RESEARCH ARTICLE

Online DE Optimization for Fuzzy-PID Controller of Semi-Active Suspension System Featuring MR Damper

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ABSTRACT In pursuit of a comfortable vehicle driving in different road profiles, intelligent methods are used to improve the vehicle's suspension system. The semi-active suspension system outperformed other suspension systems because it contains an intelligent actuator that can give the appropriate force to dissipate unwanted vibration using intelligent and real-time controllers. In this paper, MR fluid damper with Fuzzy-PID controller is examined to be optimized using a modified DE algorithm. However, in the Fuzzy-PID controller, the fuzzy logic algorithm is used to auto-tune the PID controller, but it cannot be considered as a fully real-time controller since the fuzzy algorithm uses a previous knowledge base built offline. The offline design of the Fuzzy algorithm cannot cope with unexpected real-time vibrations occurred while driving a car in different road profiles. In this paper, a Fuzzy-DE-PID controller is proposed based on a modified DE algorithm to enhance the Fuzzy logic gains in order to increase vehicle semi-active suspension system performance. Simulation and experimental tests were conducted using the proposed controller with different disturbances to prove the proposed controller's effectiveness. The results of the simulation and the experimental tests for the proposed controller showed an improvement in the vehicle's ride comfort over the Fuzzy-PID and the passive system. We believe that using this proposed controller in any other real-time application will improve the performance to the highest levels without needing a previous knowledge base for designing a real-time Fuzzy-PID controller.

INDEX TERMS MR damper, fuzzy-PID, DE optimization, online optimization.

I. INTRODUCTION

Comfort and steady driving of automobiles under unstable road conditions are the challenging trade-offs in designing an effective suspension system. Suspension systems work as an isolator for the vehicle body from road irregularities. From the 1980s, extensive research aided in improving the suspension systems from passive to active, then into semi-active suspension systems [1].

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In the passive suspension system, robust mechanical parts cannot be adjusted in response to irregular road conditions. In contrast, the active suspension system is more flexible in response to uneven road conditions since it has an actuator such as hydraulic actuators.

The semi-active suspension system has the most concern now over the active suspension systems because of using lightweight, less power consumption, and smart actuators which can be adjusted and controlled by modern control algorithms such as Fuzzy and PID algorithms.

Magnetorheological Fluid damper (MR damper) is one of the smartest actuators that has hysteresis behavior which

encourages researchers to extensively proposes different controlling strategies for it is nonlinearity [2], [3], [4]. It is nonlinearity comes from it is fluid microscopic magnetic particles that are capable of changing their properties. When exposed to a meager magnetic field by a coil existing inside the damper, the fluid of the damper converted to a viscoelastic solid state. Once the magnetic field is removed, the fluid returns to its liquid state. Controlling the applied current to the coil inside the MR damper significantly generated controllable damping force. Thus, the Semi-Active as suspension system and MR damper as the actuator is the state-of-the-art technology in suspension system researches [5], [6].

This paper suctions arranged as the following: first, an explanation for the fuzzy-PID controller and how to optimize it is parameters, next an illustration of how the quarter car model of semi-active suspension system was designed, after that the design of the simulation used to implement the proposed online optimization explained, then the results of testing the proposed system in simulation and experimental mode listed and discussion. Finally, a conclusion of this paper's outcomes is listed at the end.

II. FUZZY-PID CONTROLLER PARAMETERS OPTIMIZATION

Fuzzy-PID controller uses a Fuzzy logic algorithm to tune the PID controller parameters, as seen in Figure 1. The Fuzzy logic controller strategy consists of input parameters evaluated by the Fuzzy Inference System (FIS) to generate optimum output values. The FIS contains membership rules and functions, which need an accumulation of previous expert knowledge to design an effective FIS strategy. The Fuzzy-PID controller is considered as one of the online optimization methods. However, the Fuzzy rule base - which is built in offline mode - has no systematic framework or constant rules for its design. It cannot be modified instantly to handle real-time uncertainties, as seen in Figure 2 [7]. Consequently, the PID tuned by these fixed rules cannot be smart enough to cope with unexpected disturbances. So, adding online optimization for the Fuzzy-PID controller to improve the fuzzy logic outputs may increase the PID auto-tuning according to the different uncertain disturbances of road profiles.
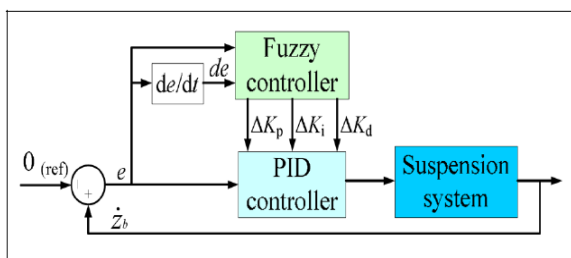

FIGURE 1. In the Fuzzy-PID controller the Fuzzy is used to tune the PID parameters [7].

In this paper, a fast DE algorithm was developed to instantly enhance the Fuzzy tuning for the PID controller
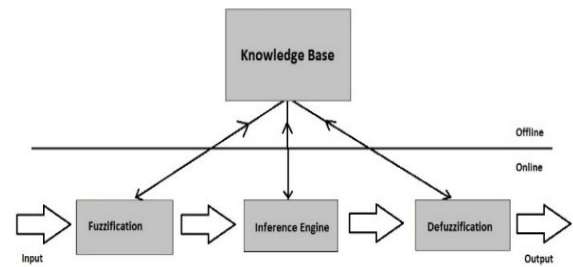

FIGURE 2. Fuzzy logic depends on a knowledge base to build an effective fuzzy model.

gains, as seen in Figure 3, and then to generate the required voltage to the MR damper to be more accurate in response to the vibration that occurred instantly on the suspension system.
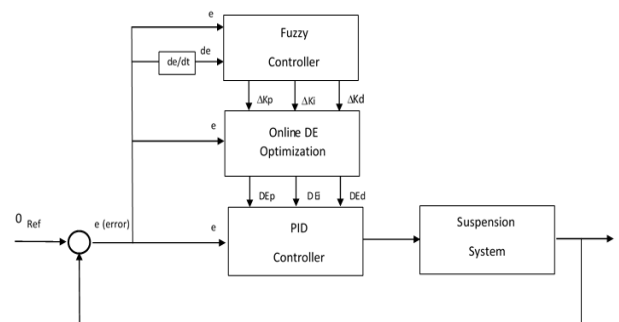

FIGURE 3. The proposed DE online optimization method.

A. DIFFERENTIAL EVOLUTION (DE)

Differential Evolution (DE) nowadays gained massive interest in optimizations and is described as ''The most powerful stochastic optimization algorithm in current use'' [8], [9]. It was first presented in 1995 by Rainer Storn and Kenneth Price as a new stochastic search and optimization method. Its simplicity and easy structure enable it to be used with just a few control parameters. The speedy nature via greedy criterion and robustness are other key features that make DE preferable in fast optimization researches [10]. DE showed successful and good convergence results when compared to other famous Evolutionary Algorithms (EA) and Swarm Intelligence Optimization (SIA). DE scores the top ranks in the EA competitions by IEEE CEC conferences, making it the best optimization algorithm for non-linear and non-differentiable models [8].

B. MODIFYING THE DE FROM OFFLINE TO ONLINE ALGORITHM

DE speeds up the operation of finding the optimum generation of parameter population members by increasing the probability of generating lower values than the current or predicted population individuals. In each iteration, a randomly selected pair of population individuals were compared to find

a weighted difference between them and then added to a third random selected population individual to generate a trail vector. This new vector is compared with the predetermined population individual and replaced if the generated vector is lower than it. In this study, DE is chosen for its ability to find the optimum parameters in a shorter time compared to the other optimization methods [11].

