Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 4560-4574

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COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

CONTROL OF STRUCTURES SUBJECTED TO DYNAMIC LOADS USING MAGNETORHEOLOGICAL DAMPERS

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Abstract

In order to mitigate vibrations in structures subjected to dynamic loads, some control devices have been studied to reduce the forces and deformations caused by these loads. One of these control devices is the magnetorheological (MR) damper, a semi-active control device that consists of a controllable fluid, called magnetorheological fluid, that can change its rheological properties quickly in the presence of a magnetic field. This damper gives the structure robustness, reliability, and high stability. MR dampers have a strong nonlinear behavior, so it is necessary to work on non-linear control algorithms, which are methods derived from mathematical formulations or intelligent methods, to achieve optimal control forces to reduce the response of the controlled structures. This paper figures out how to reduce the response of a building equipped with MR dampers subjected to different seismic loads using a classic fuzzy logic controller. The proposed controller aims to find the adequate voltage that must be applied to the damper to generate damping forces that reduce the lateral displacements and velocities generated after the dynamic load has been applied. The results show that the use of an MR damper with the fuzzy logic controller decreases the response of the structure, demonstrating that the implementation of these devices is appropriate to control structures subjected to earthquake loads.

Keywords: Structural control, magnetorheological damper, fuzzy logic, damping, optimization.

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10741.20135

1 INTRODUCTION

In recent years, researchers have been focused on finding ways to mitigate the effects of dynamic loads on structures. Environmental loads, such as earthquakes, wind, or waves, can cause significant damage to structures if not properly addressed. The challenge for engineers is to develop effective methods to protect structures from these loads reducing the forces and deformations that occur because of them [1 – 4]. A potential solution to mitigate the effects caused by dynamic loads on structures is the use of control devices such as dampers [5 – 7]. These devices can be used to reduce the vibrations thereby decreasing the damage to the structure. Additionally, structural control systems can also be employed to decrease and dissipate the energy generated by these loads [8 – 10]. By actively controlling the structural motion, these systems can greatly reduce the forces and deformations experienced by the structure as well as improve its performance and safety during a seismic event.

Semi-active control systems have been gaining attention in the academic community. These systems offer a balance because use less energy than active control systems and have the dependability of passive control systems [11 – 13]. Unlike active controllers, which require a constant energy source to operate, semi-active systems usually use the movement of the structure to generate control forces. This is achieved using response sensors that measure the excitation of the structure and can be adjusted by an external power source. This allows for a more energy-efficient system while still providing the necessary control forces to mitigate the effects of dynamic loads. Furthermore, these systems can adapt to changes in the structure or the load, making them more reliable than passive control systems [14, 15].

A magnetorheological (MR) damper is a semi-active device that uses the properties of the MR fluids to control the vibrations of the structure. This fluid changes its viscosity when it is exposed to a magnetic field. When a magnetic field is present, the fluid behaves like a semi-solid and can provide significant resistance to motion. Conversely, when the magnetic field is absent, the fluid behaves like a liquid and offers very little resistance to motion. This property allows MR dampers to adjust to vibrations quickly and efficiently in real-time, providing precise control of the structural response under dynamic loads [16, 17]. The viscosity of the MR fluid can be adjusted by varying the intensity and duration of the magnetic field, providing a fast and efficient means of controlling vibrations in structures, making it a powerful tool for seismic protection and vibration control [18, 19]. Spencer *et al.* [20] developed a non-linear phenomenological model for MR dampers in 1997, which incorporates a modified Bouc-Wen hysteresis model that is numerically manageable and can exhibit hysteretic behaviors. This model allows for the accurate prediction of MR damper behavior under various loading conditions and can be used to optimize the design of MR dampers for specific applications [21, 22].

The use of MR dampers in structural control presents a significant challenge due to their strong nonlinear behavior. It is crucial to develop a suitable controller that can generate maximum force with minimal power supply [23, 24]. Therefore, research on non-linear control algorithms is necessary to effectively utilize MR dampers in structural control systems, these algorithms can help to improve the performance of the device and therefore, the safety of structures that implement it [25, 26].

In this context, some researchers have also been investigating ways to design and optimize the performance of MR dampers. One promising method that has been studied is the use of Fuzzy logic. This approach offers several advantages, such as reducing the difficulties associated with modeling and analyzing complex systems, and the ability to incorporate qualitative aspects of human experience into its mapping laws. Fuzzy logic is made up of four main components: fuzzification, a fuzzy inference engine, a fuzzy rule base, and defuzzification.

