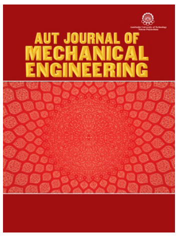

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A hybrid optimal-base fuzzy-proportional-integral-derivative controller for vibration mitigation of structural system against earthquake

S. M. Hadad Baygi*

Department of Electrical Engineering, Khorasan Institute of Higher Education, Mashhad, Iran

ABSTRACT: This paper proposes an experimental investigation of a four-story structure that is connected to a shaking table. The investigated shaking table is designed with a particular method to produce any kind of vibration amplitude. Also, the whale optimization algorithm is used for the identification of the experimental structure parameters such as mass, stiffness, and damping to show the adaptation of the results collected from the identified model on the results achieved from the linear model. The other idea of this paper is to suggest a novel control strategy that is established by combining proportional-integral-derivative and fuzzy logic control, using an optimization procedure called whale optimization algorithm for optimum tuning of controller coefficients, the hybrid control method is designed. The main objective of the hybrid optimal-based fuzzy-proportional-integral-derivative controller is to reduce the displacement of isolation system without allowing a significant increase in the acceleration of superstructure for both far-field and near-field earthquake excitations. The proposed control algorithm is designed and developed on a four-story shear frame, which contains an active tuned mass damper on each level. Numerical simulations show that the proposed controller which is a combination of two controllers better mitigates the seismic responses of a smart structure excited by a range of real-data earthquakes. .

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1- Introduction

Earthquakes and also natural hazards such as strong storms always cause serious damages to the structures. The scientists have concerns about this issue and always research how to decrease these structural responses of the structures due to a seismic situation. The last four hazard earthquakes, such as El Centro, Petrolia Cape, Athens, and Northridge, brought undeniable, irrecoverable, and destructive harms to the multi-degree of freedom structures. One of the engineers' important affections when designing a building is to minimize the risk of damage sustained as much as permissible by impact loadings such as earthquake shaking and severe winds. The concept of fuzzy systems had first proposed by Zadeh [1] in 1965. Fuzzy control profits and aids such as using heuristic knowledge in its rules and flexibility causes the researcher to use this technique for designing and developing effective controllers to solve complex systems [2-4]. The Fuzzy Logic Control (FLC) has been applicable in control systems such as robotic control, automated machines [5-7], and active and semi-active vibration attenuation of buildings against seismic excitation [8-9]. Active structural vibration is commonly controlled by the use of intelligent techniques [10] or by adding dampers and actuators on the buildings' floors [11]. In recent decades, base isolation has been the most common technique found for preserving structures and filling them with destructive effects devastating results. However, recent research shows that Near-Field (NF) earthquakes result in significant deformations at the isolator of the structure due to their long-lived vibrations with peak velocities. As an instance, in reference [12], the authors presented a hybrid control scheme for vibration mitigation of a base-isolated building, which is equipped with MR dampers. The suggested control method was a combination of two other controllers, namely LQR and Model Reference Adaptive Control (MRAC). Fu and et al. [13] addressed a new kind of fuzzy logic system for a nonlinear structure. The controller was a self-tuning fuzzy logic controller. Furthermore, in the age of hybrid controllers, the use of single control methods is widespread and simple. Taking into consideration of uncertainties in structural parameters is one of the most important factors in the field of structural control. Miah et al. [14] presented a simple control method, namely LQR control for reducing the structural responses of a structure that is equipped with a combination of passive base isolation and active structural control. Although they did not consider uncertainties. The fuzzy logic controller is one of the widely used methods in the case of vibration control [15-18]. The application of fuzzy logic in the hybrid control system was considered because of the use of human knowledge in the heart of systems [19]. Also, in recent years, the researcher introduces a new kind of fuzzy logic for evaluating the

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*Corresponding author's email: m.hadad92@yahoo.com performance of the structures under earthquake excitations. Awruch and et al. [20] addressed a new optimization procedure, namely fuzzy α-cut optimization analysis, to reduce the displacement and acceleration of the structure. Although did not consider uncertainties, the suggested method was applied to a structure that is equipped with piezoelectric dampers. The application of type one and two fuzzy logic for reducing the structural responses of the building is examined in the study of Bathaei et al. [21]. In terms of preventing a steady-state malfunction, stability, reliability towards model uncertainties, and strong disturbance elimination, Fuzzy-PID controller operates better than a fuzzy controller. Tuned Mass Damper (TMD) is one of the popular and widely encountered mechanical and dynamic distortion control devices. A TMD is typically composed of a mass, spring, and dash-pot. The TMD frequency is also often adjusted to a resonance frequency similar to the key building's first regular frequency [22]. The uncertainties in dynamic equations make it tough to get a reasonable estimate of a building's inherent vibration frequency, although it can also modify during significant earthquake excitation. In addition, TMDs are efficient in raising structural response within a limited range of load deviations. This is proposed that Active Tuned Mass Damper (ATMD) systems transcend those deficiencies. We have also drawn a wide body of work in the field of vibration mitigation of structural systems [23-24]. Fuzzy-PID controller's desirable performance in terms of load disturbance elimination, versatility, and robustness in coping with model uncertainties has resulted in enthusiasm in the potential of reaping the benefits of this controller in the area of control of the seismic-excited structures. No research work, to the best of the authors' knowledge, has been stated on the seismic control of the infrastructure conFig.d with ATMD, given the stronger efficiency of the Fuzzy-PID controller than the regular fuzzy controller in the area of seismic control. An actuator mounted between both the ATMD device and the base framework provides a simulated control force in live time to the ATMD in a structure conFig.d with ATMD, as an intelligent architecture, and its response is implemented to the main structure. A set of sensors and a control mechanism are required to prove the scale of the control force at any particular time. The proposed control methodology plays a major role in enhancing the building's seismic efficiency. The controller's optimal design issues related to seismic structure control have several local optimums and involve a lookup on a large small scale. The methodology was used for semi-active control of a structure. However, active control methods for vibration control of buildings are much more reliable than other strategies. Golnargesi et al.[25] addressed a kind of fuzzy system for vibration mitigation of buildings with attached ATMD on its floor. The designed fuzzy system was unable to consider the uncertainties in its rules, to reduce the structural response of the building, uncertainties in building parameters were not considered. To reduce the structural responses, the application of meta-heuristic algorithms for optimum tuning of PID controllers was considered [26]. Also, the PID controller with a good tune in its parameters plays a major role in the hybrid control systems. However, the controller s verified on a two-story shear frame. Also, Hadad Baygi and Karsaz [27] examined the application of meta-heuristic methods for active vibration control of a building that is equipped with ATMD. The controller was PID-LQR. Furthermore, the authors did not consider uncertainties in building parameters. Etedali et al.[28] presented a fractional order PID controller for active control of a smart structure with an active tuned mass damper attached to the last floor. Fukushima et al have proposed an active-passive concrete modified mass damper with the intention of reducing the vibrations of skyscrapers caused by wind and earthquake [29]. While there are multivariate unknown variables in building structures and the system parameters are not stable, there are various control solutions available for the active dynamic control [30]. Fuzzy logic is often used in systems where system dynamics is either very complex or exhibit a nonlinear character. Since the structural model has uncertainties, fuzzy-PID controllers are suitable control algorithms. In the age of the hybrid controller in the field of structural control, the best controller is the one who can reduce the structural response of the structure due to an earthquake. However, the last research and articles in this field which used FLC and classical PID did not consider the uncertainties and variation in building parameters such as, stiffness, mass, and damping coefficient, in this study the authors had inspired to design a new generation of hybrid controller which deal with uncertainties in the parameters related to the structure.

We propose a new hybrid PID and fuzzy logic control architecture to mitigate the vibration of a structure due to an earthquake, making the following contributions:

The proposed algorithm combines two methodologies into one architecture synergistically.

The major aim of our paper is to guarantee the hybrid control system to be stochastically stable with a PID performance index by restricting the hybrid control effort into stable margins.

To reach better performance indices in presence of uncertainties, a fuzzy logic algorithm with intelligent adaptation capabilities is used.

Because the fuzzy logic controller is used when the structural vibration is within the stable margins, the stability of the perturbed system with better performance is guaranteed.

A real-time shaking table with a frequency control system has been made that can produce various kinds of earthquake acceleration.

An experimental structure has been made in the structural dynamic lab and different results of the experimental model have been presented in this paper.

Because of the mentioned reasons, this paper suggests a new method, which is a combination of fuzzy logic control and common classical PID. By the use of differential evolutionary algorithms, the PID section of the proposed controller is tuned. The problem of variation in building parameters and effect of this reform in mass, stiffness, and damping coefficient are considered in the performance of hybrid Whale Optimization Algorithm (WOA)-base fuzzy-

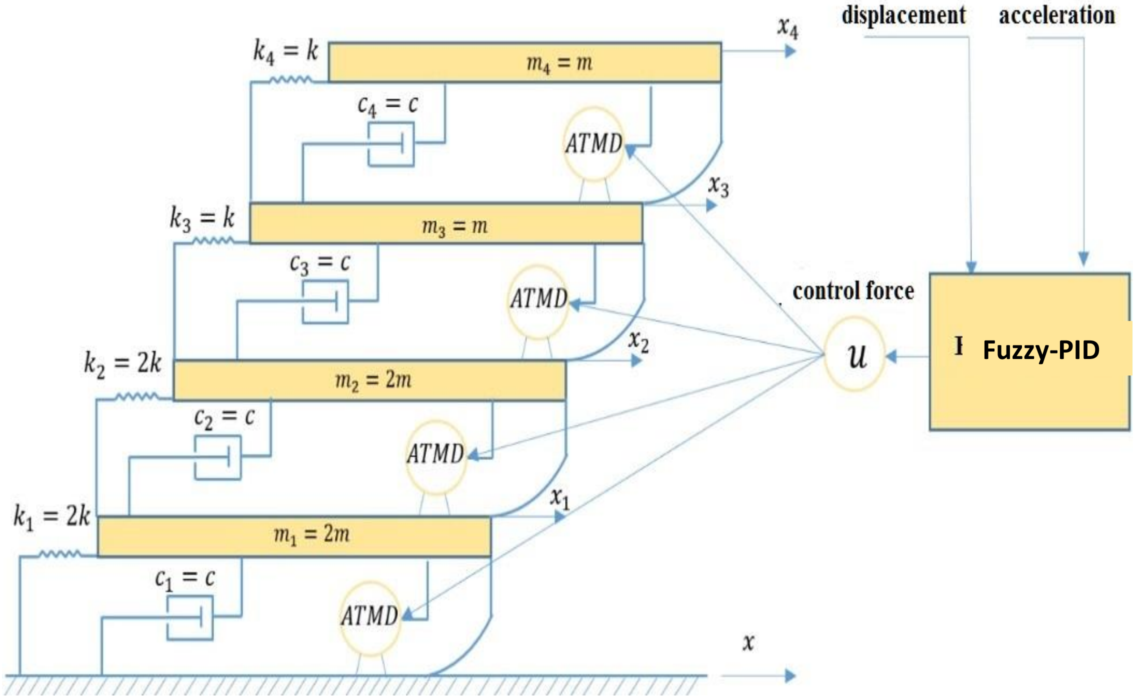

Fig. 1. The model of the structural system

PID controller in decreasing the amplitude of displacement and acceleration of each floor level of the building due to an earthquake.

