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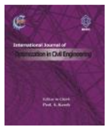

AN OPTIMAL CUCKOO SEARCH-FUZZY LOGIC CONTROLLER FOR OPTIMAL STRUCTURAL CONTROL

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ABSTRACT

An optimal semi-active Cuckoo- Fuzzy algorithm is developed to drive the hydraulic semi-active damper for effective control of the dynamic deformation of building structures under earthquake loadings, in this paper. Hydraulic semi-active dampers (MR dampers) are semi active control devices that are managed by sending external voltage supply. A new adaptive fuzzy logic controller (FLC) is introduced to manage MR damper intelligently. Furthermore, a novel evolutionary algorithm of cuckoo search (CS) was employed to optimize the placement and the number of MR dampers and sensors in the sense of minimum resultant vibration magnitude. Numerical efforts were accomplished to validate the efficiency of proposed FLC. In designer's point of view, the proposed CS-FLC controller can find the optimal solutions during a reasonable number of iterations. Finally, The simulation results show that the developed semi - active damper can significantly enhance the seismic performance of the buildings in terms of controlled story drift and roof displacement and acceleration. CS-FLC controller uses less input energy and could find the appropriate control force and attenuates the excessive responses in several buildings. The findings in this study will help engineers to design control systems for seismic risk mitigation and effectively facilitate the performance - based seismic design.

Keywords: cuckoo search (CS); Hydraulic semi-active dampers; fuzzy logic control; semi-active control; performance - based seismic design.

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1. INTRODUCTION

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Buildings are vulnerable to severe vibration when subjected to extreme hazard events, such as earthquakes and high intensity winds. To increase structural safety and serviceability in performance-based designing of buildings, the dissipation of input energy and attenuation of vibration are crucial. Practicing engineers have long recognized that structural response of buildings to strong ground motion due to earthquakes or other extreme events frequently leads to in inelastic behavior which is not acceptable in several buildings. Research on innovative control devices and materials for new and strengthening the existing buildings has demonstrated their enhanced seismic performance [1]. Increasing efforts have been directed to the development and implementation of control systems for higher seismic performance and enhanced resilience of structural buildings. For this purpose, most recent strategies can be classified as active, semi-active, passive, and hybrid control methods [2]. Active control systems have been implemented in full-scale structures, but it needs more advancing to solve the robustness incompetency and reliability. Passive devices have reasonable results in attenuating of the building responses, but the lack of adaptability with vibration conditions is one of the incompetencies in these control devices. Semi-active control systems demonstrates their attractive characteristics, including less electricity power requirements, higher reliability, and particularly higher online adaptability for seismic events and vibrations, as compared to their counterparts [3]. Hydraulic dampers are new semi active control devices which have a major potential to boost the vibration control technology in many cases worldwide with a high variety in use of semi-active control systems and hydraulic dampers. The first full-scale implementation was two semi - active hydraulic dampers which were employed at the first to fourth stories in the Kajima Shizuoka Building in 1998, in Shizuoka, Japan [4]. The most significant specification of hydraulic damper is the reliability of passive control devices which can maintain the versatility and adaptability of active control systems. The first development of semi-active hydraulic fluids and devices was done by Jacob Rabinow at the US National Bureau of Standards [5]. 200kN MR dampers have been developed and tested, in recent years [6–9]. Studies have been performed to demonstrate the efficiency of Hydraulic dampers and validate the performance during seismic excitation. Kurino et al. research on using two semi - active and passive control systems with dampers under different levels of earthquakes[10]. Spencer et al. developed a mechanical model which based on the Bouc–Wen hysteresis scheme that manages the dynamic behavior of MR dampers online [11]. Several full-scale structural buildings have been employed with supplemental damping devices to attenuate the undesirable vibrations [12]. The usage of Hydraulic dampers in engineering structures is more progressive and at the same time, the optimal design of controllers should be proposed. To reducing the cost and increasing the efficiency of control system, optimal damper placement should be done since by different arrangement of dampers, higher control levels may be achieved. Moreover, it is important to reduce the costs, which are related to the set up and maintenance of the semi active hydraulic devices. On the other side, minimizing vibration magnitude is a crucial criterion for the advantage of control systems [13]. Several researches investigated the optimal placement of dampers but none of them has assumed to find the optimal MR damper placement and sensors as two discrete subjects. Cuckoo search (CS) is a meta-heuristic optimization algorithm which is introduced based on inspiration from the obligate brood parasitism of some cuckoo species [14]. CS is inspired by some species of a bird family called cuckoo because of their special lifestyle and aggressive breeding strategy. CS has been demonstrated the particular efficiency to quickly converge in global optimization problems. CS has been utilized newly as a formidable optimization algorithm in engineering problems [15-16] but newly employed in the field of structural control [17]. The versatility of adaptive semi active controller cab not be obtained with traditional controllers with unknown structural parameters. Classical optimal control and instantaneous optimal control assumed some previous knowledge or precise information about the characteristics of a structure which could be changed by several event such as corrosion and damages [18,19]. Furthermore, semi-active controllers such as Linear Quadratic Gaussian (LQG) optimal control necessitate a solution for heavily constrained optimization problems [20]. To dominate those impediments, many studies have concentrated on soft-computing techniques such as fuzzy logic [21] and neural networks [22]. The control of systems using traditional methodologies encounter problems when dealing with non-linearity, poor mathematical definition of the problem, changes and uncertainty in the system parameters as well. This can reduce performance or even unsettle the control system designed with traditional methodologies. In this sense, control systems that are robust enough to adapt and adjust to these changes are desirable[23-25]. Recent studies demonstrated that adaptive controllers are more impressive and reliable [26-29].

The main goal of this research is semi-active adaptive optimal control of structural buildings under seismic excitation, based on the fuzzy logic controller (FLC). Effective fuzzy logic controller employed to enhance the hydraulic semi-active damper efficiency and consuming less electrical energy. In this study, separate sensors were employed independently to transmit the absolute displacement and the velocity of stories to the proposed controller. To the Author's best knowledge, there is no published research on semi active control of high-rise building with MR dampers by using separately sensor installation to manage the control forces. For this purpose, CS-FLC controller estimates the magnetic field inducing current regarding to the displacement and the velocity of the floor, which were transmitted by the sensors. The CS-FLC adaptive controller sent the inducing current to each damper based on structural responses adaptively. The proposed CS-FLC controller demonstrate its efficiency with less computational burden and cost by using Cuckoo search to find the optimal placement and the number of dampers and sensors, simultaneously.

