

# Fuzzy Control of Three-Degree-of-Freedom Systems using Multiple MR Dampers

Omar M. M. Elmeligy<sup>1</sup>, Maguid H.M. Hassan<sup>2\*</sup>

<sup>1,2</sup> *The British University in Egypt (BUE)*

## ABSTRACT

Smart structural control is now emerging as an alternative to conventional earthquake resistant design and traditional structural control techniques. Fuzzy control is one of the promising control strategies that could be used for this function. Magnetorheological (MR) dampers are considered one of the promising semi-active control devices that can be used to control the structural response of buildings under earthquake excitation. The properties of MR dampers can be controlled using several control techniques such as Fuzzy Logic.

In this paper, a fuzzy control scheme is proposed to control the response of a three degree of freedom system under earthquake excitation. The system is equipped with three MR dampers with one for each degree of freedom, i.e., floor. The system comprises an optimization component which identifies the most optimum firing sequence of the MR dampers in order to achieve the best controlled response. It is envisaged that not all three MR dampers are fired simultaneously; only selected ones are fired as per the decision of the optimization scheme. A comparative analysis is, finally, conducted in order to demonstrate the validity of the proposed scheme.

**Keywords:** *Smart Structures, Structural Control, MR Dampers, Fuzzy Control, Structural Dynamics.*

## 1 INTRODUCTION

Traditionally, structures are designed to be able to resist dynamic loads with enough ductility to ensure the ability of structures to retain its strength under severe loading conditions and provide enough warning before failure. This concept has two main disadvantages as follows [1]:

- 1-Structures depend on their constant small damping ability to dissipate the earthquake energy with no well-defined guidelines to be able to improve the damping properties of the commonly used materials in construction.
- 2-Structures depend mainly on their stiffness to resist loads which is an uneconomic solution.

Therefore, researchers were motivated to improve design methodologies and thus, the behaviour of structures. This includes the conducted research to propose different structural control strategies which can be used to reduce structural response under earthquake excitation. Magneto rheological (MR) dampers are one of the promising devices that can be used in structural response control; they are dampers filled with a smart fluid known as Magneto rheological (MR) fluids whose properties can be controlled by varying the applied voltage to the damper [2, 3, 4]. The calculation of the required voltage can be done by several control techniques such as fuzzy control [5].

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<sup>1</sup>Senior Undergraduate Student, Faculty of Engineering, The British University in Egypt (BUE), AL-Sherouk City, Cairo, EGYPT, Email: omar115517@bue.edu.eg.

<sup>2</sup>Professor, M.ASCE, M.AISC, Dean of Engineering, The British University in Egypt (BUE), AL-Sherouk City, Cairo, EGYPT, Email: mhassan@bue.edu.eg.

Based on previously conducted research [3, 6, 7, 8], it is found that few researchers have investigated the use of fuzzy control for controlling Multi-Degree-of-Freedom (MDOF) systems using multiple MR dampers. In addition, this few conducted research for MDOF systems using fuzzy control includes specific cases with specific arrangements of MR dampers that cannot be generalized to other structural systems. In this paper two fuzzy control schemes are proposed to control three MR dampers, one at each floor level. The first comprises three fuzzy controllers operating in parallel, while the second adds a fuzzy inference system that operates as a firing sequence to a selected MR damper. The performance of both control schemes is investigated and a comparative analysis to evaluate the proposed schemes relevant to each other is also conducted.

## 2 BENCHMARK PROBLEM AND DAMPERS' CONFIGURATIONS

A benchmark problem is a standard structural system that can be used in research conducted by different groups to facilitate the ability to compare different results of several control methods by excluding other factors affecting the behaviour such as dimensions, sections and seismic masses. Structural systems subjected to earthquake excitation can be modelled as follows [9] :

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = -\mathbf{m}\ddot{u}_g + \mathbf{F}_d. \quad (1)$$

Where:

- $\mathbf{M}$  is 3x3 mass matrix,  $\mathbf{C}$  is 3x3 damping matrix
- $\mathbf{K}$  is stiffness matrix
- $\ddot{\mathbf{u}}$ (acceleration vector)
- $\dot{\mathbf{u}}$  (relative velocity vector to the ground)
- $\mathbf{u}$ (relative displacement vector to the ground)
- $\ddot{u}_g$  is the ground acceleration.
- $\mathbf{F}_d$ (dampers' forces vector).

Figure 1 gives a general configuration of the benchmark problem along with the dampers' configuration. In general, the control system works by measuring the structural response using a group of sensors. This data is then received by the processor which may include other fuzzy components in addition to the fuzzy controller which calculate the required voltage for each damper; these dampers will adjust their characteristics to result in better structural response.