2- The dynamic model of the structure

The mathematical and algebraic equations of movement of the benchmark structure concerning earthquake ground acceleration can be defined as below [27]:

$$M\ddot{q}+C\dot{q}+Kq=f_e \tag{1}$$

where, q , M , C , K are movement vector, the matrix of masses, the matrix of the damping coefficient and the matrix of stiffness coefficient, and also f_e is the earthquake force vector. The model of a four-story building is shown in Fig. 1. Considering an intelligent structure, the vector of required control forces, $u(t)$ is getting into the algebraic equation of movement of the building. So, the dynamic equations for an intelligent structure can be rewritten as follow [27]:

$$M\ddot{q}+C\dot{q}+Kq=f_e+Du(t) \tag{2}$$

where D is the location matrix for the required control forces.

The state vector of the selected system is appointed by considering the physical behavior of the structural system. So, the vector $x(t)$ can be written in the following form:

$$x(t)=[q(t)^T \quad \dot{q}(t)^T] \tag{3}$$

Therefore, the dynamic equilibriums of movement of the structure in the state space form can be defined as:

$$\dot{x}(t)=Ax(t)+Bu(t)+FW(t) \tag{4}$$

where the state $x=[q^T \quad \dot{q}^T]$, is displacement and velocity of each floor level, u is control input, w , is disturbances which are earthquake signals, and z , is output observation vector. By considering uncertainties in building parameters and disturbances, Eq. (4) with uncertainties can be rewritten in the following form [27]:

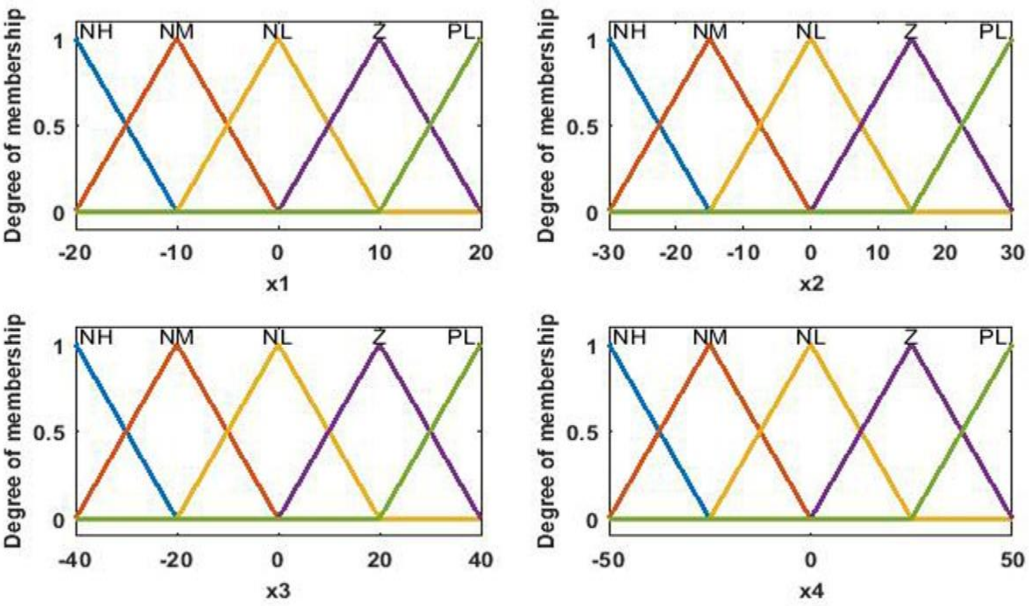

Fig. 2. Fuzzy input membership function include displacement of the first floor to the last floor of the building

Table 1. Fuzzy roles between input and output in the fuzzy control part of the proposed method

Rule number		$x_1(m)$	$x_2(m)$	$x_3(m)$	$x_4(m)$		u_1	u_2	u_3	u_4
1		NH	NH	NH	NH		PH	PH	PH	PH
2		NH	NH	NH	NH		PH	PH	PH	Z
.		.	.	.	.		.	.	.	.
.		.	.	.	.		.	.	.	.
.	if	.	.	.	.	Then	.	.	.	.
.		.	.	.	.		.	.	.	.
.		.	.	.	.		.	.	.	.
.		.	.	.	.		.	.	.	.
624		PH	PH	PL	Z		NH	NH	NH	NH
625		PH	PH	PH	PH		NH	NH	NH	NH

$$\begin{aligned}\dot{x}(t) &= (A+\nabla A)x(t)+(B+\nabla B)u(t)\\ &\quad +F(I+\nabla F)w(t)\\ A &= \begin{bmatrix}0 & I\\ -D_k & -D_c\end{bmatrix},\ \nabla A=\begin{bmatrix}0 & I\\ -\nabla D_k & -\nabla D_c\end{bmatrix},\\ B &= \begin{bmatrix}0\\ B_u\end{bmatrix} \quad ,D_k=M^{-1}K \quad ,D_c=M^{-1}C\\ \nabla B &= \begin{bmatrix}0\\ \nabla B_u\end{bmatrix} \quad ,F=\begin{bmatrix}0\\ F_w\end{bmatrix} \quad ,\nabla F=\begin{bmatrix}0\\ \nabla F_{fw}\end{bmatrix}\\ C &= \begin{bmatrix}c_1 & c_2\end{bmatrix}\end{aligned} \tag{5}$$

The disturbance vector $W\ (t)$ would include the earthquake forces.

3- Fuzzy control

In order to mitigate the structural responses and fluctuations into the stable level, fuzzy logic control is used. The fuzzy part of the proposed method is Mamdani, which have four input and also four output [1, 31]. The inputs of the fuzzy logic controller are shown in Fig. 2 where all of them are displacement vector of each floor concerning the ground (which is zero), i.e., $q(t)\text{-}q_{ref}(t)$ and also Fig. 3 shows the output of the fuzzy controller which is the control forces $u(t)$. From the physician's experience and considering the displacement of each floor, 625 Fuzzy rules are defined to establish a connection between input and output of the fuzzy system.

The selected fuzzy rules for this study are shown in Table1. In this table, the symbol N denotes Negative, Z, denotes Zero, P, displays Positive B, H, M, and L respectively denotes Big,

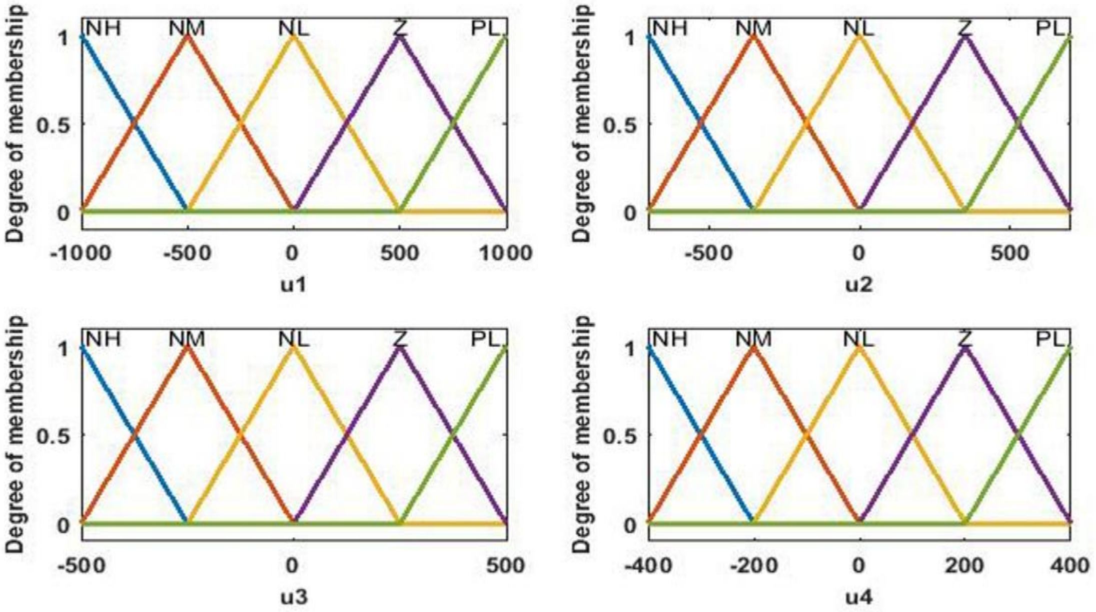

Fig. 3. Fuzzy logic control output membership function includes required control forces for each floor were demonstrated by u_i

High, Medium and Low. It is well known that for frequency responses, the first mode is the most dangerous for structures, and the maximum displacements are expected the top story of structures during earthquake excitation.

As an instance, one of the if-then Fuzzy rules can be defined as follow: If $x_1 = NH \text{ and } x_2 = NH \text{ and } x_3 = NH \text{ and } x_4 = NH$ Then$u_1 = PL \text{ and } u_2 = PL \text{ and } u_3 = PL \text{ and } u_4 = PL$. This means that if the displacement is Negative High (NH), then the force would be Positive Low (PL).

4- PID controller

PID control is one of the most important and widely practiced control algorithms which play a massive and useful role in the industry [29-32]. The critical feature of the PID controller, which makes it famous among engineer and engineering problems is the robustness and simplicity in performing. The general equation of the PID controller is as follows [30]:

$$u_{PID}(t) = K_P e(t) + K_I \int e(t)dt - K_D \frac{d}{dt} y(t) \qquad (6)$$

where: $e(t) = x_{ref}(t) - x(t)$, x_{ref} illustrate the displacement of the building's floors at the initial time, during an earthquake disturbance, which is zero Fig. 4 shows a closed-loop control system.

