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Multi-input Multi-output Semi-active Fuzzy Control of Seismic-excited Building with Evolutionary Optimization Algorithms

Hyun-Su Kim

Division of Architecture, Sunmoon University, Asan-si, Korea

hskim72@sunmoon.ac.kr

Abstract

In this study, a multi-input multi-output (MIMO) semi-active fuzzy control algorithm has been developed for vibration control of a seismically excited building structure. The MIMO fuzzy controller was optimized by evolutionary genetic algorithm. For numerical simulation, a five-story example building structure is used and two MR dampers are employed as semi-active control devices. For comparison purpose, a clipped-optimal control strategy based on acceleration feedback is employed for controlling MR dampers to reduce structural responses due to seismic loads. Numerical simulation results show that the MIMO fuzzy control algorithm can provide superior control performance to the clipped-optimal control algorithm. When the design method proposed in this study is applied, Pareto optimal solutions can be obtained in single optimization run. Therefore, an alternative solution can be easily selected by an engineer.

Keywords: *Multi-input multi-output control algorithm; seismic response control; genetic algorithms; multi-objective optimization*

1. Introduction

To date, various vibration control systems have been developed and implemented for dynamic response reduction of structures subjected to earthquake excitations [1]. Recently, active or semi-active control approach rather than passive control system is widely studied for more effective control performance [2, 3]. However, active control devices are not fully embraced by practicing engineers, primarily due to the challenges of large power requirements that may be interrupted during an earthquake, concerns about stability and robustness, and so forth. Many viable semi-active structural control systems have been proposed with some having been implemented in real structures [4, 5]. Very small power consumption, high reliability, a fail-safe mechanism, and adaptability make semi-active control one of the more promising approaches to the mitigation of damage due to seismic events in civil engineering structures. Magnetorheological (MR) dampers are one of the most promising semi-active control devices [6, 7].

Control performance of a semi-active control system significantly depends on control algorithms [8, 9]. Many research on seismic response reduction of a structure using MR damper are limited to a smart base isolation system, semi-active tuned mass damper or inter-story damping system using single MR damper [10, 11]. Namely, a multi-input single-output control system was used for semi-active control system with single MR damper. Even though several research on vibration control using more than one MR damper were performed, most of them used modified control algorithm based on active control theory. Among them, on-off clipped-optimal control strategy is widely used for controlling multiple MR dampers [9].

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Although significant studies have been conducted in recent years on developing and applying semi-active control schemes for vibration control of building structures in seismic zones, the application of intelligent controllers, including fuzzy logic controllers (FLC), has not been addressed extensively. Vibration control using fuzzy logic has attracted the attention of structural control engineers during the last few years [5, 9, 11]. As an alternative to classical control theory, FLC allows the resolution of imprecise or uncertain information. Because of the inherent robustness and ability to handle nonlinearities and uncertainties, FLC is used in this study to make multi-input multi-output (MIMO) control algorithm for operating multiple MR dampers. Not only has FLC been demonstrated to be feasible, but also expert knowledge can be incorporated into fuzzy rules. Although FLC has been used to control a number of structural systems, selection of acceptable fuzzy membership functions has been subjective and time-consuming. To overcome this difficulty, an evolutionary optimization algorithm was used. Among many evolutionary algorithms, a multi-objective genetic algorithm (MOGA) was selected to optimize fuzzy rules and membership functions of FLC. In order to compare the control efficiency of the proposed MOGA-optimized FLC, on-off clipped-optimal control algorithm was considered as the baseline in this study. Based on computed responses of a 5-story example building structure subjected to seismic excitation, the proposed approach is shown to provide better control performance for MIMO control system with multiple MR dampers compared to on-off clipped-optimal control system.