2. THE CONTROLLER EQUATIONS OF MOTION

FLC controller was proposed because of its independency to time-consuming complex calculation. Hence, the time delay issues which reducing the reliability of adaptive controller are significantly minimized. The proposed FLC gathers minimum analysis time and no requirement to adjustment during the environmental hazards which leads to more efficiency and reliability. The proposed FLC rules the MR dampers output force by transmitting external voltage supply. Few studies pursued the optimal control of structures by using optimal FLC. None of these studies have paid attention to find the optimal MR damper and sensors as two independent subjects. In this paper, sensors placement were determined independent of dampers placement to increase the efficiency. Therefore, FLC inputs changed to absolute displacement and velocity of stories which sensors were the damper was installed. Because of dynamic behavior of MR damper, the piston velocity and acceleration affect to the external forces of damper. 3, 4 and 8 Story shear buildings were investigated to show that the CS-FLC leads to better results than traditional controllers. An adaptive controller should be minimized peak of control forces, in addition to reducing the structural undesirable responses. Therefore, a model of a combinational optimization problem consists of three objective functions to be minimized. Search space is the placement of dampers and sensors in different stories. The number of utilized MR dampers and sensors are constraints for optimal placement problem. After some necessary modification on the main theory of Cuckoo search (CS). The FLC-CS is employed to deal with MR damper and sensor optimization problem. In the state space, the equations of motion for the n-story structure can be described as follows:

$$\dot{Z}(t) = A.Z(t) + B.u(t) \qquad y(t) = C.Z(t) + D.u(t) \tag{1}$$

Z(t) and y(t) are the state space and output vector, respectively. Which coefficients matrices are expressed as follows :

$$A = \begin{bmatrix} 0_{n\times n} & I_{n\times n} \\ -M_S^{-1}.K_S & -M_S^{-1}.C_d \end{bmatrix} \qquad B = \begin{bmatrix} 0_{n\times n} & 0_{n\times n} \\ -I_{n\times n} & -M_S^{-1}.D_p \end{bmatrix}$$

$$C = \begin{bmatrix} I_{n\times n} & 0_{n\times n} \\ 0_{n\times n} & I_{n\times n} \\ -M_S^{-1}.K_S & -M_S^{-1}.C_d \end{bmatrix} \qquad D = \begin{bmatrix} 0_{n\times n} & 0_{n\times n} \\ 0_{n\times n} & 0_{n\times n} \\ -I_{n\times n} & -M_S^{-1}.D_p \end{bmatrix} \tag{2}$$

$$u(t) = \begin{bmatrix} \ddot{X}_{g\,n\times 1} \\ F(t)_{n\times 1} \end{bmatrix} \qquad Z(t) = \begin{bmatrix} X_{n\times 1} \\ \dot{X}_{n\times 1} \end{bmatrix} \qquad y(t) = \begin{bmatrix} X_{n\times 1} \\ \dot{X}_{n\times 1} \\ \ddot{X}_{n\times 1} \end{bmatrix}$$

$X, \dot{x}$ and $\ddot{x}$ are displacement, velocity and acceleration vectors of the structure, respectively. M_S, K_S and C_d represent the mass, stiffness and damping matrices of the structure, respectively. D_p shows the damper location matrices. F(t) is external force and u(t) is output vector of the state space model. Control force is assumed as a function of displacement and velocity responses of the structure in closed loop control which determined by a fuzzy logic controller.

3. THE DYNAMIC BEHAVIOR OF MECHANICAL MODEL OF HYUDRAULIC DAMPER

Semi-active hydraulic fluids are a kind of controllable fluids, which can adaptively react to an applied magnetic field with an immediate modification in their rheological behavior. The essential specification of MR fluids is their ability to reversibly alter from free flowing, linear viscous liquids to semi-solids hydraulic fluids having a controllable resistance when exposed to a magnetic field in a few milliseconds. MR fluid dampers have high dynamic range, large force capacity, robustness and reliability. MR dampers with a capacity of

200kN, have been examined and designed since 1996. A lately investigated model is capable to anticipate the response of MR damper over a wide range of loading conditions and command voltages[30]. In this study, finite number of 200kN MR dampers were used. These devices are employed as semi-active hydraulic actuators where the voltage is updated by a fuzzy logic controller. The mechanical model of MR damper which is suggested by Spencer et al. [31] was employed to reproduce the force of the damper, in each time step. The governing equations are listed below:

$$f = C_1.\dot{y} + K_1.(x - x_0) \;\; \dot{y} = \frac{1}{C_0 + C_1}\left[\alpha.Z + C_0.\dot{x} + K_0(x - y)\right]$$
$$\dot{Z} = -\gamma\left|\dot{x} - \dot{y}\right|Z\left|Z\right|^{n-1} - \beta.(\dot{x} - \dot{y})\left|Z\right|^{n} + A.(\dot{x} - \dot{y}) \tag{3}$$

where y is the internal displacement of MR damper and x is the damper displacement in the x direction. α(i), C_0(i) and C_1(i) values of MR damper were experimentally obtained by Yang[31] and 'i' is the input current, in each time window.:

$$\begin{aligned}\alpha(\mathrm{i}) &= 16566.\mathrm{i}^3 - 87071.\mathrm{i}^2 + 168326.\mathrm{i} + 15114\\ \mathrm{C}_0(\mathrm{i}) &= 437097.\mathrm{i}^3 - 1545407.\mathrm{i}^2 + 1641376.\mathrm{i} + 457741\\ \mathrm{C}_1(\mathrm{i}) &= -9363108.\mathrm{i}^3 + 5334183.\mathrm{i}^2 + 48788640.\mathrm{i} - 2791630\end{aligned} \tag{4}$$

To regulate the experimental data, the additional coefficients are assumed constant as xo=0.18 m, k_1=617.31 N/m, k_o=37810 N/m, A=2679 m-1, γ and β=647.46 m-1, n=10. To accredit the dynamic behavior of this mechanical model with experimental tests, a first order filter was also utilized to correctly model the dynamics of MR fluid for reaching to rheological equilibrium [28]:

$$H(S) = \frac{31.4}{S + 31.4} \tag{5}$$

In designing controllers, the time delay related to the semi-active hydraulic damper and closed-loop response together is less than 10 ms [32]. Time delay is far from the first period of simulated buildings. So the effect of time delay can be ignored. In addition to the velocity and acceleration of the piston of MR damper during the each time step, the electrical input current had a significant rule to determining the damper force. Fuzzy logic controller managed the input current. The governing rules will be discussed in the section 5. Mechanical model and schematic figure of MR damper were displayed in Fig. 1. Some different studies related with other control methods were employed MR dampers [33-34].