This paper proposes a challenging online optimization method to enhance the MR damper performance without the need to adjust the controller parameters offline to cope with unexpected disturbances. Differential Evaluation (DE) was chosen here because it is characterized by an optimization approach that can give fast convergence in less amount of iterations. The challenging approach in this study is that while driving in rough road conditions, there is not much time for the damper occupied with a classic DE algorithm to optimize the Fuzzy-PID controller; to dissipate the vehicle's unwanted vibration. Therefore, the modified DE method will enhance the output of the intelligent Fuzzy logic online and feed the PID controller with the highest optimization level.

In a conventional DE optimization scheme, the initialization of the parameters is initiated randomly, and the stopping criteria are programmed either with a fixed or predefined number of generations. Here in this proposal, the online DE will use the output parameters of the fuzzy logic and add random numbers for each of them as initial parameters (generation) for the DE optimization process. Moreover, the stopping criteria will stop the DE process if the objective function finds enhancement in any of the optimized parameters (see Figure 4). However, the objective function will evaluate the change in the Integral Absolute Error (IAE) value of vehicle body deflection - remarkably, IAE is famous for weighting the latest errors and transient responses [12]. If the new IAE value is less than the previous IAE value, then the DE will stop iteration and start feeding the PID controller with the enhanced P, I, and D parameters. Meanwhile, if the new IAE value is more or equal to the previous IAE value, then the results of the latest fuzzy logic P, I, and D parameters will be used. In this way, the times of algorithm iteration will be reduced, and the speed of the optimization process will be increased, so the whole process will operate in a real-time – online - environment.

C. FLOWCHART OF THE STUDY METHODOLOGY

In this research, the methodology used is explained as in Figure 4. First, a modified DE was designed and added to the proposed controller. After that, simulation and experimental tests were conducted in this research to prove the enhancement of comfort driving after using the proposed controller. In the simulation test, the proposed controller added to mathematical models represents a 2DOF quarter car model using MR damper in the suspension system. All these parts are implemented into MATLAB's Simulink blocks. Then, the performance of the proposed Fuzzy-DE-PID model was validated with passive and offline Fuzzy-PID models. The results were analyzed to see if there is an improvement in

driving comfort using RMS analysis. A Q-car test rig was fabricated in the experimental test, and the proposed controller was developed using LabVIEW software. The proposed controller was validated with passive and offline Fuzzy-PID controller, and the results were analyzed to see if there is an improvement in driving comfort using RMS analysis. Finally, the simulation test results were validated and evaluated with experimental results.
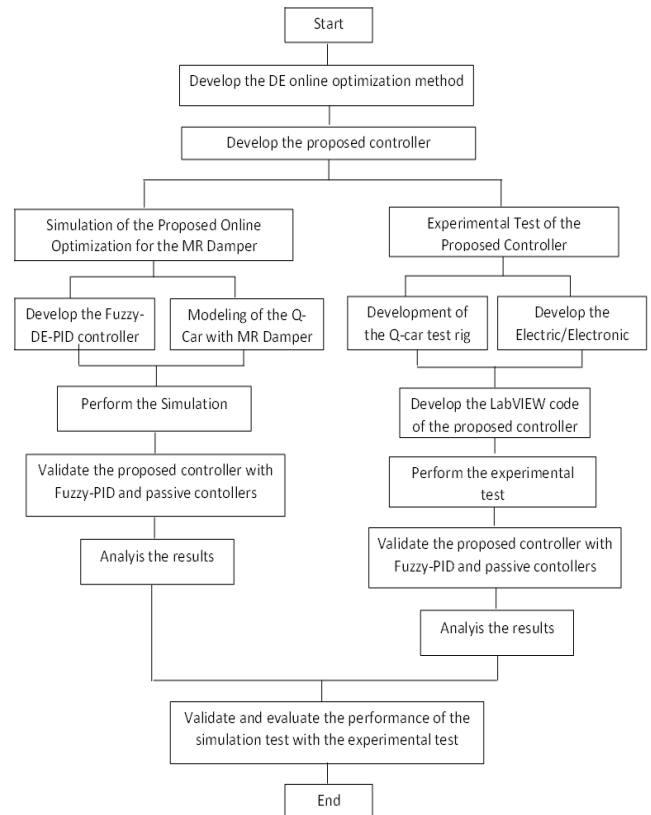

FIGURE 4. Flowchart of the study methodology.

III. QUARTER CAR MODEL OF SEMI-ACTIVE SUSPENSION SYSTEM

The first step in designing an effective suspension system is to model the Semi-Active suspension system. In this paper, two degrees of freedom (2DOF) are used to represent the suspension system of a quarter car model (Figure 5).

By applying Newton's 2nd law of motion to the 2DOF Quarter car semi-active suspension [13, p. 1], the model can be written mathematically as follows:

$$m_s \ddot{x}_s = -c_s \left(\dot{z}_s - \dot{z}_u \right) - k_s \left(z_s - z_u \right) + F_d \qquad (1)$$

$$m_u \ddot{x}_u = c_s \left(\dot{z}_s - \dot{z}_u \right) - k_s \left(z_s - z_u \right) + k_t \left(z_s - z_u \right) + F_d \qquad (2)$$

where,

F_d = MR damper controllable force
$\ddot{z}_s$ = acceleration of sprung mass
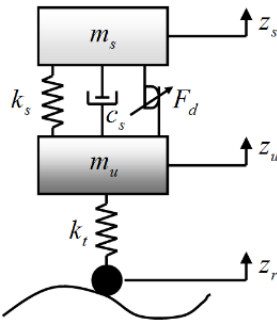$\ddot{z}_u$ = acceleration of unsprung mass

FIGURE 5. 2DOF Quarter car semi-active suspension model [6].

$\dot{z}_s$ = velocity of the sprung mass
$\dot{z}_u$ = velocity of unsprung mass
z_s = displacement of the sprung mass
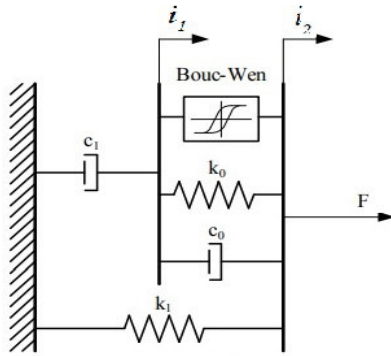z_u = displacement of unsprung mass

FIGURE 6. Modified Bouc–Wen MR damper Spencer model.

This paper uses Spencer's Modified Bouc–Wen mathematical model of MR damper since it is the most popular and accurate differential equation set that successfully represents the MR damper's hysteresis behavior [14], [15]. The hysteresis of the MR damper is a non-linear behavior that causes memory effects in the relation between input and output variables [16]. Spencer's model adds the viscous and linear-elastic components of the damper to the Bouc-Wen model [17] (see Figure 6). Spencer's model contains a set of differential equations called the evolutionary equations that describes the hysteresis property [18] as in the following equations:

$$F = c_1\dot{y} + k_1(x - x_0) \qquad (3)$$

where F is the damping force and yis expressed as:

$$\dot{y} = \frac{1}{(c_0 - c_1)}c_1\dot{y} + [\alpha z + c_0\dot{x} + k_0(x - y)] \qquad (4)$$

z is expressed as:

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

where $\dot{z}$ is an evolutionary variable proposed in the Spencer model [14]

The other variables are expressed as:

$$\alpha = \alpha a + \alpha bu \qquad (6)$$
$$c0 = c0a + c0bu \qquad (7)$$
$$c1 = c1a + c1bu \qquad (8)$$

where:
   k_1 = accumulator stiffness
   c_0 = viscous damping
   c_1 = represents MR damper dashpot
   k_0 = control stiffness at large velocities
   x_0 = initial displacement of k_1
   α, γ, β, and A = parameters to control the shape and scale of the hysteresis effect of the MR damper [19]
Also, in Spencer's model, the voltage and its effect on the damper's viscosity are in representation as in the following relations:

$$\dot{u} = -n(u - v) \qquad (9)$$

where v is the applied voltage and n is the constant proposed by [19].