Overall, the use of Fuzzy logic in MR dampers has the potential to significantly enhance their performance in structural control systems [27, 28]. The fuzzification interface takes in crisp data and transforms it into fuzzy data that can be used by the inference system. The inference system then uses the knowledge base and the fuzzy data to make decisions and generate control actions. Finally, the defuzzification interface transforms the fuzzy control action back into a real control action (crisp output) that can be implemented in the system. These components form the backbone of fuzzy logic control and work together to take decisions in a robust and efficient manner [29, 30]. In 2012, Diptesh *et al.* [31] developed a new algorithm for controlling building frames under seismic excitation. The algorithm is based on fuzzy logic, which involves the fuzzification of the MR damper characteristics.

The objective of this research is to use fuzzy logic control to optimize the forces to reduce the structural response in terms of displacement and velocity of a 25-story building under different seismic excitations. This approach aims to improve the overall performance and safety of the building during seismic events.

2 MATHEMATICAL MODELS

2.1 Space-state representation of the problem

When analyzing a shear building with n degrees of freedom, equation (1) describes the motion of the building in terms of mass, damping, and stiffness matrix represented by $\boldsymbol{M}$, $\boldsymbol{C}$, and $\boldsymbol{K}$ respectively. The relative displacement, velocity, and acceleration of the structure are defined by the vectors $\boldsymbol{x}$, $\dot{\boldsymbol{x}}$, and $\ddot{\boldsymbol{x}}$ respectively. The applied loads are represented by the vector $\boldsymbol{f}$, and $\boldsymbol{u}$ is the vector of control forces applied to the building. $\boldsymbol{E}$ is the matrix that represents the location of the external forces, and $\boldsymbol{D}$ is the matrix that represents the location of the control forces.

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t) + \boldsymbol{C}\dot{\boldsymbol{x}}(t) + \boldsymbol{K}\boldsymbol{x}(t) = \boldsymbol{D}\boldsymbol{u}(t) + \boldsymbol{E}\boldsymbol{f}(t) \tag{1}$$

The above formulation is transformed into a space-state equation for ease of use, as shown in equation (2). This allows for a more streamlined approach to solving the problem and simplifies the process of analyzing and understanding the system.

$$\dot{\boldsymbol{z}}(t) = \boldsymbol{A}\boldsymbol{z}(t) + \boldsymbol{B}\boldsymbol{u}(t) + \boldsymbol{H}\boldsymbol{f}(t) \tag{2}$$

Matrix $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{H}$ are presented in equation (3):

$$\begin{gathered}\boldsymbol{A} = \begin{bmatrix} \boldsymbol{0} & \mathbf{I} \\ -\boldsymbol{M}^{-1}\boldsymbol{K} & -\boldsymbol{M}^{-1}\boldsymbol{C} \end{bmatrix} \\ \boldsymbol{B} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{M}^{-1}\boldsymbol{D} \end{bmatrix} \\ \boldsymbol{H} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{M}^{-1}\boldsymbol{E} \end{bmatrix}\end{gathered} \tag{3}$$

2.2 Phenomenological model of the MR damper.

The force generated by the MR damper can be represented by the modified Bouc-Wen model [20] illustrated in Figure 1. This model considers the hysteretic behavior of the damper and describes it in terms of a hysteresis loop. In this model, a damper is placed in series with a parallel spring. The force generated by the damper is represented by equation (4).

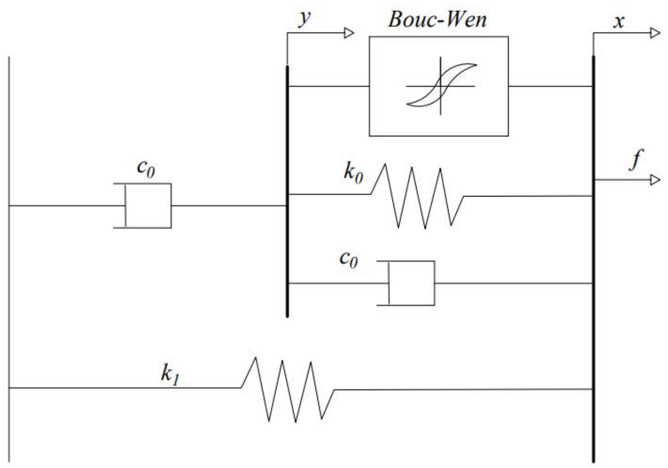


Figure 1: Phenomenological model for MR damper.

