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Optimal Fuzzy Logical Control for Magnetorheological Damper-Building System Using Imperialist Competitive Algorithm

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Abstract

Magnetorheological (MR) dampers are prominent semi-active control devices for vibration mitigation of structures under seismic excitation. To get the best fuzzy logic controller (FLC) that is optimized by imperialist competitive algorithm (ICA) for MR damper-building system is aimed in this paper. In order to establish optimal command voltage of MR dampers and determine fuzzy logical controller parameters, the ICA that considers multiple objectives simultaneously is proposed. The objective is to minimize structure responses, including maximum displacement and acceleration. A 3-story building equipped with MR dampers is investigated to demonstrate the effectiveness of the proposed control strategy. Simulation results with different control strategies are compared, it is demonstrated that the proposed method significantly reduces seismic responses and achieve better performance than genetic algorithm in multi-input multi-output (MIMO) system. Meanwhile, it is verified that the presented controller algorithm offers flexibility and simplicity for structure using MR damper with nonlinearities and uncertainties.

***Keywords**: ICA; MR dampers; FLC; Structure response; Optimum design; MIMO system*

1. Introduction

To find an effective means to protect structures, subjected to dynamic hazards such as earthquakes and strong winds, is one of the major challenges that civil engineers must face. With many shock absorption and control devices applied in the practical engineering, control schemes, such as passive control, active control and semi-active control have been an integral part of structural systems over the past two decades [1]. Compared with the active control, the semi-active control can obtain the resemblance performances, and has more practical value due to its more simple structure and lower cost. The MR damper is one of the most promising new semi-active devices for structural vibration reduction, because of its mechanical simplicity, high dynamic range, low power requirements, large force capacity and robustness [2]. Besides, the MR damper is reliable and fail-safe because the damper becomes passive if the control hardware is without power input [3].

However, because of the intrinsically nonlinear dynamics of the MR dampers, it is an interesting and challenging task to design a suitable control algorithm that can fully utilize the unique characteristics of these devices [4]. Numbers of control algorithm are proposed for the control of the MR systems including Lyapunov based control algorithm [5], clipped-optimal control algorithm [6] and modulated homogeneous friction algorithm [7]. However, theses control algorithms for MR dampers are fully dependent on accurate mathematical models of the dampers. Furthermore, most of these algorithms set the command voltage either zero or maximum value to the MR damper based on feedback from the structure and the characteristics of magnetorheological fluid (MRF) is limited.

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Moreover, the sudden swift change of voltage can produce a large external control force which may increase the structure response and may introduce local damages in the structure.

Among the studied semi-active damping control strategies, control strategies such as FLC have attracted much attention since they do not need precise mathematical model and are strongly robust against parameter uncertainties, high nonlinearities and heuristic knowledge, etc [8]. However, in conventional FLCs, it is difficult to convert expert knowledge into control rules, especially in a MIMO FLC which is needed when a structure is installed with more than one damper. To solve the problem, combining FLC system with evolutionary algorithms such as genetic algorithm (GA), bee colony algorithm [4] and shuffled frog-leaping algorithm are a trend. GA has been used for the optimization of FLC to drive hybrid mass damper and the result has been found to be very effective [9]. The rule extraction strategy for semi-active fuzzy control is carried out by GA [10-11]. But both of these studies focus on optimizing fuzzy rules, while other parameters of FLCs predetermined. Besides, ICA, a recently developed metaheuristic, introduced by Atashpaz-Gargari and Lucas [12], is a very promising evolutionary algorithm for optimization which is inspired by imperialistic competition. ICA is a global search technique that has been presented for dealing with different optimization tasks and is widely used in industrial engineering, civil engineering, mechanical engineering, electrical engineering, petroleum engineering, computer engineering, etc [13].

In this paper, a multi-objective cost function is presented based on ICA to optimize the FLC parameters including membership functions (MFs), fuzzy rules and input scaling gains so that the fuzzy correlation between the inputs (structure responses) and the outputs (command voltages) can be optimal. The NS component of the 1940 El-Centro ground acceleration is used as seismic excitation during the whole design process. By comparing with other control strategies, it is demonstrated that the proposed control strategy is much better than other control algorithms, especially in a MIMO system. The rest of this paper is organized as follows: Details of FLC-ICA is presented in Section 2. In Section 3, a MR damper-building system is established. In Section 4, numerical simulations are carried out for a three-story building frames equipped with single and multiple dampers.

2. FLC-ICA System

2.1. Brief Introduction of ICA

Evolutionary algorithms are meta-heuristic optimization algorithms that use biology-inspired mechanisms like mutation, crossover and natural selection for different optimization problem [14]. Just as genetic algorithm and particle swarm optimization, ICA is an evolutionary algorithm and is inspired by socio-political behaviors. Similar to other evolutionary algorithms, ICA starts with an initial population called country. At first, some of the countries with the lowest cost function values are regarded as imperialists and the rest are colonies of these imperialists. Having been divided, these colonies start moving toward their relevant imperialist countries and then empires are created. The total power of an empire is determined by the power of imperialist country and the colonies. All empires try to take possession of colonies of other empires and then imperialistic competition brings about the change of imperial power. Powerless empires will collapse in the imperialistic competition and only the most powerful empire will be remained.