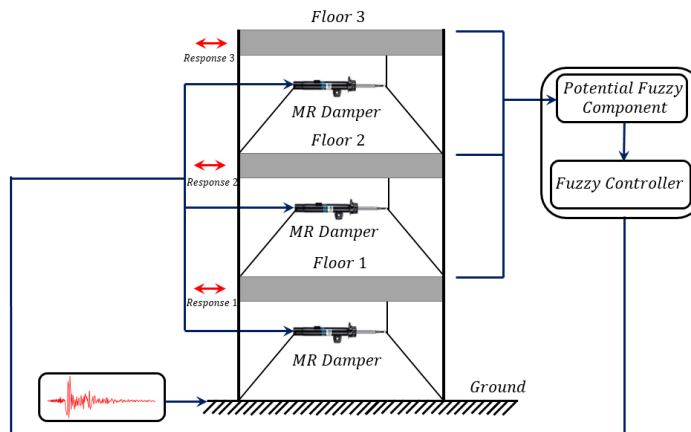


Figure 1—A schematic diagram for the modelled system.

The structural parameters of the used benchmark can be expressed as follows [10]:

$$\mathbf{M} = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} kg, \quad \mathbf{C} = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} \frac{N \cdot sec}{m} \quad \& \quad \mathbf{K} = \begin{bmatrix} 12 & -6.84 & 0 \\ -6.84 & 13.7 & -68.4 \\ 0 & -6.84 & 68.4 \end{bmatrix} 10^5 N/m$$

In order to calculate the force generated by an MR damper, it is required to use one of the models available in the literature. The most widely accepted model, used in civil engineering applications, is based on Bouc-Wen Model which can be expressed as follows [2, 4]:

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}). \quad (2)$$

$$\dot{y} = \frac{1}{c_0 + c_1} (\alpha z + c_0 \dot{x} + k_0(x - y)). \quad (3)$$

$$F = c_1 \dot{y} + k_1(x - x_0). \quad (4)$$

Where:

- $k_1$  is the stiffness of the accumulator.
- $c_0$  is damping at large velocity.
- $c_1$  is damping at lower velocities.
- $x_0$  is the initial displacement representing the accumulator.
- $k_0$  is the stiffness at larger velocities.
- $F$  is the force generated by the damper

The previous equations have several parameters that depend on the specific used damper;  $\gamma$ ,  $\beta$ ,  $A$ ,  $\alpha$ ,  $c_0$ ,  $c_1$  which should be tuned to reflect the damper behaviour.  $k_1$ ,  $k_0$  and  $x_0$  depend on the damper specifications. For the 3000-N MR dampers, which are used in this paper, these parameters were given by Spencer et al. [2].

The process of controlling MR dampers is to determine the voltage required to be applied to the damper based on the system response to change the properties of the MR fluid to improve the system's behaviour. The problem here lies in the fact that the relation between the electric current applied to the damper and the force generated by the damper is nonlinear; therefore, it has always been an important point of research to develop effective control strategies to calculate the electric current or voltage to be able to obtain full usage of MR dampers. The use of fuzzy logic is one of the promising control techniques that can be used [11].

### 3 PROPOSED CONTROLLERS

In this paper two different fuzzy control schemes are proposed aiming at the control of a three-degree-of-freedom system using multiple MR dampers. The first scheme employs multiple fuzzy controllers, operating in parallel, while the second employs a firing procedure to optimize the use of individual dampers. The following presents a brief description of each scheme.

#### 3.1 Control Scheme 1 (Multiple Fuzzy Controllers)

In control scheme 1, the fuzzy controller comprises three underlying fuzzy controllers operating in parallel. In order to incorporate the interaction between consecutive floors, relative responses between floors are used as inputs for each controller. For example, to control the damper placed between the second and third levels, the relative displacement and velocity of these floors, with respect to each other, are used as inputs to its controller; the same applies for the other two

dampers, as indicated schematically in figure 1. Figure 2 shows the proposed rule base of one of these controllers.

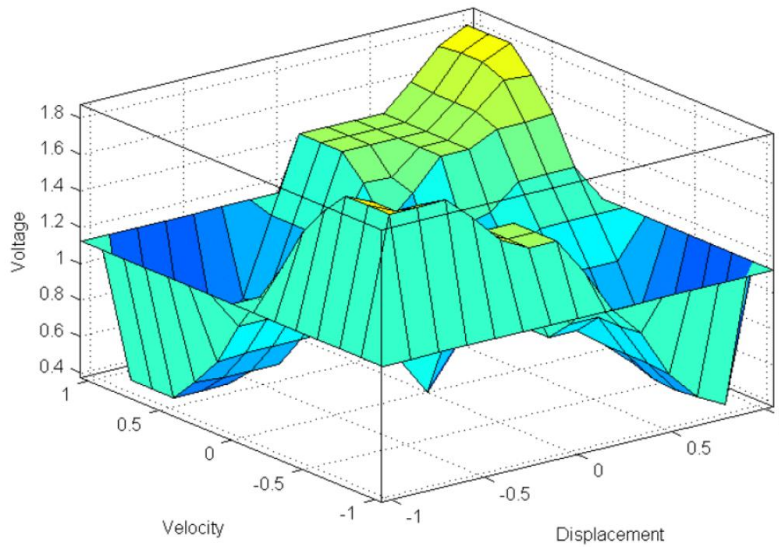


Figure 2 – Sample rule base of one of the three parallel fuzzy controllers.

