].

We combined the FOPID parameters onto a single chromosome. The following formula establishes the relationship between real parameters and binary system coding genes:

$$X = min + (max - min)/(2^{10} - 1) \times b \quad (17)$$

where b is a binary value system and max and min are the upper and lower bounds of the controller's free parameters [41]. After coding, we display the FOPID's chromosomes in Fig. 3:

K_p	K_i	λ	K_d	μ

Fig. 3. FOPID Chromosomes after coding

The main steps of a genetic algorithm for maximising the FOPID parameters [42] are shown in the following:

First, set the population's parameters using a random solution; second, choose the crossover, mutation, and number of clusters; third, specify the number of generations and the coding mode; fourth, define and assess the fitness function's value; fifth, carry out the crossover and mutation operations and create the new generation; sixth, repeat step 02 until the optimal value is reached.The Most Important Task In Ga Is The Selection Of The Objec-Tive Function (Fitness) For The Evaluation Of The Suitability Of Each Chromosome. In this paper, the following objective function is used [43] [44]:

$$J = \int_0^T t|e(t)|dt \quad (18)$$

Equation (20) [43] [44] illustrates how we utilise the fitness value to direct the search for the optimal solution to the problem, where e is the error to be employed to minimise the objective J:

$$Fitness\ Value = \frac{1}{J} \quad (19)$$

PARTICLE OPTIMISATION OF SWARM

Fish crowding and avian social behaviour served as inspiration for the technique known as particle swarm optimisation. Drs. Kenedy and Eberhart created this technique in 1995 [45]. Its basic idea is to use an objective function to simultaneously explore a wide area for the solution [46].

Initialising an n-swarm of particles that travel randomly in a_j dimensional search space in terms of position and velocity is the foundation of the PSO algorithm [47]. In less time, a high-quality solution can be produced [48].

An i^{th} particle of the swarm's position and velocity X_i and V_i are updated in the manner described below [49]:

$$V_{ij}(i+1) = wV_{ij} + C_1r_1\left(Pbest_{ij} - X_{ij}\right) + C_2r_2\left(Gbest - X_{ij}\right) \quad (21)$$

$$X_{ij} = V_{ij} + X_{ij} \quad (22)$$

With

$$w = w_{max}\left(\frac{iter}{maxiter}\right)(w_{max} - w_{min}) \quad (23)$$

Where j is a dimension of the search space, r_1 and r_2 are random values between $(0,1)$, and $i = 1,2,\dots,n$ is the number of particles in the swarm. w_{max} , is the final weight, w_{min} is the initial weight, maxiter is the maximum iteration number, and iter is the current

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iteration number. C_1, and C_2 are correction factors; C_1 is a cognitive parameter that pulls each particle towards a local best position, and C_2 is a social parameter that pulls the particle towards a global best position.

Similar to the GA method, particle swarm optimisation requires an objective function to minimise [50]. Equation (20)'s fitness function is used to modify the PID and FOPID parameters. The following [51] illustrates the steps of the particle swarm algorithm:

- Step 1: Establish the goal function;
- Step 2: Establish the PSO parameters;
- Step 3: Position and velocity initialisation
- Step 4: Assessing the objective function is the fourth step.
- Step 5: Update Pbest and Gbest in Step 5;
- Step 06: Determine the position handling boundary and velocity;Step 07 : Stop while getting the best value.

The parameters of the controllers optimised by GA shown in Table 2:

Table 2. Parameters tuned by GA

GA properties	PID	FOPID
Fitness of Function	ITAE	ITAE
Population size	50,01	50,01
Max Generations	103	103
Selection	Roulette	Roulette
Crossover	Two Point	Two Point
Mutation	Uniform with Rat=0.01	Uniform with Rat=0.01
PID's Interval	0<kp<10.01 0<ki<0.0853 0<kd<1.34*10^4	0<kp<10.01 0<ki<0.0853 0<kd<1.34*10^4, 0<λ<0.260, 1<μ<1.100

Table 3 present the parameters of controllers optimized by:

Table 3. Parameters tuned by pso

PSO properties	PID	FOPID
Function's Objective	ITAE	ITAE
Function Tolerance	1×10-6	1×10-6
Inertial Range	[0.1 1.1]	[0.1 1.1]
Max Iteration	6000	10000
Swarm Size	30	50
PID's Interval	0<kp<10.01 0<ki<0.0853 0<kd<1.34*10^4	0<kp<10.01 0<ki<0.0853 0<kd<1.34*10^4, 0<λ<0.260, 1<μ<1.100

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The simulations of the suggested approach for optimising the fractional-order PID control for an active suspension system applied to a quarter vehicle model will be shown in this section. It should be noted that the road profile is regarded as the system's input and is selected as either a bumpy road (sinusoidal input) or a step input. Table 4 lists the automobile parameters' numerical values [19].