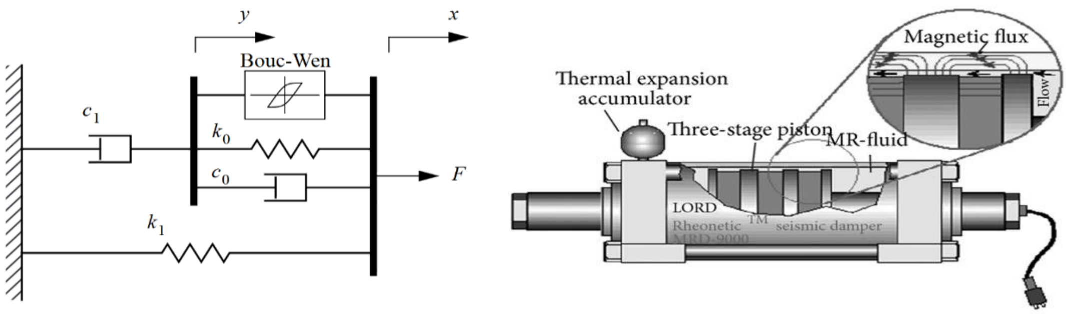

Figure 1. Mechanical model and schematic figure of MR damper[11]

4. FUZZY LOGIC CONTROL

The proficiency of conventional controllers (e.g., linear quadratic Gaussian, H_2, etc.) fully relies on the precision of dynamics structures specification. Complex structural systems have nonlinearities and uncertainties in both structural properties and the magnitude of the loading. It is difficult to recognize an accurate dynamic model for designing the conventional controllers. The new controllers can improve the modeling imprecisions and uncertainties without necessitating any heavily constrained optimization problems to solve. The FLC (Fuzzy Logic Control) is based on the fuzzy set theory[21], can be used for these Shortcomings. FLC essentially consists of four components to simulate the logical reasoning of human beings. These components were named: fuzzification interface, rule base, decision making and defuzzification interface. In this study, to deal with the imprecision and uncertainty which was not determined in the design process, an intelligent FLC controller has been introduced. A FLC can be incorporated into a closed-loop control system similar to conventional feedback controllers. An independent sensor for each MR damper was determined. Hence, the velocity and displacement of the sensors are the input variables. The output variable of FLC is inducing current, which regulates the MR damper control force. Range of Membership functions for the input variables is [-1, 1] and for the output variables is [0,1]. When the velocity and the displacement of the dampers are in the same direction, the rule-bases utilize a major current to produce a large control force. If they are in different directions, no significant control force is mandatory. Gaussian curve membership function was utilized. The sensors signal convert into linguistic fuzzy values through the fuzzification process. The Mamdani-type fuzzy logic was determineed which is well suited for adaptive controllers. The scale factor and quantification factor are very important to determine the control force. The selection of the fuzzy functions, fuzzyfication and de-fuzzyfication were determined by trial and error to achieve the best responses. The membership functions for both input and output variables were shown in Fig. 2. The details of inference rules were demonstrated in Table 1. Resulted mechanical model of MR damper was represented in Fig. 3. Each of the input and output fuzzy variables are defined in the fuzzy space, in the form of nine linguistic values namely ND (Negative Displacement), ZD (Zero Displacement), PD (Positive Displacement), NV (Negative Velocity), ZV (Zero Velocity), PV (Positive Velocity), Z(Zero), S(Small) and L(Large).

Table 1: Inference regulations employed in the proposed FLC

	NV	ZV	PV
ND	L	S	Z
ZD	S	Z	S
PD	Z	S	L

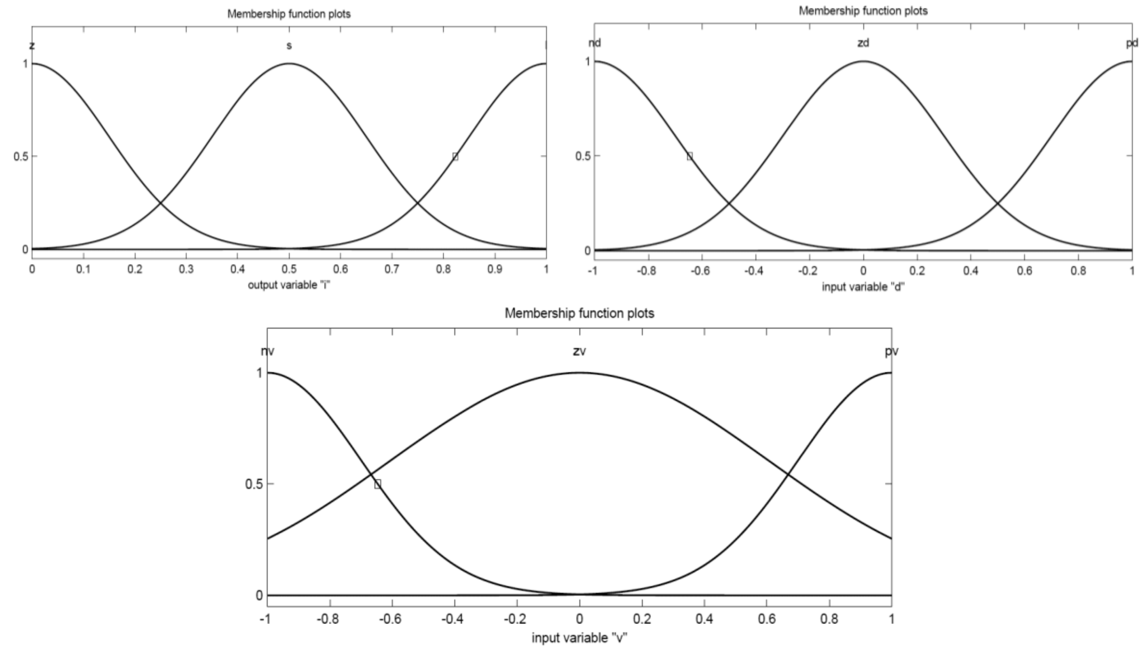

Figure 2. Membership functions employed for input and output variables of the proposed FLC

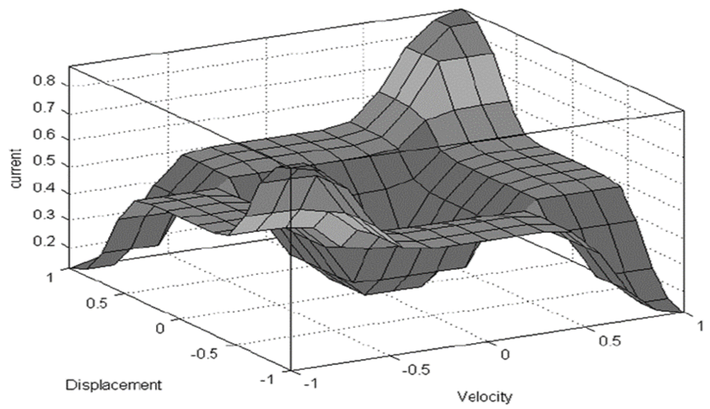

Figure 3. Fuzzy logic controller

5. CUCKOO SEARCH OPTIMIZATION ALGORITHM (CS)

Yang and Deb introduced a novel meta-heuristic optimization algorithm, which was named cuckoo search (CS) algorithm[14]. CS is resulted by some species of a bird family called cuckoo because of their special lifestyle and aggressive breeding strategy. These birds locate their eggs in the nests of other host with astonishing abilities to increase survival probability of their eggs. On the other side, some of host birds can distinguish the eggs of cuckoos and throw out the discovered eggs or build their new nests in new locations. Therefore, CS algorithm consists of a population of nests or eggs to simulate this strategy. The main simple rules of utilized CS are expressed as follows: (I) each cuckoo sets only one egg at a time and dumps it in a randomly chosen host nest; (II) the best nests with high quality of eggs are utilized in the next generations; and (III) the number of available host nests is constant and assumed before algorithm start; (IV) the probability of discovering of the guest egg which is laid by a cuckoo, is expressed by p_a in the range of [0,1]. This assumption can be estimated by the fraction pa of the n nests are replaced by new ones (with new random solutions). Each egg in a nest indicates a solution and a cuckoo egg indicates a new one. If the cuckoo egg is very familiar to the host eggs, the probability of discovering the cuckoo egg is reduced. The fitness function should be related to the quality or fitness of a solution which can simply be proportional to the objective function. The aim is to employ the new and potentially better solutions (cuckoos) to replace a not-so-good solution in the nests. The structure of CS can be summarized as shown in Fig. 4.

