International Journal of Emerging Engineering Research and Technology
Volume 3, Issue 3, March 2015, PP 13-24
ISSN 2349-4395 (Print) & ISSN 2349-4409 (Online)

Semi-Active Control of Structures Equipped with FDSAB Using Integrated Genetic Algorithm-Fuzzy Controller and Neutral Networks

Hosein Ghaffarzadeh[1]

[1]*Department of Civil Engineering Faculty of Structural Engineering, University of Tabriz, 29 Bahman Blvd., Tabriz, Iran*

ABSTRACT

In this paper, an integrated fuzzy rule-based control strategy for building structures incorporated with semi active friction system with amplifying braces (FDSAB) subjected to earthquake excitation was developed. A genetic algorithm (GA) is used for optimization of the fuzzy logic controller. The main purpose of employing a GA is to determine appropriate fuzzy control rules as well to adjust parameters of the membership functions. To improve the performance of control strategy in reducing time delay between the response measurement and the control action, an expertly trained artificial neural network was constructed based on the information of seismic structural response against an earthquake excitation which obtained from several dynamic time history analysis of a structure. The efficiency of the developed system is demonstrated by the numerical simulation of a seven storey shear frame configured with FDSAB devices at each storey. The controlled response of the frame was compared with results obtained from the classical linear quadratic regulator (LQR) method. The results showed the proposed control strategy was highly effective in reduction of both the seismic response and time delay effect in control scheme.

Keywords: Semi active control system, Fuzzy controller, Genetic Algorithm (GA), Artificial Neural Network (ANN), Regulator Linear Quadratic (LQR), Time delay, Friction System with Amplifying Braces (FDSAB)

INTRODUCTION

Structural control strategies have been a subject of intensive research and have been recognized as a promising approach for response suppression in recent decades. Generally, several vibration control technologies have been developed. Structural control systems can be classified to active, semi-active and passive control methods. Semi-active structural control has received considerable attention since they possess some remarkable advantages over passive and active systems. In fact, they not only maintain the reliability of passive control systems, but also provide the versatility of active control systems with a much lower power requirement which is of a great importance in structural control during earthquakes [1].

The control effectiveness of structural systems is highly dependent on the control strategy used for designing semi-active control law. Conventional control algorithms are reliant on having an accurate model of the system including clipped-optimal algorithm [2] optimal controllers [3, 4, 5] Lyapunov stability theory [6] skyhook controllers and continuous sliding mode (CSM) controllers [7] decentralized bang-bang, maximum energy dissipation [8] linear quadratic regulator (LQR) [9] and others of that ilk. Although these model-based strategies have been successful suppression of structural vibrations, they suffer from some inherent shortcomings for structural applications and their performance is strongly affected by the accuracy of the model selected. The other approaches, as alternative to the classical control algorithms, consists of methods which do not rely on a system model. They are based on the actual measured responses of the system. This category includes neural network and fuzzy control methods [10, 11, 12].

Because of inherent robustness, easiness to handle the uncertainties, nonlinearities and heuristic knowledge, fuzzy logic control (FLC) theory has attracted the attention of researchers for vibration control of structural systems. Fuzzy control systems have been successfully applied to wide variety of

Address for correspondence

ghaffar@tabrizu.ac.ir

control problems. A semi-active fuzzy control strategy for seismic response reduction using a magneto-rheological (MR) damper has been proposed by Choi et al [13]. Fuzzy-logic control strategy for protecting buildings against severe excitations using magneto-rheological (MR) dampers has been widely investigated [14, 15, and 16].

Genetic algorithms have been applied as effective search techniques to many fields of optimization problems. In structural control applications, GA can be utilized as an optimization technique to pursue the ultimate goal of reducing the structural responses that determines the structural safety. In design of FLC, choosing appropriate membership functions is a significant and time-consuming part. Some valuable efforts were achieved towards the application of a genetic algorithm (GA) to the design of a FLC [16, 17, 18, and 19]. In this manner, the GA optimized FLC is used to adjust the parameters of the fuzzy membership functions and finding appropriate fuzzy control rules. The reason is their simplicity, ease of operation, minimal requirements and parallel and global perspective.

In recent years, neural network techniques have been widely used for the vibration control in civil engineering [20, 21]. Neural networks are powerful computational tools may also be trained to predict the modal response of the structures, and then obtain the required control force to be applied to the structure. Neural-network-based control algorithms have the promise of evolving into powerful adaptive controllers. A hybrid fuzzy logic and neural network controller was proposed to improve the control performance of multiple-input multiple-output control systems [22]. Application of a neuron-control method for semi-active vibration control of stay cables using MR dampers [10] showed that the proposed control strategies could effectively implement semi-active vibration control of stay cables with the use of MR dampers. Although previous researches have made full use of the advantages of the neural network and fuzzy logic controller, few researches have adopted both tools to resolve the time-delay and instantaneous choosing of control parameters in semi-active control or active control. A neural network as a controller, act as estimator in which, control force needed for the next time step is fully determined from the information available at the current time. Consequently, the time delay associated with the control algorithm is eliminated. This benefit of ANN controller can be widely implemented in the control strategy of structures. ZhaoDong and Ying Qing [23] developed an integrated control strategy in which the time-delay problem was solved by a neural network and the control currents of the MR dampers were determined quickly by a fuzzy controller.