2. Example Structure and Earthquake Load

In order to develop MIMO semi-active FLC for effective control of multiple MR dampers, a 5-story example building structure shown in Figure 1 is employed in this study. This example structure is developed based on a scaled 3-story shear building model used in the previous research [6]. As shown in this figure, two MR dampers are rigidly connected to the first floor and the second floor of the structure, respectively. The equations of motion of the structure are given by

$$\mathbf{M_S}\ddot{\mathbf{x}} + \mathbf{C_S}\dot{\mathbf{x}} + \mathbf{K_S}\mathbf{x} = \Gamma f - \mathbf{M_S}\Lambda\ddot{x}_g \tag{1}$$

where f is the MR damper forces, $\mathbf{x} = [x_1, x_2, x_3, x_4, x_5]'$ is a vector of the displacements of the five floors relative to the ground, $\Gamma = [-1,-1,0,0,0]$ is a location vector of MR dampers, Λ is a unit vector with a size of [5x1]. The system matrices are

$$\mathbf{M_S} = \begin{bmatrix} 98.3 & 0 & 0 & 0 & 0 \\ 0 & 98.3 & 0 & 0 & 0 \\ 0 & 0 & 98.3 & 0 & 0 \\ 0 & 0 & 0 & 98.3 & 0 \\ 0 & 0 & 0 & 0 & 98.3 \end{bmatrix} kg \tag{2}$$

$$\mathbf{C_S} = \begin{bmatrix} 175 & -50 & 0 & 0 & 0 \\ -50 & 100 & -50 & 0 & 0 \\ 0 & -50 & 100 & -50 & 0 \\ 0 & 0 & -50 & 100 & -50 \\ 0 & 0 & 0 & -50 & 50 \end{bmatrix} N\sec/m \tag{3}$$

$$\mathbf{K_S} = \begin{bmatrix} 12.0 & -6.84 & 0 & 0 & 0 \\ -6.84 & 13.7 & -6.84 & 0 & 0 \\ 0 & -6.84 & 13.7 & -6.84 & 0 \\ 0 & 0 & -6.84 & 13.7 & -6.84 \\ 0 & 0 & 0 & -6.84 & 6.84 \end{bmatrix} N/m \qquad (4)$$

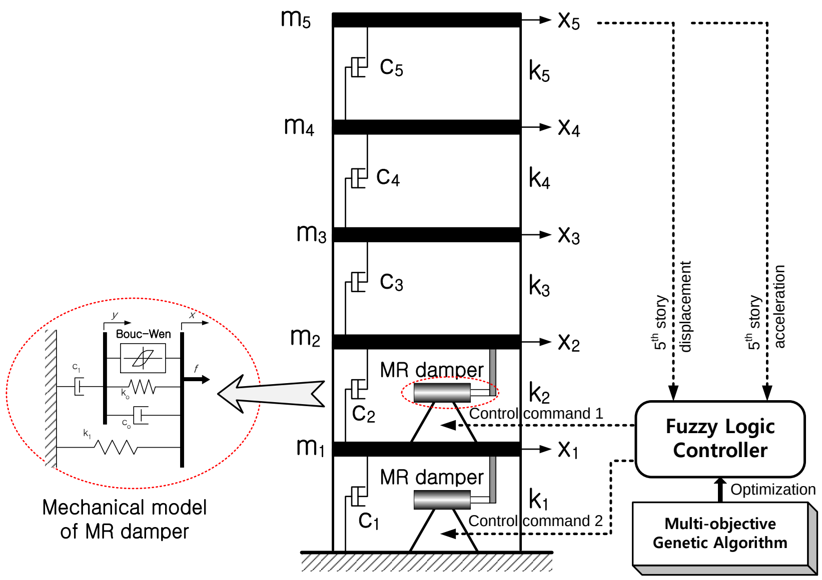

Figure 1. 5-story Example Building Model

The first five natural frequencies of the example structure model are 3.62, 10.57, 16.94, 22.07 and 25.41 Hz, respectively. In this study, the modified Bouc-Wen model [6] is used to describe how the damping force is related to the velocity and the applied command voltage. The mechanical model for the MR damper based on the Bouc-Wen hysteresis model is shown in Figure 1. The detailed description and specific values of the parameters for the MR damper model are presented in Dyke *et al.*'s work [6]. This MR damper model has a maximum generated force of about 1500 N depending on the relative velocity across the MR damper with a saturation voltage of 2.25 V. Typical force-velocity hysteresis loops for this device model are shown in Figure 2.