2.2. Design of Fuzzy Logical Controller Based on ICA

In this study, ICA is employed to determine appropriate FLC parameters of the FLC system. FLC parameters have a critical influence on the final control effect and this isn't an easy task in a MIMO control system. ICA optimally establishes a reasonable fuzzy correction among the structure responses and the command voltages required by the MR dampers so as to mitigate maximum displacement and acceleration responses of the building. The main task is to use ICA to find the best parameters for FLC. Design of the FLC is described in the following steps.

2.2.1. Fuzzifying Input and Output

In the view of comfort properties, the acceleration response of a structure is an important indicator. Besides, it can be easily measured by accelerometers in any parts of the house. Therefore, the accelerations are taken as inputs. Here, five membership functions are designed for each input and output. The definition of the fuzzy input lingual variables is namely as follows: Negative Large (NL), Negative Small (NS), Zero (Z), Positive small (PS), and Positive Large (PL). The output variable is denoted as Zero (Z), Very small (VS), Small (S), Large (L) and Very large (VL). The acceleration input variables are normalized over the discourse of [-1, 1] before entering the fuzzy controller. The input scaling gains are optimized by the ICA and then adopted as multipliers to normalize the corresponding accelerations. The output value is normalized to a damping coefficient ranging [0 1]. A generalized triangle-shape of membership function is used because in a practical application it is more widely used. A triangle-shape membership function can be defined as follows:

$$f(x,a,b,c)=\begin{cases}0 & x<a\\ \dfrac{x-a}{b-a} & a\le x<b\\ \dfrac{c-x}{c-b} & b\le x<c\\ 0 & x\ge c\end{cases} \tag{1}$$

The triangle-shape is determined by parameters a, b and c which are selected by ICA. Because both the input and output have five MFs, all the total numbers of MFs parameters can be calculated as follows:

$$n=3\times 5\times\left(n_{in}+n_{out}\right). \tag{2}$$

Here, n_{in} and n_{out} are the numbers of inputs and outputs of the fuzzy controller, respectively. The number of the input scaling gains denoted by n_{gains} is equal to the above defined n_{in}.

2.2.2. Defining FLC Rules

Fuzzy control rules are the core of fuzzy controller design. They are essentially a section of fuzzy conditional statements set summary and obtained by the practical experience of operator. Fuzzy control employs a set of control rules with same structure but different values to describe the reaction control in various situations. Since there are two inputs and one output, the fuzzy control rules can be taken as follows:

$$Rule:\ if\ A=a_i\ and\ B=b_j\ then\ C=c_i;\ i,j=1,2,...,n \tag{3}$$

Where A and B are input variables, C is the out variable and n is the number of the fuzzy rules. a_i and b_j are linguistic values for the two inputs, while c_i is linguistic value for the output. The number of control rules can be calculated as follows:

$$n_{rules} = \prod_{i=1}^{n} N_i = N_1 \cdot N_2 \cdots N_n \tag{4}$$

Where, n is the input number and N_i is the linguistic value number of each input.

2.2.3. Optimization of FLC Using the ICA

As mentioned above, ICA is employed to optimally design the FLC parameters. The objective of the control proposed is to minimize both peak displacement and peak absolute acceleration of the structure under seismic-excited. Here, the ICA is used with the following specification:

- Generating initial empires

In this study, we form an array of variable values called "country" to be optimized. The FLC is an N_{72}-dimensional optimization problem and a country is a $1 \times N_{72}$ array. A country includes the total parameters above-defined n_{MFs}, n_{gains} and n_{rules}. The array is defined by:

$$country = \left[p_{N1,a}, p_{N1,b}, p_{N1,c}, \ldots, p_{Ni,a}, p_{Ni,b}, p_{Ni,c}, p_{N46}, \ldots, p_{N70}, p_{N71}, p_{N72} \right] \tag{5}$$

where $p_{Ni,\mathrm{a}}$, $p_{Ni,\mathrm{b}}$, $p_{Ni,\mathrm{c}}$ (i=1,2,3,...,15) represent parameters of each triangle a, b and c of 15MFs, respectively. While p_{N46} to p_{N70} denote 25 output values in fuzzy rules. p_{N71} and p_{N72} stand for input scaling gains. The cost of a country is found by evaluating the cost function of the variables ($p_{N1,\mathrm{a}}$ $p_{N1,\mathrm{b}}$ $p_{N1,\mathrm{c}}$,..., p_{N71} p_{N72}):

$$cost = f\left(country\right) = f\left(p_{N1,a}, p_{N1,b}, p_{N1,c}, \ldots, p_{N71}, p_{N72}\right) \tag{6}$$

Then, some of the best countries, having the lowest cost function values, become imperialists and the rest are to be colonies belong to the imperialists.