IV. SIMULATION OF THE PROPOSED ONLINE OPTIMIZATION OF MR DAMPER CONTROLLER

The simulation test helps emulate real-life, expensive, and time-consuming applications in a virtual environment so it can be designed, modified, tested, and evaluated without needing to build it physically. In this paper, the simulation of the proposed online controller model consists of Fuzzy and PID controllers. The fuzzy results were tuned and improved using modified DE to cope with the online requirements for modifying the fuzzy results. The next subsection explains the proposed controllers, starting with how the DE is modified and then how it will help improve the fuzzy results and then injected into the PID controller.

A. DE ONLINE OPTIMIZATION METHOD

The general concept of the DE did not change in our simulation. Still, the DE in our proposed model consists of the normal four stages: initialization, mutation, crossover, and selection. The critical approach in our proposed DE optimization method is that the generation of a new DE population will depend on comparing the Fuzzy output with the last generated population. If it is less in error -IAE value- than the Fuzzy outputs, then the DE will stop generating more population (see Figure 7).

The population for each generation is set to 30, while the dimension of the DE optimization is set to 3 representing the PID parameters. And the Crossover Rate (CR) is set to 0.9, where the Scale Factor (F) is set to 0.1, as in the DE parameters and setting of Table 1 below.

B. DESIGN OF THE FUZZY LOGIC

In this paper, the fuzzy logic design used is the conventional Fuzzy design because the aim is to enhance the Fuzzy logic
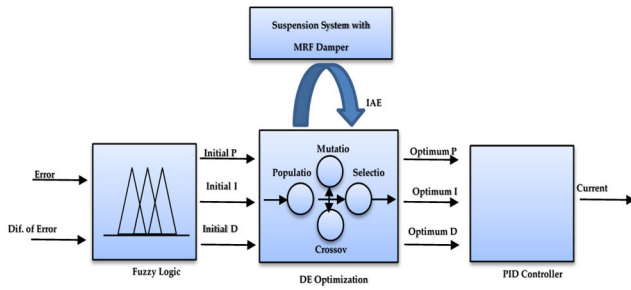
FIGURE 7. The proposed Fuzzy-DE-PID modeling.

TABLE 1. Parameters of the DE.

Parameter	Value
Population	30
Dimension	3
Generation	according to the results
Crossover Rate (CR)	0.9
Scale Factor (F)	0.1

results without the knowledge base. The fuzzy logic construction here contains the conventional three steps fuzzification, inference engine, and defuzzification. In the fuzzification step, the inputs are the error (e) in the displacement of the suspension system - after applying the controller to the suspension system - and the change on the error (de) fuzzified into a fuzzy set, then the fuzzy inference system tunes the output according to the fuzzy rules.

Figure 8 shows the Fuzzy logic input and output design, where the "e" and the "de" are the input, while the outputs are kpf, kdf and kif. The settings used for the inputs and the outputs memberships, which are results of previous trial and error tests to get optimum PID performance are shown in Figure 9 and Figure 10.
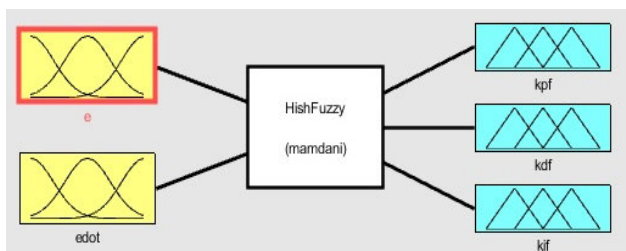

FIGURE 8. Input and the output configuration of the Fuzzy logic system.

The knowledge base used for the fuzzy logic system is represented in IF-THEN rules according to the linguistic rules (Table 2 and Figure 11), where the error "e" is classified into three categories: High, Good, and Low. The derivative of the error (de) is also categorized into Max, Good, and Low according to the (e) and (de) triangular membership design. The output of the Fuzzy logic inference system, the Kp, kd,
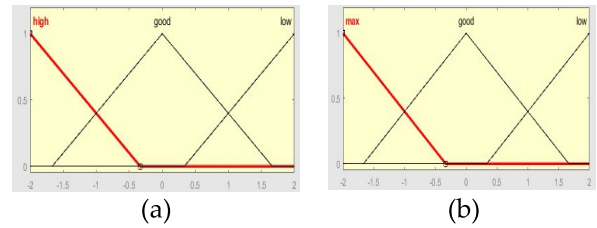

FIGURE 9. Membership settings of the inputs: (a) the error (e); (b) derivative of the error (de).
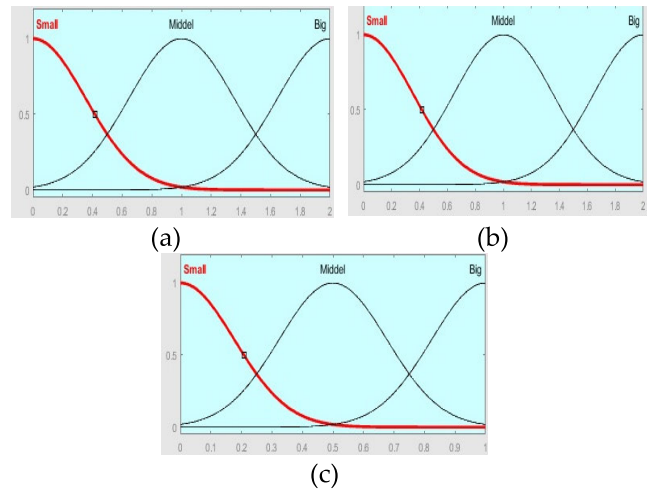

FIGURE 10. Membership settings of the outputs: (a) the Kp factor (Kpf); (b) the Kd factor (Kdf); (c) the Ki factor (Kif).

and ki are distributed to three states Big "B", Middle "M", and Low "L" according to Gaussian membership design.

TABLE 2. Rule based of the Fuzzy algorithm.

e / de	High	Good	Low
High	BBB	BMB	BLB
Good	MBB	MMM	MML
Low	LBB	LML	LLL

C. DESIGN OF THE SIMULATION

The simulation model is applied using Matlab/Simulink (Mathworks, R2017a, Massachusetts, USA). The simulation tests three schemes of suspension models simultaneously (Figure 12). The first one is the proposed online optimization model, the second is the conventional Fuzzy-PID model, and the third is the passive suspension model. So, the results will evaluate the performance of these suspension models and identify any progress occurrence after using the online model.