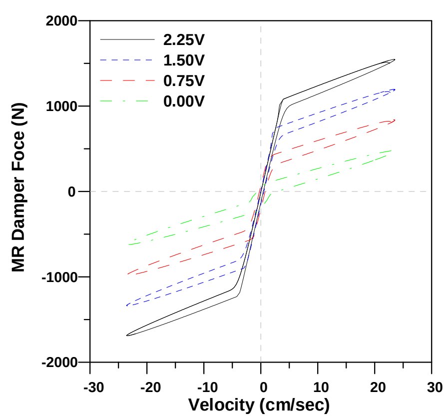

Figure 2. Force-velocity Relationship of MR Damper

In numerical analysis, the model of the example structure is subjected to the NS component of the 1940 El Centro earthquake shown in Figure 3. Because the system under consideration is a scaled model, the earthquake must be reproduced at five times the recoded rate. This time scaled ground motion data provided in Dyke *et al.*'s work [6] was employed in this study.

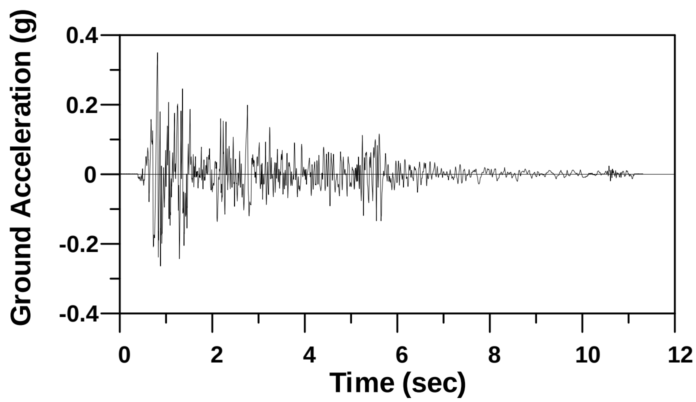

Figure 3. Time Scaled Ground Acceleration of El Centro EQ. (1940, NS)

3. Design of Control Algorithms

As described previously, the MIMO fuzzy control algorithm is developed to effectively control two MR dampers. Because even an expert engineer needs much time and a lot of efforts to make an optimal FLC, a multi-objective genetic algorithm is employed for optimization of the MIMO FLC. In this study, the 5th floor displacement and the 5th floor acceleration are selected for two input variables of FLC, and the output variables are the command voltages sent to two MR dampers as shown in Figure 1. Fuzzy rules and membership functions are optimized by evolutionary optimization algorithm. In the case of structural control of a building structure subjected to earthquake excitation, a trade-off exists between the displacement and the acceleration of the building structure. For example, if the damping force of an MR damper is increased in order to reduce structure displacements, acceleration responses of the building structure manifest a concomitant increase. Conversely, while acceleration responses can be reduced by decreasing the MR damper force, they can lead to increased structure displacements. Therefore, it is impossible for minimum displacements and minimum accelerations of the building structure to occur simultaneously.

In solving multi-objective structural engineering problems, engineers may be interested in a set of Pareto optimal solutions that provide alternative structural designs for a controller, instead of a single solution. Since a genetic algorithm (GA) works with a population of solutions, it seems natural to use a GA in multi-objective optimization problems in order to capture a number of optimal solutions simultaneously. Among many available GA-based multi-objective optimization strategies, the fast elitist Non-dominated Sorting Genetic Algorithm version II (NSGA-II) is employed in this study [13]. In order to verify the control performance of the NSGA-II optimized FLC, a clipped-optimal controller based on acceleration feedback [6] is selected as a comparative control algorithm. In this study, the reduction of peak responses of the 5th floor displacement and acceleration are selected as two objectives in a multi-objective optimization process. As shown in Table 1, each response controlled by the NSGA-II optimized FLC is normalized by the corresponding response controlled by the clipped-optimal control algorithm in each objective function. Therefore, if the objective function values are less than 1, it means that the control performance of the NSGA-II optimized FLC is superior to that of the clipped-optimal controller.