- Cost function

As mentioned previously, ICA use a cost function value for ICA operators, and this function reflects the desired objective. The control goal is to minimize the maximum acceleration and displacement of the building. It is necessary to establish the relationship between the ICA and the structure responses. A set of evaluation criteria based on those used in the second generation linear control for building are proposed in the reference [15] In this study, to ensure the safety of the building and comfort of the occupants at a certain level, a multi-objective function is proposed as follows:

$$J = \beta J_1 + (\alpha - \beta) J_2 + (1 - \alpha) J_3 \tag{7}$$

Where α and β are weighting coefficient reflecting the importance of acceleration and displacement of the structure respectively. J_1, J_2 and J_3 are defined as follows:

$$\begin{cases} J_1 = \max\limits_{t,1}\left(\dfrac{\left|x_1(t)\right|}{x^{\max}}\right) \\ J_2 = \max\limits_{t,i}\left(\dfrac{\left|x_i(t)\right|}{x^{\max}}\right) \\ J_3 = \max\limits_{t,i}\left(\dfrac{\left|\ddot{x}_{ai}(t)\right|}{\ddot{x}_a^{\max}}\right) \end{cases} \tag{8}$$

Here, the maximum displacement of the structure (J_2) and the first floor of displacement (J_1) are both considered at the same time. By adjusting the weighting coefficient, a more reasonable distribution of displacement of the structure would be obtained. J_3 is another important index reflects the maximum acceleration of the structure. Where $x_i(t)$ and $\ddot{x}_{ai}(t)$ are the relative displacement and the absolute acceleration of the *i*th floor over the entire response; $x_{\max}$ and $\ddot{x}_a^{\max}$ denote the uncontrolled maximum displacement and acceleration response.

3. MR Damper-Building Systems

3.1. Dynamic Model of MR Damper

To date, many dynamic models are put forward to describe the characteristics of MR damper. Among them, the phenomenological model is the most accurate and effective to predict the response of MR damper over a wide range of operations [16]. The total force produced by MR damper can be written as:

$$\begin{cases} F = c_1\dot{y} + k_1(x - x_0) \\ \dot{y} = \dfrac{1}{c_0 + c_1}[\alpha z + c_0\dot{x} + k_0(x - y)] \\ \dot{z} = -\gamma\left|\dot{x} - \dot{y}\right| z \left|z\right|^{n-1} - \beta(\dot{x} - \dot{y})\left|z\right|^n + A(\dot{x} - \dot{y}) \end{cases} \tag{9}$$

Here, k_1 is the accumulator stiffness, c_0 is viscous damping observed at large velocities, x_0 is the initial displacement of spring associated with nominal damper force due to accumulator, c_1 is the viscous damping at low velocities and k_0 is present to control stiffness at large velocities. γ, β and A are hysteresis parameters for the yield element.

The relation between the coefficient and the applied voltage is as follows:

$$\begin{cases} \alpha = \alpha(u) = \alpha_a + \alpha_b u \\ c_1 = c_1(u) = c_{1a} + c_{1b}u \\ c_0 = c_0(u) = c_{0a} + c_{0b}u \end{cases} \tag{10}$$

Where u is given as the output of a first-order filter by:

$$\dot{u} = -\eta(u - v) \tag{11}$$

And v is the commanded voltage applied to the driver. All of the 14 parameters of the phenomenological model are listed in Table 1.

Table 1. Parameters of the MR Damper Model [3]

Parameter	Value	Parameter	Value
c_{0a}	21.0 N s cm^{-1}	α_a	140 N cm^{-1}
c_{0b}	3.50 N s cm^{-1}	α_b	695 N cm^{-1}
k_0	46.9 N cm^{-1}	γ	363 cm^{-2}
c_{1a}	283 N s cm^{-1}	β	363 cm^{-2}
c_{1b}	2.95N s cm^{-1}	A	301
k_1	5.00N cm^{-1}	n	2
x_0	14.3cm	η	190 s^{-1}

3.2. State Equation of the System

An l degree-of freedom structure with m MR dampers is considered in the linear range subjected to the ground excitation. The equation of motion can be express as follows:

$$M_s\ddot{x} + C_s\dot{x} + K_s x = \Gamma f - M_s\Lambda\ddot{x}_g \tag{12}$$

Where M_s, K_s, and C_s represent the mass, structural stiffness and damping matrices of the structure, respectively; $\ddot{x}_g$ is the ground acceleration; x is the n-dimensional relative displacement vector with respect to the base; f is the vector of control force, and its coefficient Γ is matrix denoting the location of controller in the structure; Λ represents the influence of the earthquake excitation. With the state vector z=[x $\dot{x}$]^T, the equation can be written in state-space form as:

$$\dot{z}(t) = Az(t) + Bu(t) \tag{13}$$

Where A is the system matrix, B is the input matrix. They are given as follows:

$$A = \begin{bmatrix} -M_s^{-1}C & -M_s^{-1}K \\ I & 0 \end{bmatrix} \quad B = \begin{bmatrix} \Lambda & M_s^{-1}\Gamma \\ 0 & 0 \end{bmatrix} \quad u = \begin{bmatrix} \ddot{x}_g \\ f \end{bmatrix}$$

With the output vector y= [$\ddot{x}_g$ x $\dot{x}$]^T and $\ddot{x}_g$ is the absolute acceleration, the output equation is defined as:

$$y = Cz(t) + Du(t) \tag{14}$$

Where

$$C = \begin{bmatrix} -M_s^{-1}C_s & -M_s^{-1}K_s \\ I & 0 \\ 0 & I \end{bmatrix} \qquad D = \begin{bmatrix} 0 & M_s^{-1}\Gamma \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

4. Numerical Results

In this part, numerical simulations are carried out for a three-story building frame equipped with single and multiple dampers to evaluate the effective of the proposed method. The simulation procedure is implemented by MATLAB (R2013a).