Among many semi-active control devices, semi-active friction systems with amplifying braces (FDSAB) are more attractive to use because of mechanical simplicity, their small size and low operating power requirement. Also, the control forces required when FDSAB is used are smaller compared with structures controlled by friction dampers connected either to chevron or diagonal braces [24]. This makes FDSAB more effective to use in structural control especially for structures that may be subjected to severe earthquakes.

In this paper, a combined application of genetic algorithm (GA), fuzzy logic controller (FLC) and artificial neural network (ANN) is adopted for semi-active control of building frames using FDSABs. In order to design an accurate fuzzy logic controller, membership functions and fuzzy rules were optimized using the GA optimizer. An expertly trained ANN model is used to reduce time delay between the response measurement and the control action. The ANN was constructed based on the information of seismic structural response against an earthquake excitation which obtained from several dynamic time history analysis of a structure. In a numerical example, the developed FLC is applied to a ten storey building and time history analyses are conducted to evaluate the performance. To verify effectiveness of the developed strategy, a linear quadratic Regulator (LQR) controller is designed and considered in the simulations for comparison purposes. The design process developed in this paper can be used to design new structures or for upgrading of existing buildings.

FRICTION DAMPING SYSTEM WITH AMPLIFYING BRACES

Ribakov and Gluck [25] proposed an active FD connected between the chevron braces and the top floor diaphragms. The results indicated FDs can effectively suppress the vibrations of a structure in both cases. Semi-active Friction Dampers (FDs) were described and tested experimentally by Nishitani et al [26]. Over the past few years, friction dampers have been widely investigated as an energy dissipation system to mitigate the structural response due to dynamic loading [1, 27]. Several variable friction dampers have been conceptually investigated and some have been implemented. As noted earlier, FDSAB system is more effective to use as control system than similar semi-active friction dampers connected either chevron or diagonal braces due to lower amount of control forces required. Consequently, in this study, FDSAB system is used to vibration control of structure. The other feature of FDSAB device is its large amount of dissipated energy at each cycle of loading. The friction damping system with amplifying braces (FDSAB) is a semi active device consists of a square frame, with bars connected by hinges, a system of cables and a semi-active friction damper as shown in Figure 1. The proposed friction damper consists of an external cylinder, two internal half-cylinders and a pneumatic camera .The damper is connected to the top and bottom floor diaphragms by means of cable.

In FDSABs, the air pressure in the pneumatic camera of each damper adjusts the slip force level according to the optimal solution yielding the required friction forces based on control algorithm. Typical force–displacement hysteretic loop for a friction damper has rectangular shape. Assuming that the cable length remains constant, the amplified displacement transferred to the FD at each floor level i takes the form:

$$d_{FD,i} = \frac{b_i^* - \sqrt{(b_i^*)^2 - 4c_i^*}}{2} \quad (1)$$

Where: $b_i^* = 2\sqrt{2}b_i$, $c_i^* = 2B_{st,i}d_i\cos\theta_i + d_i^2\cos^2\theta_i$. The energy dissipated at the ith floor is given by:

$$E_i = d_{FD,i}F_{FD,i} \quad (2)$$

Where $F_{FD,i}$ is the control force at the i th floor. In current study, a seven story frame equipped with FDSAB system is designed to investigate the efficiency of the proposed control strategy in such systems.

LINEAR QUADRATIC REGULATOR CONTROL METHOD

The classical linear quadratic regulator algorithm (LQR) has been extensively used for semi active control. This control method requires that all the values of the state variables to be available. In this algorithm, the control force u(t) is determined by minimizing the performance index over duration of excitation.

A discrete-time linear system is defined by:

$$x(k+1) = Ax(k) + Bu(k) \quad (3)$$

In this system, the optimal control force takes the form $u(k) = -Gx(k)$. G is a $m \times 2(n+m)$ feedback gain matrix where n is number of stories and m is the number of FDSAB systems applied to control the building responses. This optimal control force is obtained by minimizing the performance index given by [9]:

$$J = \sum_{k=0}^{\infty}(x^T(k)Qx(k) + u^T(k)Ru(k)) \quad (4)$$

Where the symmetric weighting matrices Q and R are the weighting matrices to be applied to the response and control energy respectively. Q is a $2(n+m) \times 2(n+m)$ positive semi-definite matrix; and R is a $m \times m$ positive definite matrix. The control force u(k) is weighted in the performance index to allow regulation without using excessive control energy. Control force vector u(k) regulated by state vector x(k) is determined as:

$$u(k) = -Gx(k) = -((R + B^TPB)^{-1}B^TPA)x(k) \quad (5)$$

And

$$P = Q + A^T(P - PB(R + B^TPB)^{-1}B^TP)A \quad (6)$$

Where G and P are the solution of the classical discrete time algebraic Riccati equation. The choice of suitable Q and R for a specific problem is usually difficult and requires experience and engineering insight. Here, weighting matrices, P and Q are considered as:

$$Q = I_{14\times14} \qquad R = 10^{-12} \times I_{7\times7} \quad (7)$$

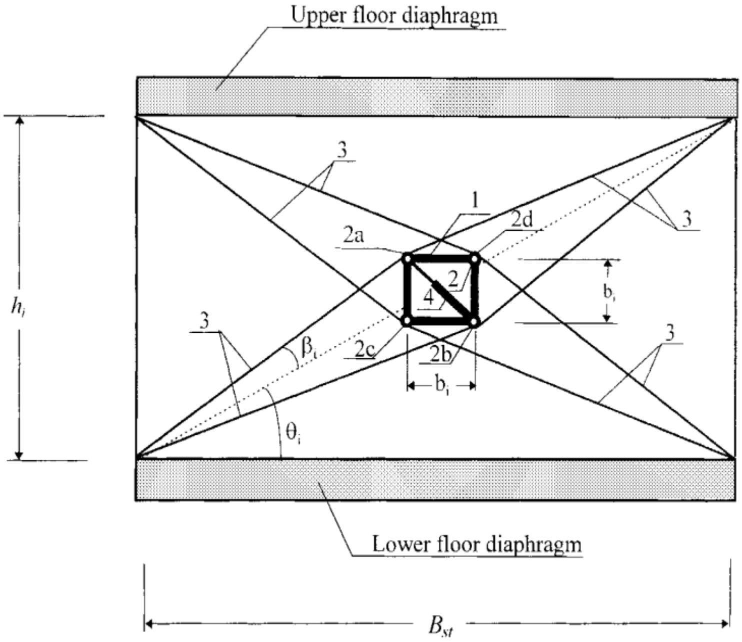


Figure1. *Construction scheme of FDSAB Device*

CONTROL STRATEGY

The proposed control strategy integrates fuzzy logic and Genetic Algorithm and employs artificial neural network as an effective analyzer as illustrated in Figure 2. The controller consists of two parts. One is fuzzy logic controller (FLC), which calculates the control forces; the other is the artificial neural network (ANN) part which is used as the predictor for controller to reduce time delay of computing control forces. Interaction relationship between the structural responses and control output signals is difficult to determine by conventional methods. In this manner, the FLC can be effectively used for the control problem to establish a correlation between a set of inputs and outputs. Displacement and velocity response of system are used as the inputs of a fuzzy logic controller. The fuzzy controller output signals are propagated to control device in order to generate damping forces that mitigate the system response.

Appropriate design of a FLC is an important part of a control scheme. In an ordinary control method, the membership functions and associated rules of a fuzzy controller are usually determined by trial and error. For efficiency, an optimal design of fuzzy control rules and membership functions of the fuzzy controller is desired. In this study GA is employed as an efficient approach to optimally design a fuzzy logic controller. Fuzzy controller parameters such as the distribution of the membership functions and fuzzy rules are updated from initial membership functions and fuzzy rules by GA's powerful searching and self-learning ability. The integrated GA-FLC uses GA to produce an effective fuzzy rule base that establishes a proper correlation between selected input and output of the FLC.

In order to solve inherent time-delay problems that exist in traditional control strategies, the integrated GA-FLC is mobilized by artificial neural network to achieve a powerful control scheme, in which ANN acts as predictor to minimize response time of the control device. Time delay is eliminated by computing the state of structure in the proposed GA-ANN-FLC.

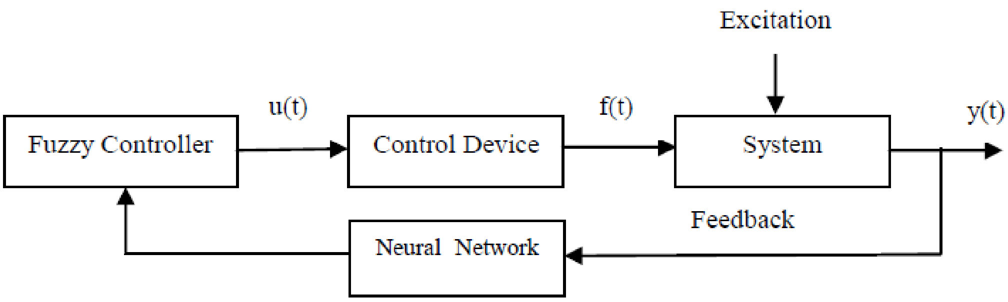


Figure2. *Integration of fuzzy logic, genetic algorithms and neural network for control strategy using FDSAB*

NUMERICAL STUDY

A seven story shear frame configured with FDSAB devices per floor was selected to investigate the performance of the integrated semi-active control strategy in reducing structural responses. The configuration of uncontrolled and controlled frame is illustrated in Figure 3. The structural matrices are:

$$M = 10^{4}\begin{bmatrix} 8.75 & & & & & & 0 \\ & 8.75 & & & & & \\ & & 7.75 & & & & \\ & & & 7.75 & & & \\ & & & & 7.75 & & \\ & & & & & 7.75 & \\ 0 & & & & & & 6.55 \end{bmatrix} kg$$

$$K = 10^{7}\begin{bmatrix} 33.90 & -16.95 & & & & & 0 \\ -16.95 & 33.90 & -16.95 & & & & \\ & -16.95 & 30.96 & -14.01 & & & \\ & & -14.01 & 28.02 & -14.01 & & \\ & & & -14.01 & 25.13 & -11.12 & \\ & & & & -11.12 & 22.24 & -11.12 \\ 0 & & & & & -11.12 & 11.12 \end{bmatrix} Nm^{-1}$$

In order to evaluate the adaptability of the proposed strategy, the model of the structure is subjected to seismic motions. Excitation records that are used for numerical simulation are El Centro S00E (1940) and Kobe NF17 (1995). Figure 4 illustrates ground acceleration time history for the selected earthquakes. The results of the example frame responses controlled by the combined scheme are compared with those controlled by LQR control methods.