Table 1. Multi-objective Functions

Objective Function	Description
J_1	$\dfrac{\text{Peak displacement of } 5^{th} \text{ story controlled by FLC}}{\text{Peak displacement of } 5^{th} \text{ story controlled by clipped-optimal}}$
J_2	$\dfrac{\text{Peak acceleration of } 5^{th} \text{ story controlled by FLC}}{\text{Peak acceleration of } 5^{th} \text{ story controlled by clipped-optimal}}$

The optimization procedure for an FLC using NSGA-II is presented in Figure 4. After evaluating the control performance of an FLC based on structural responses, NSGA-II optimizes the FLC toward improvement of control performance. Encoding is the genetic representation of an FLC solution. All of the information represented by the FLC parameters is encoded in a structure called a chromosome or string. Gaussian membership functions are used for all input and output variables of the FLC since they can approximate almost all other types of membership functions by changing the parameters. In the optimization procedure through NSGA-II, the population of size N is initially composed of completely randomized values that reside within a user-defined range. After the control performance of all individuals in the population is evaluated, a non-domination rank of each individual is calculated. Subsequently, the fundamental GA operators such as selection, crossover and mutation are used to create the child population. The crossover process is a tournament style procedure where two randomly selected chromosomes exchange a portion of their chromosomes in a single point exchange. Occasionally, data are changed at random during the crossover to keep the generation cycle from becoming static; this operation is termed a mutation. After the child population is created and the control performances of each individual in the child population are evaluated, the parent and child populations are combined. This combined population is sorted according to non-domination rank. The new parent population is formed by adding solutions to the next generation starting from the best individual until N individuals are found. This process continues until stopping criteria is met.

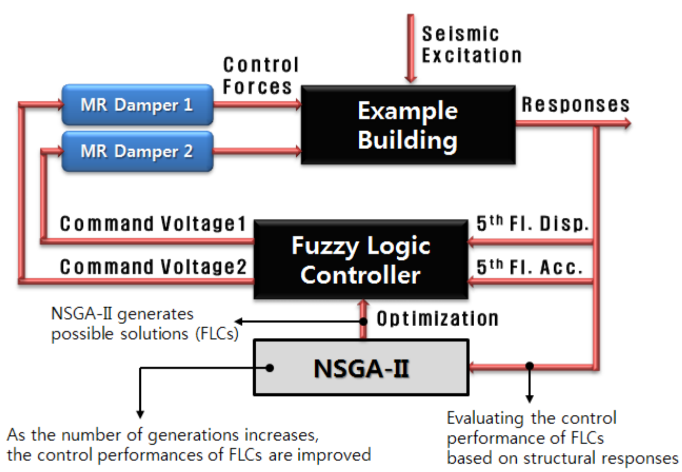

Figure 4. Optimization Process with NSGA-II

4. Control Performance Evaluation

A numerical model of the 5-story example building structure with two MR dampers is implemented in SIMULINK and MATLAB. SIMULINK is a graphical extension to MATLAB for modeling and simulation of systems. It is integrated with MATLAB and data can be easily transferred between the programs [14]. Time history analyses of 12 seconds with a time step of 0.004 sec are performed using this numerical model in order to investigate the control performance of MR dampers controlled by the NAGA-II optimized FLC. The NSGA-II based optimization is performed with the population size of 100 individuals. An upper limit on the number of generations is specified to be 1000. As the number of generations increases, the control performance of the elite (i.e. non-dominated) individuals is improved. After optimization run, Pareto-optimal front (a set of Pareto-optimal solutions) is found as shown in Figure 5. Among them, an FLC presented as a solid circle is selected in this study since it can appropriately control both displacement and acceleration responses.