4.1. Single Damper Case

The MR damper is rigidly connected between the ground and the first floor of the structure. The physical structure properties are as follows [3]:

$$C_s = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} \frac{Ns}{m} \quad M_s = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} kg \quad K_s = 10^5 \begin{bmatrix} 12.0 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \frac{N}{m}$$

Table 2. Peak Structure Response under El-Centro Earthquake with Different α and β

FLC-ICA	α=0 β=0	α=0.2 β=0.05	α=0.5 β=0.1	α=0.8 β=0.2	α=0.8 β=0.4	α=1 β=1
x_i (cm)	0.084	0.088	0.104	0.118	0.095	0.089
	0.197	0.206	0.232	0.219	0.205	0.203
	0.300	0.304	0.309	0.293	0.289	0.300
d_i (cm)	0.084	0.088	0.104	0.118	0.095	0.089
	0.144	0.151	0.143	0.129	0.122	0.140
	0.105	0.100	0.086	0.082	0.095	0.103
$\ddot{x}_{ai}$ (cm/s^2)	274	277	392	346	251	260
	416	443	525	444	418	415
	733	692	598	568	658	713
F(N)	861	979	783	712	824	825

Here, the first 20s of the NS component of the 1940 El-Centro ground acceleration is used as seismic excitation. However, the earthquake acceleration is produced at five times the recorded rate to adapt the structure similitude. The accelerations of the 2th floor and 3th floor normalized by according input scaling gains are selected as inputs. The ICA is started with 15 countries including 3 empires. According to Eq. (12), $\Gamma = [-1\ 0\ 0]^T$, $\Lambda = [1\ 1]^T$ and $f = f_1(t)$ for the three-story building with single damper rigidly connected between the ground and the first floor. The ICA will stop either the maximum iterative time reaches to 50 or only one empire is remained. Table 2 details about the peak structure responses under El-Centro earthquake with different α and β. x_i, d_i, $\ddot{x}_i$ are maximum displacement relative to the ground, peak inter-story (*i.e.*, x_i-x_{i-1}) and maximum absolute acceleration of the *i*th (*i*=1, 2, 3) floor respectively. *F* is the maximum damping force applied on the structure during the earthquake.

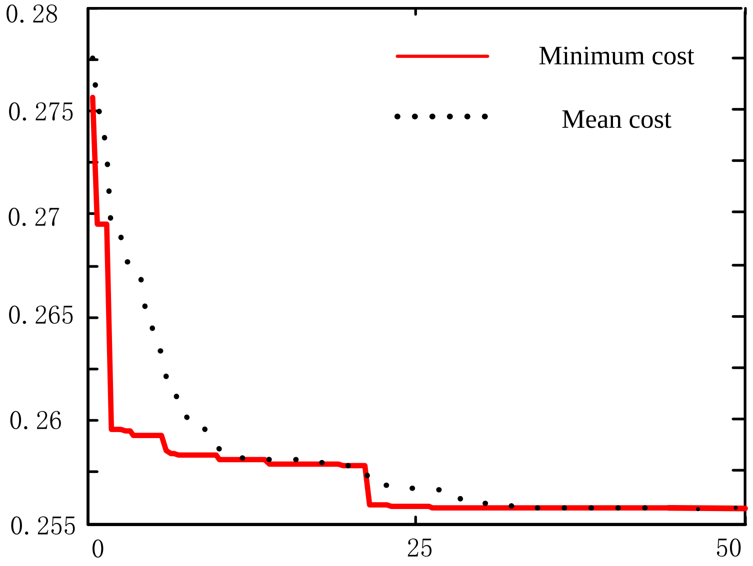

Figure 1. Object Function Value of the Three-Story Building Frame with Single Damper under the 1940 El-Centro Earthquake

Table 3. Fuzzy Control Rule Base Optimized by FLC-ICA

2th Acceleration	3th Acceleration				
	NL	NS	Z	PS	PL
L	M	S	L	VL	VL
NS	VS	S	S	VS	S
Z	VL	VL	S	VL	S
PS	VL	VS	VS	VS	VL
PL	VL	S	S	L	VL