### 3.2 Control Scheme 2 (Optimized Firing Fuzzy Controller)

In control scheme 2, an additional fuzzy component is integrated within the control mechanism in order to operate as a firing sequence. The main objective is to optimize the firing and operation of multiple MR dampers instead of activating such dampers to function simultaneously at all times. This scheme is designed especially for multi-degree-of-freedom systems, where the number of multiple MR dampers is expected to be large. The firing sequence is achieved by using a fuzzy pattern identifier which provides a deformed pattern describing the real-time displaced position of the structure, using sensor data. The fuzzy pattern identifier was developed by Hassan (2013)[12]. Using the deformed shapes estimated by the pattern identifier, certain dampers will receive voltage, calculated by the relevant fuzzy controller, based on the location of maximum displacement of the detected deformed shape.

The resulting patterns are abstract deformed shapes and thus, as such, do not provide accurate information about the location of the maximum lateral displacement within the system. Therefore, a detailed dynamic analysis was conducted in order to investigate which patterns are commonly obtained and what are the corresponding locations of maximum displacements. This piece of information is used in firing the damper allocated at the level with maximum displacement. At the same time, the remaining dampers are expected to operate as passive dampers with no voltage applied.

## 4 TESTING OF PROPOSED CONTROLLERS

The proposed controller schemes were tested using a total of ten earthquakes in order to ensure its validity. The resulting response reduction achieved by each scheme was calculated and a comparative analysis was then conducted to identify the best control scheme. Table 1 outlines the basic information of the earthquakes used in testing the proposed controllers. Table 2 provides a summary of results of controlled and uncontrolled responses for both proposed control schemes.

Referring to table 2, it is found that both proposed control schemes were able to reduce both displacement and acceleration responses of all floors under all testing earthquakes.

*Table 1: Earthquake used in validation of proposed controllers*

Number	Name	Location	Year of Occurrence	Magnitude ( $M_w$ )
1	Kobe	Japan	1995	6.9
2	Kern Country	USA	1952	7.3
3	Chile	Chile	1960	9.4-9.6
4	Hawaii	Hawaii	1952	9
5	El-Centro	USA-Mexico	1940	6.9
6	Trinidad	USA	1983	3.2
7	Northridge	USA	1994	6.7
8	San Fernando	USA	1971	6.5-6.7
9	Lander	USA	1992	7.3
10	Caldiran	Turkey	1976	7.3

Referring to table 2, it is found that the first control scheme was able to show consistent reduction in response parameters of all three floors for all ten earthquakes. It is further evident that an average reduction in displacement of all three floors of 69%, as compared to the uncontrolled displacement was achieved. This is calculated based on an average reduction ratio of 0.31. In addition, it can be stated that an average reduction in acceleration of all three floors of 81%, as compared to the uncontrolled acceleration was achieved. This is calculated based on an average reduction ratio of 0.19. Figure 3 shows the time history of the controlled and uncontrolled responses of the third floor, using control scheme 1 under Kobe earthquake. In addition, figure 4 shows the controlled and uncontrolled maximum displacements and accelerations of all three floors, using control scheme 1 under Kobe earthquake.

Referring to table 2, it is also evident that the second control scheme was able to show consistent reduction in response parameters of all three floors for all ten earthquakes. It is further apparent that an average reduction in displacement of all three floors of 61%, as compared to the uncontrolled displacement was achieved. This is calculated based on an average reduction ratio of 0.39. In addition, it can be stated that an average reduction in acceleration of all three floors of 73%, as compared to the uncontrolled acceleration was achieved. This is calculated based on an average reduction ratio of 0.27. Figure 5 shows the time history of the controlled and uncontrolled responses of the third floor, using control scheme 2 under Kobe earthquake. In addition, figure 6 shows the controlled and uncontrolled maximum displacements and accelerations of all three floors, using control scheme 2 under Kobe earthquake.

Based on the results outlined in table 2 and figures 3, 4, 5 and 6 it is evident that both proposed control schemes are successful in achieving a significant reduction in response parameters of the benchmark problem, under the testing earthquake records. It is further required to conduct a comparative analysis in order to identify the best control scheme for the benchmark problem under consideration. It is also important to identify the most optimum control scheme if both schemes turned out to be close in their efficiency.

Table 2: Summary of results of the two proposed controllers tested under ten earthquakes