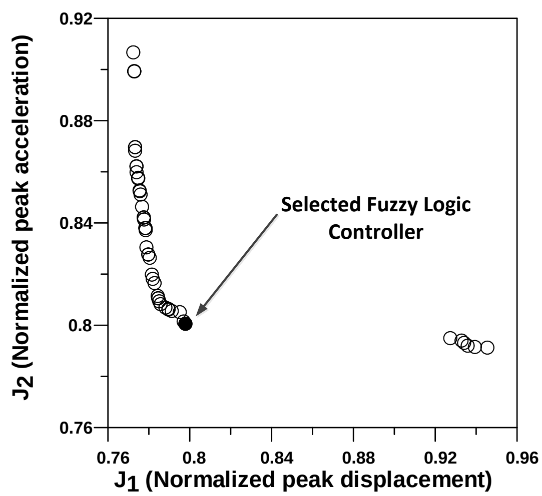

Figure 5. Pareto Optimal Solutions after NSGA-II Optimization

As shown in Figure 5, J_1 and J_2 of every solution are less than 1, which means that the NSGA-II optimized FLCs can provide better control performance in reducing both displacement and acceleration responses compared to the clipped-optimal controller. Consequently, one controller has been selected among the Pareto optimal FLCs and it is presented as a solid circle in Figure 5. The values of J_1 and J_2 of the selected FLC are both 0.8 and it means that the selected MIMO FLC can reduce both the peak 5th floor displacement and acceleration responses by 20%, compared to the clipped optimal controller. The peak responses of the MIMO FLC, clipped-optimal controller, and uncontrolled case for the five floors of the seismic-excited example building structure are compared in Table 2.

Table 2 shows that the peak displacements and accelerations of the 5th floor of the MIMO FLC are 20% smaller than those of the clipped optimal controller. The peak displacement of the 5th floor of the uncontrolled case is 0.930 cm. On the other hand, the peak displacement of the 5th floor of the MIMO FLC is 0.218 cm, which is only 30 % of the uncontrolled case. The peak acceleration of the 5th floor of the MIMO FLC is reduced by 65 % compared to the uncontrolled case. The story drifts of the MIMO FLC are also about 20% smaller than those of the clipped-optimal controller. In Table 2, it is recognized that seismic responses of the uncontrolled building structure can also be greatly reduced when two semi-active MR dampers are used and appropriately controlled.

Table 2. Comparison of Peak Story Responses

Story	Displacement (cm)			Drift (cm)			Acceleration (cm/sec^2)		
	Uncon-trolled	Clipped-optimal	MIMO Fuzzy	Uncon-trolled	Clipped-optimal	MIMO Fuzzy	Uncon-trolled	Clipped-optimal	MIMO Fuzzy
1	0.355	0.099	0.116	0.355	0.099	0.116	592.2	559.4	293.2
2	0.574	0.187	0.179	0.219	0.099	0.064	693.8	378.7	336.3
3	0.723	0.266	0.240	0.203	0.092	0.084	485.3	387.7	248.7
4	0.847	0.329	0.269	0.192	0.074	0.073	543.3	313.5	268.3
5	0.930	0.352	0.281	0.123	0.053	0.042	858.7	368.1	294.7

The 5th floor displacement time history of the MIMO FLC is compared with that of the clipped-optimal controller in Figure 6. Figure 6 shows that the MIMO FLC presents better control performance compared to the clipped-optimal controller in reducing the peak responses, which may induce damage in the structure.

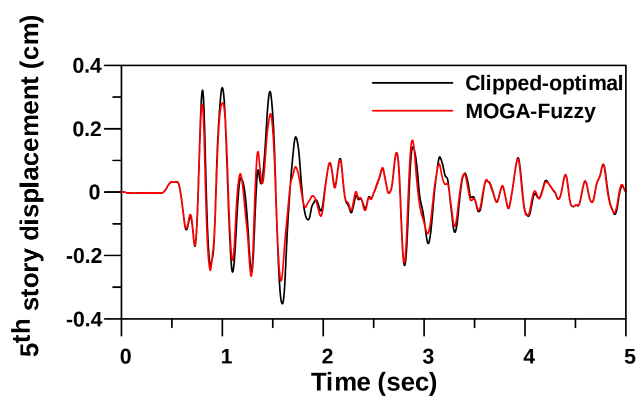

Figure 6. Comparison of Displacement Time Histories

When the building structure is subjected to earthquake excitation, the command voltage to control the MR damper is determined promptly by each control algorithm. The time histories of the 2nd floor MR damper command voltage provided by the clipped-optimal controller and the MIMO FLC are presented in Figure 7. Because the clipped-optimal control strategy consists of a Bang-Bang (on-off) controller which causes the MR damper to generate a desirable control force determined by an "ideal" active controller, it provides passive-on (2.25 V) or passive-off (0 V) state only. However, the command voltage generated by the MIMO FLC continuously varies between '0 V' and '1.4 V' during real-time control.