Table 4. Quarter car suspension parameters

Parameters	Values	Units
M_s	972.2	Kg
M_u	113.6	Kg
K_s	42,719.6	N/m
K_t	101,115	N/m
C_s	1,095	N.s/m
C_t	14.6	N.s/m

Figure 3 (Fig.3) displays the flowchart of the Genetic Algorithm (GA) and Particle Swarm Optimisation (PSO) used to determine the optimal parameters for the Fractional Order PID (FOPID) controller and PID. These parameters include fractional derivative order (μ), fractional integral order (λ), derivative gain (K_d), proportional gain (K_p), and integral gain (K_i). Both GA and PSO employ the optimisation process depicted in the flowchart to lower the error criterion and enhance the overall stability, robustness, and response speed of the FOPID controller.

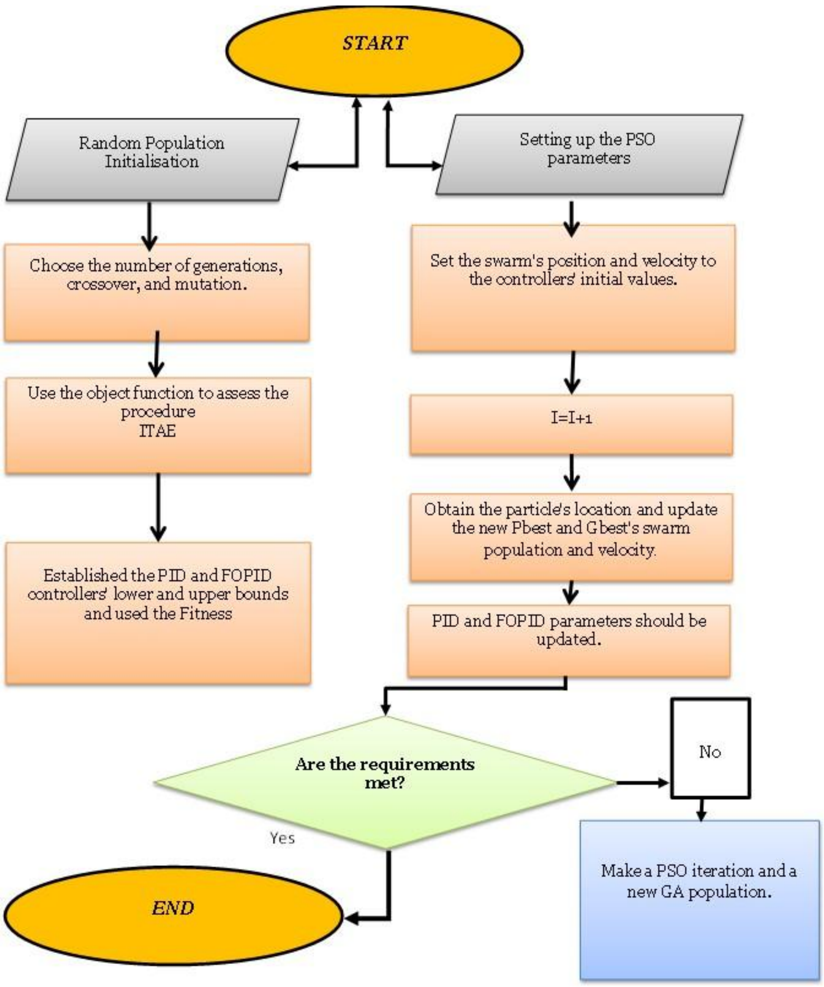

Fig. 4. Flow Chart of Ga and Pso Algorithm

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The optimized parameters of FOPID presented in Table 5; they are obtained with three types of optimizations: Trial and error, GA and PSO.

Table 5. Optimized Parameters of PID and FOPID.