$$f = \alpha z + c_0\,(\dot{x} - \dot{y}) + k_0\,(x - y) + k_1\,(x - x_0) \tag{4}$$

Where c_0 and c_1 represent the viscous damping at long and low speeds respectively, k_0 is the stiffness of the damper at high speeds, k_1 represents the stiffness of the damper, x_0 is the initial displacement of the spring, x is the relative displacement at one end of the MR damper, $\dot{x}$ is the speed of the damper, y is the internal displacement of the damper, and z is the evolutionary variable calculated with the equation (5):

$$z = -\gamma|\dot{x} - \dot{y}||z||z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A\,(\dot{x} - \dot{y}) \tag{5}$$

In the model, parameters γ, β, and A affect the shape of the hysteresis cycles, while α and n control the internal state z and its relation to the force f and its progression. $\dot{y}$ is defined by the following equation (6):

$$\dot{y} = \frac{1}{(c_0 + c_1)}\,[\alpha z + c_0\dot{x} + k_0\,(x - y)\,] \tag{6}$$

In the equation, the parameter y represents the internal displacement of a MR damper. Despite its appearance in the equation, this parameter is purely fictitious and does not correspond to any actual physical displacement within the MR damper [32]. Parameters α, c_0 and c_1 depend on the applied voltage and are calculated using the following equations (7).

$$\begin{aligned} \alpha &= \alpha_a + \alpha_b u \\ c_0 &= c_{0a} + c_{0b} u \\ c_1 &= c_{1a} + c_{1b} u \\ \dot{u} &= -\eta(u - v)\,u \end{aligned} \tag{7}$$

Where α_a, α_b, c_{0a}, c_{0b}, c_{1a}, and c_{1b} are fixed parameters, determined by experimental results that connect the force of the damper with the voltage and *u, v,* and η are the input voltages, output voltages, and the time constant for the first-order filter, respectively.

Table 1 presents the parameters used in the phenomenological model in this paper. The MR damper voltage ranges from 0 V to 10 V.

Parameters used in the phenomenological model			
c_{0a}	110 kN·s/m	α_a	46.2 kN/m
c_{0b}	114.3 kN·s/m/V	α_b	41.2 kN/m/V
c_{1a}	8359 kN·s/m	γ	164 1/m^2
c_{1b}	7482.9 kN·s/m	β	164 1/m^2
k_0	0.01 kN/m	A	1107.2
k_1	0.485 kN/m	n	2
x_0	0	η	100 1/s

Table 1: Parameter of the model.

3 CONTROLLER BASED ON FUZZY LOGIC

The fuzzy logic was introduced by Zadeh [33] in 1965, this classical model uses linguistic control rules to connect fuzzy implication and compositional inference rules through a fuzzy logic controller (FLC). This approach contemplates the modeling of systems with imprecise or uncertain information. It allows for the representation of human thought processes and decision-making and is widely used in control systems, artificial intelligence, and expert systems. The FLC is a rule-based system that can handle ambiguity and uncertainty, making it suitable for complex and dynamic systems.

The main components of an FLC are:

- A knowledge base that holds the linguistic control rules.
- A fuzzification interface that converts real data into fuzzy data.
- An inference system that uses the knowledge base to make decisions.
- A defuzzification interface that transforms the fuzzy control action into a real control action.

Fuzzy systems behavior is determined using membership functions and fuzzy control rules. Membership functions are used to indicate how well an element fits into a particular set and can take on various shapes. Fuzzy control rules form the reasoning system of the controller and are typically written in the format of "if... then." If certain conditions are met, a set of outcomes can be inferred. The configuration of a conventional FLC is often illustrated in a diagram, such as shown in Figure 2.