Earthquake	Floor	Max Absolute Displacement					Max Absolute Acceleration				
		Uncontrolled ( $d_0$ ) (cm)	Controller 1		Controller 2		Uncontrolled ( $a_0$ )	Controller 1		Controller 2	
			$d_1$ (cm)	$d_1/d_0$	$d_2$ (cm)	$d_2/d_0$	$a_0$ (cm/sec <sup>2</sup> )	$a_1$ (cm/sec <sup>2</sup> )	$a_1/a_0$	$a_2$ (cm/sec <sup>2</sup> )	$a_2/a_0$
1	1	0.77	0.37	0.48	0.39	0.50	771.66	71.57	0.09	183.55	0.24
	2	1.21	0.56	0.46	0.59	0.49	1202.81	92.04	0.08	251.73	0.21
	3	1.44	0.65	0.45	0.68	0.47	1426.46	109.17	0.08	272.25	0.19
2	1	2.74	0.56	0.21	0.88	0.32	3443.57	449.02	0.13	709.18	0.21
	2	4.33	0.89	0.21	1.34	0.31	5319.55	434.91	0.08	1009.46	0.19
	3	5.20	1.04	0.20	1.54	0.30	6312.66	558.72	0.09	1158.32	0.18
3	1	29.37	9.68	0.33	11.03	0.38	32996.80	9123.37	0.28	11613.92	0.35
	2	46.48	15.75	0.34	17.73	0.38	52450.09	15555.61	0.30	18053.00	0.34
	3	55.86	19.04	0.34	21.21	0.38	63013.82	20200.76	0.32	21883.85	0.35
4	1	53.15	8.87	0.17	10.70	0.20	58922.81	10183.59	0.17	11587.99	0.20
	2	84.63	13.64	0.16	16.69	0.20	97663.23	14072.83	0.14	17812.58	0.18
	3	102.17	16.34	0.16	20.07	0.20	121083.87	17679.11	0.15	22824.77	0.19
5	1	0.68	0.09	0.14	0.17	0.25	818.41	64.94	0.08	119.76	0.15
	2	1.08	0.14	0.13	0.26	0.24	1265.47	120.87	0.10	243.02	0.19
	3	1.30	0.17	0.13	0.29	0.23	1516.51	105.15	0.07	281.87	0.19
6	1	0.21	0.04	0.19	0.09	0.44	243.72	9.26	0.04	36.60	0.15
	2	0.33	0.08	0.23	0.15	0.44	378.56	20.56	0.05	87.24	0.23
	3	0.40	0.09	0.24	0.17	0.43	472.22	26.78	0.06	98.42	0.21
7	1	24.12	14.48	0.60	14.45	0.60	16452.94	4800.48	0.29	6787.81	0.41
	2	36.43	21.47	0.59	21.35	0.59	26012.03	8566.60	0.33	10416.16	0.40
	3	42.57	24.86	0.58	24.70	0.58	31654.89	11135.50	0.35	12366.33	0.39
8	1	20.33	6.65	0.33	7.17	0.35	24730.40	5060.49	0.20	5853.32	0.24
	2	32.34	10.64	0.33	11.29	0.35	37611.52	8217.35	0.22	8650.24	0.23
	3	39.03	12.73	0.33	13.31	0.34	45339.39	10485.59	0.23	10258.68	0.23
9	1	3.35	0.72	0.22	1.27	0.38	4388.65	996.86	0.23	1923.90	0.44
	2	5.32	1.14	0.22	2.04	0.38	6339.33	1500.13	0.24	2845.28	0.45
	3	6.40	1.35	0.21	2.33	0.36	7368.69	1688.95	0.23	3060.90	0.42
10	1	1.11	0.48	0.43	0.59	0.53	1381.70	451.88	0.33	457.64	0.33
	2	1.74	0.80	0.46	0.92	0.53	2075.90	738.33	0.36	731.42	0.35
	3	2.07	0.93	0.45	1.04	0.50	2577.80	850.60	0.33	757.02	0.29
<b>Average</b>	-	-	-	<b>0.31</b>	-	<b>0.39</b>	-	-	<b>0.19</b>	-	<b>0.27</b>