5- proposed method

The fuzzy control principle was introduced by Zadeh in 1970 which helps to model complex systems like linear and non-linear structural systems. The response indices like increasing inter-story drift, acceleration, increasing displacement and steady-state error may be affected in the presence fuzzy controller due to the fixed scaling factors. To overcome these issues a novel adaptive self-tuning fuzzy-PID controller is projected here. In this research article, a hybrid controller is suggested for active vibration control of a four-degree-of-freedom building, which is equipped with ATMD. The proposed strategy established by the combination of FLC and classical PID controller, an optimization procedure called WOA, is selected for optimum tuning of the PID coefficient in the PID section of the hybrid method. The hybrid WOA-base fuzzy-PID is used for stabilizing the building's floor displacement and acceleration due to an earthquake excitation to the average level (which is zero). The logical consequences of the rule base like IF-THEN rules contain all the data of input and output variables. Fuzzy inference helps to obtain fuzzy output by taking proper decisions according to the fuzzy rules. The transformation of fuzzy output variables into a crisp value is called the defuzzification process that may involve the center of gravity method, the mean of maximum method or weighted mean method. The proposed control algorithm is designed and developed on a four-story shear frame, which contains ATMD on each level. The problem of variation in building parameters and effect of this reform in mass, stiffness, and

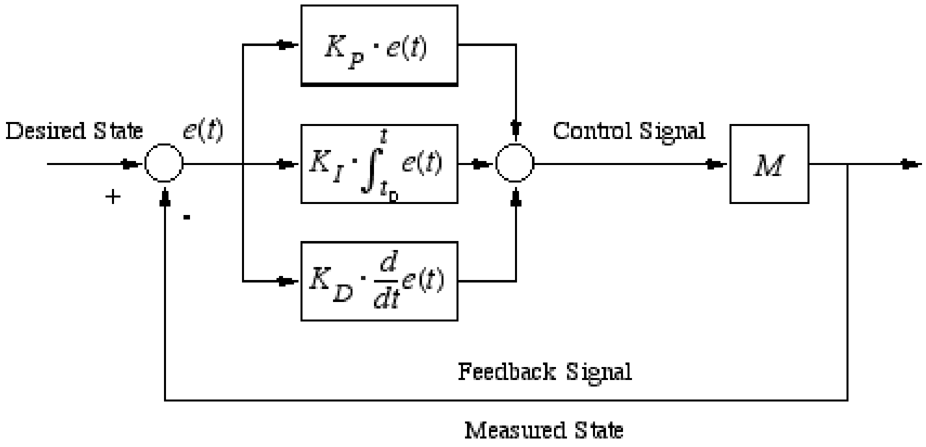

Fig. 4. block diagram of closed-loop PID control

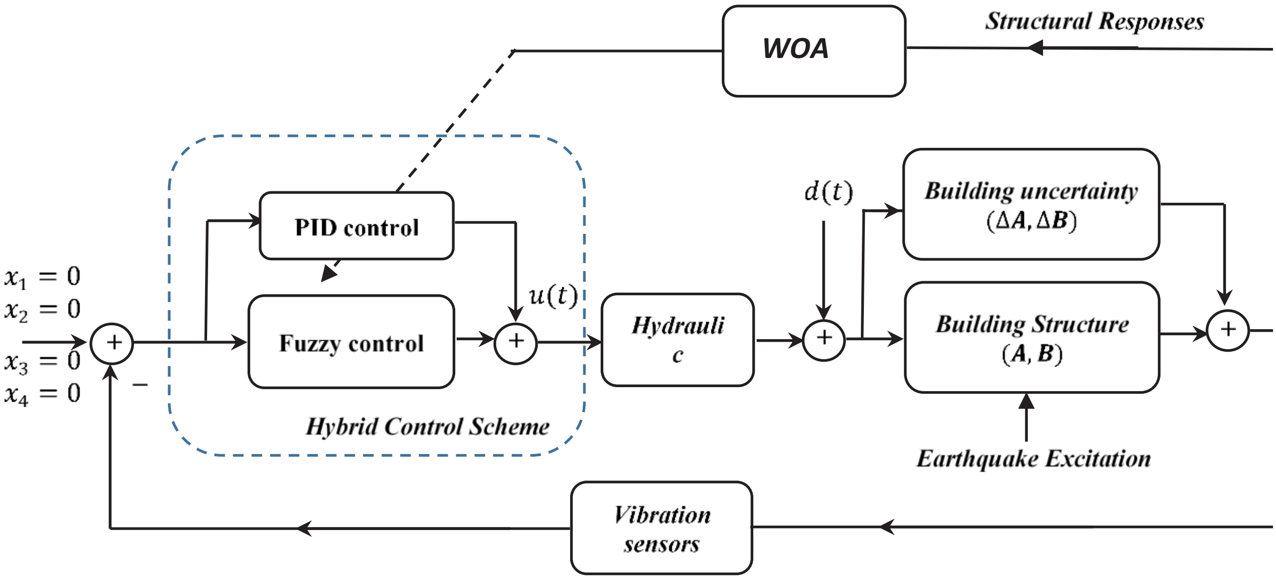

Fig. 5. Block diagram of the hybrid controller

damping coefficient are considered in the performance of hybrid WOA-base fuzzy-PID controller in decreasing the amplitude of displacement and acceleration of each floor level of the building due to earthquake excitation. Fig. 5 shows the block diagram of the proposed hybrid scheme.

5- 1- Whale optimization algorithm

Whale optimization algorithm is first proposed by Mirjalili et al. [36] as an optimization procedure for solving engineering problems. This algorithm is inspired by hunting behavior and the bubble-net hunting method of humpback whale. It is worth mentioning here that bubble-net feeding is a unique behavior that can only be observed in humpback whales. Properties of heuristic algorithms are as follows:

1- Rely on rather simple concepts and are easy to implement.

2- Do not require gradient information.

3- Can bypass local optima.

WOA can be utilized in a wide range of problems covering different disciplines.

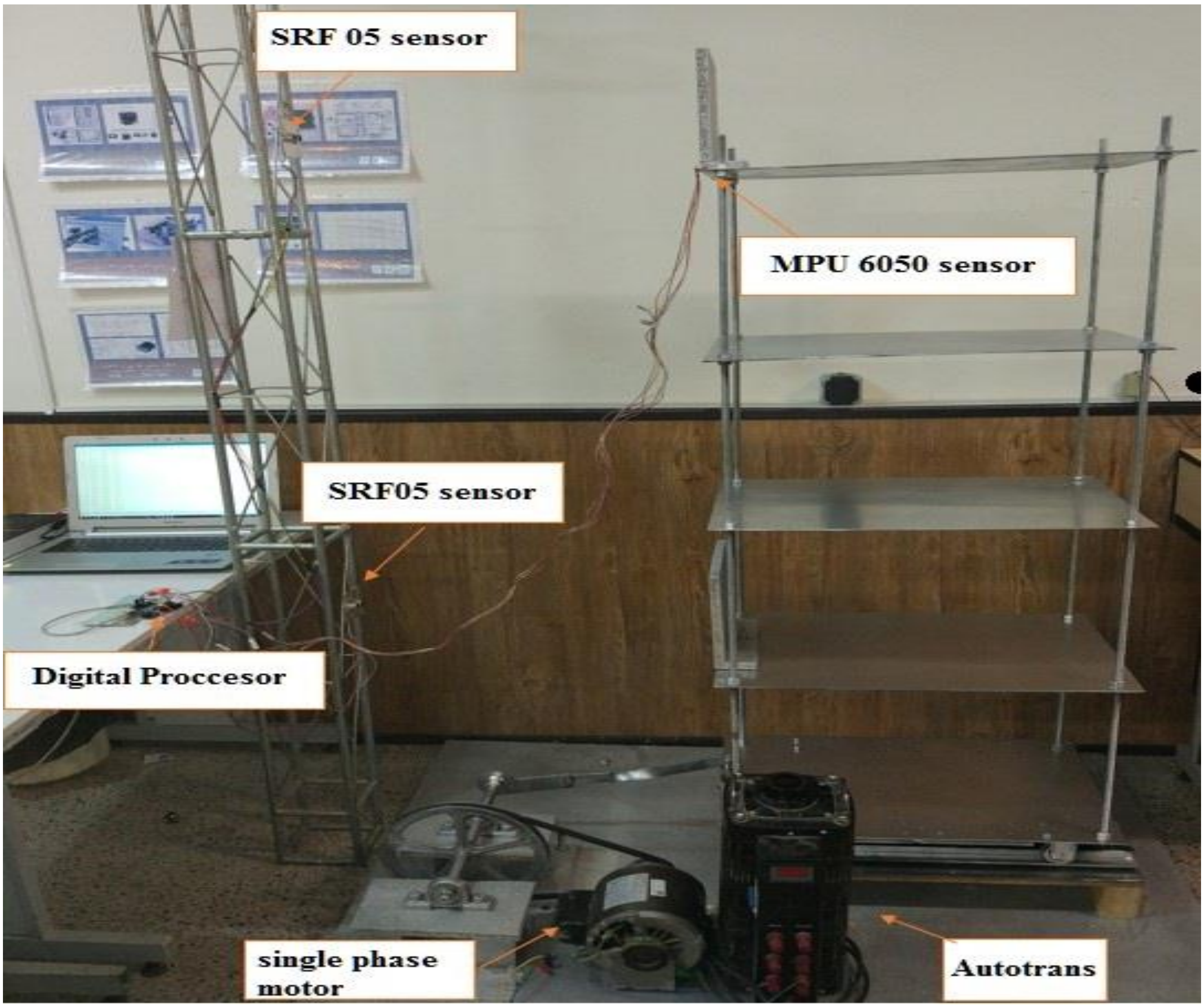

Fig. 6. A view of the constructed structure in the research lab for identification of structural parameters

5- 2- Identification of experimental structure parameters by the use of WOA

Fig. 6 shows the view of the constructed structure in the laboratory for the extraction of unknown parameters of the building. The process of installation of sensors, actuators, and digital processors has been done after constructing the model. The linear algebraic equation introduced in the last section provides an explicit adaptation of identified parameters of the experimental structure such as mass, stiffness, and damping with results obtained from the mathematical rules and meta-heuristic methods. In fact, by recording the amplitude of displacement and acceleration of experimental model floors. Also, after processing, refining, and filtering the displacement sensors and accelerometer data, we are pursuing to produce an allowable and identical amplitude of structural responses of the structure by the correct identification of unknown structural parameters. The data processing has been done to show the adaptation of the results achieved from the experimental setup on data obtained from the simulations of the linear model.