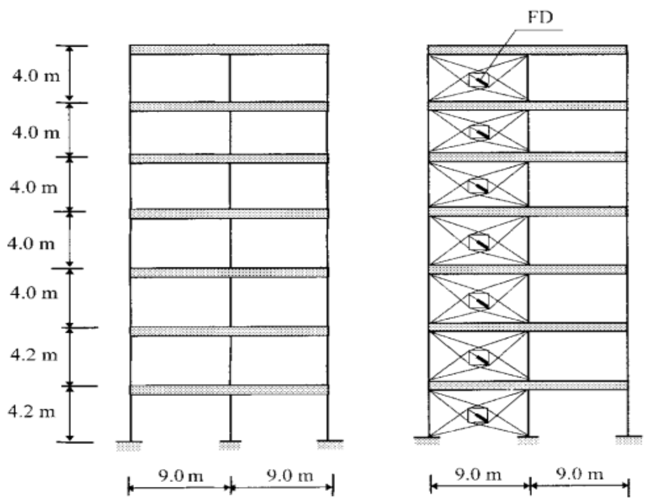


Figure3. *Seven-story structure (a) uncontrolled, (b) with FDSAB*

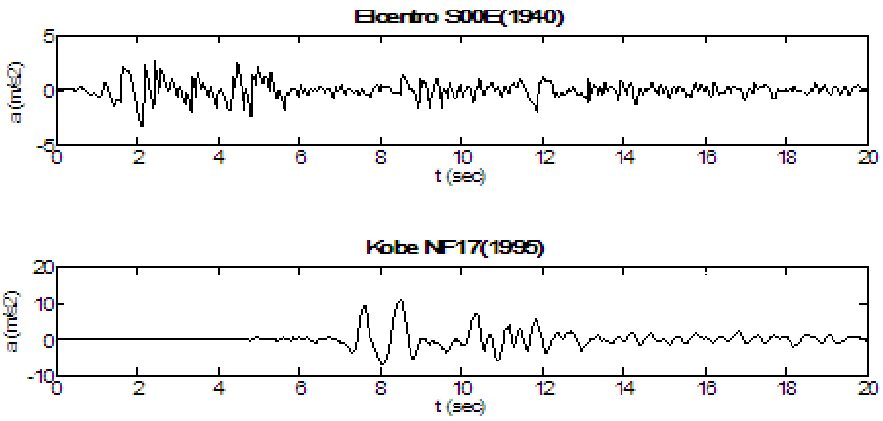


Figure4. *Ground motions used in this study*

Design and Optimization of the FLC

FLC is employed to describe a complex mapping between a set of inputs and a set of outputs. The design of the semi-active fuzzy controller involves specification of the response quantities to be used as input to the fuzzy controller and the distribution and type of membership functions to be used for the selected input variables and the definition of the output variables. The FLC structure takes velocity and displacement of stories as an input and provides control force as an output. Input variables are defined by seven membership functions defined on the normalized universe of discourse [−1, 1]. Output variable having eleven membership functions are also defined on the normalized universe of discourse [-1, 1]. A reasonable range of input values must be selected for the input membership functions since if the range is too large or too small, the outermost membership functions will rarely or essentially be used, respectively, and thus limit the variability of the control system. The membership functions chosen for the input and output variables are common triangular shaped in genetic fuzzy systems, as illustrated in Figure 6. The definitions of the fuzzy variables of input membership function are as follows: NL = Negative Large, NM = Negative Medium, NS = Negative Small, ZR =Zero, PS = Positive Small, PM = Positive Medium and PL = Positive Large. The definitions of the fuzzy variables of the output membership function are as follows: NVL= Negative Very Large, NL = Negative Large, NM = Negative Medium, NS = Negative Small, NVS = Negative Very Small, ZE =Zero, PVS = Positive Very Small, PS = Positive Small, PM = Positive Medium and PL = Positive Large, PVL = Positive Very Large. Since normalized universes of discourse were used for both inputs and for the output to the fuzzy controller, scaling factors were required to map the variables to these domains. In this paper 20, 2 and 400000 was selected as constant scaling factors of displacement, velocity and control force, respectively, which were obtained according to control of the frame using LQR method. The fuzzy rule base is determined to represent the relationship between input and output fuzzy variables, where the output varies in proportional to the scale of each given input. The rule base module is constructed by specifying a set of if -premise-then-consequent statements. For example, the multiple-input multiple-output IF–THEN rules of the fuzzy control are shown in the form:

$$\begin{aligned} R^{j}:\quad & If\ x_{1}\ is\ A_{1}^{j}\ and\ \cdots\ and\ x_{p}\ is\ A_{p}^{j} \\ Then\quad & y_{1}\ is\ B_{1}^{j}\ and\ \cdots\ and\ y_{m}\ is\ B_{m}^{j} \end{aligned} \tag{8}$$

where R j denotes the j-th rule of the fuzzy inference rule, j =1,2, . . . ,q, x1, x2, . . . , xp are the inputs of the fuzzy controller, A_i^j is the linguistic value with respect to xi of rule j , y1, y2, . . . , ym are the outputs of the fuzzy controller and B_i^j is a fuzzy singleton function defined by experts. The fuzzy rule-base for all possible if -premise-then-consequent statements can be listed in a tabular form, which is referred to as a fuzzy rule table. The defuzzification module, the last component of the fuzzy logic, operates on the fuzzified outputs obtained from the inference mechanism. As noted earlier, we adopt the center of gravity (COG) defuzzification method in this study.