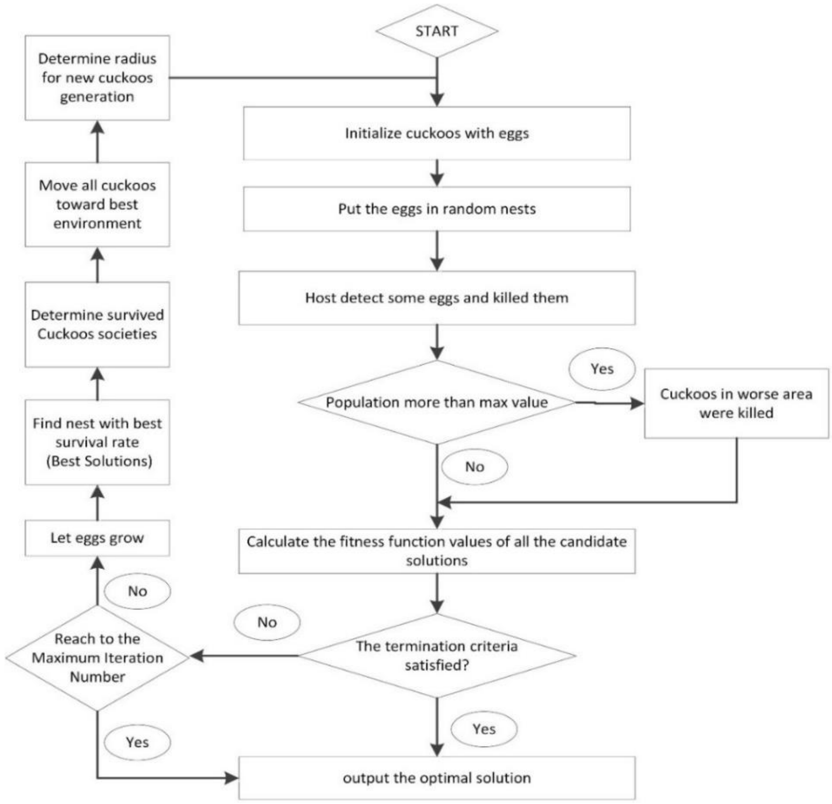

Figure 4. the structure of CS algorithm

The CS parameters are set in the first step. The dimension of search space is confined to be between [0,5]. The random candidate value for δ_i is utilized to compute the control energy-weighting matrix [R] of the i-th window to accomplish the appropriate control of the structural responses. These parameters are number of nests (n), step size parameter (a), probability of discovering the eggs (p_a) and maximum number of iteration as the stopping criterion. The first locations of the nests are determined by the set of values assigned to each decision variable randomly is expressed by the following equation:

$$nest^0(i,j)=round(x(j)_{min}+rand(x(j)_{max}-x(j)_{min})) \tag{6}$$

where $nest^0(i,j)$ determines the initial value of the j_{th} components of the i_{th} nest; $x(j)_{min}$ and $x(j)_{max}$ are the minimum and maximum allowable values for the j_{th} component; and rand is a random number in the interval [0, 1]. For next step, all of the nests except for the best location so far are replaced in order of quality by new cuckoo eggs produced with Lévy flights from their positions as

$$nest^{t+1}(i,j)=nest^t(i,j)+\alpha.S.r.(nest^t(i,j)-nest^t(best)) \tag{7}$$

where $nest^{t+1}(i,j)$ is the j_{th} component of i_{th} nest in t+1 iteration, a is the step size parameter, which is assumed to be 0.1 in this paper, S is the Lévy flights vector as in Mantegna's algorithm, r is a random number from a standard normal distribution between [0, 1] and $nest^t(best)$ is the position of best nest so far. The alien eggs discovery procedure is accomplished for all of the eggs except the best location by utilizing the probability matrix for each component of each solution. By deciding the quality by fitness function, existing eggs are replaced by newly generated ones from their current position by random walks with step size:

$$S=rand.(nests[permute1[i]][j]-permute2[i]][j]) \tag{8}$$

where *rand* is random number, *nests* is matrix which contains candidate solutions along with their parameters, *permute1* and *permute2* are different rows permutation functions applied on *nests* matrix. The generation of new cuckoos and the discovering of the alien eggs steps are performed alternately until a termination criterion is satisfied. The maximum number of frame analyses is assumed as the algorithm's termination criterion. The stopping criterion is assumed as a maximum number of iterations, which is limited to be 60 iterations. Finally the population size, N, is specified to be 70. The selection of these values are based on trial and error to reach the most suitable convergence speed and required accuracy in the CS optimization algorithm. The fitness function for each time-window is expressed as follows:

6. NUMERICAL SIMULATIONS AND RESULTS

In numerical simulations, the state-space model of structural building and FLC were utilized. The components of numerical simulations contain the shear-building models, hydraulic semi-active dampers, main computer controller, sensors and the ground motion time history of acceleration. The State-space representation was utilized to estimate the dynamic behavior of structure in MATLAB [34]. The responses of the structure during seismic excitation were compared with the passive-off and passive-on responses. For the current studies, three fitness functions were defined as the following equations:

$$J_1 = \frac{\sum^n RMS(x_{FLC})}{\sum^n RMS(x_{Poff})} \quad J_2 = \frac{\sum^n RMS(d_{FLC})}{\sum^n RMS(d_{Poff})} \quad J_3 = \frac{\sum^n RMS(\ddot{x}_{FLC})}{\sum^n RMS(\ddot{x}_{Poff})} \tag{12}$$

where x is the displacement of the each floor, d is the inter-story drift, $\ddot{x}$ is the absolute acceleration of the floors and RMS shows the root mean square of variables. The P_{OFF} superscript denotes the case where the MR dampers are operated in the passive-off mode and no command voltage is sent to the dampers. The final case is the fuzzy logic control which is noted by the abbreviation FLC. The voltage range of each MR damper is 0 to 1 V.