Figure 13 shows the block diagram of the suspension model for the 2DOF quarter car modeled using Newton's 2nd law of motion. The parameters used for the suspension system
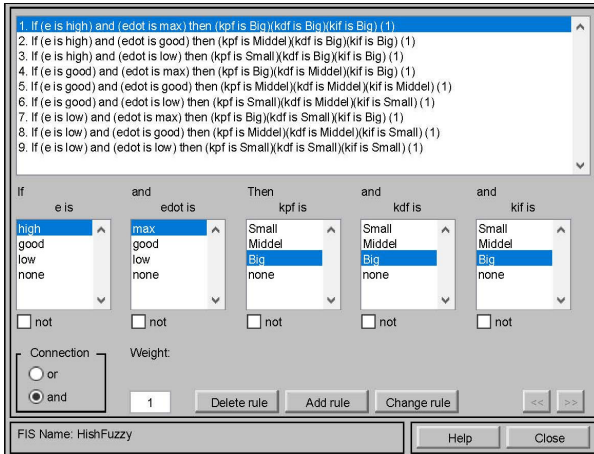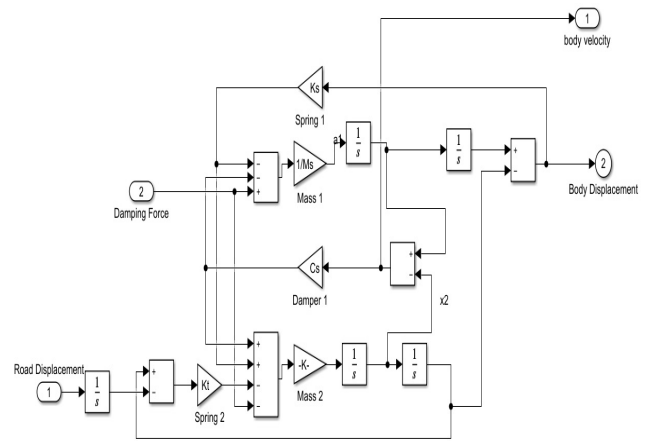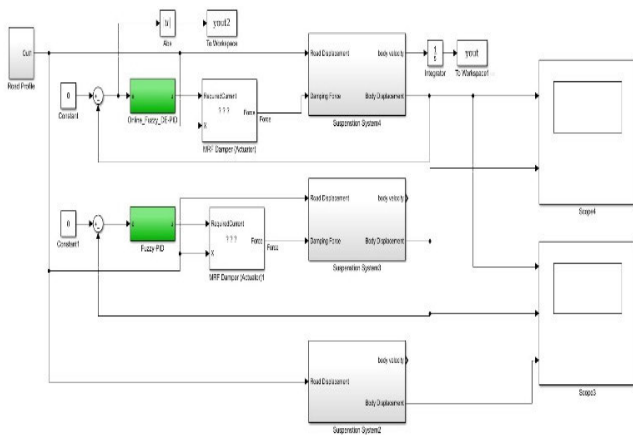
FIGURE 11. FIS membership rules.

FIGURE 12. The MATLAB simulation model consists of Online Optimized Fuzzy-PID, Fuzzy-PID, and Passive Suspension systems.

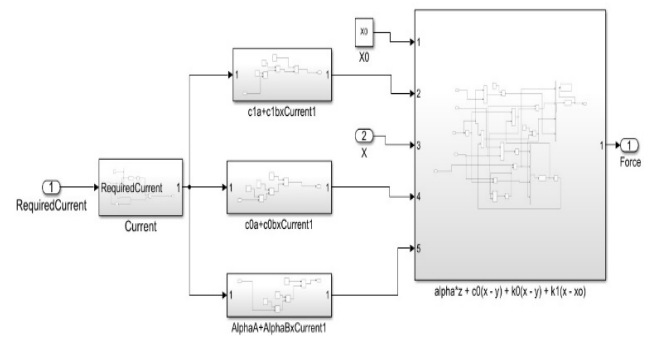**FIGURE 13.** Suspension system modeling.

FIGURE 14. MR damper simulation model.

parameter values are taken from the MR damper prototype as used by Spencer [19] since this paper is concern about improving damper performance and not focuses on the MR damper prototype.

TABLE 4. Parameters of the MR damper [19].

Parameter	Value	Parameter	Value
γ	200	C1a	283
β	200	C1b	2.95
A	207	K0	14
α_a	140	K1	5.4
α_b	695	X0	18.9
$C0_a$	21.0	Viscous Coff.(n)	90
$C0_b$	3.50		

are listed in Table 3. Figure 14 shows the block diagram of the MR damper modeled using the modified Bouc-Wen model, and the model's parameters are listed (Table 4). The proposed online DE will compare the suspension system error with the optimum DE results at each time to help predict the optimum PID parameters.

TABLE 3. Parameters of the suspension system.

Parameter	Value
Mass of the Body (Quarter)	290 kg
Mass of the Tyre	60 Kg
Stiffness of the body spring	16200 N/m
Stiffness of the Tyre spring	191000 N/m
Damper Coefficient	2500 Ns/m
Sinusoidal disturbance Amplitude	9 cm
Sinusoidal disturbance Frequency	2 Hz
Random disturbance Amplitude	9 cm

As indicated earlier, the MR damper mathematical model used in this paper is Spencer mathematical model. Also the

V. EXPERIMENTAL TEST OF THE PROPOSED ONLINE OPTIMIZATION OF MR DAMPER CONTROLLER

In this study, the experimental setup of the controller is built as in Figure 15. As seen in Figure 16, the quarter car test rig consists of one wheel with tyre pressures of 40psi (2.7 bar), springs with a stiffness of 15000N/m, MR damper with damping coefficients 418N-s/m to 673N-s/m, and carriage for carrying the load. The specifications of the test rig are

listed in Table 5. The test rig's shaker represents the road input and consists of a real vehicle tyer on a plate that can travel vertically up and down by a pneumatic cylinder mounted on the bottom of the plate. The air on the pneumatic cylinder is controlled by using a 3-2 way solenoid electric valve, which is used to generate the required vibration - road disturbance – on the tyer and the body according to the signals generated from the LabVIEW code. The LabVIEW code is programmed to send a control signal to the 3-2 way valve and also to read data from the accelerometer sensors installed on the test rig body and the tyre by using NI-SCC68 connector block. The LabVIEW code also can read the MR damper's vertical movement by LVDT linear displacement sensor attached to the MR damper.
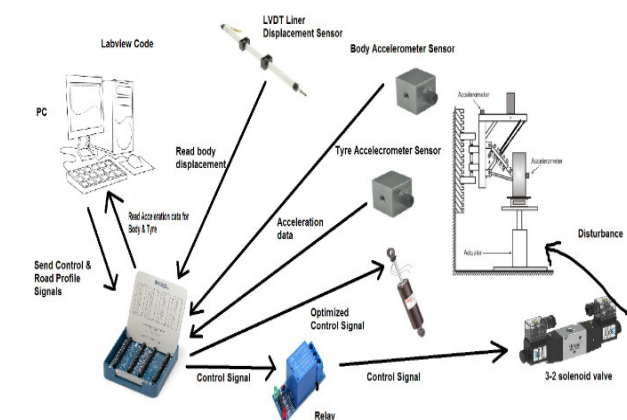

FIGURE 15. Experimental setup of the Proposed controller with Q-car test rig.

The damper used in this experiment is the MR damper (RD-8041-1) from Lord Corporation. The internal damper containers are: the rod, coil, piston, lead, damper cylinder filled with MR fluids, and accumulator. The whole length of the damper is 248 mm, and its body Diameter is 42.1 mm. more details of the MR damper specifications are listed in Table 6

TABLE 5. Parameters of the test rig.