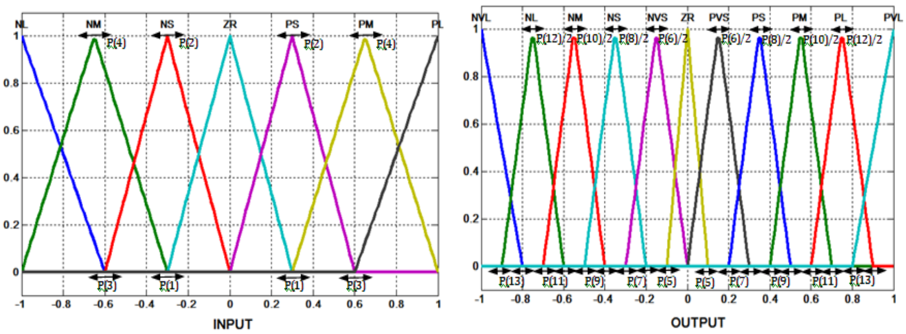


Figure5. *Input and output membership functions of fuzzy controller*

In FLC design, defining several parameters such as membership functions is a knowledge-based process which is obviously not an optimal solution. GA optimally establishes a reasonable fuzzy correlation between the selected structural responses and the corresponding control forces provided by FDSAB. Consequently, GA is employed as an adaptive method for optimizing the FLC system according to a fitness function that specifies the design criteria in a quantitative manner. The maximum displacement response of the example frame due to earthquake excitation is taken as objective of the optimization problem, which should be minimized. Therefore, this maximum displacement response is used in the fitness function. In this stage, to design the GA-FLC, the fuzzy membership functions and rule base in fuzzy system are adjusted. In order to adjust the membership functions used for input and output variables, 13 parameter of P(1)-P(13), as shown in Figure 5 are considered, in which using the GA optimizer, the performance of the designed FLC system can be optimized. Due to symmetry, parameters of only half of the input and output membership functions, described earlier, have been considered as design variables. Figure 6 shows the final optimized membership functions for input and output vectors.

The parameters of input and output membership functions should be optimized while the rule base remains unchanged. After optimization of membership functions, the rules of the fuzzy controller are optimized based on the final membership functions. Optimized rule base table of fuzzy controller is tabulated in Table 1.

Proper GA operator parameters are very important in improving the GA tournament. These parameters such as population size, crossover rate and mutation rate are chosen according to the problem's type. These parameters are given in Table 2 for membership functions and rule base optimization. The constraint of convergence is considered as 100 generations of the population.

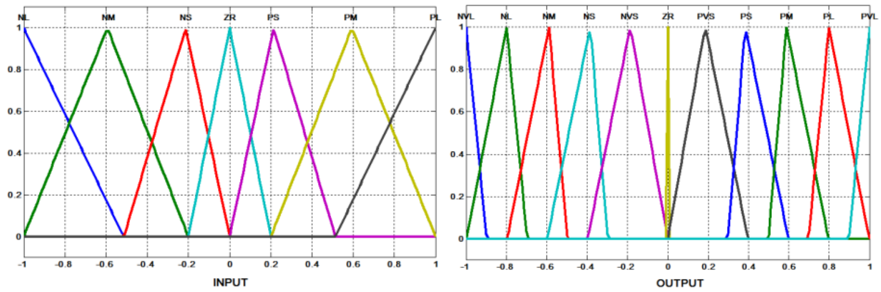


Figure6. *Optimized Input and output membership functions*

Table1. *Optimized rule base of fuzzy controller*

		Velocity						
		NL	NM	NS	ZR	PS	PM	PL
Displacement	NL	PVL	PL	PM	PM	PS	PVS	R
	NM	PL	PM	PM	PS	PVS	ZR	NVS
	NS	PM	PM	PS	PVS	ZR	ZR	NS
	ZR	PM	PS	ZR	ZR	ZR	NS	NM
	PS	PS	ZR	ZR	NVS	NS	NM	NM
	PM	PVS	ZR	NVS	NS	NM	NM	NL
	PL	ZR	NVS	NS	NM	NM	NL	NVL

Seismic Response Mitigation of GA-FLC Controller

To verify the control design validity and the effectiveness of proposed method, the results of the example frame responses controlled by the genetic algorithms and fuzzy logic controller (GA-FLC) method are compared with those controlled by LQR algorithm while the uncontrolled system response is used as the base line. In this stage, time delay effect is not considered and neural network estimator is not included in the controller. Figure 7 provides the results of controlled displacement response of 7th floor of the example frame calculated by the GA-FLC compared with the corresponding uncontrolled ones. It can be seen that GA-FLC results in significant reduction of roof displacement due to seismic motions. The maximum response reduction is about 62% and 56% for Elcentro and Kobe earthquakes, respectively. The efficiency of the proposed control strategy is further evaluated by comparison with results of LQR control method in Figure 8. As can be observed, GA-FLC is more effective than the traditional LQR algorithm in displacement response mitigation. GA-FLC results in about 11% and 10% maximum response reduction more than LQR for Elcentro and Kobe earthquakes, respectively. Furthermore, Figure 9 provides control force of 7th floor needed for obtaining the response reductions in the GA-FLC system. It can be seen that the required control force in GA-FLC control scheme is more than that of the LQR system. However, more displacement suppression in the GA-FLC system leads to more reduction in member size of the designed building which is of a great importance from the economical point of view. Another noteworthy point that should be taken into consideration is that, as noted earlier, LQR control method requires that all the values of the state variables to be available. This means that the electronic sensors must be installed in all stories of the building which impose extra expenses.