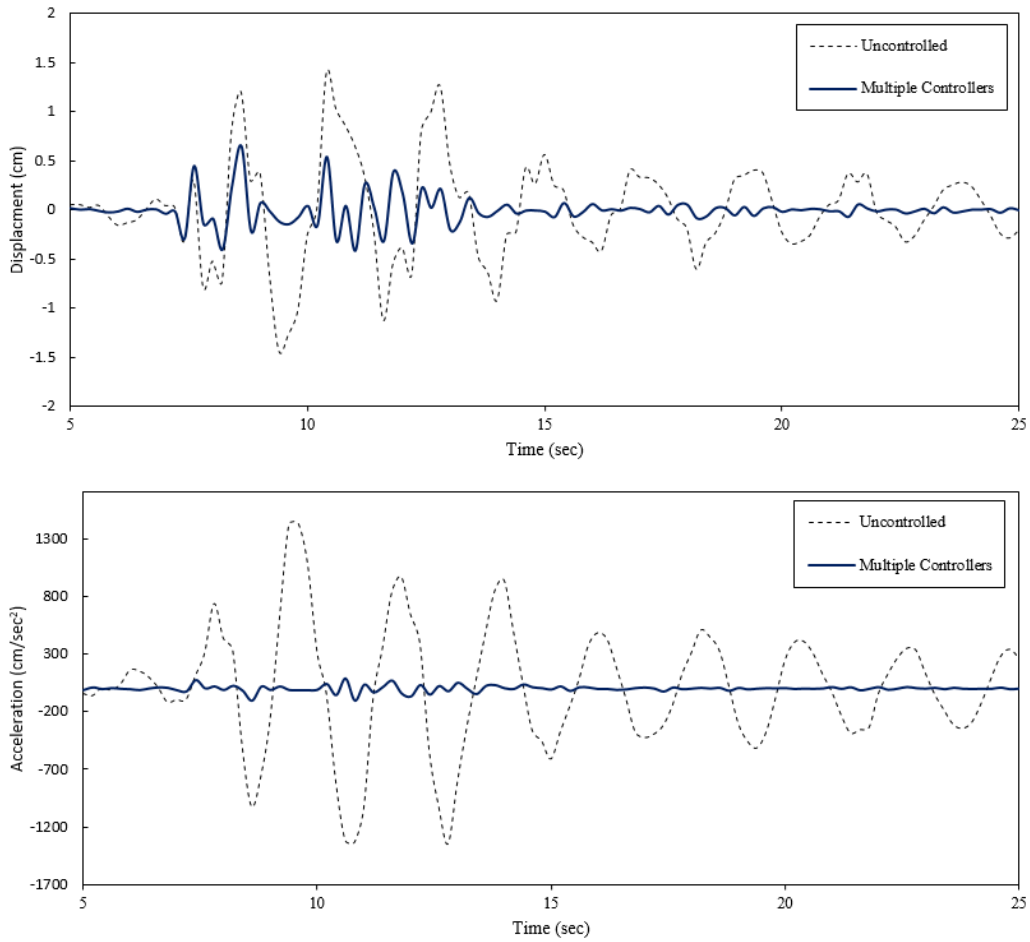


Figure 3 – Displacement and acceleration time histories of the third floor under Kobe Earthquake for uncontrolled system and scheme-1 controlled system.

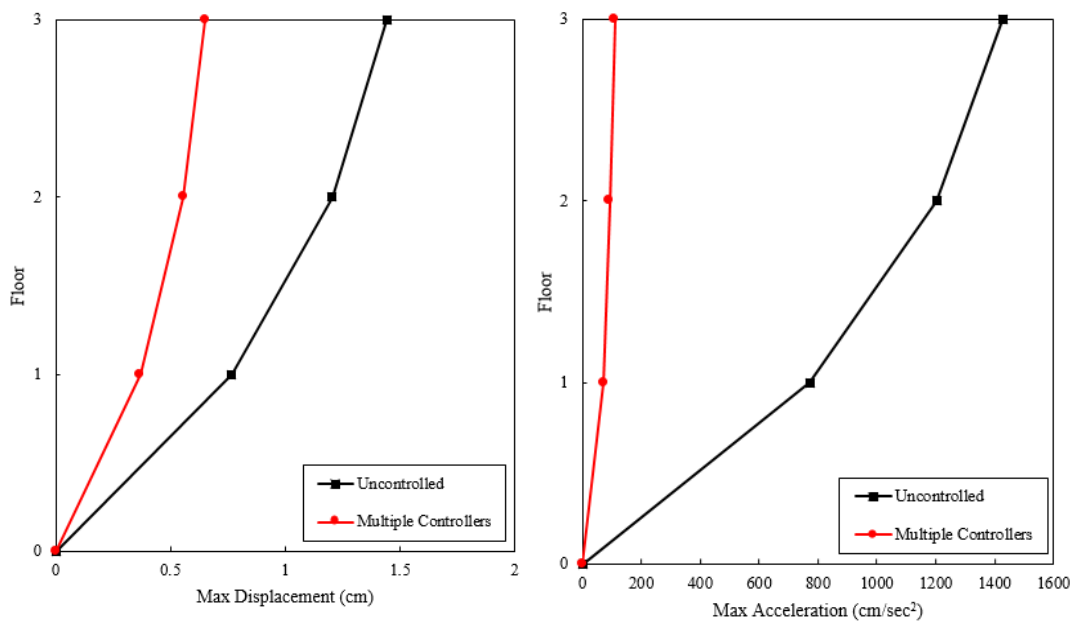


Figure 4 – Max Displacement and acceleration of all three floors under Kobe Earthquake for uncontrolled system and scheme-1 controlled system.