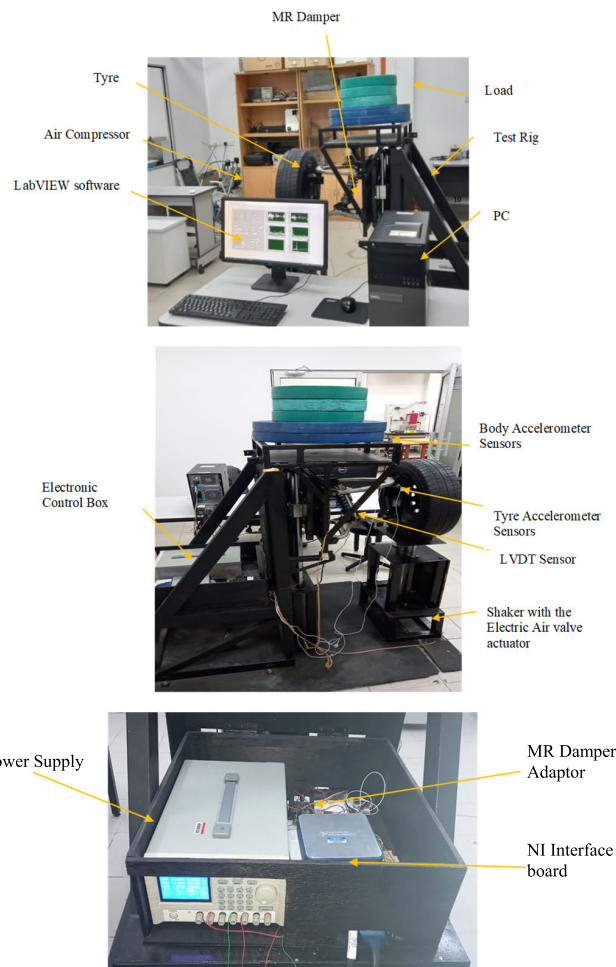| Parameter	Value
Mass of the Body (Quarter)	150 kg
Mass of the Tyre	73 Kg
Stiffness of the body spring	20750 N/m
Stiffness of the Tyre spring	150000 N/m
Damper Coefficient	635 Ns/m
Sinusoidal disturbance Amplitude	9 cm
Sinusoidal disturbance Frequency	2 Hz
Random disturbance Amplitude	9 cm

FIGURE 16. Experimental test rig components.

TABLE 6. Lord MR damper typical properties.

Model No.	RD-8041
Stroke,(mm)	74
Extend length, (mm)	248
Body diameter, (mm)	42.1
Shaft diameter,(mm)	10
Tensile strength, N	8896
Damper force, N 5 cm/sec @ 1A 20cm/sec @ 0A Operating temperature,	>2447 <667 71 max

The spring used in this experiment is attached with an MR damper to support the body. Its stiffness is estimated as 20,750 N/m, and the damping coefficient of the sprung part was estimated as 635 N/m [20].

The tyre used in this experiment is SP Sport J5 155/70 R12 from Dunlop [21], which has 155mm width and 73 Kg and the tyre's stiffness is estimated to be 150 kN/m [22].

The experimental controller was programmed using NI LabVIEW 2016 (32-bit) installed on Dell OptiPlex 7010 with Intel i7-3770 CPU @ 3.40GHz processor, RAM 8 GB, and Windows 10 pro operating system.
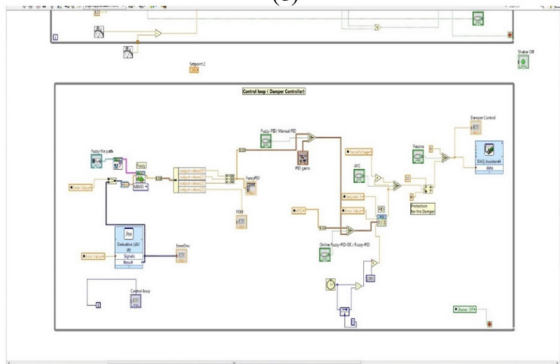
The graphic user interface (GUI) of the LabVIEW code contains many options to control the MR damper and the shaker performance. Also, there are graphs representing the data collected from the sensors installed on the body and the tyer of the test rig, see Figure 17.(a).
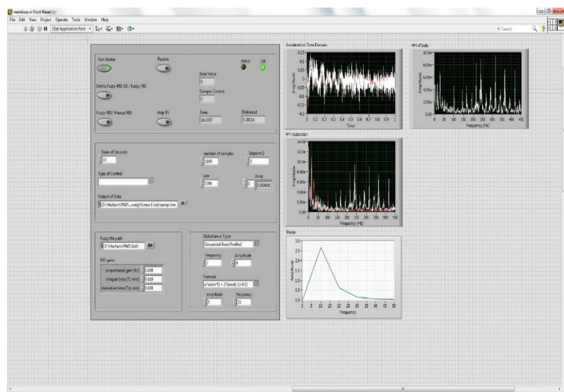
(a)
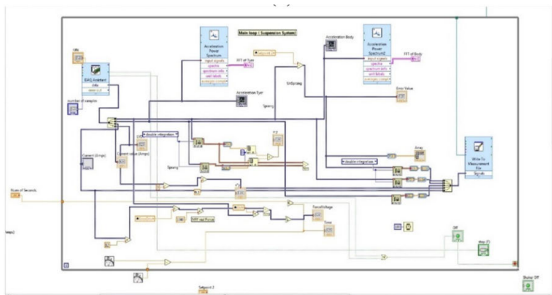
(b)

(c)

FIGURE 17. LabVIEW code containing: a) Main GUI Screen, b) Main loop, c) Control loop, d) Disturbance loop.

Using this GUI screen, the experiment settings can be adjusted easily, and the data collected from the experimental test rig can be monitored. In the LabVIEW code – see

Figure 17.(b) and (c) - there are three loops; the main loop reads the acceleration and displacement data from the test rig's sensors. A second loop contains the DE, Fuzzy-PID, AFC codes, and a third loop contains codes for generating the sinusoidal and random disturbance signals.

The sequence of running the code is as the following:
1) Choose the controller mode (passive, Fuzzy-PID or Fuzzy-DE-PID).
2) Choose the disturbance type (Random or Sinusoidel)
3) Can adjust the time of running and also the frequency of the disturbance.
4) Chose the file location to save the recorded data.
5) Choose the ''Run Shaker'' option to run the shaker.
6) Run the code from the LabVIEW run button.

Once the code runs, the disturbance code will send the signal with pattern to the shaker airvalve, and the tyer will move up and down in a sequence according to the disturbance signal pattern. The graphs will show the current status of the accelerometer sensors and the LVDT sensor according to the data collected. This sequence can be repeated using the Fuzzy-DE-PID, Fuzzy-PID, and the passive controllers, and the data collected from the sensors will be saved each time for each controller.

In this study, many tests were conducted for the Fuzzy-DE-PID, Fuzzy-PID, and passive controllers. The data collected from each controller was compared and analyzed statistically using MATLAB codes, the results illustrated in the following section.

VI. RESULTS AND DISCUSSION

This section lists the results of simulation and experimental tests for optimizing the Fuzzy-PID controller using the proposed modified DE, compared to the results of Fuzzy-PID and passive system tests.

A. SIMULATION RESULTS OF TESTING FUZZY-PID CONTROL SCHEME TUNED USING EVOLUTIONARY ALGORITHM

This section contains the simulation results after applying the proposed online optimization model to the 2DOF semi-active suspension systems of the MR damper. The results showed improvement in reducing the body vibration, proving the effectiveness of the proposed online optimization of the Fuzzy-PID controller in enhancing the performance of the semi-active suspension systems.