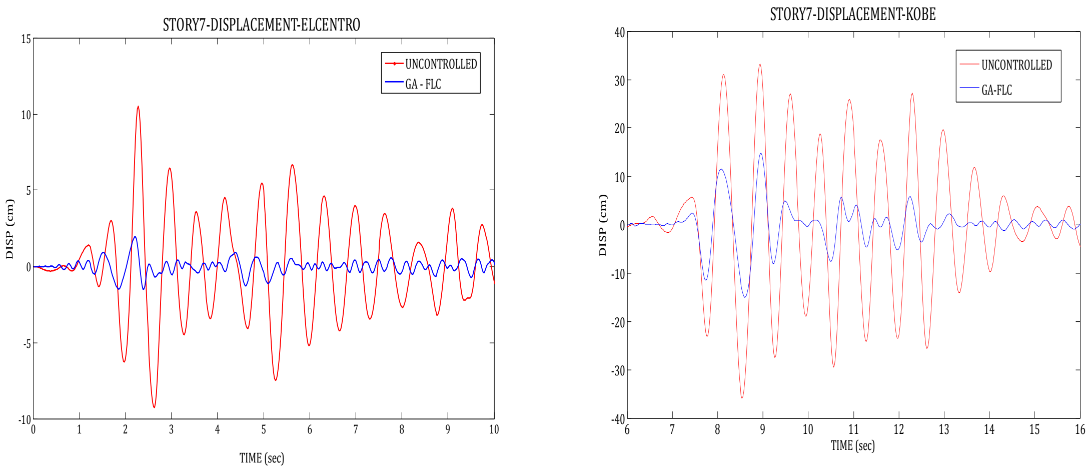


Figure7. *Comparison of controlled roof displacement of the example frame calculated by the GA-FLC system with the uncontrolled ones*

Design of the Neural Network

In order to reduce time delay between measured response and control action in the proposed scheme, the control forces must be calculated based on applying state, not measured state. Consequently, the GA-FLC controller is improved with ANN to modify the input state vector that has been placed before the fuzzy controller. In other words, the main goal of the neural network is to predict the dynamic responses of the structure as inputs to the fuzzy controller to determine control force of FDSAB.

Table2. *GA operator parameters*

Membership functions optimization							
Population size	Selection type	Elite count	Crossover type	Crossover rate	Mutation type	Mutation rate	Stopping generation
40	Tournament	20	Scattered	0.85	Uniform	0.01	100
Rule base optimization							
Population size	Selection type	Elite count	Crossover type	Crossover rate	Mutation type	Mutation rate	Stopping generation
50	Tournament	25	Scattered	0.85	Uniform	0	100

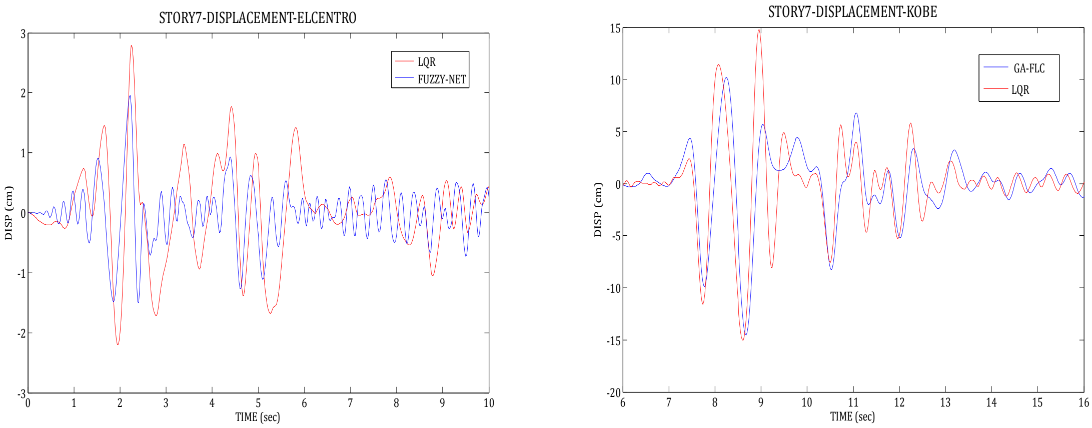


Figure8. *Comparison of controlled roof displacement of the example frame calculated by the GA-FLC system with the LQR controller*

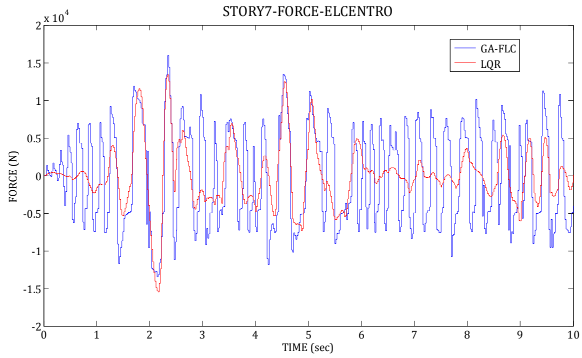
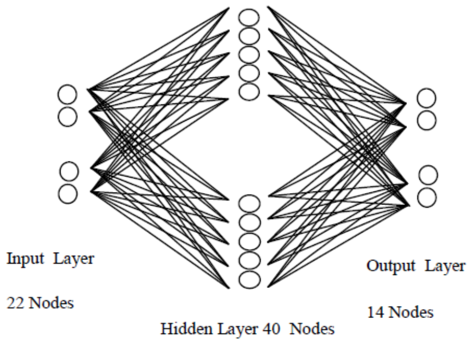


Figure9. *Comparison of roof control force of the example frame calculated by the GA-FLC system with the LQR controller*

The network was constructed based on the information of seismic structural response against an earthquake excitation which obtained from several dynamic time history analysis of a structure. Capability to learn from data and generalization power of its result on a set of test patterns enables the neural network to become a strong predicting and classification tool. In this study, a feed forward neural network with an adaptive back propagation training method was constructed and trained to generate prediction of reactive velocity and displacement at the current state from previous measurements. In the back propagation training, the learning rate is determined by ensuring the decrease of the error function of the input-output training patterns at each training cycle. The neural network consists of an input layer that consists of 22 neurons, a middle hidden layer including 40 neurons and an output layer with 14 neurons as shown in Figure 10.