The investigated structure hardware is made of steel plates and has a total weight of 23kg connected to a shaking table. By the use of an autotransformer and an electrical motor, the shaking table developed. The main feature of the investigated shaking table is the ability to make changes in frequency to establish different kinds of vibrations with various amplitude vectors. Various experiments have been done on the developed structure. Fig. 7 shows the recorded data related to the acceleration of the shaking table during 30 seconds of motions by a sampling rate of 11ms, which is recorded by an MPU6050 sensor. Also, it shows the 2545 sample data recorded at the time of implementation. Moreover, the frequency spectra of the shaking table are presented in Fig. 8. Furthermore, the recorded data obtained from the ultrasonic

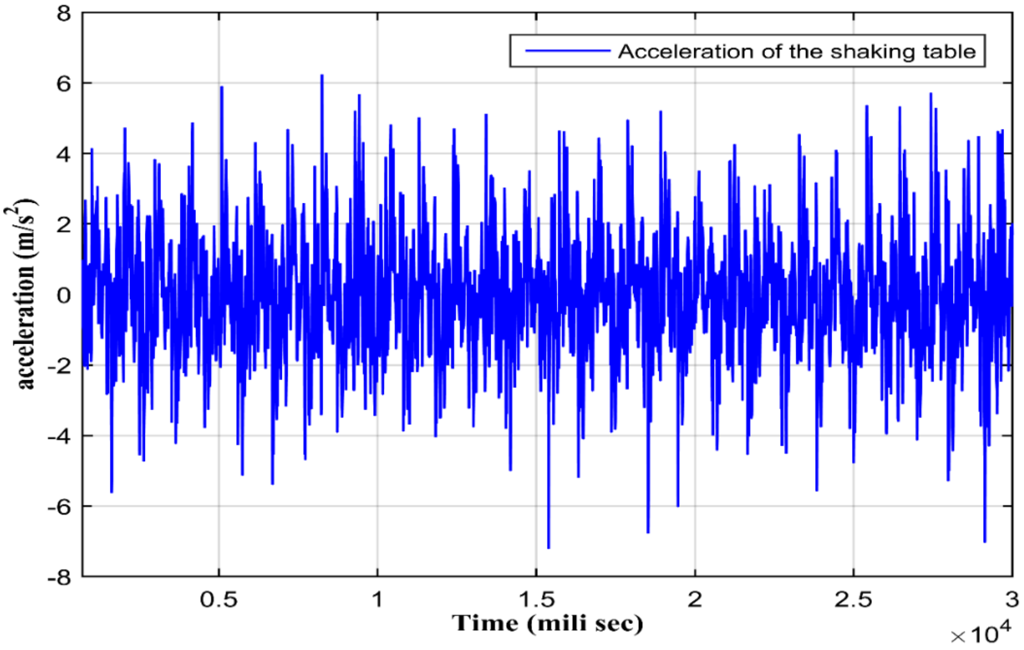

Fig. 7. Recorded acceleration of shaking table which is collected from SRF05 sensors

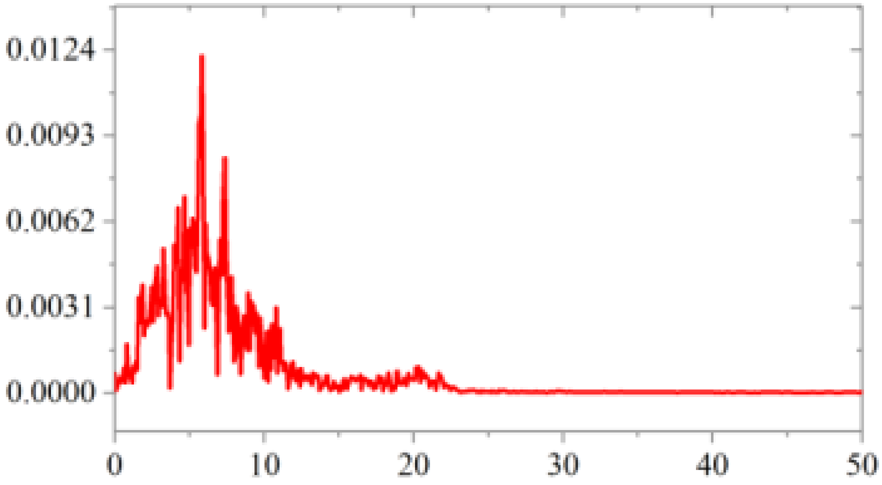

Fig. 8. Frequency spectra of the shaking table

sensors, which are related to the displacement of the first floor and fourth floor of the experimental building, are shown in Figs. 9 and 10, respectively. Moreover, Figs. 11 and 12 illustrate the recorded acceleration of the first floor and fourth floor of the constructed structure during 30 seconds of motions.

MATLAB is used for the identification procedure of unknown parameters of the structure to adapt the vibration data with the structural model. Fig. 13 shows the recorded and refined data related to the displacement of the fourth floor of the building which is obtained from ultrasonic sensor SRF05 due to 30 seconds of seismic-excitation (blue chart) in comparison with the fourth-floor displacement of the structure which its parameters such as mass, stiffness, and damping are identified by whale optimization algorithm (red chart). Considering the linear model and application of WOA

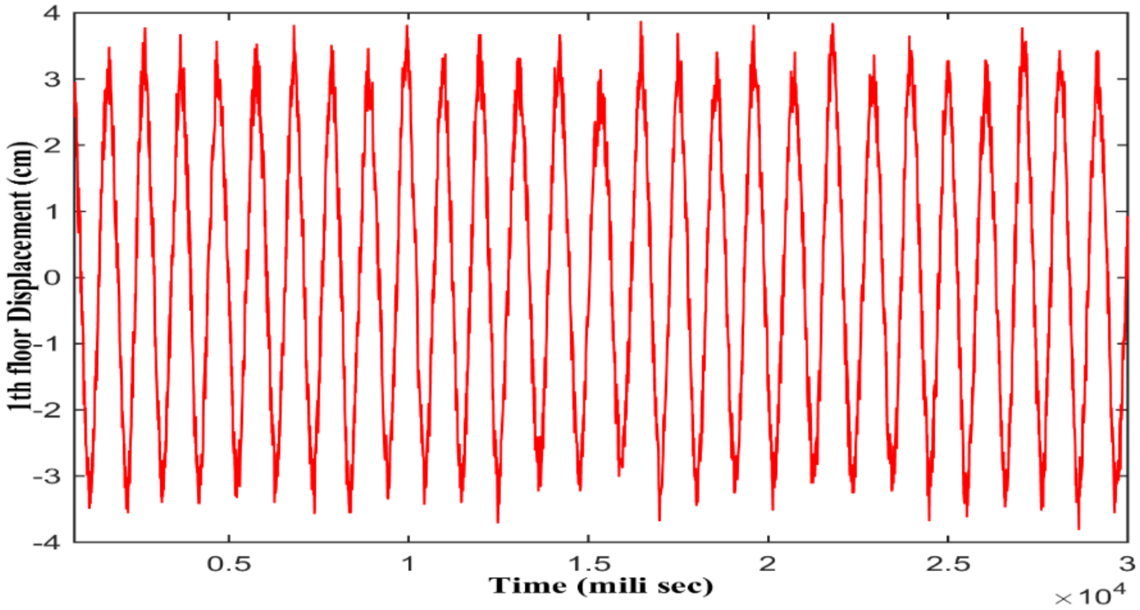

Fig. 9. The time history of the first-floor displacement of the experimental structure

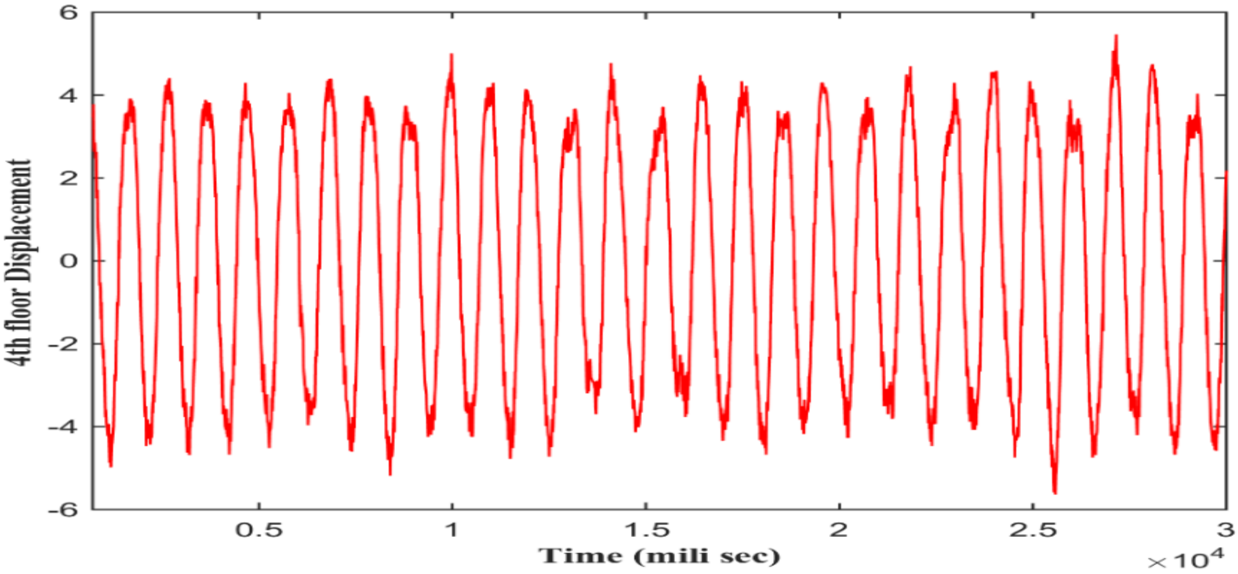

Fig. 10. The time history of the fourth-floor displacement of the experimental structure

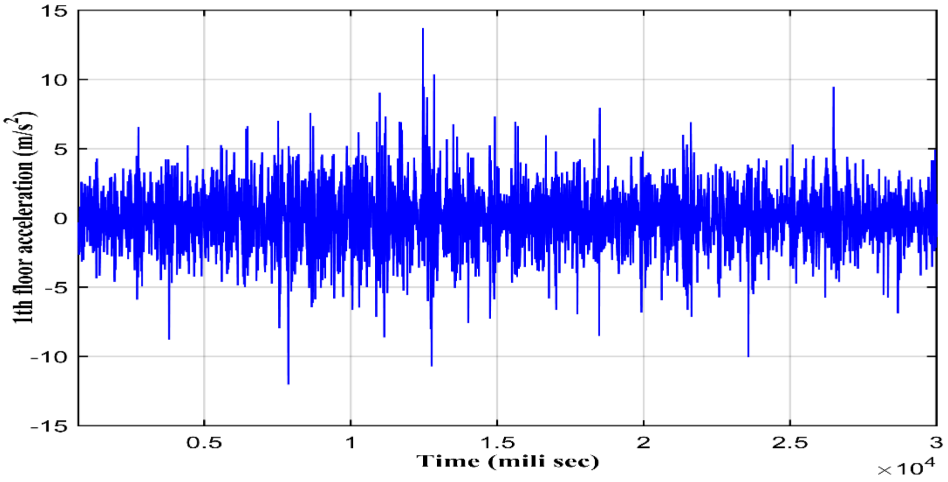

Fig. 11. Time history related to the acceleration of the first floor of the investigated structure which recorded by SRF05