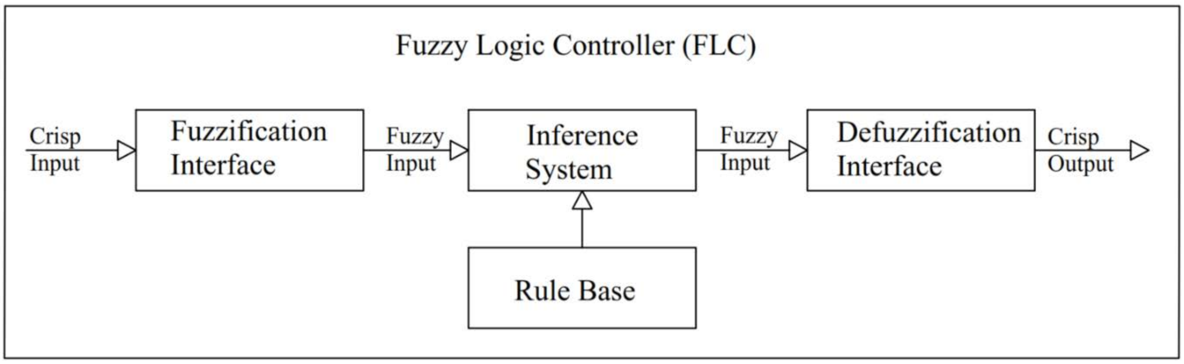


Figure 2: Configuration of a FLC.

The goal of this controller, which is based on the principles stated by Liu *et al.* [34] is to maintain the structure in a fixed position. If the structure moves away from this point, the controller increases the voltage to enhance damping and stabilize the structure. Nevertheless, if the structure is moving towards the equilibrium point, the controller decreases or stops applying a voltage as it is not necessary.

In the fuzzification interface, seven triangular membership functions are employed to define the displacement and velocity within the range [-1, 1]. These functions are used to assign a degree of membership to each value of displacement and velocity, based on their proximity to the defined linguistic variables. Scale factors, n_d for displacement and n_v for velocity, are also needed. Equations (8) provide the formulas for calculating these parameters:

$$n_d = k_d x$$
$$n_v = k_v \dot{x} \tag{8}$$

These equations consider the scaling factors k_d for displacement and k_v for velocity and use input values x and $\dot{x}$ for displacement and velocity on the first floor of the building. The output voltage is determined by using four triangular membership functions defined in the range [0,1]. These functions calculate a voltage value using the centroid method. The transformation of the output voltage from a fuzzy control action to a real control action [0, 10] is carried out by using equation (9) [35].

$$V = 10\left(\frac{5}{3}s - \frac{1}{3}\right) \tag{9}$$

Where V is the voltage to be applied to the damper and s is the output value using the centroid method in the FLC.

The controller's inference system, as presented in Table 2, is made up of seven fuzzy rules that use linguistic parameters such as NL (negative large), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive medium), and PL (positive large).

Vel / Dis	NL	NM	NS	ZO	PS	PM	PL
NL	PL	PL	PL	PM	ZO	ZO	ZO
NM	PL	PL	PL	PS	ZO	ZO	PS
NS	PL	PL	PL	ZO	ZO	PS	PM
ZO	PL	PM	PS	ZO	PS	PM	PL
PS	PM	PS	ZO	ZO	PL	PL	PL
PM	PS	ZO	ZO	PS	PL	PL	PL
PL	ZO	ZO	ZO	PM	PL	PL	PL

Table 2: Inference system.

4 CASE OF STUDY

4.1 Structure

In this paper, was considered a 25-floor building as a case of study. The building is in an urban area, and it provides the characteristics of a medium-rise building. In Figure 3, is presented the elevation configuration and the plant of the building under study.