$[\boldsymbol{input}]_{1\times22}$	$\left[[a_g]_{1\times1},[u]_{1\times7},[d]_{1\times7},[v]_{1\times7}\right]_{1\times22}$
$[\boldsymbol{output}]_{1\times14}$	$[\,[d]_{1\times7},[v]_{1\times7}]_{1\times14}$

Figure10. *Architecture of the neural network*

The sigmoid function and linear function are chosen as the activation function of hidden and output layer, respectively. In order to predict the dynamic responses of the structure accurately, the most directly and important factors affecting the predicted dynamic responses are considered. Therefore, inputs to this network are the delayed outputs (velocity and displacement), the delayed control forces, and the delayed earthquake inputs (acceleration). The structure of input and output training vectors is shown in Figure 10. In order to increase ability of training and generalization of network, input and output data were normalized by scaling in [-1, 1]. As the inputs are applied to the neural network, the difference between the network outputs and the measured responses is processed back through the network to update the weights and biases of the neural network until the outputs match closer the measured responses. This process continues for all the training data set until the objective error is satisfied. In this paper, the sum square error function is adopted to assess the network.

Seismic Response Mitigation of GA-ANN-FLC Controller

In order to evaluate the contribution of the incorporation of the neural network response prediction and investigate the efficiency of the proposed control strategy to enhance time delay effect, the control process is established by considering time delay of 0.06 seconds. Figure 11 illustrates influence of the time delay under Elcentro earthquake. When time delay happens, GA-FLC system is not able to suppress structural response appropriately. It can be seen that the neural network is able to estimate the dynamic responses of the structure as inputs to the fuzzy controller to determine control force of FDSAB and GA-ANN-FLC control scheme greatly reduces the roof displacement when neural network is integrated in the control strategy. The required control force of the GA-FLC system is also compared to required control force of GA-ANN-FLC strategy with time delay of 0.06 seconds in Figure 12 for displacement mitigation of 7th floor subjected to Elcentro excitation. As can be observed, integrating the neural network also results in reducing control force and GA-ANN-FLC system is able to solve time delay problem. However, as discussed previously, LQR algorithm is superior in reducing control force.

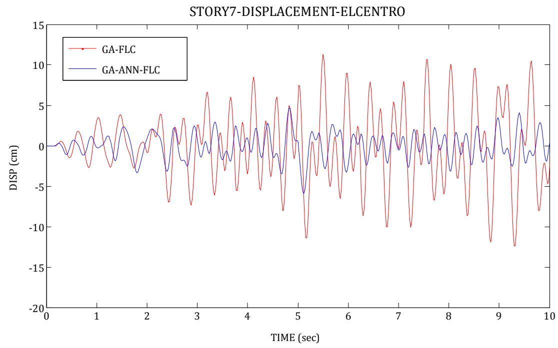


Figure11. *Comparison of controlled roof displacement of the example frame calculated by the GA-ANN-FLC system with the GA-FLC controller for the time delay of T = 0.06 seconds.*

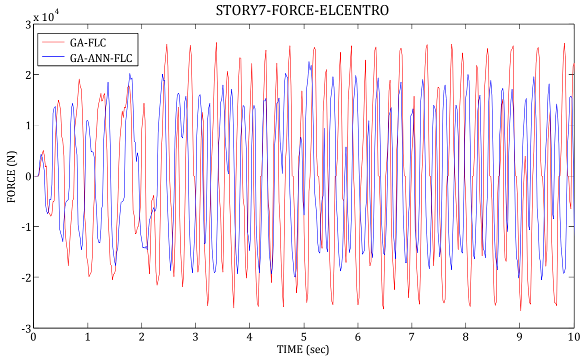


Figure12. *Comparison of roof control force of the example frame calculated by the GA-ANN-FLC system with the GA-FLC controller for the time delay of T = 0.06 seconds*

CONCLUSION

This study investigates performance of a GA-designed FLC (GA-FLC) for vibration control of structures equipped with friction damping system with amplifying braces (FDSAB). In the design of the FLC system the velocity and displacement of stories are considered as the feedback to the FLC. The genetic algorithm is used to optimize the parameters of membership functions and find appropriate fuzzy control rules in order to gain the maximum displacement mitigation. The proposed control strategy (GA-FLC) is implemented for control of a seven story shear frame configured with FDSAB. For comparison purposes, LQR controller system is also designed to control the building response. Based on numerical study, while GA-FLC controller requires more control force, it is more effective than LQR method in displacement response reduction. In the case of time delay problem, a neural network is employed in control strategy as a state estimator (GA-ANN-FLC) and the control forces of the FDSAB are determined quickly by the fuzzy controller. The displacement response of controlled frame significantly decreases, when neural network is integrated with the genetic-fuzzy controller. GA-ANN-FLC has capability to enhance time delay effect and appropriately controls the displacement response of the frame. Based on numerical modelling of the example frame, the proposed methodology can be used to control of FDSAB equipped systems in an effective way to decrease structural vibrations.