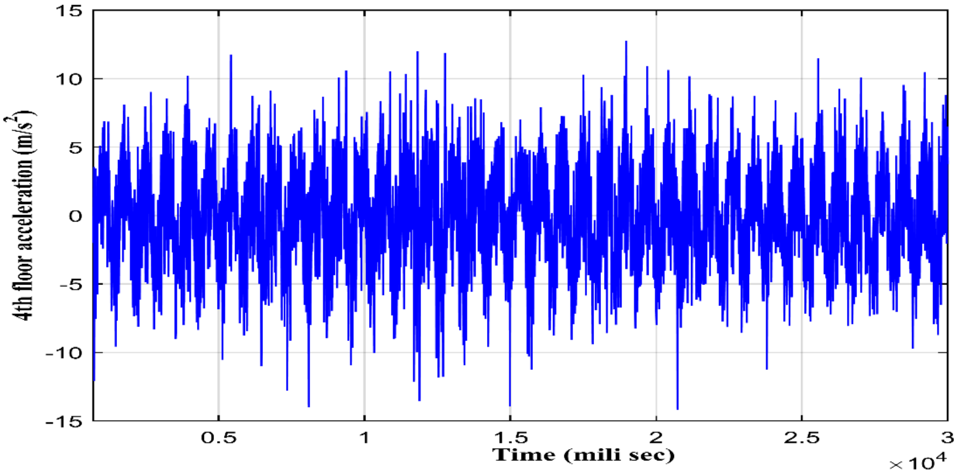

Fig. 12. Time history related to the acceleration of the fourth floor of the investigated structure which recorded by SRF05

as a meta-heuristic method for identification procedure, the unknown parameters of the experimental investigation find a value of 5.9kg, 3465.5N/m and 222.3 N.s/m for mass, stiffness, and damping, respectively. Furthermore, the proper adaptation and the performance of the whale optimization algorithm as an identification method can be found from this figure.

5- 3- Sensors information and digital processor structure

Table 2. illustrates the information related electronic equipment of the investigated structure.

By utilization, an Arduino board, the displacement, and acceleration data which comes from sensors have been collected and transferred to MATLAB, and then by the use of the whale optimization algorithm proceed to analyze and compare the results with those achieved by the experimental setup. Fig. 14 illustrates the structure and connectivity of the digital processor and its sensors.

6- Numerical simulation and results

In order to show the performance of the proposed method a numerical example of a four-degree-of- freedom building is

Table 2. illustrates the information related electronic equipment of the investigated structure.

Element	application	Additional information
MPU6050 accelerometer	Area of measurement: 0-16g Voltage limitation: 3-6^{v}	Communication protocol: I_2c Frequency: 10-40 kHz Current: 10 mA
HY-SRF05 displacement sensor	Area of measurement: 2-450 cm Accuracy: 2mm	Frequency: 40 kHz Working voltage: 5V Current: 10-40 mA
UNO Arduino board	Input voltage limitation: 6-20V The maximum current of each pin: 20mA	Processing speed: 16MHz Type of microcontroller: Atmega328p

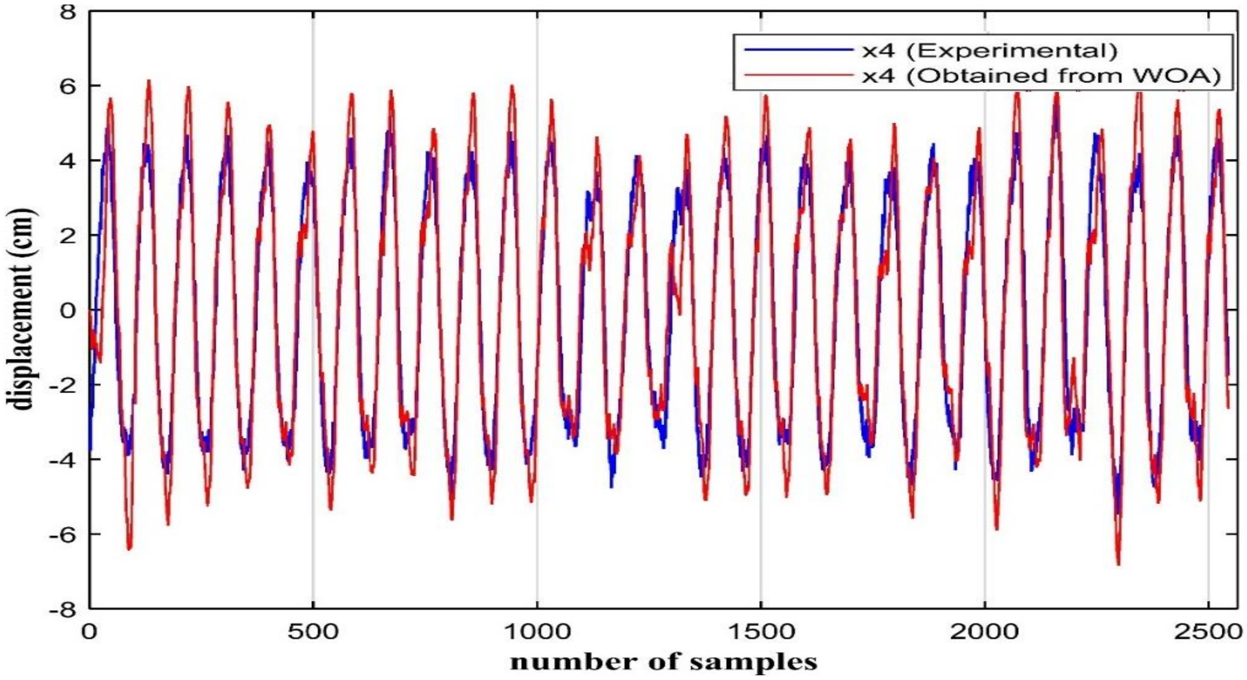

Fig. 13. Recorded time history by ultrasonic sensor SRF05 (blue chart) in comparison with those identified by whale optimization algorithm (red chart)

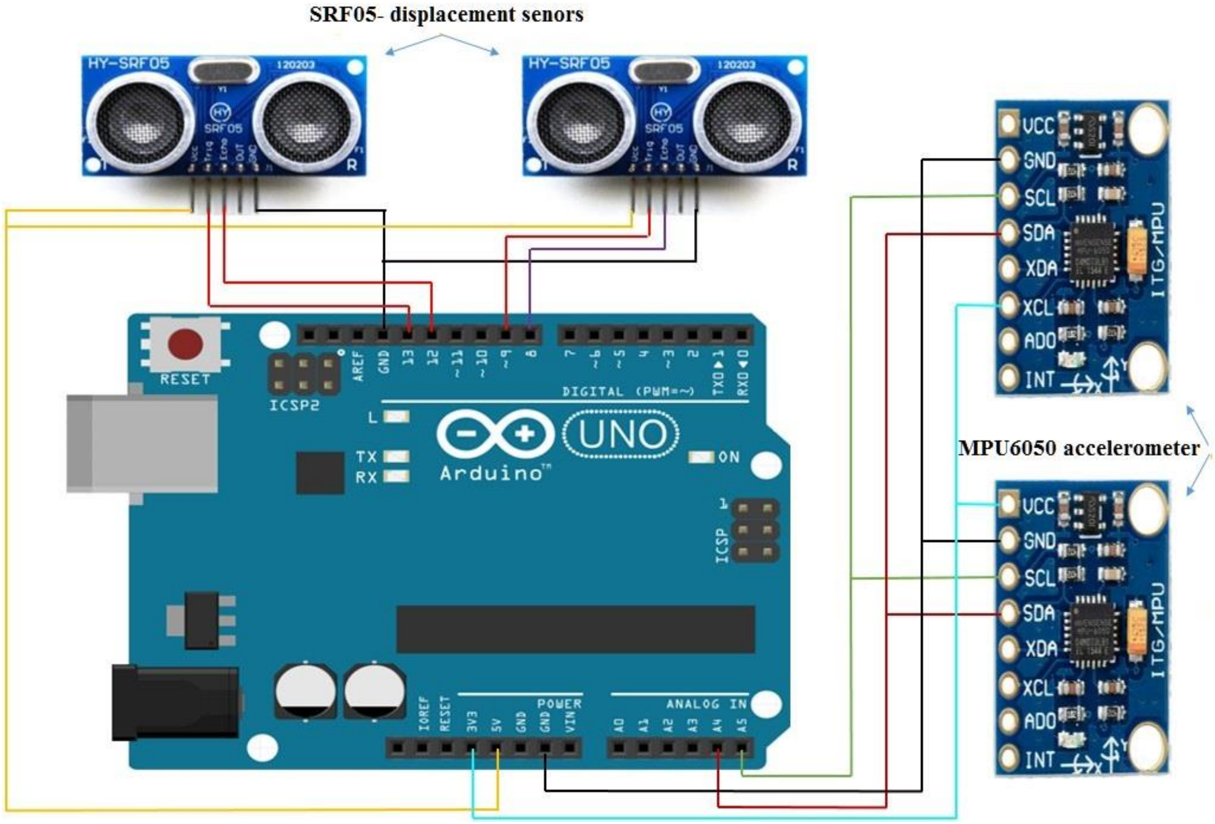

Fig. 14. Structure of the digital processor and its sensors

presented (see Fig.1). For this structure in James et al. [35], K = 350×10^6 N/m, M = 1.05×10^6 kg, C = 1.575×10^6 .N.s/m, and the total weight is 61.74 MN. The dynamic equilibrium of the system is described as:

$$K=175\times10^6\begin{bmatrix}8&-4&0&2\\-4&6&-2&0\\0&-2&4&-2\\0&0&-2&-2\end{bmatrix}$$

$$,C=1.575\times10^6\begin{bmatrix}2&-1&0&0\\-1&2&-1&0\\0&-1&2&-1\\0&0&-1&1\end{bmatrix}, \tag{7}$$

$$M=1.05\times10^6\begin{bmatrix}2&0&0&0\\0&2&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

Matrix A has the values of:

$$D_k=\begin{bmatrix}\frac{2000}{2}&\frac{-1000}{3}&0&0\\\frac{-1000}{3}&500&\frac{-500}{3}&0\\0&\frac{-500}{3}&\frac{2000}{3}&\frac{-1000}{3}\\0&0&\frac{-1000}{3}&\frac{1000}{3}\end{bmatrix} \tag{8}$$

$$D_c=\begin{bmatrix}1.5&-0.75&0&0\\-0.75&1.5&-0.75&0\\0&-0.75&3&-1.5\\0&0&-1.5&1.5\end{bmatrix}$$