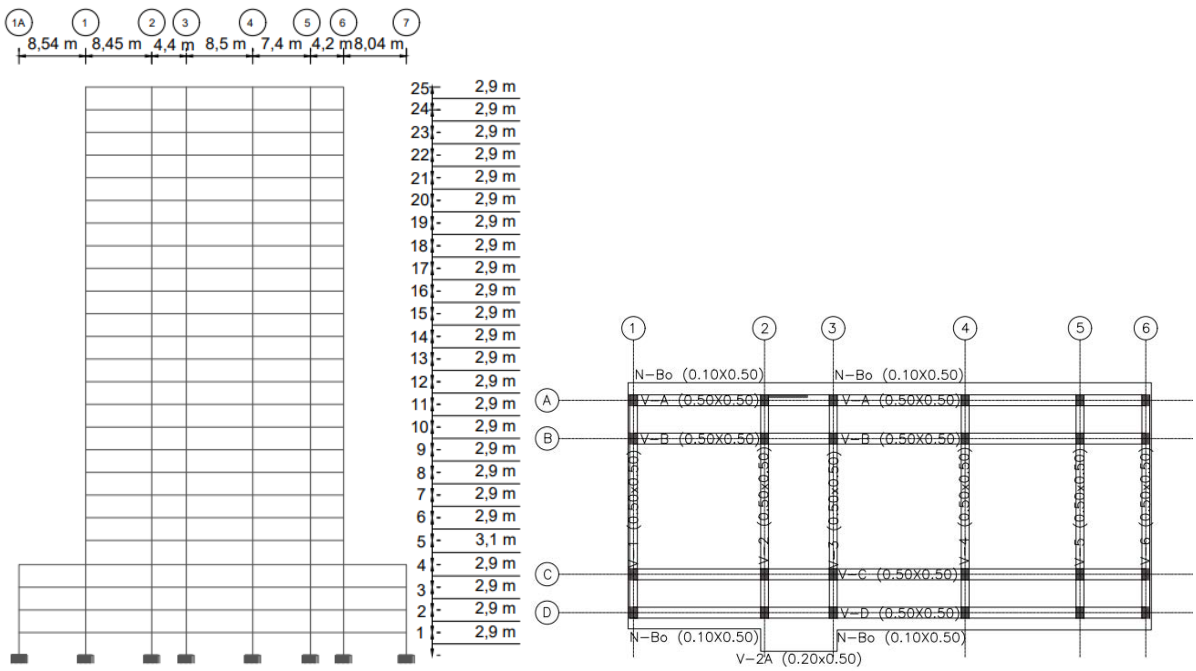


Figure 3: Building configuration.

The structural analysis for this project was conducted by reducing the stiffness matrix to a single degree of freedom for each floor of the building, this is obtained by assuming that the floor diaphragms are infinitely rigid and using static condensation to eliminate the rotational degrees of freedom. This allowed for a more detailed examination of the behavior of the structure during different ground accelerations. The mass matrix is represented as a diagonal matrix, where the entries in the diagonal represent the mass of each floor, and the matrix is used in conjunction with the stiffness matrix to calculate the dynamic response of the structure. The damping matrix was determined through the application of Rayleigh damping, with 5.0% of critical damping (ξ) assigned to the initial and final structural modes of the building. Below in equation (10), it is presented the general form of the mass, stiffness, and damping matrix of the structure.

$$\boldsymbol{M}=\begin{bmatrix} m_1 & 0 & \cdots & \cdots & \cdots \\ 0 & m_2 & 0 & \ddots & \cdots \\ \vdots & 0 & m_3 & \ddots & \cdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ \vdots & \vdots & \vdots & 0 & m_n \end{bmatrix}$$

$$\boldsymbol{C}=\begin{bmatrix} c_1+c_2 & -c_2 & 0 & \cdots & \cdots \\ -c_2 & c_2+c_3 & c_3 & \ddots & \dots \\ 0 & c_3 & \ddots & \ddots & \cdots \\ \vdots & \ddots & \ddots & \ddots & -c_{n-1} \\ \vdots & \vdots & \vdots & -c_{n-1} & c_{n-1}+c_n \end{bmatrix} \quad (10)$$

$$\boldsymbol{K}=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & \cdots & \cdots \\ -k_2 & k_2+k_3 & -k_3 & \ddots & \dots \\ 0 & -k_3 & \ddots & \ddots & \cdots \\ \vdots & \ddots & \ddots & \ddots & -k_{n-1} \\ \vdots & \vdots & \vdots & -k_{n-1} & k_{n-1}+k_n \end{bmatrix}$$

4.2 Seismic excitations

In this work, four different seismic excitations are used to demonstrate and validate the effectiveness of the damper. By conducting experiments with various levels of seismic activity, the study aims to provide a comprehensive assessment of the damper's performance and its ability to reduce structural vibrations. The results obtained from the different excitations will be analyzed and compared to establish the damper's effectiveness in reducing structural vibrations and improving the overall stability of the structure.

Table 3 presents the seismic excitations used in this study, which were obtained from the Center for Engineering Strong Motion Data [36]. The table includes information such as the location, year, and magnitude of the seismic event, as well as the component (direction), peak ground acceleration, and duration of each excitation.

Seismic record	Event	Year	Station	Component	Magnitude	PGA [g]	Duration [s]
1	El Centro	1940	El Centro	S90W	6.9	0.348	53.70
2	Central Chile	1985	Melipilla	0	7.8	0.686	79.36
3	Mexico	1985	La Union	S00E	8.1	0.169	62.90
4	Morgan Hill	1984	USGS	250	6.1	0.640	28.91

Table 3: Seismic excitations.