B. SIMULATION RESULTS

After applying the proposed fuzzy-DE-PID controller to different sinusoidal vibration settings (4 cm, 8 cm, and 12 cm), and random disturbances, the results were compared with Fuzzy-PID, the passive system. The suspension system travel, and the results were plotted and analyzed using MATLAB software in time and frequency domain terms.

In the time domain analysis - as seen in Figure 18 - the suspension travel response controlled by the proposed Fuzzy-DE-PID shows superiority over the offline optimized and
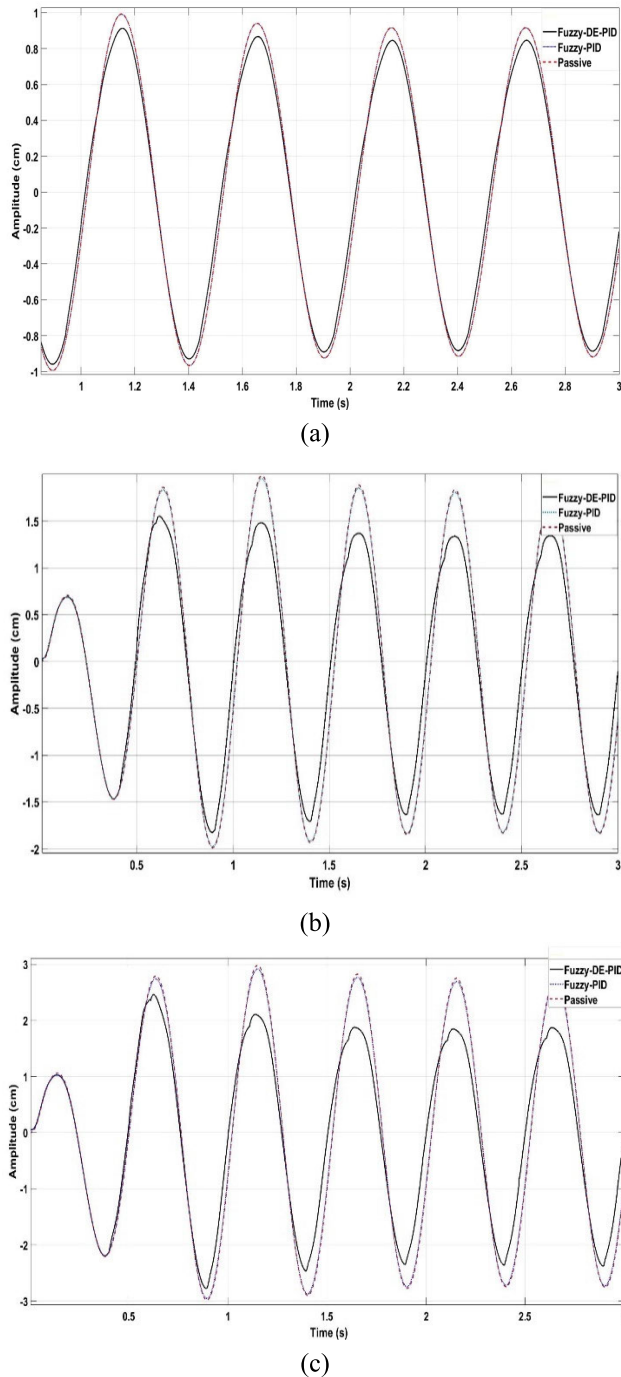
(a)

(b)

(c)

FIGURE 18. Time response of the suspension travel for the Fuzzy-DE-PID, Fuzzy-PID, and the passive system using sinusoidal disturbance at: (a) 4 cm, (b) 8 cm, and (c) 12 cm.

passive models in three different sinusoidal amplitudes (4 cm, 8 cm, and 12 cm). These results showed that the modified DE had a notable effect, improved the Fuzzy-DE-PID performance, and enhanced the suspension travel response better than the Fuzzy-PID controller passive suspension. Also noted from these results, the increase in the disturbance amplitude leads to an increase in the proposed controller performance.

Noted also that the results did not exceed the constraints of $\pm 0.1m$ as per [23] recommended. It is worth knowing that the Fuzzy-DE-PID and Fuzzy-PID models have the same Fuzzy design and membership functions.

Figure 19 shows very clear vibration dissipation - after converting the time domain results into the frequency domain - and supports the superiority of the proposed Fuzzy-DE-PID controller in scoring less vertical vibration compared to the offline optimized Fuzzy-PID and the passive suspension controllers.

Another evidence of the superiority of the proposed model when applying random disturbance is shown in Figure 20. Astonishingly, the proposed Fuzzy-DE-PID scored a better response than the other models illustrated in the improvement of the suspension road control in dissipating the vibration. The results converted to a frequency domain and showed enhancement of the suspension system performance where the proposed model scored less vertical vibration, as seen in Figures 21 and 22.

1) SIGNIFICANT DIFFERENCES APPROVED STATISTICALLY

After using the proposed Fuzzy-DE-PID, a comparison to the other controllers studied in this paper. The Root Mean Square (RMS) of the vehicle's body acceleration in sinusoidal and random disturbances was calculated to identify if there are tangible improvements in driving comfort. [24] over the offline optimized Fuzzy-PID and the passive models.

TABLE 7. Results of calculating the vehicle's body acceleration RMS for the different test settings.

Road profile	Fuzzy–DE-PID	Fuzzy-PID	Passive
Sinusoidal 4 cm	2.539e^{-1}	3.223e^{-1}	3.244e^{-1}
Sinusoidal 8 cm	8.050e^{-2}	8.419e^{-2}	5.218e^{-1}
Sinusoidal 12 cm	1.0591	1.0669	5.1274
Random	0.1082	0.1131	0.1191

TABLE 8. Improvement percentage of ride comfort for the suspension system after using the Fuzzy-DE-PID in sinusoidal and random road disturbance.

Road profile	Fuzzy-PID	Passive
Sinusoidal 4 cm	21%	22%
Sinusoidal 8 cm	4%	85%
Sinusoidal 12 cm	1%	79%
Random	4%	9%

From Table 7, the proposed online optimization of the Fuzzy-PID model scores less RMS value than the offline
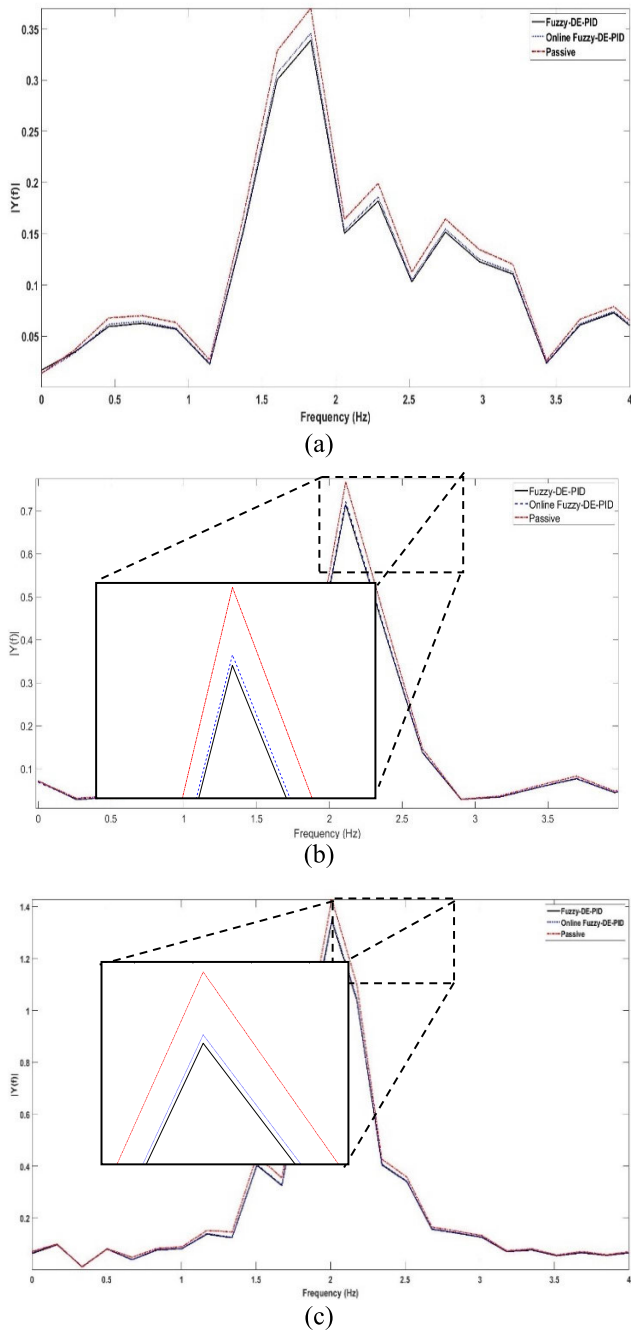
(a)