Four earthquake ground motions such as El Centro, Northridge, Athens, and Kocaeli are applied to the base of the benchmark structure where the ground accelerations of each

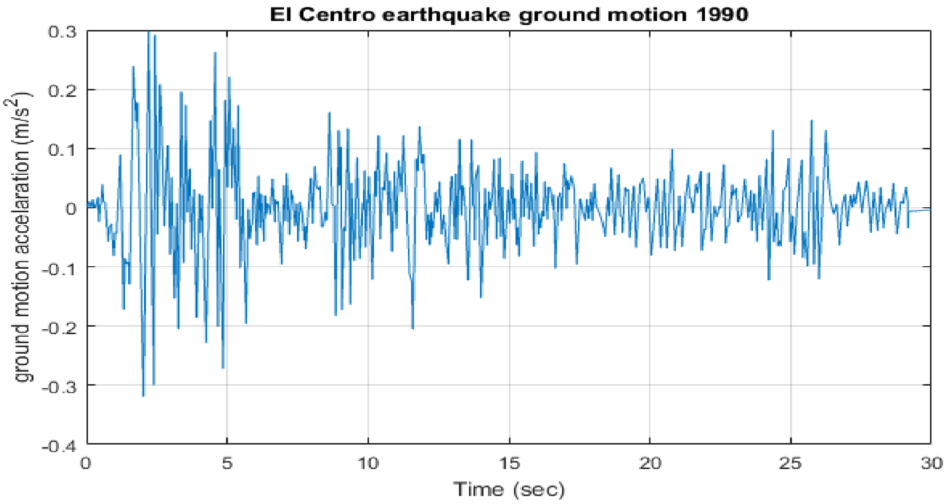

Fig. 15. El Centro 1940 earthquake ground motion with the PGA of 0.316g

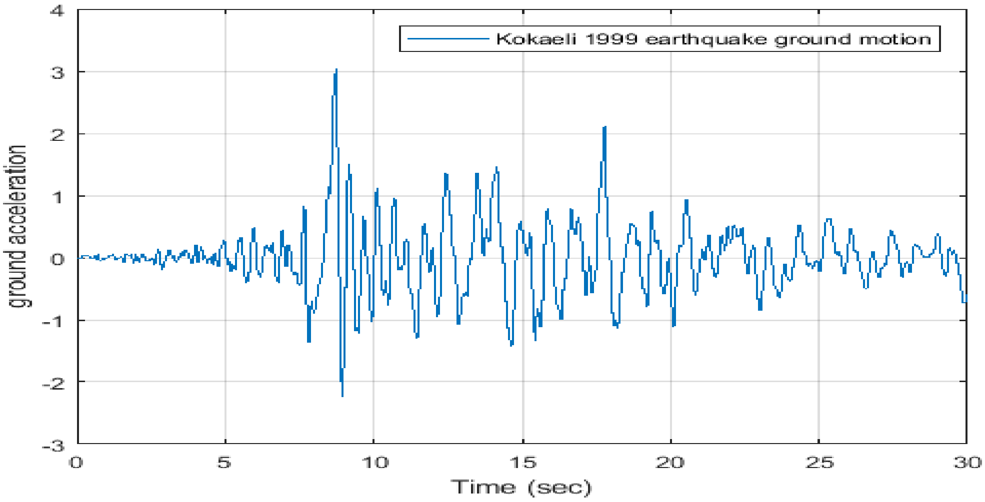

Fig. 16. Kocaeli 1999 earthquake ground motion with the peak ground acceleration of 0.36g

of the mentioned earthquakes are shown in Figs. 15 to 18.

Results in inertial load effects, $f_{ei}\left(t\right)$, i = 1,. .., 4, at each floor level. For simplicity, if only an earthquake loading is considered, then, F , and $w\left(t\right)$ are:

$$F_w = M^{-1}[2 \quad 2 \quad 1 \quad 1]^T$$
$$F_{wl} = \left[1 \quad 1 \quad 1 \quad 1\right]^T,\ w(t) = w_e(t) \tag{9}$$

where $w_e\left(t\right)$ is an earthquake force. Furthermore, if it is assumed that each story has an active control device that is connected to the building, then:

$$B_{ch} = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$B = \begin{bmatrix} 0 \\ M^{-1}B_{ch} \end{bmatrix},\quad B_u = M^{-1}B_{ch} \tag{10}$$

Specifying state variables and output variables to be the displacement and velocity at each floor level, it follows that $z\left(t\right) = x\left(t\right)$ and $C = I$. Norm-bounded uncertainties are

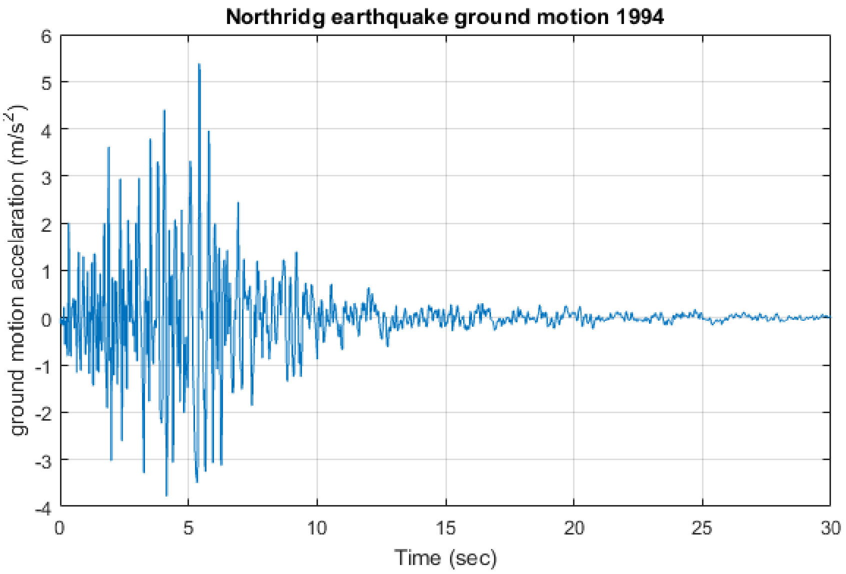

Fig. 17. Northridge 1994 earthquake ground motion with the peak ground acceleration of 0.589g

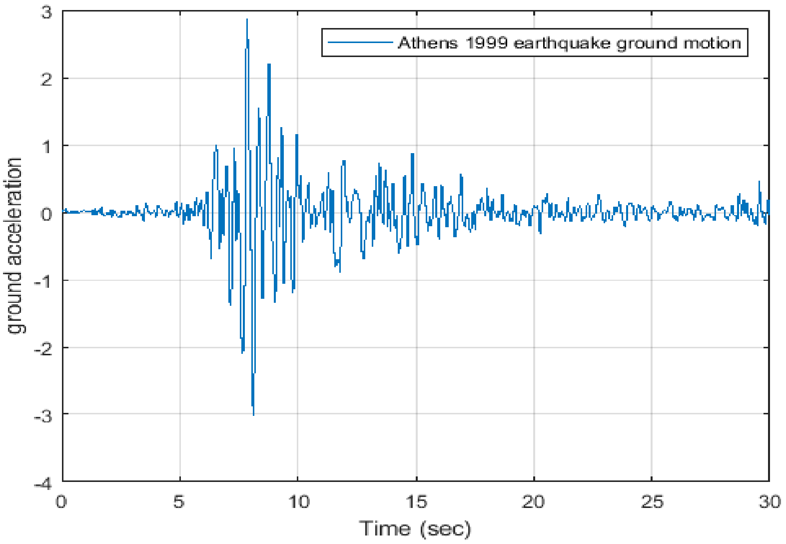

Fig. 18. Athens1999 earthquake ground motion with the peak ground acceleration of 0.3g

taken to be +15% of the mass, stiffness, and damping, i.e., $\nabla m = \pm 15\% m$, $\nabla k = \pm 15\% k$, $\nabla c = \pm 15\% c$

Note that it is evident that the disturbance input matrix F, has uncertainties when the mass changes or has uncertainties. Since B, is invertible, the system is a matched uncertainty model so:

$$\nabla B_{Bu} = M^{-1}\nabla B_u , \quad \nabla B_{Bk} = B_u^{-1}\nabla D_k ,$$

(11)

$$\nabla D_{Bc} = B_u^{-1}\nabla D_c , \quad F_{Bw} = F_B = B_u^{-1} F_w$$

The TMD is based on a linear spring and a viscous damper mounted at the top floor. It is normal for the frequency ratio, β, to be determined by dividing the TMD's natural frequency into the primary structure's first modal frequency. Therefore, the TMD mass is selected to have become αpercent of the structure's total mass and the TMD damping ratio is assumed to be approximately αpercent of the main damping amount. A genetic algorithm in reference [21] calculates the optimum values of α, м and β as 3 percent, 7 percent and 1.2, respectively. The ideal amounts of α, α and, β for the ATMD are indeed measured as 3%, 7% and 1.0, respectively. Both first and second regular frequencies of the uncontrolled framework are measured as ω_2 =6,5727 and ω_2 =19,355