REFERENCES

[1] Gaul L, Hurlebaus S, Wirnitzer J, Albrecht H. "Enhanced damping of lightweight structures by semi- active joints. " Acta Mech 195:249-261. 2008.

[2] Dyke SJ, Spencer BF Jr, Sain MK, Carlson JD. "Modeling and control of magnetorheological dampers for seismic response reduction." Smart Mater Struc 5:565–575. 1996.

[3] Xu YL, Qu WL, Ko JM. "Seismic response control of frame structures using magnetorheological/ electrorheological dampers." Earthq Eng Struc Dyn 29:557–575. 2000.

[4] Yi F, Dyke SJ, Caicedo JM, Carlson JD. "Experimental verification of multi-input seismic control strategies for smart dampers." J Eng Mech 127(11):1152–1164. 2001.

[5] Zhang J, Roschke PN. "Active control of a tall structure excited by wind." J Wind Eng Ind Aerodyn 83:209–223. 1999.

[6] McClamroch NH, Gavin HP. "Closed loop structural control using electrorheological dampers." In Proceedings of the American control conference, Seattle. 1995.

[7] Hiemenz GJ, Choi Y-T, Wereley NM. "Seismic control of civil structures utilizing semi-active MR bracing systems." In Proceedings of smart systems for bridges, structures, and highways conference, Newport Beach. 2000.

[8] Jansen LM, Dyke SJ. "Semiactive control strategies for MR dampers: comparative study." Journal of Engineering Mechanics (ASCE) 126(8):795–803. 2000.

[9] Paraskevopoulos PN. Modern Control Engineering. Marcel Dekker, Inc. 2002.

[10] Ni YQ, Chen Y, Ko JM, Cao DQ. "Neuro-control of cable vibration using semi-active magnetorheological dampers." Eng Struc 24:295–307. 2002.

[11] Zhou L, Chang CC, Spencer BF Jr. "Intelligent technology-based control of motion and vibration using MR dampers." Earthq Eng Eng Vib 1(1):100–110. 2002.

[12] Xu ZD, Shen YP, Guo YQ. Semi-active control of structures incorporated with magnetorheological dampers using neural-networks. Smart Mater Struc 12:80–87. 2003.

[13] Choi KM, Cho SW, Jung HJ, Lee IW. "Semi-active fuzzy control for seismic response reduction using magnetorheological dampers." Earthq Eng Struc Dyn 33:723–736. 2004.

[14] Wilson CMD, Abdullah MM. "Structural vibration reduction using fuzzy control of magnetorheological dampers." ASCE Structures Congress, New York. 2005.

[15] Ok SY, Kim DS, Park KS, Koh HM. "Semi-active fuzzy control of cable-stayed bridges using magneto-rheological dampers." Engineering Structures 29: 776–788. 2007.

[16] Das D, Datta TK, Madan A. "Semiactive fuzzy control of the seismic response of building frames with MR dampers." Earthquake Engng Struct. Dyn 2011. DOI: 10.1002/eqe.1120.

[17] Kima HS, Roschke PN. "Design of fuzzy logic controller for smart base isolation system using genetic algorithm." Engineering Structures 28: 84–96. 2006.

[18] Bidokhti K.K., Moharrami H. and Fayezi A. "Semi-active fuzzy control for seismic response reduction of.building frames using SHD dampers." Structiral Control and Health Monitoring. 19(3), 417-435. 2010.

[19] Bitaraf M, Ozbulut OE, Hurlebaus S, Barroso L. "Application of semi-active control strategies for seismic protection of buildings with MR dampers." Engineering Structures 32: 3040-3047. 2010.

[20] YK Wen J, Ghabusi P, Nikzad VK. "Control of Structures Using Neural Networks." Smart Master structures 4, 149-157. 1995.

[21] Zhang J, Roschke PN. "Neural network simulation of magnetorheological damper behavior." International Conference on Vibration Engineering, Dalian, China, 25-30. 1998.

[22] Huang SJ, Lian RJ. "A combination of fuzzy logic and neural network controller for multiple-input multiple-output systems." Int J Sys Sci 31(3): 343-357. 2000.

[23] ZhaoDong X, YingQing G. "Integrated intelligent control analysis on semi-active structures by using magnetorheological dampers." Science in China Series E: Technological Sciences 51: 2280-2294. 2008.

[24] Gluck J, Ribakov Y. "Semi-active Friction System with Amplifying Braces for Control of MDOF Structures." The structural design of tall buildings, N.10, 107-120. 2001.

[25] Ribakov, Y., Gluck, J. "Active Controlled Friction Damped MDOF Structures with Variable Stiffness" 8th Canadian Conference on Earthquake Eng., Vancouver, pp. 409-414. 1999.

[26] Nishitani A, Nitta Y, Ishibashi Y. "Structural control based on semi-active variable friction dampers." Proceedings of the 12th World Conference on Earthquake Engineering, New Zealand.

[27] Mualla IH, Belev B. "Performance of steel frames with a new friction damper device under earthquake excitation." Eng Struct 24(3):365–71. 2002.

AUTHOR'S BIOGRAPHY

Hosein Ghaffarzadeh received his PhD in Structural Engineering 2005 from Shiraz University, Iran. His research interests are Structural Dynamics, Structural Control and Damage detection. He is currently an associate professor in the Department of Civil Engineering at the University of Tabriz, Tabriz, Iran.