The time histories of the 2nd floor MR damper force of two controllers are compared in Figure 8. Because of the characteristics of on-off control algorithm, the MR damper force generated by the clipped-optimal controller sharply varies compared to the MIMO FLC. On the other hand, sudden variation in the MR damper force of the MIMO fuzzy is rarely observed.

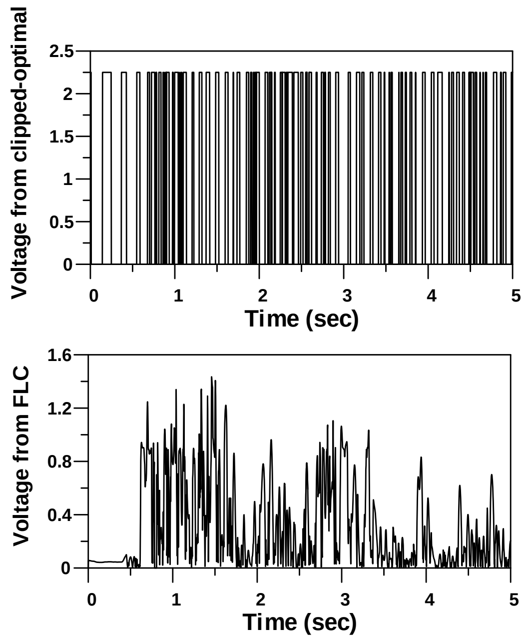

Figure 7. Comparison of voltage

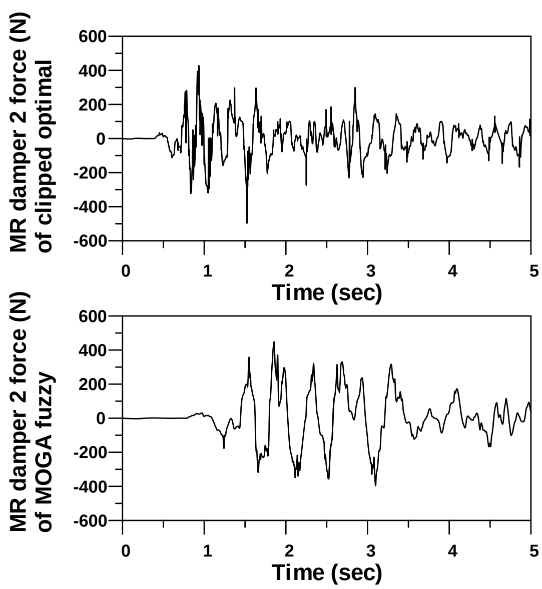

Figure 8. Comparison of MR Damper Force

5. Conclusions

This study investigates the control performance of a multi-input multi-output semi-active fuzzy control system for response reduction of a seismic excited building structure. For this purpose, a scaled 5-story shear building model was used. As a semi-active control device, two MR dampers were used at the first and second stories. The MIMO semi-active FLC was optimized by an evolutionary optimization algorithm (NSGA-II) and a clipped-optimal control algorithm is considered as the baseline for comparison purpose. Based on numerical simulations, it can be seen that semi-active MR dampers can greatly reduce seismic response of the example building structure if appropriate control algorithms are used. The MOGA-optimized MIMO FLC can effectively reduce both displacement and acceleration responses of the building structure by 20% compared to the clipped optimal control algorithm. After single optimization run using NSGA-II, an engineer can simply select another FLC that satisfies the desired performance requirements from among a number of Pareto optimal solutions. It may be important characteristics of the NSGA-II based optimization compared to other optimization methods.

Acknowledgements

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Author

Hyun-Su Kim

Hyum-Su Kim received the B.S., M.S. and Ph.D. degrees in architectural engineering from Sungkyunkwan University, Korea, in 1995, 1998 and 2002, respectively. Since March 2008, he has been at Sunmoon University, where he is currently an associate professor of the Division of Architecture. His research areas include earthquake engineering, vibration control, structural dynamics, and structural optimization.