5 RESULTS

In-house MATLAB routines are used to simulate the behavior of the structure and generate the results presented in this study. Fulfilling the proposed goal, control forces are generated to reduce the displacement and velocity caused by the earthquake by using fuzzy logic for an MR damper. The decision to implement three dampers in the structure, located on the first floor, tenth floor, and twentieth floor, was made after a thorough iterative process. The results of the process showed that using three dampers on those floors was one of the most effective ways to reduce the response of the structure, resulting in a significant improvement in its overall performance and optimization.

For each seismic excitation, a comparative analysis was conducted to evaluate the maximum displacement and velocity on the last floor. The analysis also included the maximum voltage required and the maximum force, which provided a comprehensive understanding of the system's response to different seismic events.

Figure 4 and Figure 5 display the graphical results of the displacement and velocity on the highest floor, respectively. The figures provide a clear illustration of the behavior of the system, with the blue line representing the response of the structure without control and the orange line representing the response with control.

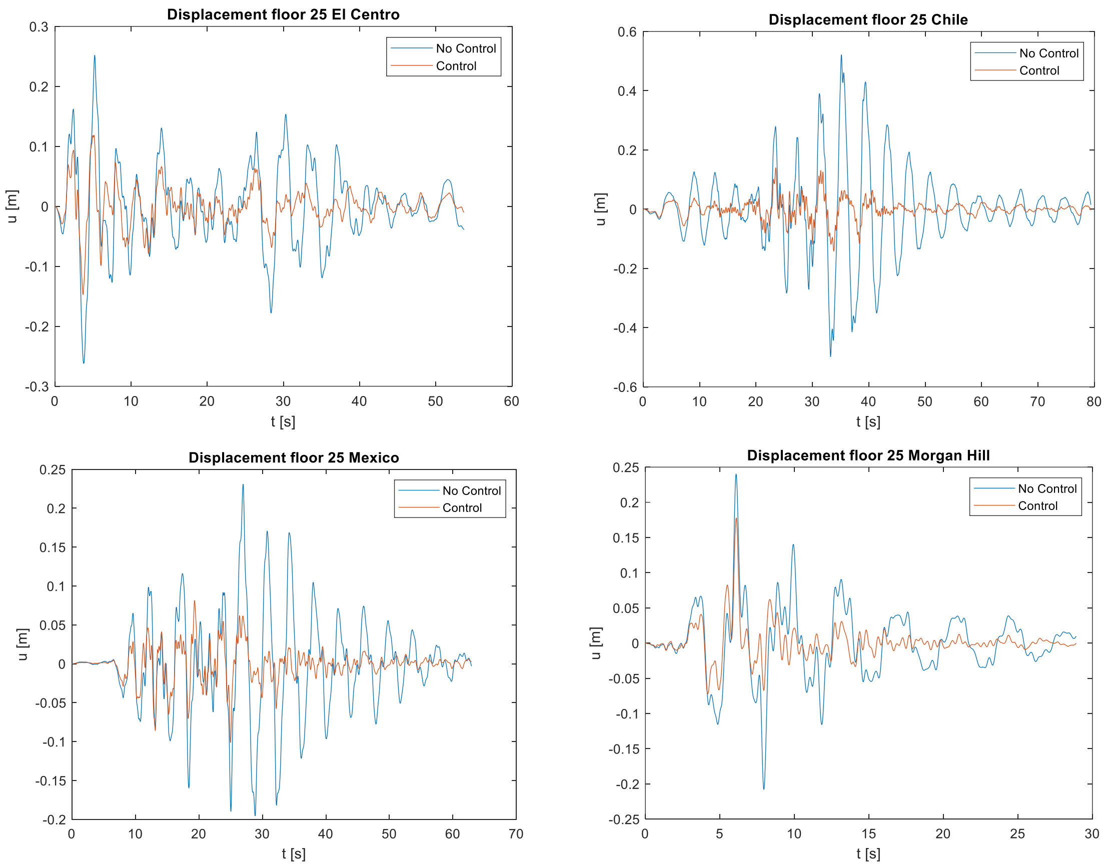
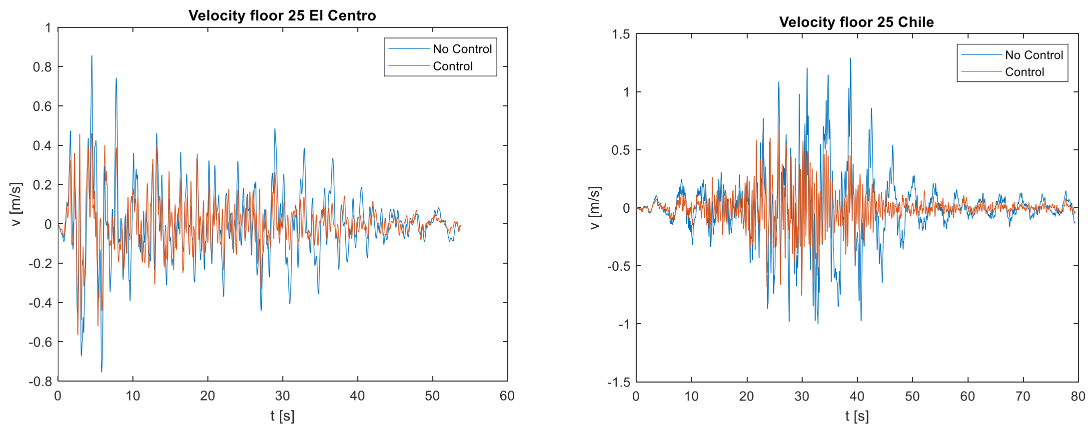