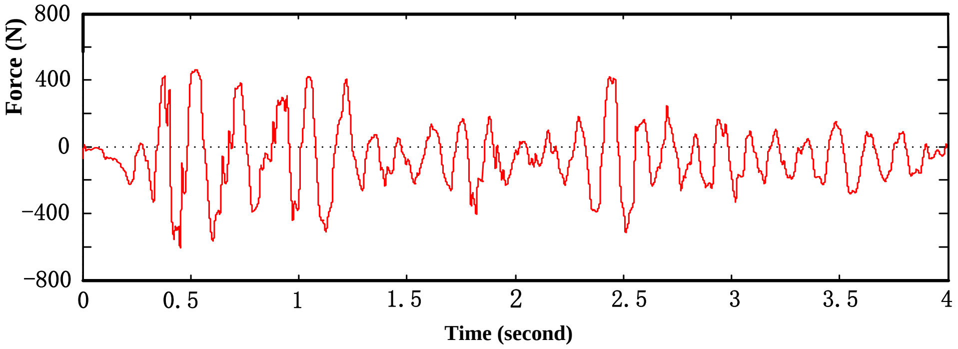

Figure 2. Force Produced by MR Damper

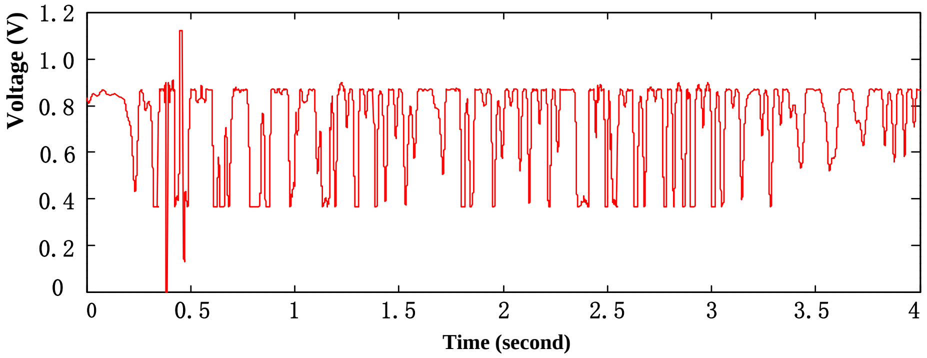

Figure 3. Command Voltage Optimized by ICA

It can be seen from Table 2, when $\alpha=\beta=0$, *i.e.*, in the object function Eq. (7) only the maximum acceleration is considered, x_1 and x_2 attain its minimum displacement while $\ddot{x}_3$ reaches its maximum. d_2 (peak inter-story, *i.e.*, x_i-x_{i-1}) is larger compared with others while $\alpha=0.2$ and $\beta=0.05$. Meanwhile, F attains its maximum (979) among the different values of α and β. When it comes to $\alpha=0.8$ and $\beta=0.2$, F is 712N which is almost only 67% of the maximum value (1055N, Table 4) and $\ddot{x}_3$ has dropped significantly but at the expense of the increase of $\ddot{x}_1$. In the case of $\alpha=\beta=1$, $\ddot{x}_3$ and F are all increased significantly compared with $\alpha=0.8$ and $\beta=0.2$. Through above analysis, we can see that there are optimal values of α and β that are more conducive to decrease both the peak displacement and acceleration. Here, $\alpha=0.8$ and $\beta=0.2$ are adopted as the weight values of the proposed object function in the following study.

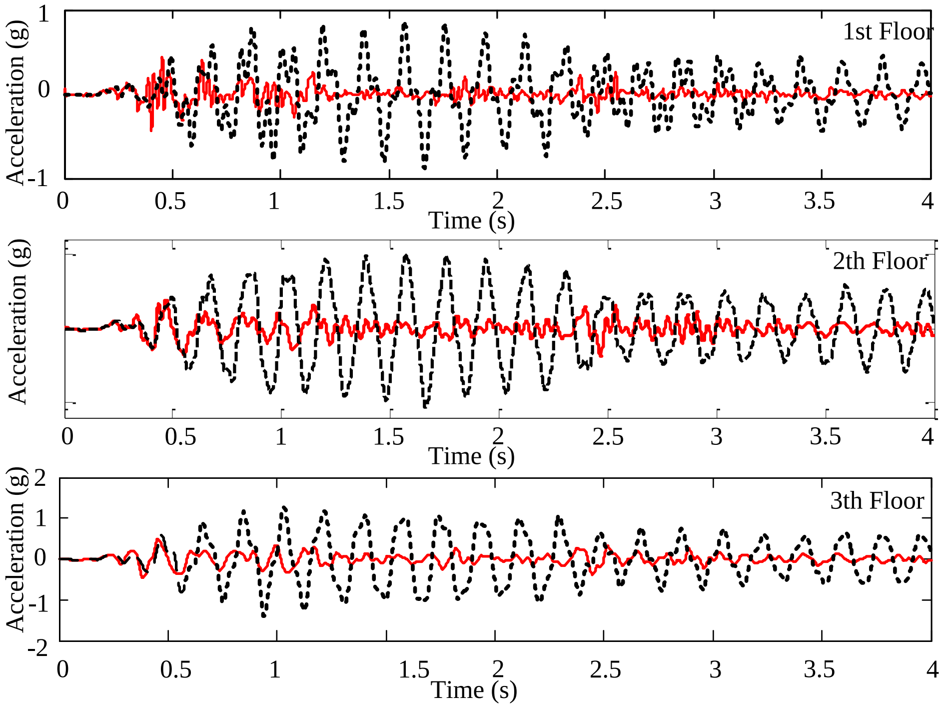

Figure 4. Absolute Acceleration with ICA-Optimized FLC When α=0.8, β =0.2 (Solid Line) and Uncontrolled (Dash Line)