A near-fault forward-directivity El-Centro time-history of N-S acceleration was employed to excite the benchmark structures. Fig. 5 illustrates ground acceleration for station H-E0230.

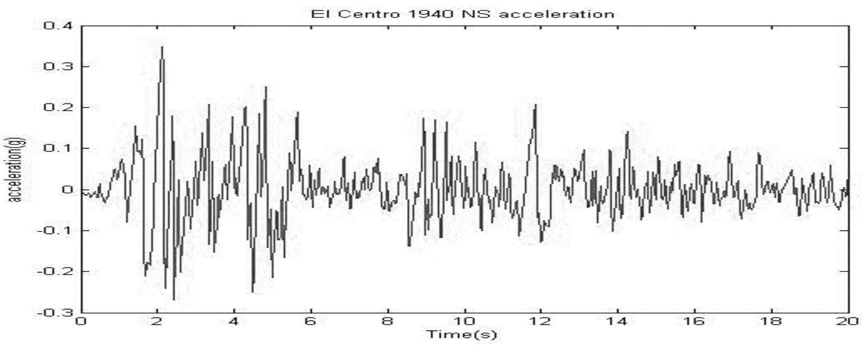

Figure 5. N-S component of El-Centro time history of acceleration

A three-story shear building was chosen to determine the effectiveness of fuzzy logic controller. The building properties are listed in Table 2.

Table 2: Inference rules employed in the proposed FLC

Floor Mass	50000 Kg
Floor Stiffness	20000 kN/m
Damping Coefficient (ζ)	1%

After the simulation, CS with respect to three fitness functions shows that one MR damper and sensor should be employed and installed in the third story. The dynamic analysis with El-Centro time history excitation was performed by MATLAB software. Proposed FLC manages the MR dampers mechanical behavior by sending external voltage supply. Table 3 summarizes the results for each control cases. Significant reductions were observed with respect to J_1 and J_2 that correspond to the RMS (Root Mean Square) of the story displacement, the RMS of inter-story drifts and the RMS of the absolute acceleration responses. Less favorable results are observed with respect to J_3, which corresponds to the peak absolute acceleration response. On average, the FLC performance is superior to passive-on with respect to all cases except the peak absolute acceleration. First story acceleration in the FLC has decreased just less than the P_{ON}. In this study, the priority of the reduction of structural responses is the inter-story drifts, the displacement and the acceleration of stories, respectively.

Table 3: Results of numerical evaluation

	Displacement(m)			**Drift (m)**			**Acceleration (m/s^2)**		
Story	1	2	3	1	2	3	1	2	3
POFF	0.067	0.121	0.151	0.067	0.055	0.032	7.347	10.029	12.838
FLC	0.022	0.038	0.042	0.022	0.017	0.014	5.088	7.343	7.634
Fitness values		J_1 0.296			J_2 0.341			J_3 0.658	
PON	0.024	0.039	0.047	0.027	0.018	0.016	4.983	7.453	7.925
Fitness values		J_1 0.318			J_2 0.388			J_3 0.670	

Results demonstrate that damper and sensor placement can significantly improve the performance of a controlled structure. CS particles include the number and the placement of the dampers and their sensors, independently. The fitness of the population gradually improves with respect to J_1, J_2 and J_3, with next algorithm generations. To improve the probability of finding the global optimal solution in heuristic optimization, five independent CS algorithms were began simultaneously. Global best and local best parameters were shared in each 50 iterations. To demonstrate the efficiency of the CS-FLC, a previously studied example was utilized [35]. Two different cases are presented which the MR damper is utilized in a passive mode to investigate the behaviors of control structural system in semi-active and passive cases. The first passive case is denoted by 'P_{OFF}', which the inducing current to the MR damper is retained at 0A and the second passive case is indicated by 'P_{ON}', in which the inducing current to the MR damper is kept at the maximum current (3.0 A). A previously studied clipped-optimal controller is compared to illustrate the efficiency of CS-FLC more precisely. The simulation results are presented in Table 4.

Table 4: Peak results of 3-story structural system [35] due to Elcentro earthquake

Responses	Uncontrolled Structural System	Controlled Structural System			
		P-OFF	P-ON	clipped-optimal controller[35]	CS-FLC
1st story displacement (cm)	0.34	0.16	0.11	0.12	0.11
3rd story displacement (cm)	0.76	0.43	0.35	0.41	0.38
Control Forces(KN)	0	2.965	4.262	4.165	3.984

Results demonstrate that proposed CS-FLC reached to an advisable level of performance. The P_{OFF} controller attenuates the maximum displacement of the third story by 43% of the uncontrolled values, the P_{ON} controller exhibits a 54% attenuation, the clipped-optimal controller demonstrates a 46% attenuation and the CS-FLC decreases the responses up to 53%. Nevertheless, the maximum control force should be taken into account to demonstrate the efficiency of a controller. Although the P_{ON} controller decreases the maximum displacement of the third story by 54%, selecting a passive mode that employs the largest damping control forces may not be the most appropriated strategy to safeguard structural system. The CS-FLC consumes 7% less control forces in comparison with P_{ON} on Elcentro earthquake. Table 4 exhibits that CS-FLC can significantly enhance the performance of the structural system. To the author's best knowledge, there is no published research on optimal semi active control of low-rise or high-rise buildings with MR dampers by using separately sensor installation to manage the control forces more efficient. Two different eight and twenty story shear-buildings have been utilized to illustrate the efficiency of the CS-FLC controller. The control system and the behavior of buildings were assumed linear during excitation. The excitation is the first 20s of the N-S component of El-Centro earthquake with the peak acceleration of 0.31g. The first structure is an eight-story shear building with the following characteristics:

$$\begin{gathered} m_1 = m_2 = 400 \ \ ton \ , \ m_3 = m_4 = m_5 = m_6 = m_7 = m_8 = 350 \ \ ton \\ k_1 = k_2 = k_3 = 3\times10^5 \ KN/m \ , k_4 = k_5 = k_6 = 2.5\times10^5 \ KN/m \ , k_7 = k_8 = 1.8\times10^5 \ KN/m \\ \xi = 1\% \end{gathered} \tag{13}$$

It is obvious that more hydraulic dampers results in more reduction in the structural response but the economical parameters should be paid attention to choose the number of dampers. Hence, J_1, J_2 and J_3, a penalty function method should be employed to obtain the optimal number of dampers. For the eight-story shear building, the following penalty function (PF) is employed:

$$PF = (2\times j_1 + 1\times j_2 + 0.8\times j_3)\times(1 + ND\times 0.07) \tag{14}$$

where ND is the number of dampers, J_1, J_2 and J_3 are three objective values, which were defined in section 7.1. By using 100 initial particles, after nine iterations algorithm reaches to the optimum solution. The optimum solution for this four-story building is:

$$W = [Dp = [0 \quad 2 \quad 1 \quad 2 \quad 2 \quad 0 \quad 2 \quad 0] \quad Sp = [- \quad 1 \quad 8 \quad 3 \quad 6 \quad - \quad 8 \quad -]] \tag{15}$$

where Dp is the damper placement vector and Sp is the sensor placement vector. In eight story shear-buildings, two-200kN MR damper should be installed in the second story, one in the third story, two in the fourth story, two in the fifth story and two in the seventh story of structure. Their sensors should be installed in the first, eighth, third, sixth and eighth story, respectively. It can be seen four sensors are adequate. Simulation results of eight-story building are shown in Table 5. Fig. 6 shows the displacement, acceleration and drift responses in time and Fig. 7 shows the applied control forces of hydraulic dampers.