Tuned Methods		k_p	k_i	k_d	λ	μ
Classical Methods	Z-N_PID	54.9	0.1716	4391.5	–	–
	Manual_FOPID	15.01	0.1	######	1.3	1
	GA_PID	6.314	0.081	12772	–	–
Metaheuristic Method	GA_FOPID	2.09	0.011	12849	0.037	1.01
	Pso_PID	5.01	0.007	12850	–	–
	Pso_FOPID	0.0617	0.0088	1.34*10^4	0.0628	1.01

For comparison purposes, we also present in Table 5 similar optimized values for PID controller. Simulation results presented in figures 5, 6, 7 and 8. Each figure contains four output responses body displacement (position), velocity, acceleration and deflection. Note that each figure is relative to a specific input (road profile). Results of passive suspension also showed in the figures.

- First Road is a Step Road Input:

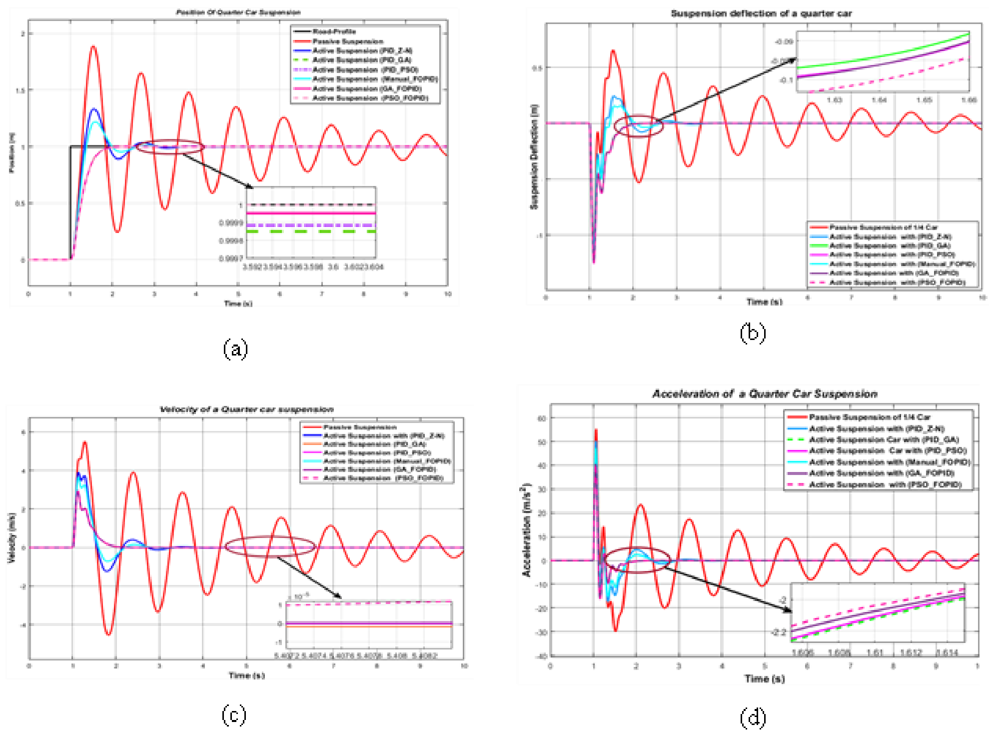

Fig. 5. Step Reactions of optimal FOPID and Optimal PID Controllers :(a) Body Position, (b) Body Deflection, (c) Body Velocity and (d) Body Acceleration.

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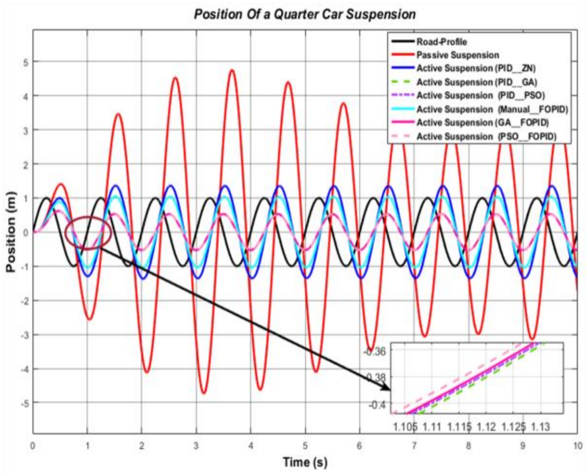
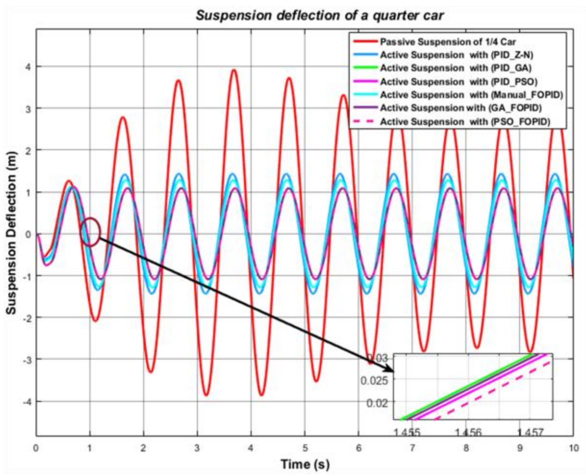
The body location, body deflection, body velocity, and body acceleration are shown in Fig. 5 along with the step responses for optimised PID and FOPID controllers. The findings contrast passive suspension and intelligent controllers with traditional PID and FOPID.