As we can see from Figure 1, the optimization process converges after 30 iterations. Table 3 presents the fuzzy control rule base optimized by ICA when α=0.8 and β=0.2. Figure 2 shows the force produced by MR damper and Figure 3 presents the command voltage optimized by ICA. It can be concluded from Figure 4 and 5 that the proposed method can significantly reduce the structure responses of the relative displacement and absolute acceleration.

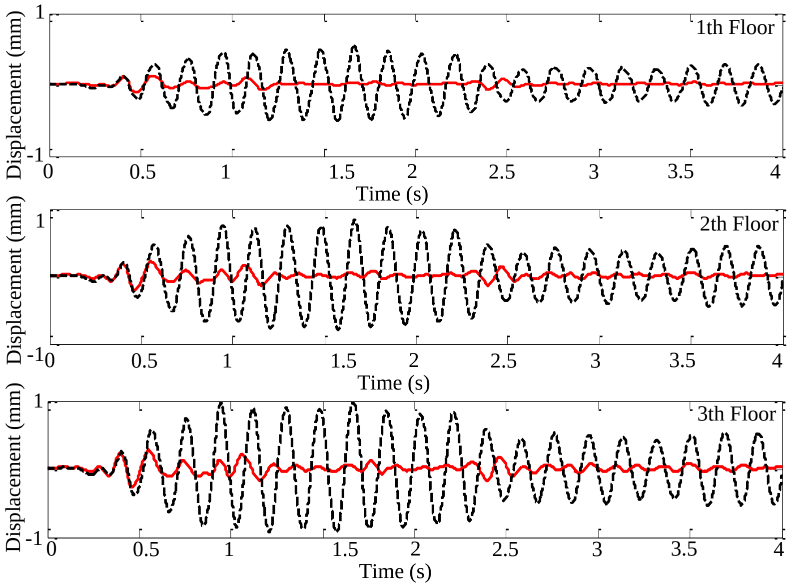

Figure 5. Relative Displacement with ICA-Optimized FLC When α=0.8, β =0.2 (Solid Line) and Uncontrolled (Dash Line)

Table 4. Peak Structure Response under El-Centro Earthquake with Different Control Strategies

Control strategy	Uncontrolled	Passive-off	Passive-on	Clipped-optimal control	Ideal active control	Fuzzy GH$_2$	FLC-ICA (α=0.8 β=0.2)
x_i(cm)	0.549	0.227	0.084	0.114	0.108	0.156	0.118
	0.836	0.374	0.185	0.185	0.154	0.270	0.219
	0.973	0.469	0.297	0.212	0.236	0.334	0.293
d_i(cm)	0.549	0.227	0.084	0.114	0.108	0.156	0.118
	0.318	0.155	0.117	0.090	0.132	0.119	0.129
	0.203	0.105	0.072	0.101	0.082	0.066	0.082
$\ddot{x}_{ai}$ (cm/s^2)	879	432	287	696	445	273	346
	1069	495	517	739	393	388	444
	1411	731	781	703	569	448	568
F(N)	-	332	1055	941	941	673	712