Figure 4: Displacements on the last floor.



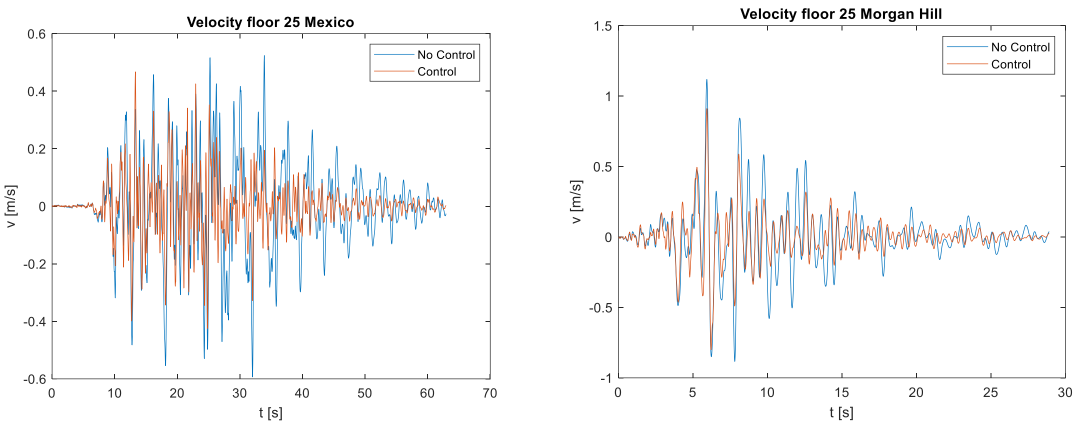


Figure 5: Velocities on the last floor.

Table 4 and Table 5 presents the results for the maximum displacement and the maximum velocity of the system in each excitation, respectively. The controller had an average reduction of 49.67% in the displacement and an average reduction of 28.8% in the velocity values compared to the values obtained without the controller.

Maximum Displacements			
Event	Uncontrolled [m]	Controlled [m]	Reduction [%]
El Centro	0.2619	0.1472	43.80
Central Chile	0.5210	0.1418	72.78
Mexico	0.2308	0.1012	56.15
Morgan Hill	0.2401	0.1778	25.95

Table 4: Maximum displacements.

Maximum Velocities			
Event	Uncontrolled [m/s]	Controlled [m/s]	Reduction [%]
El Centro	0.8562	0.5657	33.93
Central Chile	1.2898	0.7554	41.43
Mexico	0.5934	0.4672	21.27
Morgan Hill	1.1186	0.9110	18.56

Table 5: Maximum velocities.

Figure 6 displays the necessary voltage that must be applied to the damper in order to generate the forces required to control the structure. The results indicate that the maximum voltages are necessary to achieve the maximum responses without control.