Figures (b), (c), and (d) demonstrate the stability of the active suspension system with PSO_FOPID and better reduce road vibration, while Figure (a) demonstrates the efficacy of the active suspension controller with FOPID optimised by PSO algorithms, as seen in the zoom section. Figure 5 (a) (part zoom) illustrates how the suspension behaves in various stages (passive and active) in relation to RMS error. For a step road input, the rms error varies between 6.48% and 8.25%.

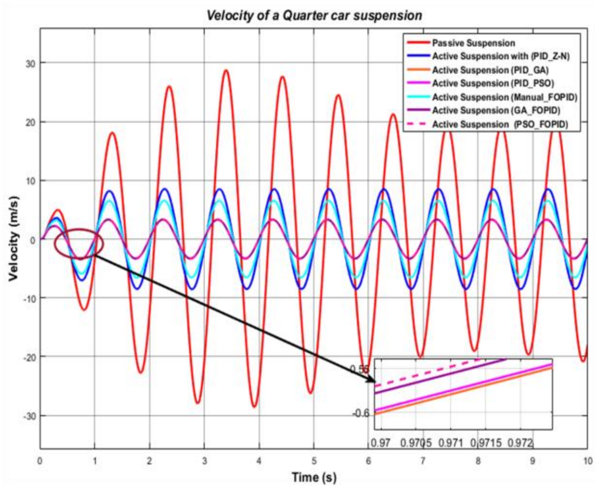
- Second road is a bumpy road input:



(a)



(b)



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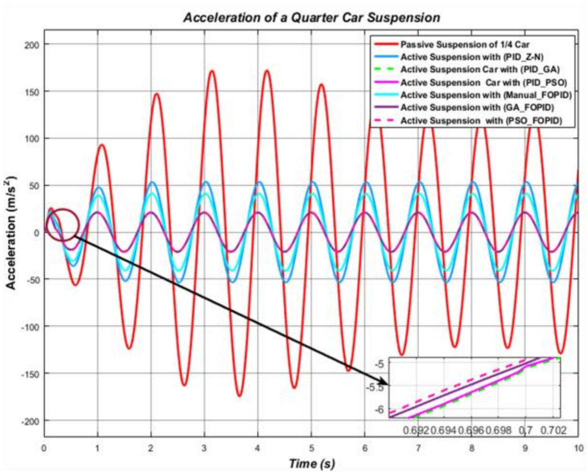

(d)

Fig. 6. Optimal PID and Optimal FOPID Controller Road Responses With :(a) Body Position, (b) Body Deflection, (c) Body Velocity and (d) Body Acceleration.

The results compare passive and active suspension utilising classical and intelligent controllers with various vehicle scenarios (displacement, velocity, acceleration, and deflection). The rough road profile (sinusoidal input) is shown in Fig. 6. When compared to the other approaches, the figures (a), (b), (c), and (d) demonstrate improved stability of an

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active suspension using PSO_FOPID (fractional-order PID optimised by PSO algorithms). The RMS error levels for all suspension system types examined in this section range from 67% to 86%, indicating the effectiveness of the suggested controller.