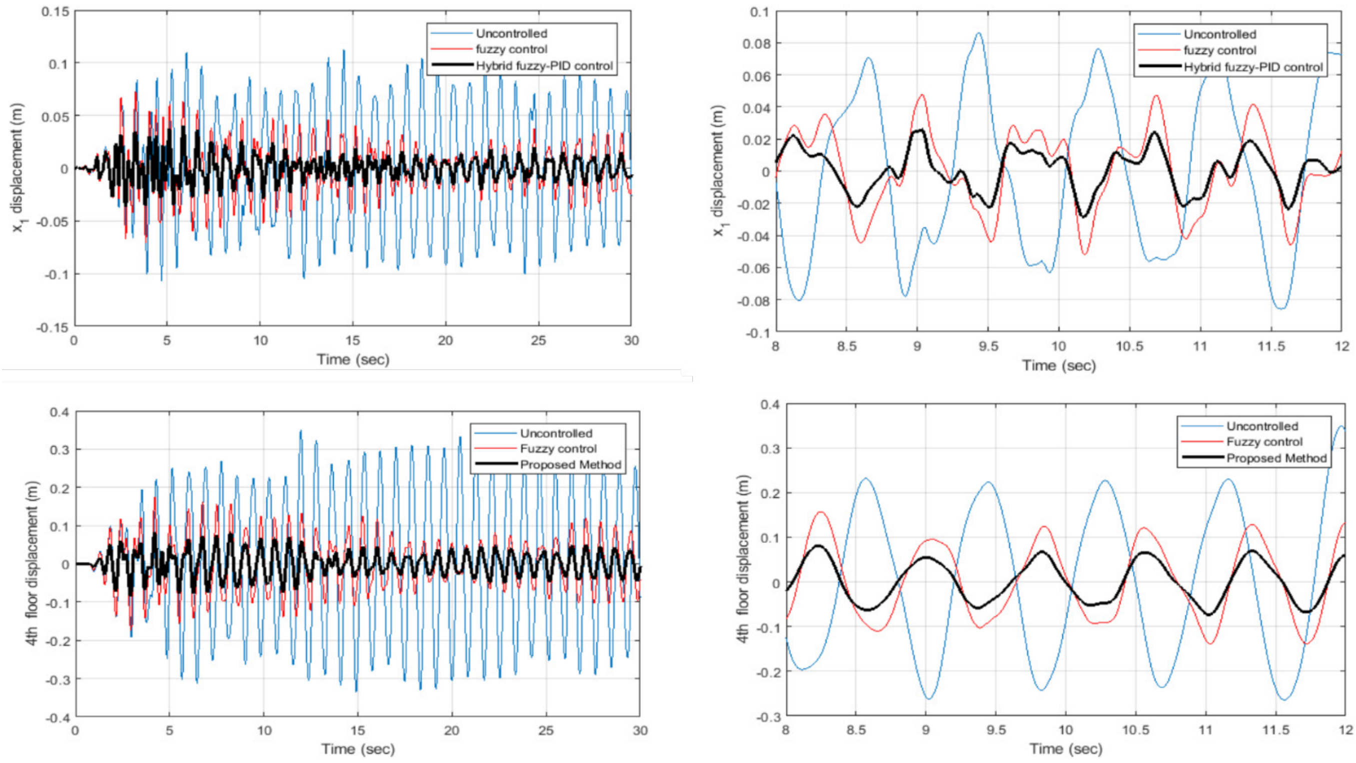

Fig. 19. Time histories of the first floor and the top floor displacements for uncontrolled, controlled by fuzzy logic and optimal PID-Fuzzy controller subjected to the El Centro earthquake (displacement)

rad/s. Using the fundamental damping ratio as the 5% of the essential damping factor for the first two modes i.e., the damping matrix can be determined using the damping method of Rayleigh [28].

For comparison, the same structure is used for numerical simulation. The output of the numerical simulation for the uncontrolled, fuzzy control, and finally optimal fuzzy-PID hybrid control are shown in Figs. 19 to 21, for 30 sec of motion. These graphs illustrate drift, acceleration, and velocity for the first floor and top floor of the benchmark building, respectively, for the perturbed model that is excited by selected real data of each earthquake. The uncertain values from its nominal values have selected %15 of variations for all parameters, including mass, stiffness, and damping.

There are different indices of the control error for the validation of results. The mean absolute error (MAE) is useful criteria, and it is defined as:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|x_i - \hat{x}_i\right| = \frac{1}{N}\sum_{i=1}^{N}\left|e_i\right| \tag{12}$$

where $\hat{x}_i$ is the controlled value of x_i. Also, the mean square error (MSE) defined as:

$$mse = \frac{1}{N}\sum_{i=1}^{N}[e_i - \bar{e}_i]^2 \tag{13}$$

where $e_i = x_i - \hat{x}_i$ and $\overline{e_i}$ is the average of e_i.

Analytical time-history of the four-degree of freedom building is carried out using MATLAB/code software. For this purpose, four earthquakes, such as El Centro (1940), Northridge (1994), Athens (1999), and Kocaeli (1999), are considered. The Peak Ground Acceleration (PGA) of these earthquakes are taken to be 0.316, 0.589, 0.30, and 0.36g, respectively.

Figs. 19 to 21 illustrate the displacement, velocity, and acceleration of the first and the top stories due to the El Centro earthquake, respectively. Also, these figures indicate that ATMD, as an active device, reduces the structural responses of the seismic-exited building due to the El Centro. Also, it can be seen from these figures that the proposed

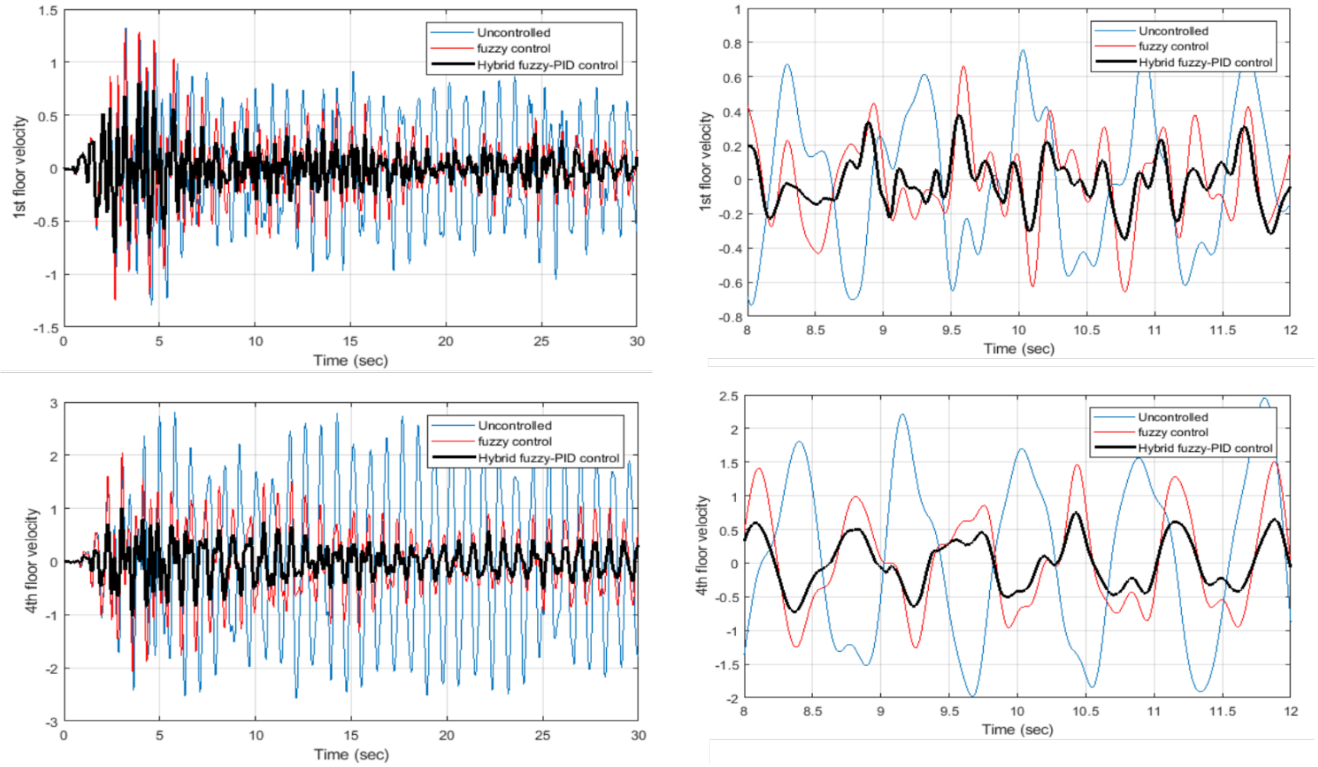

Fig. 20. Time histories of the first floor and the top floor displacements for uncontrolled, controlled by fuzzy logic and optimal PID-Fuzzy controller subjected to the El Centro earthquake (velocity)

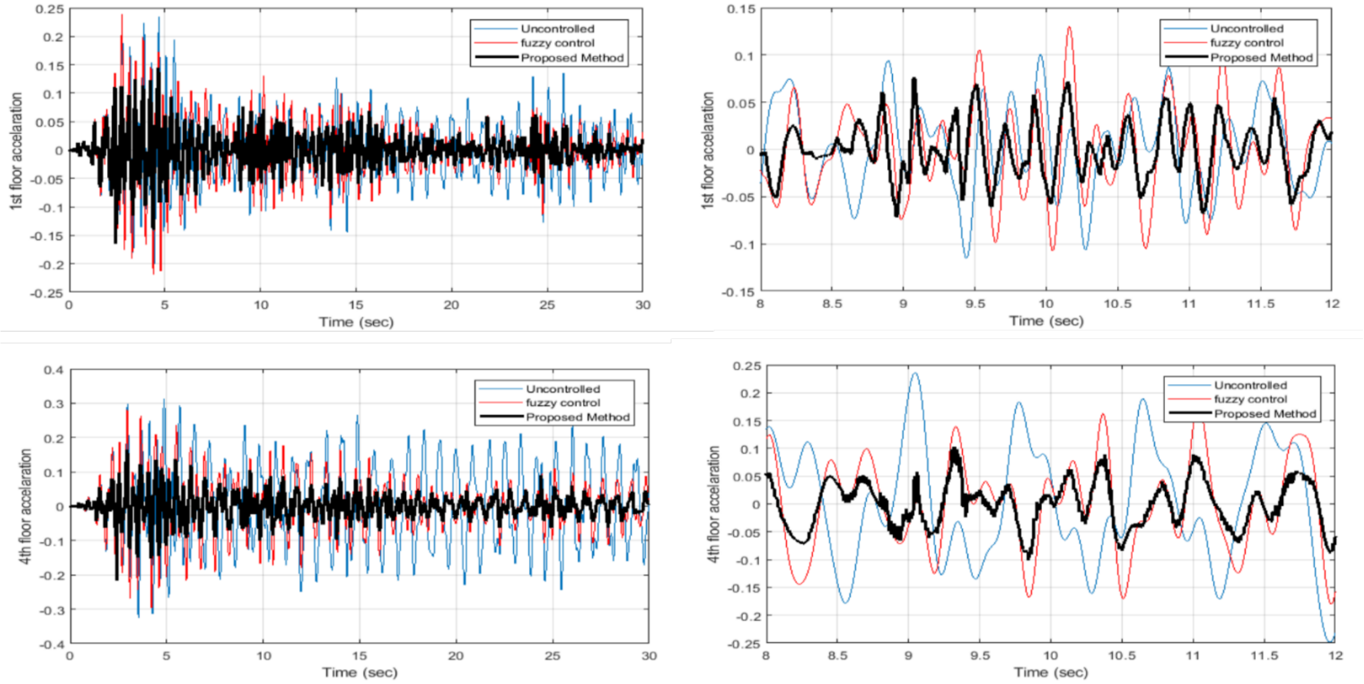

Fig. 21. Time histories of the first floor and the top floor displacements for uncontrolled, controlled by fuzzy logic and optimal PID-Fuzzy controller subjected to the El Centro earthquake (acceleration)

Table 3. structural responses of benchmark building due to the El Centro earthquake