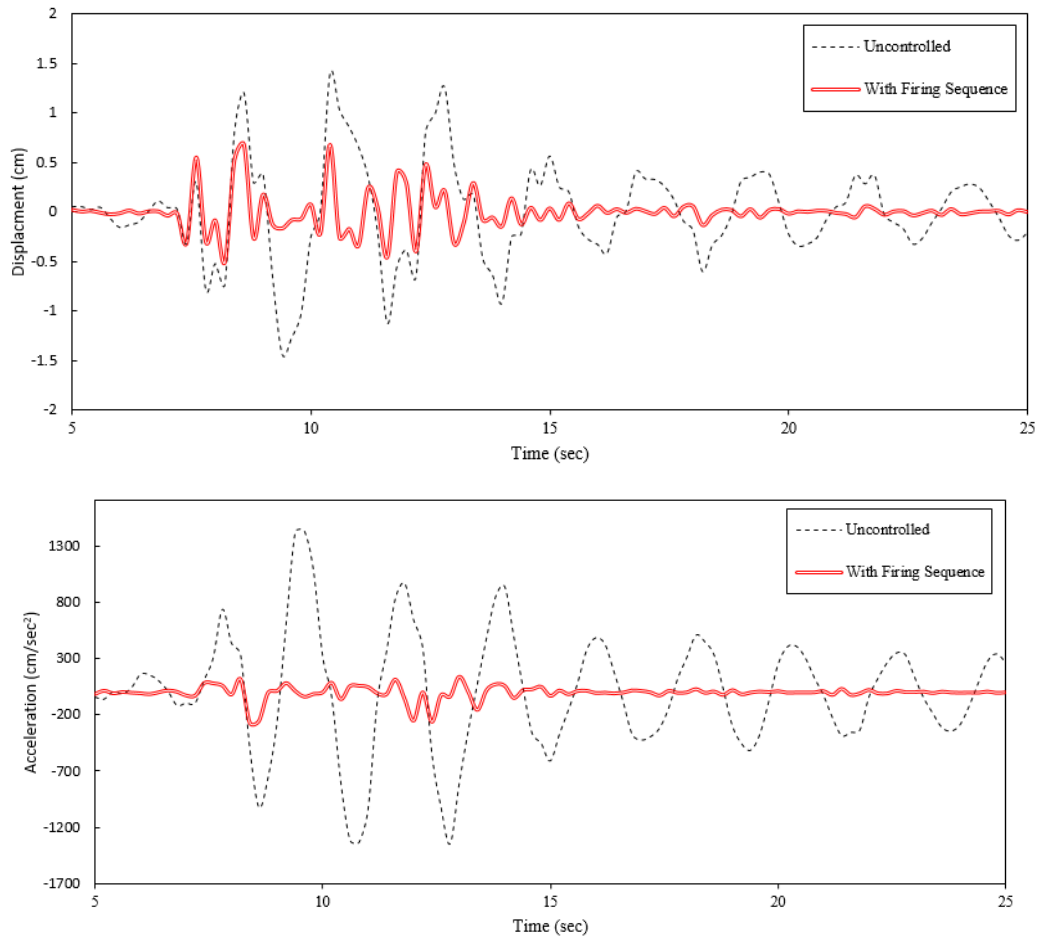


Figure 5 – Displacement and acceleration time histories of the third floor under Kobe Earthquake for uncontrolled system and scheme-2 controlled system.

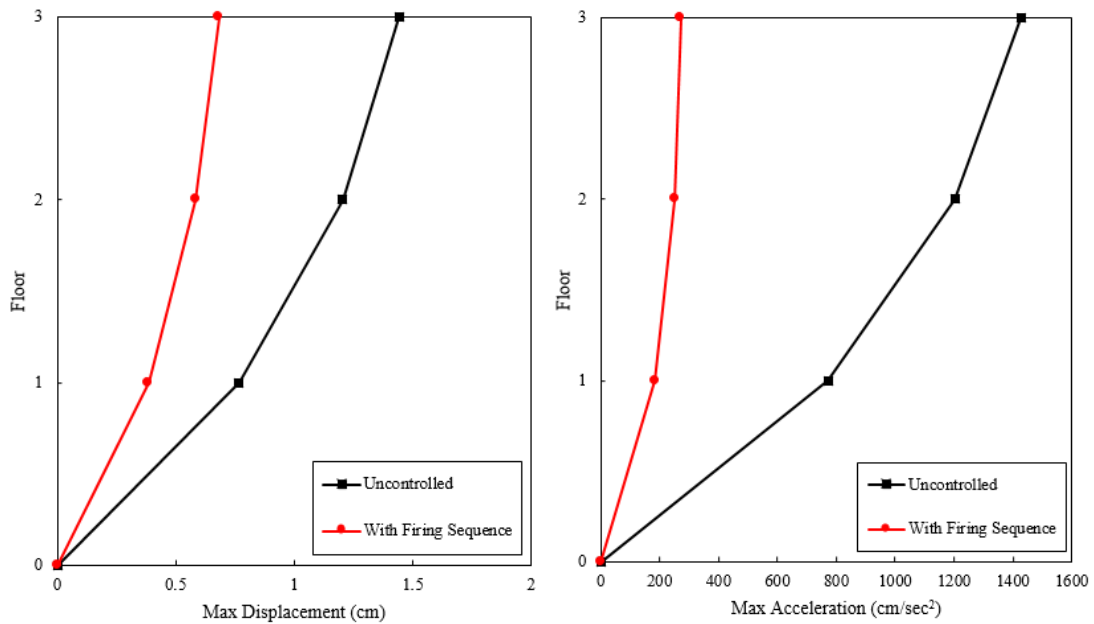


Figure 6 – Max Displacement and acceleration of all three floors under Kobe Earthquake for uncontrolled system and scheme-2 controlled system.



## 5 COMPARATIVE ANALYSIS OF PROPOSED CONTROL SCHEMES

This paper has presented two proposed fuzzy control schemes with the main objective of controlling a three-degree-of-freedom system, using multiple MR dampers. According to the analysis of results of both control schemes, it is evident that both proposed schemes proved to be effectively capable of reducing the response parameters of the benchmark problem. It is then an important step to conduct a comparative analysis in order to identify which scheme is the most effective in controlling the response of the benchmark problem. Such analysis would consider the relative reductions of both control schemes in addition to the required average voltage communicated to MR dampers. The scheme that is capable of achieving the highest reduction in response parameters with minimum operation of MR dampers is considered to be the most effective.