- Third road is an excavated road input:

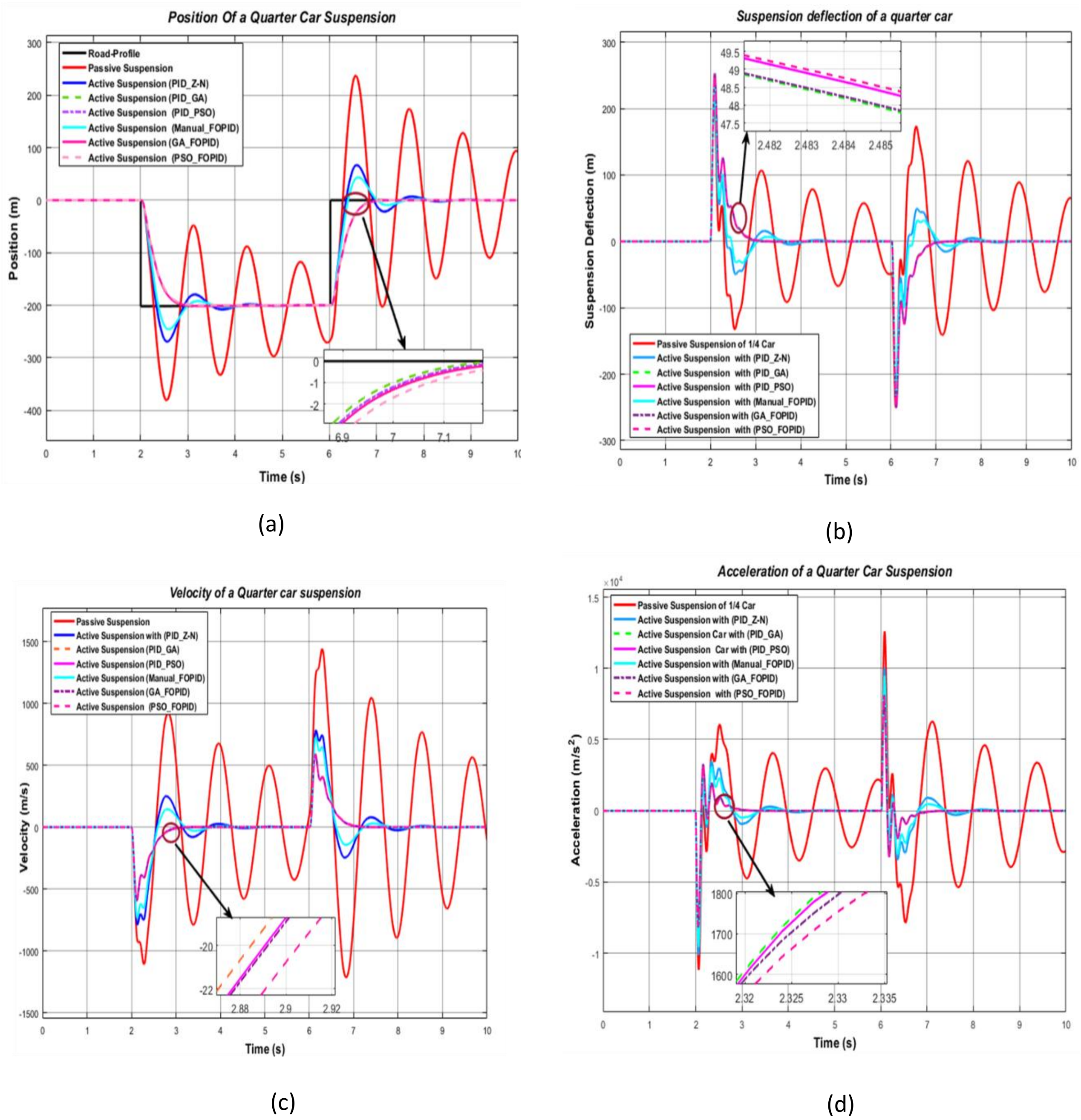

Fig. 7. Responses of the Best PID and FOPID Controllers to Excavated Roads :(a) Body Position, (b) Body Deflection, (c) Body Velocity And (d) Body Acceleration.