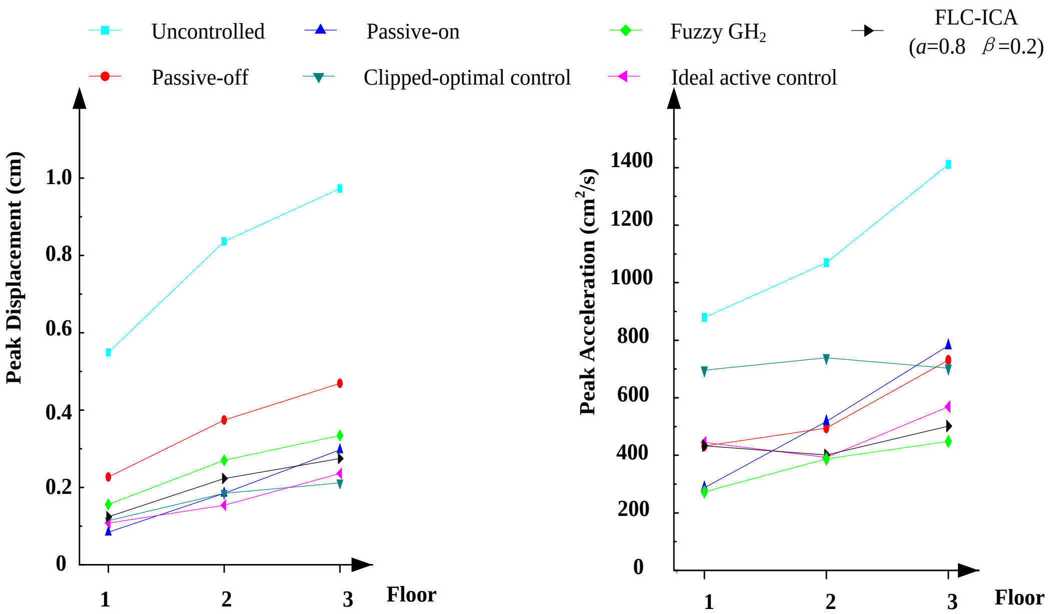

Figure 6. Peak Responses of Each Floor of Structure under the 1940 El-Centro Earthquake

In order to compare and prove the effect of the proposed control strategy, results for two passive control strategies named passive-on and passive-off in which the command voltage is set to zero and maximum, respectively, two semi-active controllers including the clipped-optimal control and Fuzzy GH$_2$ control and ideal active control are cited in Table 4 [3, 17]. Among the above different control strategies, the maximum force produced by FLC-ICA is relatively small-that is, the method proposed can utilized the MR damper more efficient and economical efficient. Although the acceleration based on Fuzzy GH$_2$ is smaller than that of the FLC-ICA, the maximum relative peak displacement optimized by FLC-ICA reduced at least 12.3% (x_3) compared with the result of Fuzzy GH$_2$. The passive-off control strategy can save energy without current, but peak structure response of the third floor is much bigger compared with ideal active control and FLC-ICA. The force produce by passive-on is up to 1055N with the voltage set to maximum, in other words, it will cost too much energy. It can be seen from Figure 6 about the control effects of the proposed control strategies more directly. From the aspects of peak displacement, the FLC-ICA has a better control effect than Fuzzy GH_2, but worse than Ideal active control. Meanwhile, FLC-ICA can effectively control the peak acceleration and can obtain the similar effect with the idea active control.

4.2. Multiple Dampers Case

In order to prove the proposed FLC-ICA is very suitable for designing a MIMO system, the three-story building frame installed with two dampers is considered in this case. One damper is rigidly connected between the ground and the first floor, while the other is rigidly connected between the first floor and the second floors. With the control strategies mentioned above, the peak relative displacement, peak inter-story, and peak absolute acceleration are presented in Table 5. For purposes of comparison two passive control strategies are also listed in Table 5. It can be seen that the control effect of FLC-ICA are better than the Passive-off and Uncontrolled strategies. Compared with Passive-on strategy, the maximum displacement (x_i) and peak inter-story (d_i) of FLC-ICA are almost the same, while $\ddot{x}_{a3}$ reduces 20% at the cost of $\ddot{x}_{a2}$ slightly increases 4.8%. Figure 6 shows the voltages sent to the dampers based on FLC-ICA and the force produced by MR damper when α=0.8, β=0.2. The maximum force is 736N which is produced by the damper installed between the ground and the first floor. There is no doubt that the control effect is further improved compared with those results listed in Table 4. As we can see in Figure 7, the control strategy of FLC-ICA is more effective to reduce the structure response compared with that of Fuzzy GH_2 [17].

Table 5. Peak Structure Response under El-Centro Earthquake with Multiple Dampers

Control strategy	Uncontrolled	Passive-off	Passive-on	FLC-ICA (α=0.8,β=0.2)
x_i(cm)	0.549	0.198(63.9%)	0.060(89.1%)	0.061(88.8%)
	0.836	0.326(61.0%)	0.103(87.7%)	0.106(87.3%)
	0.973	0.400(58.9%)	0.133(86.3%)	0.138(85.8%)
d_i(cm)	0.549	0.198(63.9%)	0.060(89.1%)	0.061(88.8%)
	0.318	0.128(59.7%)	0.044(86.2%)	0.047(85.2%)
	0.203	0.076(62.6%)	0.050(75.4%)	0.051(74.9%)
$\ddot{x}_{ai}$ (cm/s^2)	879	308(64.9%)	309(64.8%)	290(67.0%)
	1069	397(62.9%)	313(70.7%)	328(69.3%)
	1411	528(62.6%)	432(69.4%)	352(75.1%)
F_1(N)	-	298	920	736
F_2(N)	-	262	643	587