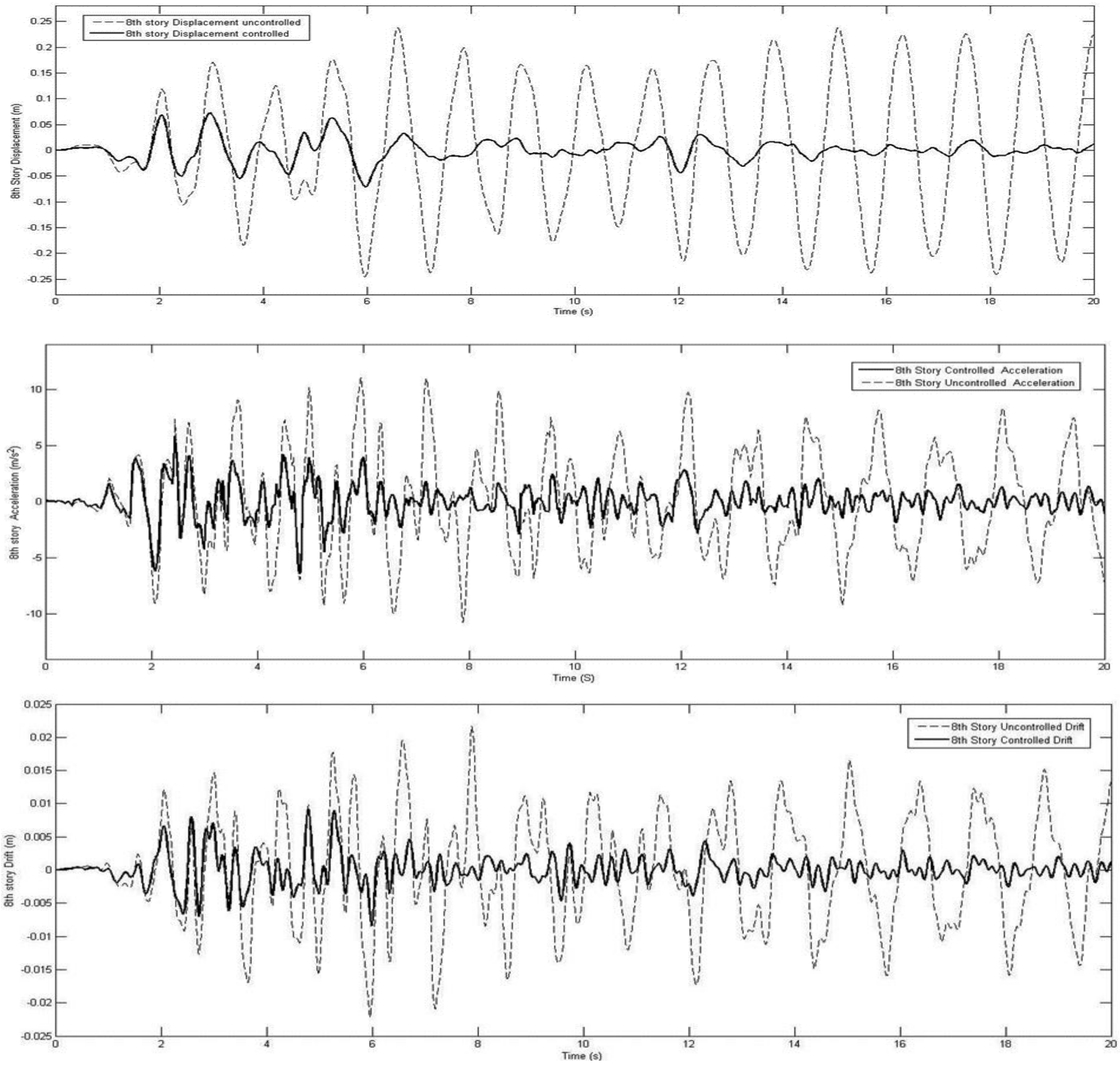

Figure 6. Eighth-story time history of displacement, acceleration and drift responses of eight-story building

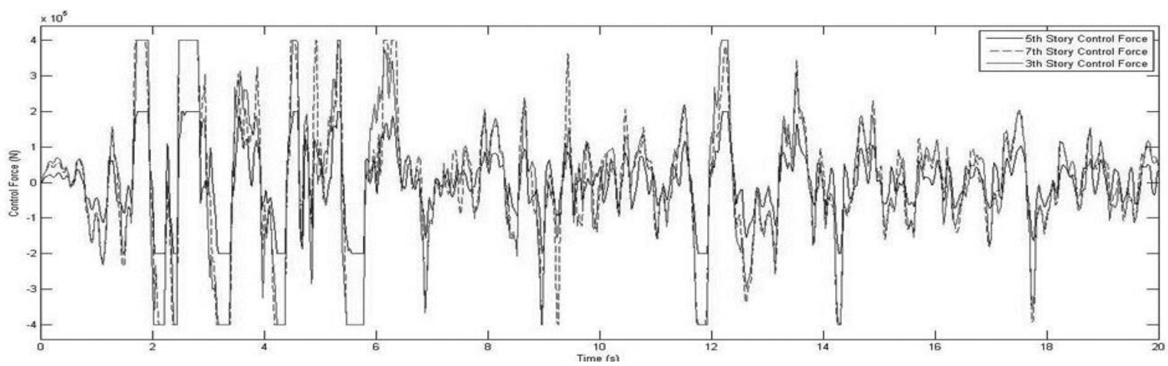

Figure 7. Applied control force in the third, fifth and seventh story of eight-story building

Table 5: Numerical evaluation results of eight-story building

Story		1	2	3	4	5	6	7	8
Number of dampers		-	2	1	2	2	-	2	-
Control force average (kN)			129.9	66.7	129.9	134.3		135.1	
Displacement (m)	Uncontrolled	0.042	0.082	0.112	0.146	0.178	0.204	0.228	0.246
	Controlled	0.011	0.021	0.029	0.039	0.047	0.056	0.066	0.073
	Reduction Percentage	73.0	73.8	73.8	73.0	73.7	72.4	71.2	70.4
Drift (m)	Uncontrolled	0.042	0.039	0.034	0.039	0.039	0.035	0.038	0.022
	Controlled	0.011	0.011	0.011	0.014	0.012	0.011	0.013	0.009
	Reduction Percentage	73.0	73.0	68.8	64.4	68.5	68.5	67.0	59.5
Acceleration (m/s^2)	Uncontrolled	5.022	6.512	7.968	9.184	7.734	7.388	10.070	11.050
	Controlled	4.888	5.741	5.177	4.807	4.741	5.698	5.195	6.317
	Reduction Percentage	2.7	11.9	35.0	47.7	38.7	22.9	48.4	42.8