We examined the passive and active suspension with standard and intelligent controllers, using the excavated road (variable-step) as the input for the car suspension (Fig. 7). The various examples demonstrate the effectiveness of fractional-order PID optimised by PSO algorithms (PSO_FOPID) in lowering the dug road's vibration. The final road

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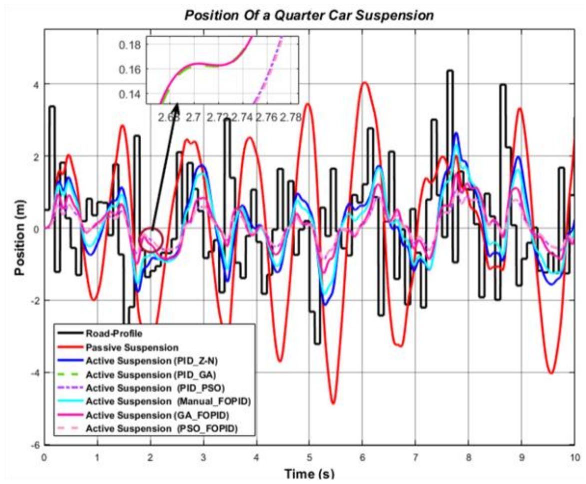
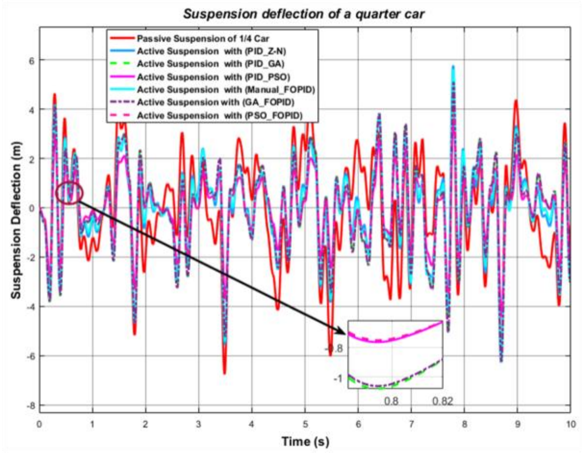
selected was noisy ; high-intensity vibrations are a feature of this kind of road. We performed the same comparison as in the previous figures in figure 8 (Fig. 8), and we found that the active suspension has a high ability to lessen the effect of the car's vibrations. In particular, the active suspension controlled by fractional-order control optimised by PSO algorithms produced better results in terms of the car's road stability and vibration reduction, as well as improved comfort for the driver and passengers.

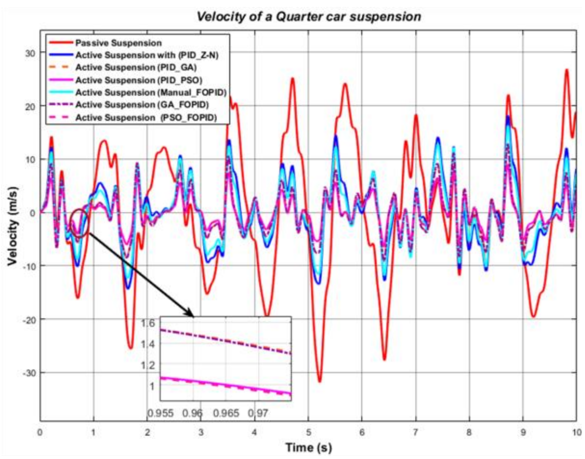
- Fourth road is a noisy road input



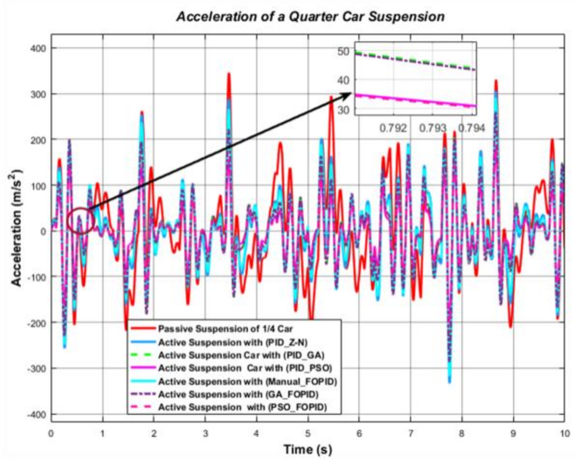
(a)



(b)



(c)



(d)

Fig. 8. Responses of Optimal PID and Optimal FOPID Controllers to Noisy Roads : (a) Body Position, (b) Body Deflection, (c) Body Velocity and (d) Body Acceleration.

Fig.7 and Fig.8 show the suspension response for two types of roads, excavated and noisy road. The values of RMS error for the excavated road are between 18% to 22%, and for a noisy road are between 64% to 85%. The simulation results are shown in (Fig. 5 to Fig. 8), explain the effectiveness of the active suspension controller with proposed FOPID tuned by PSO in all types of road profiles, especially the road with a big vibration.