(b)

(c)

FIGURE 19. Frequency response of the suspension travel for the Fuzzy-DE-PID, Fuzzy-PID, and the passive system using sinusoidal disturbance at: (a) 4 cm, (b) 8 cm, and (c) 12 cm.
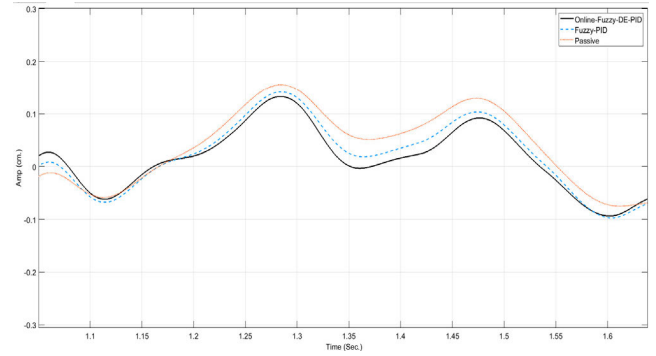

FIGURE 20. Time response of suspension travel for the Fuzzy-DE-PID, Fuzzy-PID, and the passive system using random excitation road profile.
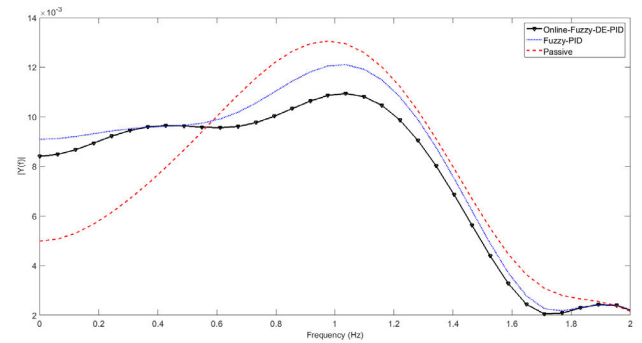

FIGURE 21. Frequency response of suspension travel for the Fuzzy-DE-PID, Fuzzy-PID, and the passive system using random excitation road profile.
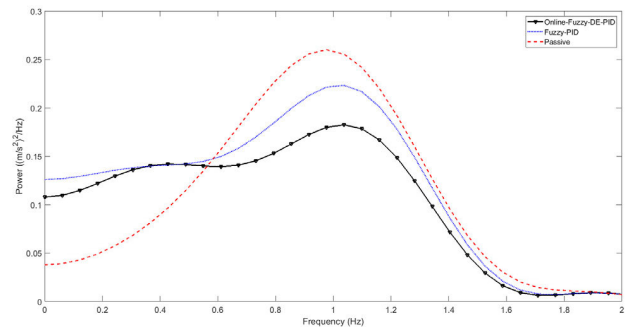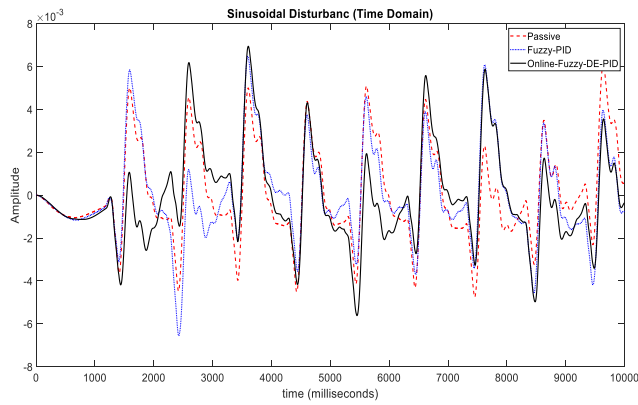

FIGURE 22. Time domain results for the sinusoidal test clarify the improvement after using the Fuzzy-DE-PID controller. (a) 4cm, (b) 8m, (c) 12m, amplitudes.

optimized fuzzy-PID and the passive. In Table 8, the proposed controller achieved a higher improvement percentage than the offline optimized Fuzzy-PID model, which presents evidence that the proposed optimization method can improve online dissipating road uncertain disturbances without needing previous knowledge. Table 8 shows that the percentage scored in this model can be considered a good score according to [25], who stated that the percentage range of RMS reduction usually is from 4.6% to 9.01%. Moreover, according to ISO 2631-1:1997 standards, the RMS values recorded in these

tests are considered as ''Not uncomfortable'' ride comfort level as it is less than 0.315 (m/s2) [26], [27], [28].

C. EXPERIMENTAL OF FUZZY-PID CONTROL SCHEME TUNED USING EVOLUTIONARY ALGORITHM

In the experimental test, the proposed Fuzzy-DE-PID controller on the quarter car test rig was evaluated with the Fuzzy-PID controller and the passive suspensions system. This section lists the sinusoidal and random test results represented in time and frequency domains to investigate the system's dynamic response. Then a statistical analysis of these results
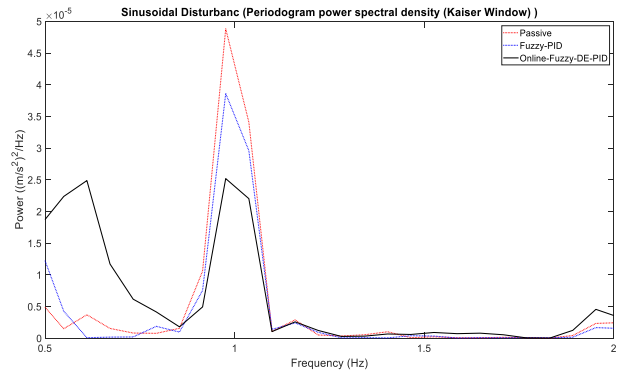
(a)
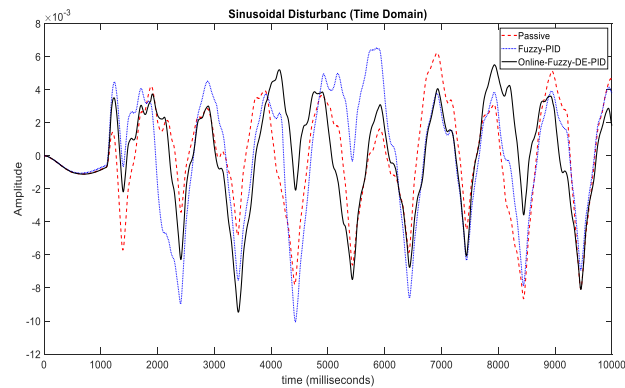
(b)
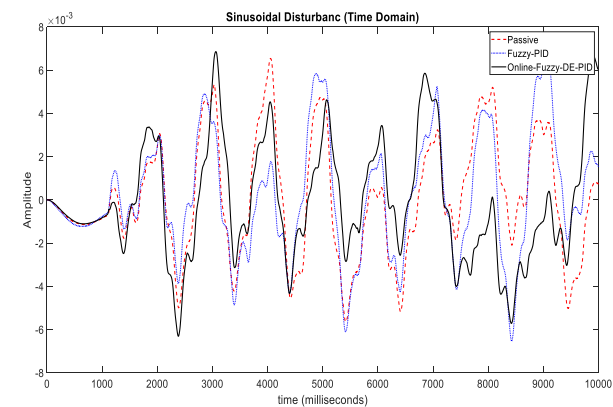
(c)