The placement of hydraulic dampers in structures demonstrates that in mid-rise buildings, the dampers and the sensors should be distributed in bottom stories to achieve more appropriated responses and CS-FLC controller could find the optimum solution in exact. The second structure is an twenty-story shear building with the following specifications:

$$\begin{aligned} & m_1 = 1126\ ton\ ,\ m_2 = m_3 = \cdots = m_{19} = 1100\ ton\ , m_{20} = 1170\ ton \\ & k_1 = \cdots = k_5 = 862.07 \times 10^3\ {KN}/{m}\ ,\ k_6 = \cdots = k_{11} = 554.17 \times 10^3\ {KN}/{m} \\ & k_{12} = k_{13} = k_{14} = 453.51 \times 10^3\ {KN}/{m}\ , k_{15} = k_{16} = k_{17} = 291.23 \times 10^3\ {KN}/{m} \\ & k_{18} = k_{19} = 256.46 \times 10^3\ {KN}/{m}\ , k_{20} = 171.7 \times 10^3\ {KN}/{m} \qquad \xi = 5\% \end{aligned} \tag{16}$$

For the twenty-story shear building the following penalty function (PF) is employed:

$$PF = (2 \times j_1 + 1 \times j_2 + 0.8 \times j_3) \times (1 + ND \times 0.025) \tag{17}$$

where ND is the number of dampers, J_1, J_2 and J_3 are three objective functions. CS determines the number and the placement of the sensors and dampers by utilizing four objective functions PF, J_1, J_2 and J_3. The proposed algorithm uses 80 initial particles and after eleven iteration reaches to the optimum solution and in the next generation, the optimum solution remains constant. The optimum solution for this twenty-story building is:

$$\begin{bmatrix} Dp = [0\quad 4\quad 6\quad 6\quad 5\quad 4\quad 4\quad 2\quad 2\quad 1\quad 0\quad 3\quad 1\quad 6\quad 2\quad 2\quad 1\quad 0\quad 2\quad 0] \\ Sp = [-\quad 5\quad 13\quad 11\quad 4\quad 16\quad 8\quad 8\quad 13\quad 6\quad -\quad 6\quad 10\quad 9\quad 11\quad 11\quad 12\quad -\quad 17\quad -] \end{bmatrix} \tag{18}$$

where Dp is the damper placement vector and Sp is the sensor placement vector. It means that the optimum number of dampers is 51. It can be seen that separate sensors installation is more appropriated in this structure. Fig. 8. shows the time history of the displacement, the velocity and acceleration responses in tenth floor. Fig. 9 shows the hydraulic damper external forces. It can be seen that proposed CS-FLC and optimum arrangement of actuators and sensors attenuated the excessive drift, displacement and acceleration responses of structure to the acceptable magnitudes.

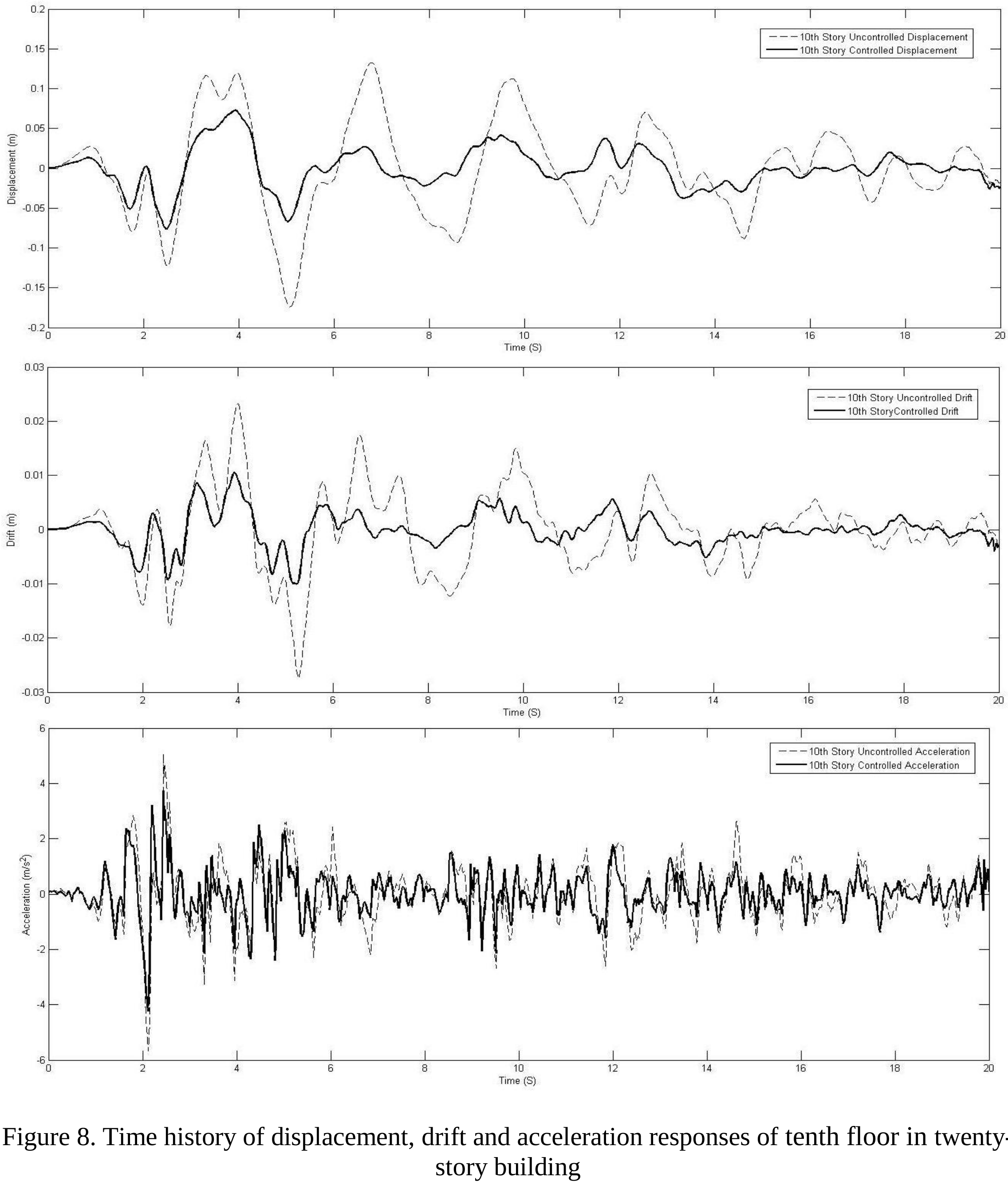

Figure 8. Time history of displacement, drift and acceleration responses of tenth floor in twenty-story building