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In order to test the robustness and adaptive properties of the proposed suspension system under the considered approaches, three quality criterions chosen: Rise Time, Setting Time and Maximum Overshoot. This test applied on body displacement with a step input for road profile. Robustness results listed in Table 6. The results shown in this table prove the effectiveness of the active suspension with FOPID optimized by using PSO.

Table 6. Comparison of PID and FOPID Controllers Reponses.

	Technique Methods			Rise Time (s)	Setting Times (s)	Maximum Over-shoot
Body displacement of	Passive suspension			55.5624	$3.3909e^{+02}$	$1.0577e^{+02}$
	Active Suspension Systems	PID	ZN	76.8740	$8.8083e^{+02}$	33.5227
			GA	1.6879^{+02}	$3.3656e^{+02}$	0.0555
			PSO	$1.7036e^{+02}$	$3.4007e^{+02}$	0.03817
		FOPID	Manual	86.3427	$6.4177e^{+02}$	21.8080
			GA	$1.7072e^{+02}$	$3.4211e^{+02}$	0.0262
			PSO	$1.7360e^{+02}$	$3.5106e^{+02}$	0.0102

INTERPRETATIONS OF RESULTS

The system performances (vehicle ride comfort and handling performance) in the time domain are assessed in this section using the criterion rms error (Root Mean Square). The RMS error values for each approach that was employed are displayed in Table 6.

The RMS statistics use the actual difference between the estimated and measured values to provide information about the system's short-term performance. The best controller performances were achieved with FOPID PSO-optimized, according to the RMS data shown in Table 6. The vehicle's status dynamic (position, velocity, acceleration, and deflection suspension) as seen in Figures 5 through 8 unquestionably demonstrated its ability to resist fluctuations of at least 8% in all system parameters and up to 87% for all types of road input.

The findings demonstrate that when the road profile is altered, the fractional-order PID controller PSO-optimized has a better resilient ability, a preferred solution, and a balanced achievement between ride comfort and handling performance.

Table 6. The active suspension system's RMS error for a quarter car

	Technique Methods			Step Road Input	Bumpy Road Input	Excavated road input	Noisy Road Input
Body displacement of step road input (m)	Passive suspension			1.058	2.740	$1.763e^{+02}$	2.456
	Active Suspension Systems	PID	ZN	$9.894\ e^{-01}$	$9.063\ e^{-01}$	$1.440\ e^{+02}$	$8.897\ e^{-01}$
			GA	$9.711\ e^{-01}$	$3.696\ e^{-01}$	$1.385\ e^{+02}$	$5.356\ e^{-01}$
			PSO	$9.710\ e^{-01}$	$3.676\ e^{-01}$	$1.384\ e^{+02}$	$3.776\ e^{-01}$
		FOPID	Manual	$9.856\ e^{-01}$	$7.036\ e^{-01}$	$1.426\ e^{+02}$	$7.679\ e^{-01}$
			GA	$9.710\ e^{-01}$	$3.682\ e^{-01}$	$1.384\ e^{+02}$	$5.344\ e^{-01}$
			PSO	$9.707\ e^{-01}$	$3.643\ e^{-01}$	$1.377\ e^{+02}$	$3.757\ e^{-01}$

CONCLUSION

The three primary categories of vehicle suspension systems—passive, semi-active, and active suspensions—are characterised by their inherent complexity and nonlinearity. Whereas the semi-active suspension offers some flexibility, the passive suspension depends only on the spring and damper. On the other hand, a controller included into the active suspension system enables the system to adapt dynamically to road irregularities.

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In this work, we examine how to improve a quarter-car active suspension system's stability and robustness. The suggested control strategy tunes both PID and FOPID controllers using meta-heuristic optimisation techniques, namely Genetic Algorithm (GA) and Particle Swarm Optimisation (PSO). The outcomes are contrasted with traditional tuning techniques, specifically the manual tuning approach for the FOPID case and Ziegler–Nichols for the PID example.
By obtaining lower root mean square (RMS) values, less overshoot, a shorter settling time, and a faster rise time, the comparison study shows that the PSO-optimized FOPID controller works better than alternative strategies. These upgrades guarantee improved road-holding performance and riding comfort in a variety of road disturbances.

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