Table 3 shows a comparison between the performance of control scheme 1 as opposed to control scheme 2 under the ten testing earthquake records. The table shows the ratio between maximum controlled displacements using control scheme 2, with respect to control scheme 1, for all three floors. If the ratio exceeds one this indicates that control scheme 1 is achieving better displacement reductions than control scheme 2. By inspection it is evident that in general control scheme 1 is better than control scheme 2 where it results, on average, in 73% of the displacements resulting by employing control scheme 2. In addition, the table also shows the ratio between maximum controlled accelerations using control scheme 2, with respect to control scheme 1, for all three floors. By inspection it is evident that in general control scheme 1 is again better than control scheme 2 in controlling accelerations of all three floors, where it results, on average, in 80% of the accelerations resulting by employing control scheme 2. Figure 7 shows the time history of the controlled responses of the third floor, using both control schemes under Kobe earthquake. In addition, figure 8 shows the controlled maximum displacements and accelerations of all three floors, using both control schemes under Kobe earthquake. Both figures confirm the previously concluded remark regarding the performance of control scheme 1 in comparison to that of control scheme 2.

It should be noted, though, that due to the small size of the benchmark problem, the efficiency and economy of the employed control scheme might not be evident and/or a major factor. However, as the structural system gets larger with more MR dampers, it is envisaged that control scheme 2 might be considered an optimum compromise.

*Table 3: Comparative Results of Proposed Control Schemes*

Earthquake	Floor	$d_2/d_1$	$a_2/a_1$	Average Voltage (v)		$v_1/v_2$
				Controller 1	Controller 2	
<b>1</b>	1	1.04	2.56	1.20	0.43	2.77
	2	1.05	2.74			
	3	1.05	2.49			
<b>2</b>	1	1.56	1.58	1.21	0.40	3.00
	2	1.50	2.32			
	3	1.48	2.07			
<b>3</b>	1	1.14	1.27	1.14	0.38	3.02
	2	1.13	1.16			
	3	1.11	1.08			
<b>4</b>	1	1.21	1.14	1.15	0.38	3.06
	2	1.22	1.27			
	3	1.23	1.29			
<b>5</b>	1	1.80	1.84	1.18	0.42	2.83
	2	1.84	2.01			
	3	1.76	2.68			
<b>6</b>	1	2.27	3.95	1.19	0.42	2.80
	2	1.93	4.24			
	3	1.80	3.68			
<b>7</b>	1	1.00	1.41	1.13	0.37	3.01
	2	0.99	1.22			
	3	0.99	1.11			
<b>8</b>	1	1.08	1.16	1.14	0.38	3.03
	2	1.06	1.05			
	3	1.05	0.98			
	2	1.71	1.21			
	3	1.52	1.08			
<b>9</b>	1	1.76	1.93	1.18	0.39	3.04
	2	1.78	1.90			
	3	1.73	1.81			
<b>10</b>	1	1.24	1.01	1.19	0.39	3.05
	2	1.15	0.99			
	3	1.11	0.89			
<b>Average</b>	-	<b>1.37</b>	<b>1.83</b>	-	-	<b>2.96</b>

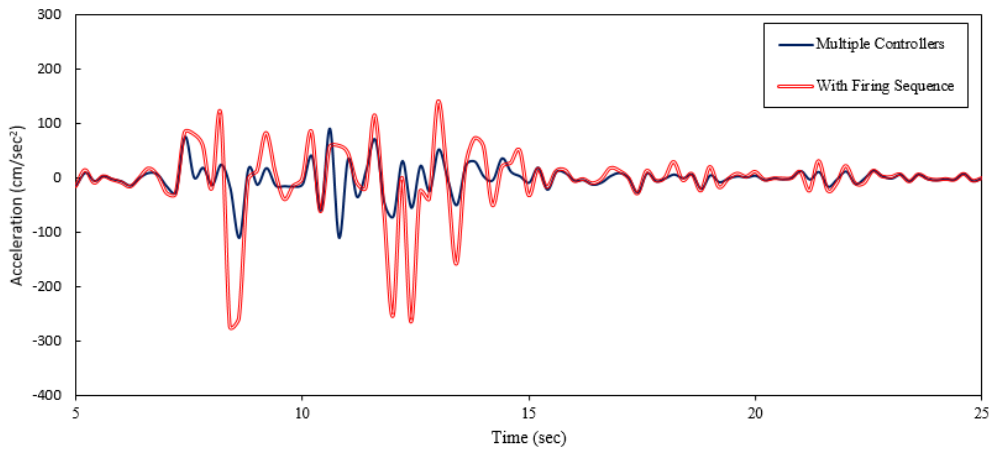
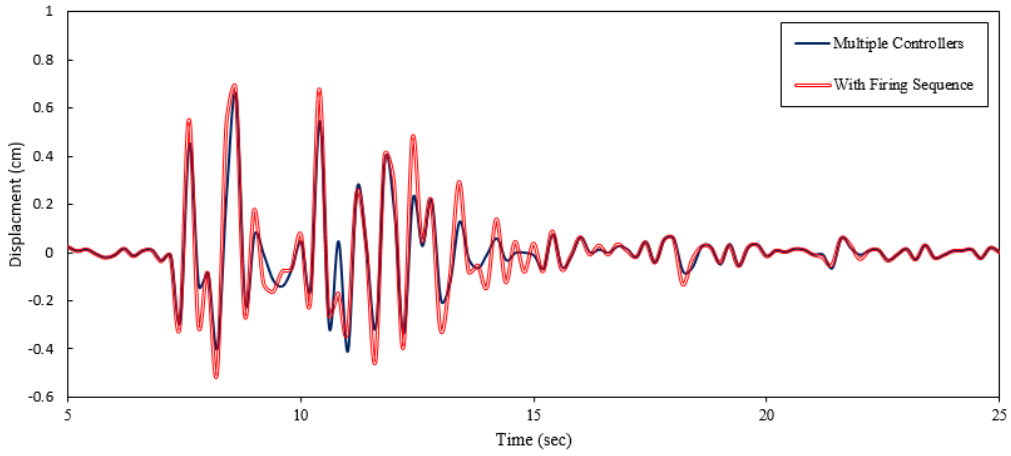