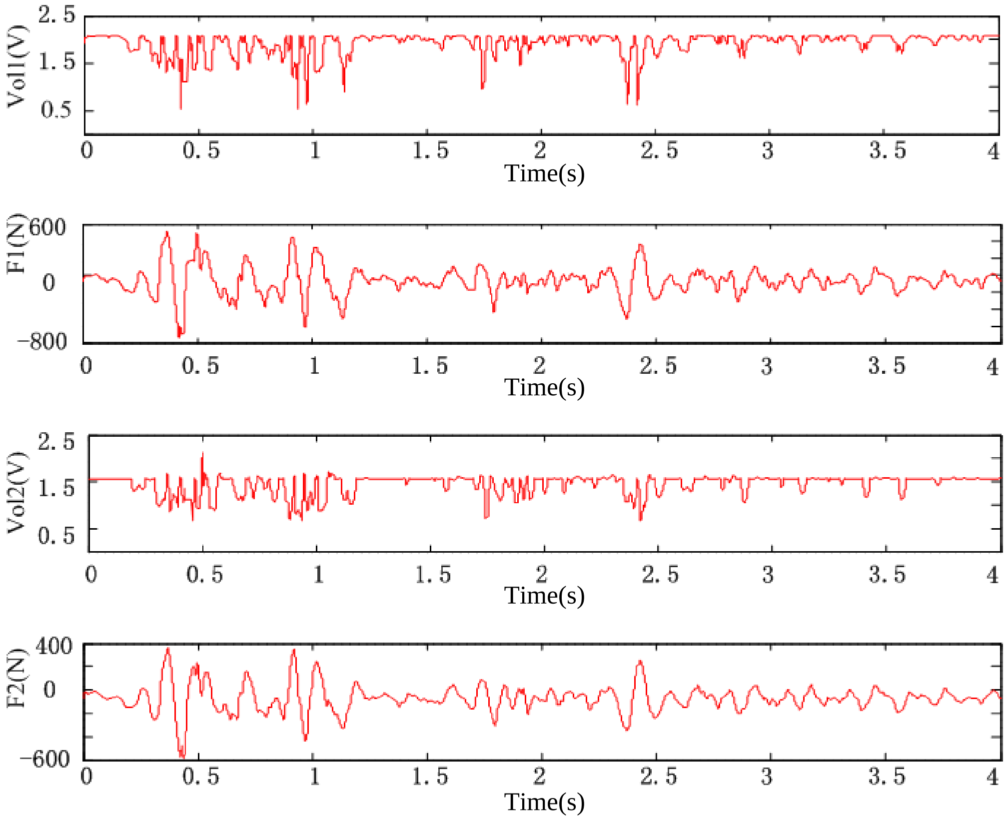

Figure 7. Voltages Sent to MR Dampers and Forces Produced by MR Dampers

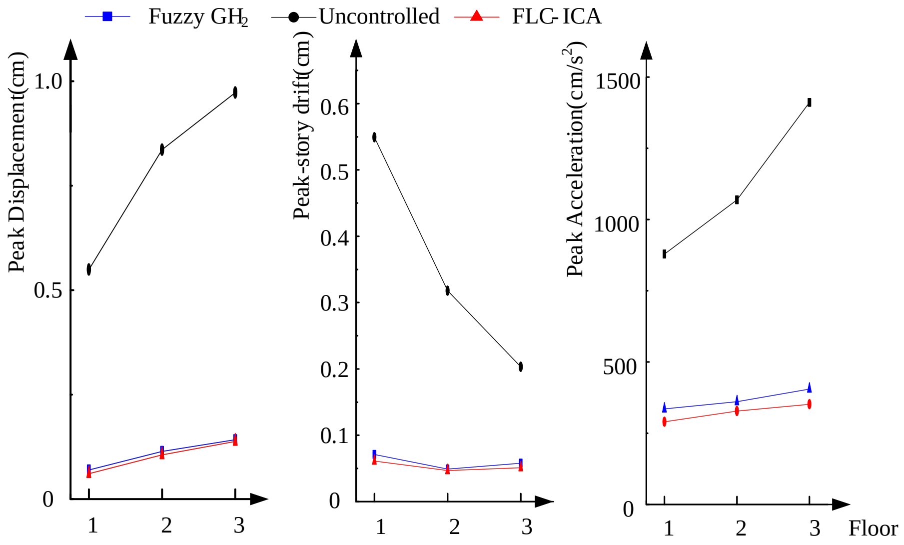

Figure 8. Peak Responses of Each Floor of Structure in Multiple Damper Cases

5. Conclusion

This paper presents a new control strategy based on ICA for semi-active fuzzy logical control to reduce the seismic responses of a three-story structure installed with MR dampers. The promising evolutionary algorithm-ICA is used to optimize parameters of the triangular function, input gain matrix and fuzzy rules. In order to minimize the structure responses under seismic excitation, a multi-objective fitness function is proposed to simultaneously reduce the peak absolute acceleration and the maximum relative displacement. The simulation results show that the FLC-ICA can greatly reduce the structure responses to a low level under seismic excitation. In single MR damper case, the peak displacement and maximum acceleration reduced at least 69.9% and 59.7%, respectively; and in the multiple dampers case the reduction is up to 85.8% and 67%, respectively. Simultaneously, the results are compared with other control algorithms (clipped-optimal, ideal active control, Fuzzy GH_2) mentioned in previous literatures and it demonstrates that the presented controller algorithm offers flexibility and simplicity for structure using MR damper with nonlinearities and uncertainties. In addition, the result indicates that the control strategy proposed is especially suitable for designing a MIMO system. Finally, further study is under way to propose a more efficient multi-objective fitness function and to improve the FLC-ICA more efficiently. Experiments verification will be considered in the further study.

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