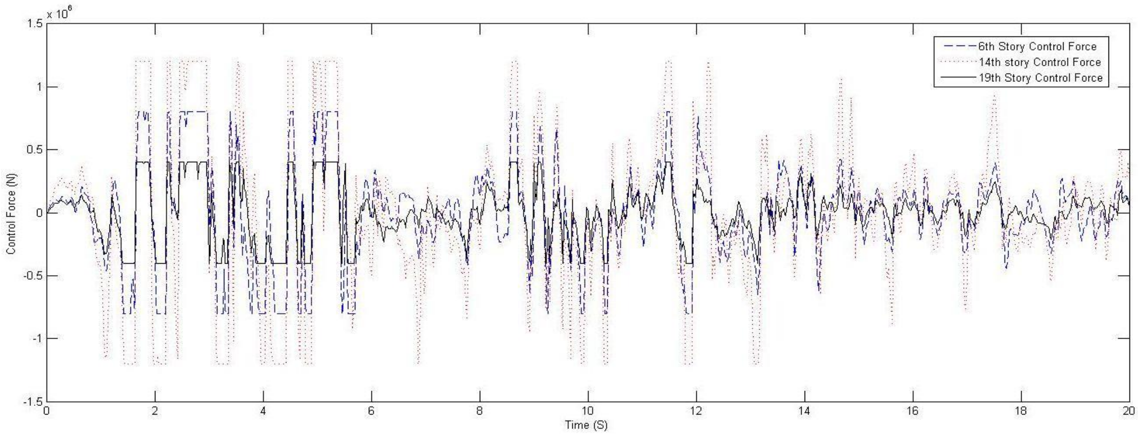

Figure 9. Hydraulic damper external forces.

Table 6. demonstrates the robustness and effectiveness of the proposed method by comparing the average reduction ratios (controlled to uncontrolled displacement, drift and acceleration ratio) for the El-Centro earthquakes in all of stories in twenty-story building. Fig. 10 shows the hydraulic damper force-displacement and for velocity diagram which installed in 19th floor of twenty story building.

Table 6: Numerical simulation results of twenty-story building

Story		2	4	6	8	10	12	14	16	18	20
Number of dampers		4	6	4	2	1	3	6	2	-	-
Control force average (kN)		292	441	284	144	69	204	446	152	-	-
Displacement (m)	Uncontrolled	0.04	0.07	0.11	0.15	0.17	0.20	0.24	0.03	0.32	0.33
	Controlled	0.02	0.03	0.05	0.06	0.08	0.09	0.11	0.13	0.14	0.15
	Reduction Percentage	50	57	57	57	56	52	53	55	57	54
Drift (m)	Uncontrolled	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03
	Controlled	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
	Reduction Percentage	55	47	55	62	62	59	54	57	57	49
Acceleration (m/s^2)	Uncontrolled	5.52	5.25	4.45	5.58	5.68	4.83	4.53	4.29	3.6	4.76
	Controlled	5.08	4.64	4.17	4.21	4.23	3.91	3.76	2.94	3.08	3.93
	Reduction Percentage	8	11.7	6	25	25	19	17	32	14	17

Simulation results exhibits that proposed optimal Cuckoo search-fuzzy logic controller (CS-FLC) could reach to the optimum location and number of sensors and dampers. Simultaneously, CS-FLC can adaptively optimize the resulted control forces of hydraulic dampers. In 20-story shear building, CS-FLC is capable of reducing the maximum displacement, drifts and acceleration of building to about 55, 55 and 21 percent of uncontrolled average responses, respectively. Thus, CS-FLC is very effective based on the result and numerical efforts to reach in a specific performance based-design level. Furthermore, the adaptability in the design of the proposed CS-FLC to account for the variation in the excitation content in time via FLC controller makes it more robust and effective controller for seismic vibration control of structural systems.

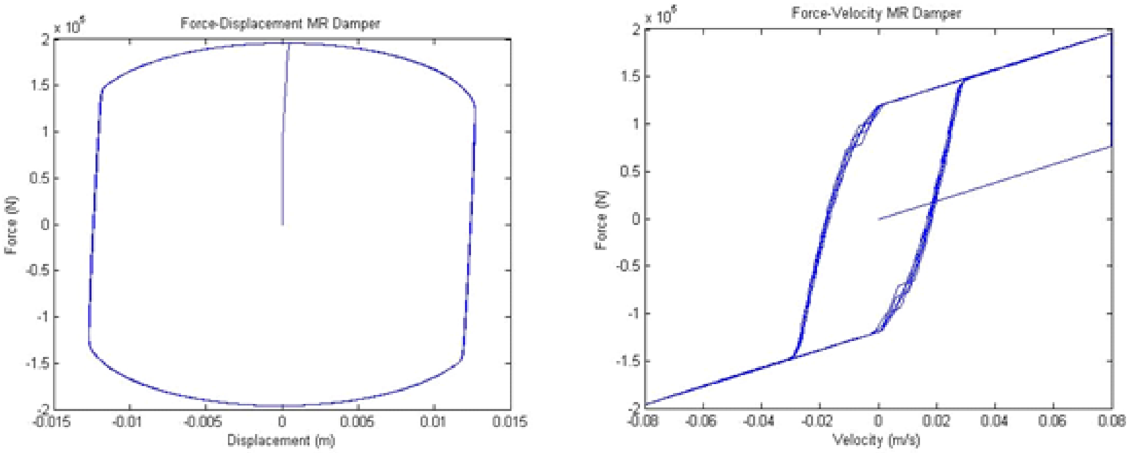

Figure 10. Hydraulic damper force-displacement and for velocity diagram

7. CONCLUSIONS

In this study, a new developed semi - active Cuckoo search-fuzzy logic controller (CS-FLCC) was investigated to enhance seismic performance for the multistory buildings. In addition to its simplicity, the proposed CS-FLCC controller demands fewer input to manage inducing input current of the installed MR dampers and, accordingly, the controlling force. A new modified CS was employed to optimize the MR damper and sensor number and placement for the reduction of building responses and costs subjected to a near-fault forward-directivity El-Centro time-history. The adaptability in the design of the proposed CS-FLC to account for the variation in the excitation content in time via CS-FLC controller makes it more robust and effective controller for seismic vibration control of structural systems. To evaluate the performance and effectiveness of CS-FLCC controller, we create and analyze three analytical models.

The results demonstrate that without using a massive cost to supply more dampers and with less input data, the proposed controller can significantly reduce the seismic response of structures to the desirable seismic design level. The optimum number and the location of controllers were determined with the least iteration. Furthermore, numerical evaluations exhibit that the location of dampers should be distributed all over the building to mitigate the displacement, drift and acceleration.

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