Figure 7– Displacement and acceleration time histories of the third floor under Kobe Earthquake for scheme-1 and scheme-2 controlled systems.

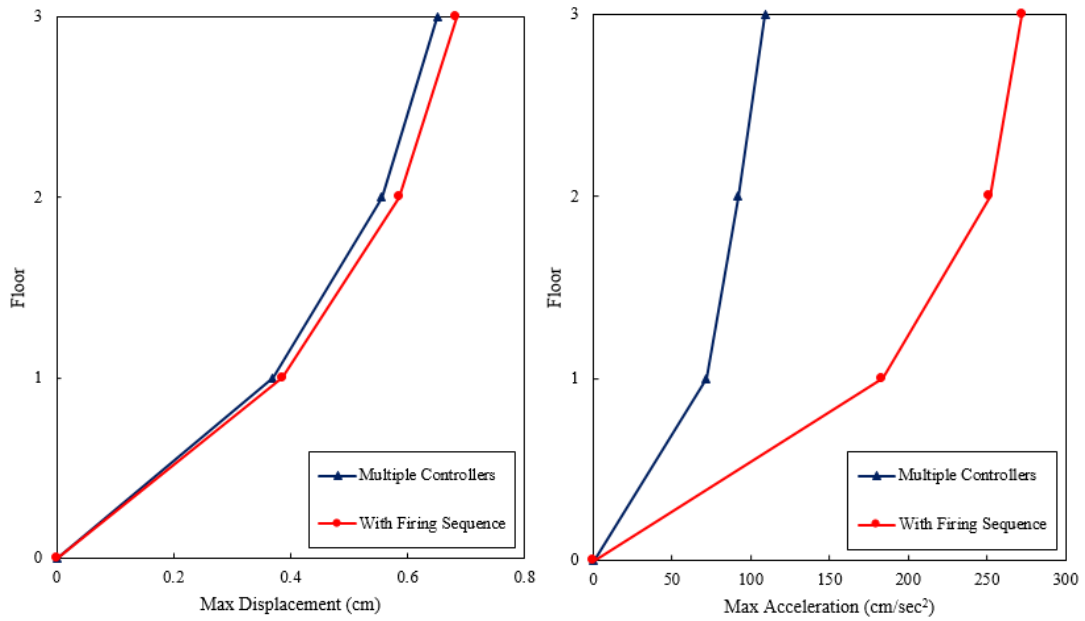


Figure 8 – Max Displacement and acceleration of all three floors under Kobe Earthquake for scheme-1 and scheme-2 controlled systems.

## 6 SUMMARY AND CONCLUSIONS

Fuzzy-controlled MR dampers are considered one of the promising techniques that can be used in structural response control. Much research was done to investigate the possibility of using this technique and how much it is effective in structural response reduction. Most of the research done in this area was focused on single-degree-of-freedom systems and specific damper configurations for MDOF systems. In this paper, the use of multiple MR dampers to control the response of a three-degree-of-freedom benchmark problem is investigated.

Two control schemes are proposed where control scheme 1 comprises multiple fuzzy controllers, operating in parallel, based on the relative response parameters between each two consecutive floors. Control scheme 2, on the other hand, comprises an additional fuzzy inference system that results in voltage to be sent to specific dampers, based on the structure's abstract deformed shape, which is identified using a fuzzy inference system. It is found that both control schemes are able to significantly reduce the structural response, as compared to the uncontrolled response of the benchmark problem. However, control scheme 1 results in higher response reduction, with higher power requirement, compared to control scheme 2.

It is evident that due to the small size of the controlled system and the limited number of MR dampers, the efficiency of any given control scheme is not a significant factor. However, it is envisaged if multi-degree-of-freedom systems, with a large number of MR dampers, are investigated the efficiency and economy of the proposed control scheme shall play a major role in selecting the best control strategy. It remains a significant element of validating fuzzy control algorithms to ensure their reliability. The reliability assessment of fuzzy controllers is currently an active area of research of the same group.

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