	Relative displacement			Absolute acceleration		
floor	Uncontrolled	Fuzzy control	Proposed Method	Uncontrolled	Fuzzy control	Proposed Method
Performance index : MSE						
1	0.25	0.12	**0.03**	0.3	0.26	**0.10**
2	0.78	0.39	**0.09**	0.47	0.38	**0.11**
3	1.86	0.92	**0.21**	0.69	0.49	**0.13**
4	2.72	1.34	**0.31**	1.25	0.9	**0.23**
Performance index : MAE						
1	0.42	0.29	**0.15**	0.42	0.38	**0.23**
2	0.75	0.53	**0.26**	0.54	0.49	**0.26**
3	1.18	0.82	**0.4**	0.69	0.57	**0.29**
4	1.42	0.99	**0.47**	0.91	0.76	**0.38**

controller performs better than the fuzzy control in reducing the maximum displacement of all floors. During the El Centro earthquake, the fuzzy control and optimal PID-Fuzzy controllers give a reduction of 55% and 88% in comparison with uncontrolled ones for the first floor, respectively. To evaluate the performance of the proposed controller during different earthquake excitations, relative displacement and absolute acceleration of the structure are listed in Tables 3 to 6 With 20% uncertainties due to El Centro, Northridge, Athens and Kocaeli earthquakes, respectively. Table 7 indicates the inter-story drift of each floor level for the same structure exited by all selected earthquakes. The values are for the uncontrolled structure, the structure equipped with ATMD that is controlled by fuzzy logic control and the optimal PID-Fuzzy controllers. Considering all earthquakes, the results also show that the proposed controller performs better than fuzzy control in the reduction of the relative displacement, absolute acceleration, and velocity of stories. For example, the inter-story drift of the top story due to the El Centro earthquake is 0.1m and 0.05m for the fuzzy control and finally, the optimal PID-fuzzy controllers.

Considering El Centro and Northridge earthquakes, the bar diagrams related to the building's floors regarding inter-story displacement of the building equipped with ATMD which is controlled by both fuzzy logic and optimal PID-Fuzzy methodologies, are compared with the according to the uncontrolled ones in Figs. 22 and 23, respectively.

7- conclusions

To increase the performance of the PID controller and FLC in the field of structural control, a new generation of hybrid controllers, namely fuzzy-PID, was designed and developed in this research. The suggested hybrid method was established by combining two well-known controllers, namely PID control and fuzzy logic control. The proposed hybrid fuzzy-PID controller while containing the heuristic knowledge of fuzzy logic is easy to use for active vibration attenuation of buildings against earthquakes. This paper proposes an experimental investigation of a four-story structure that is connected to a shaking table. The investigated shaking table is designed with a particular method to produce any vibration amplitude. Also, the whale optimization algorithm is used for the identification of the experimental structure parameters such as mass, stiffness, and damping to show the adaptation of the results collected from the identified model on the results achieved from the linear model. However, it is used for optimum tuning of PID coefficients. The numerical analysis was established and designed on a four-story building. Four different earthquake real-data of ground motions were selected and entered the simulation. The

Table 4. structural responses of benchmark building due to the Northridge earthquake

	Relative displacement			Absolute acceleration		
floor	Uncontrolled	Fuzzy control	Proposed Method	Uncontrolled	Fuzzy control	Proposed Method
Performance index : MSE						
1	0.11	0.09	**0.03**	0.69	0.83	**0.30**
2	0.22	0.14	**0.04**	0.76	1.05	**0.29**
3	0.32	0.05	**0.02**	0.51	0.40	**0.15**
4	0.59	0.21	**0.05**	1.44	1.57	**0.45**
Performance index : MAE						
1	0.25	0.19	**0.10**	0.49	0.55	**0.32**
2	0.38	0.24	**0.13**	0.55	0.62	**0.33**
3	0.46	0.17	**0.08**	0.51	0.37	**0.21**
4	0.64	0.32	**0.16**	0.80	0.77	**0.41**

Table 5. structural responses of benchmark building due to the Athens earthquake

	Relative displacement			Absolute acceleration		
floor	Uncontrolled	Fuzzy control	Proposed Method	Uncontrolled	Fuzzy control	Proposed Method
Performance index : MSE						
1	0.04	0.03	**0.01**	0.14	0.10	**0.04**
2	0.10	0.07	**0.02**	0.17	0.13	**0.05**
3	0.20	0.17	**0.04**	0.11	0.11	**0.03**
4	0.34	0.25	**0.05**	0.38	0.26	**0.06**
Performance index : MAE						
1	0.14	0.12	**0.06**	0.25	0.20	**0.11**
2	0.24	0.20	**0.09**	0.29	0.23	**0.12**
3	0.36	0.31	**0.15**	0.25	0.24	**0.12**
4	0.45	0.38	**0.19**	0.44	0.35	**0.17**

Table 6. structural responses of benchmark building due to the Kocaeli earthquake

	Relative displacement			Absolute acceleration		
floor	Uncontrolled	Fuzzy control []	Proposed Method	Uncontrolled	Fuzzy control	Proposed Method
Performance index: MSE						
1	0.49	0.26	**0.06**	0.21	0.20	**0.06**
2	1.61	0.86	**0.20**	0.56	0.50	**0.13**
3	4.02	2.08	**0.48**	1.25	0.84	**0.20**
4	5.77	2.96	**0.69**	1.90	1.40	**0.33**
Performance index: MAE						
1	0.51	0.38	**0.19**	0.34	0.33	**0.18**
2	0.92	0.69	**0.33**	0.56	0.53	**0.27**
3	1.44	1.08	**0.52**	0.82	0.69	**0.33**
4	1.74	1.28	**0.62**	1.03	0.89	**0.43**

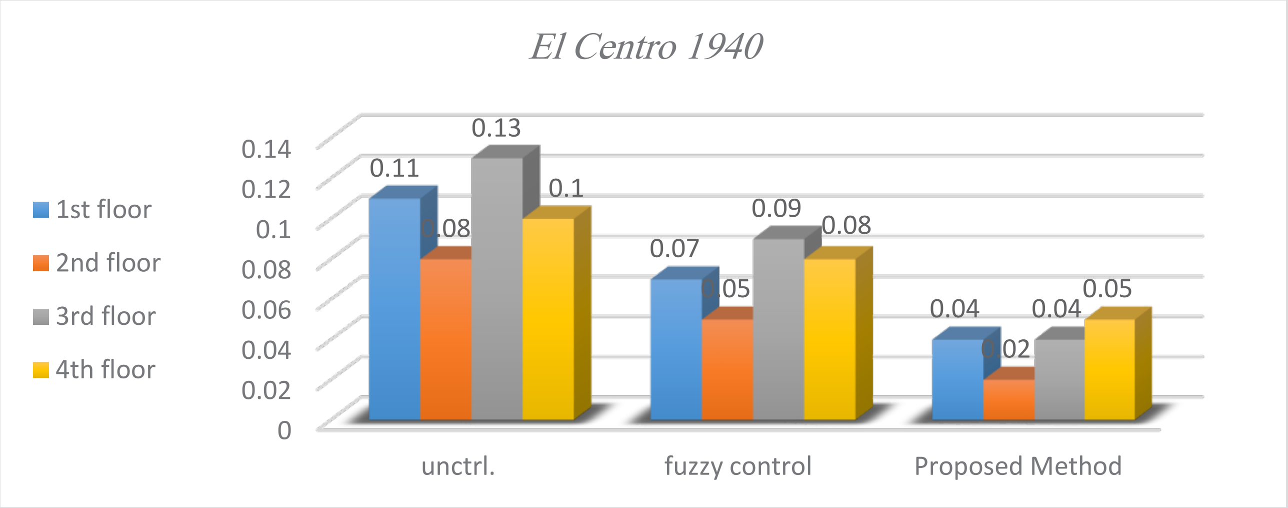

Fig. 22. Peak displacement of each floor subjected to the El Centro

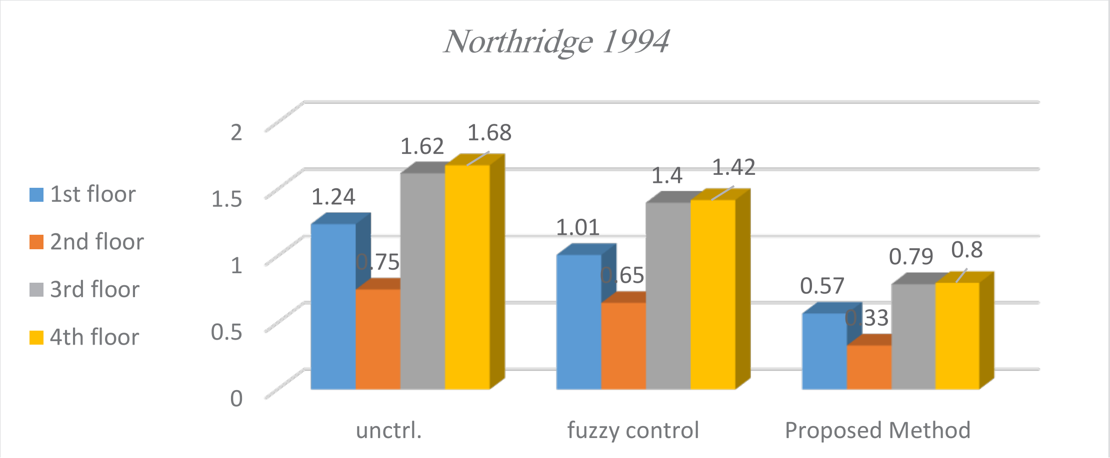

Fig. 23. Peak displacement of each floor subjected to the Northridge 1994

Table 7. 7. Maximum inter-story drift of structure due to earthquake

floor	Uncontrolled	Fuzzy control	Proposed method
		El Centro 1940	
1st floor	0.11	0.07	**0.04**
2nd floor	0.08	0.05	**0.02**
3rd floor	0.13	0.09	**0.04**
4th floor	0.10	0.08	**0.05**
		Northridge 1992	
1st floor	1.24	1.01	**0.57**
2nd floor	0.75	0.65	**0.33**
3rd floor	1.62	1.40	**0.79**
4th floor	1.68	1.42	**0.80**
		Athens 1999	
1st floor	0.57	0.64	**0.29**
2nd floor	0.35	0.39	**0.21**
3rd floor	0.85	0.80	**0.37**
4th floor	0.62	0.61	**0.30**
		Kocaeli 1999	
1st floor	1.59	1.28	**0.64**
2nd floor	1.32	0.99	**0.48**
3rd floor	1.65	1.32	**0.59**
4th floor	0.98	0.79	**0.35**

results showed the strong ability of the suggested fuzzy-PID controller among other designed methodologies in the field of structural control, especially in reducing the amplitude of displacement and acceleration of all floors of the seismic-excited benchmark building.

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