FIGURE 23. Frequency domain results for the sinusoidal test clarify the improvement after using the Fuzzy-DE-PID controller in (a) 4 cm, (b) 8 m, (c) 12 m amplitudes.
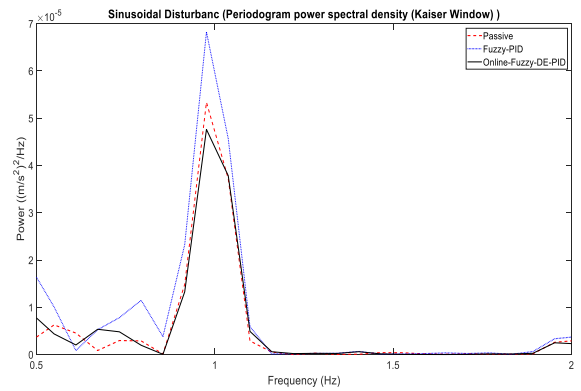

(a)

(b)

(c)

FIGURE 24. Power Spectral Density (PSD) Frequency response of suspension travel for the Fuzzy-DE-PID, Fuzzy-PID, and the passive system using random excitation road profile.

was also conducted to prove the effectiveness of applying the proposed controller on the quarter car test rig.
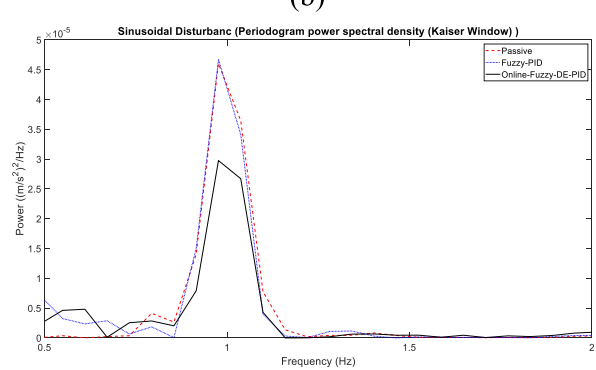
1) TIME AND FREQUENCY DOMAIN RESULTS

Figures 23 and 24 show that the Fuzzy-DE-PID had notable decreases in the suspension travel responses in the 4 cm, 8 cm, and 12 cm sinusoidal road profiles tests compared to

the Fuzzy-PID and passive controllers. These results mean that the Fuzzy-DE-PID has achieved minor discomfort riding than the other controller's schemes.

Figures 25 and 26 show that the Fuzzy-DE-PID controller improved the suspension system control in random road profile conditions more than the Fuzzy-PID controller and passive controllers. This result indicates that the modified DE scheme effectively enhances the Fuzzy-DE-PID controller performance, which is demonstrated clearly in the time and frequency domain graphs.
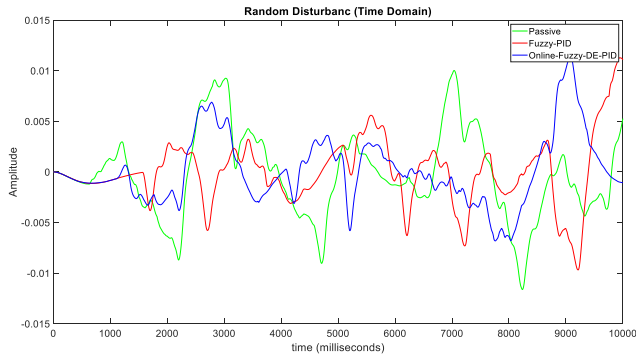
FIGURE 25. Time domain results for the random test clarify the improvement after using the Fuzzy-DE-PID controller.
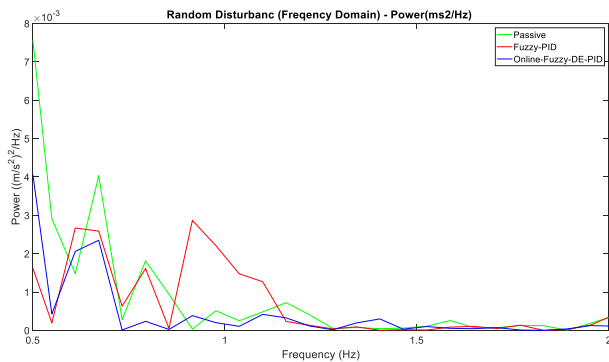

FIGURE 26. Frequency domain results for the random test clarify the improvement after using the Fuzzy-DE-PID controller.

2) SIGNIFICANT DIFFERENCES APPROVED STATISTICALLY

Table 9 's results show that the Fuzzy-DE-PID's RMS is less than the Fuzzy-PID and the Passive suspension system. These results prove that using the Fuzzy-DE-PID has improved riding comfort more than the other controllers and verify that the modified DE gives the proposed Fuzzy-DE-PID controller more robustness. Moreover, The Fuzzy-DE-PID has more ride comfort even in the random road condition than the other controlling schemes.

TABLE 9. Results of calculating the vehicle's body acceleration rms for the different test settings.

Road profile	Fuzzy-DE-PID	Fuzzy-PID	Passive
Sinusoidal	1.596e-08	3.237e-08	3.237e-08
Random	2.153e-08	6.551e-10	1.53e-08

VII. CONCLUSION

In conclusion, the proposed online optimization using a modified Differential Evolution (DE) proved in a simulation and an experimental test improvement on the Fuzzy PID controller results without the need for previous knowledge to rebuild the fuzzy logic rules or to modify the Fuzzy logic design.

This holds true even in a challenging process like real-time activity, where there is a very short time for calculating and predicting the optimum controller's parameters. The proposed method uses Fuzzy results as a base for modified DE optimization to feed the PID controller with the best PID gains online. Simulation and real-time experimental tests were conducted on the proposed controller and compared with Fuzzy-PID and passive system to prove its efficiency and reliability. Both tests recorded better ride comfort than the Fuzzy-PID and passive system control schemes. Moreover, according to ISO 2631-1:1997 standards, the RMS values recorded on these tests are considered as "Not uncomfortable" ride comfort level as it is less than 0.315 (m/s2).

This modified DE algorithm can be used in future work on advanced motion control applications which need a fast decision, such as mobile robots' motion control [29], [30].

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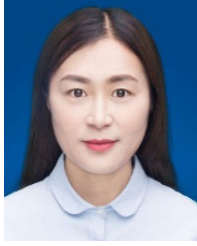
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