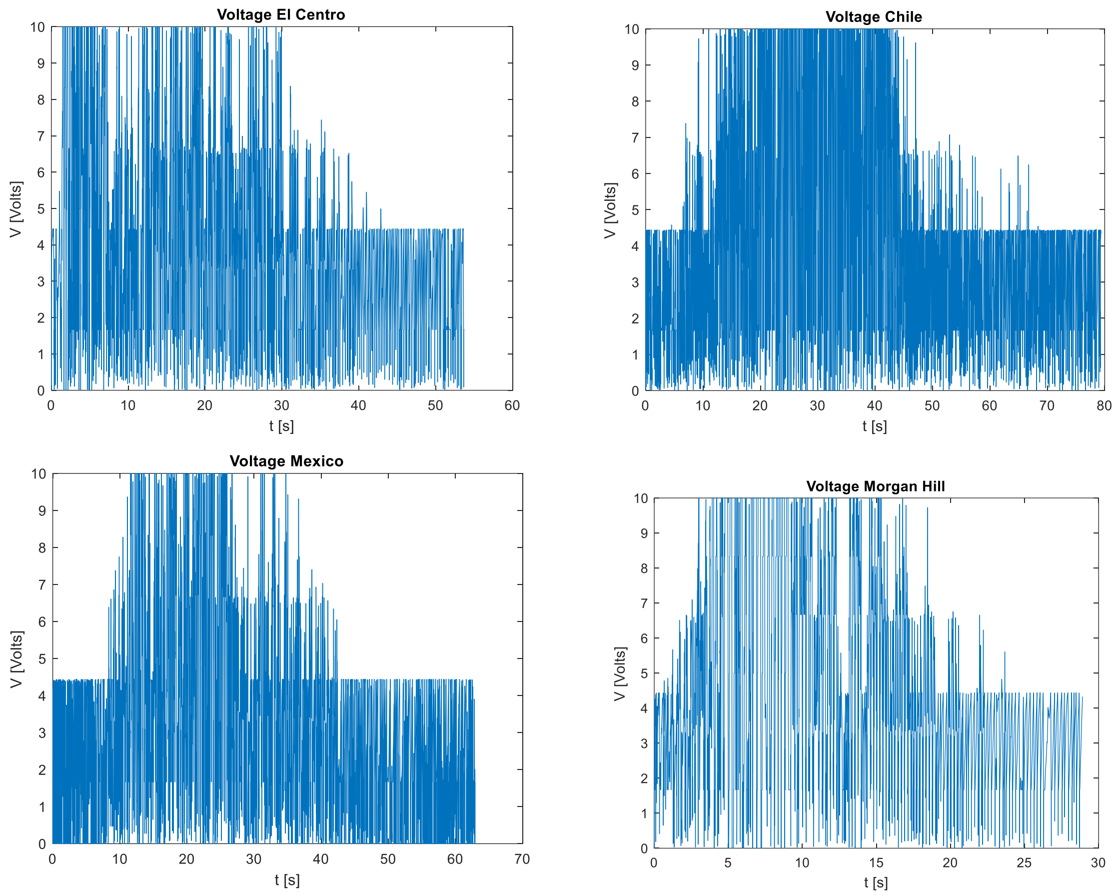
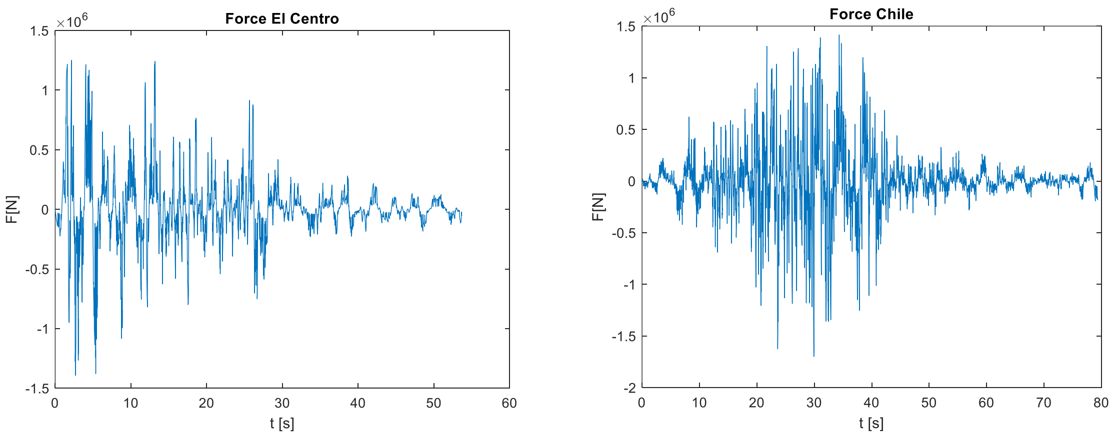


Figure 6: Voltage needed to reduce the response of the system.

The results of the study also showed that the force generated by the voltage shown above, exhibited the same behavior as the response of the structure when no control was present. According to Figure 7, the highest levels of the force applied occurred when the system experienced the highest levels of velocity and displacement showing a correlation between them.



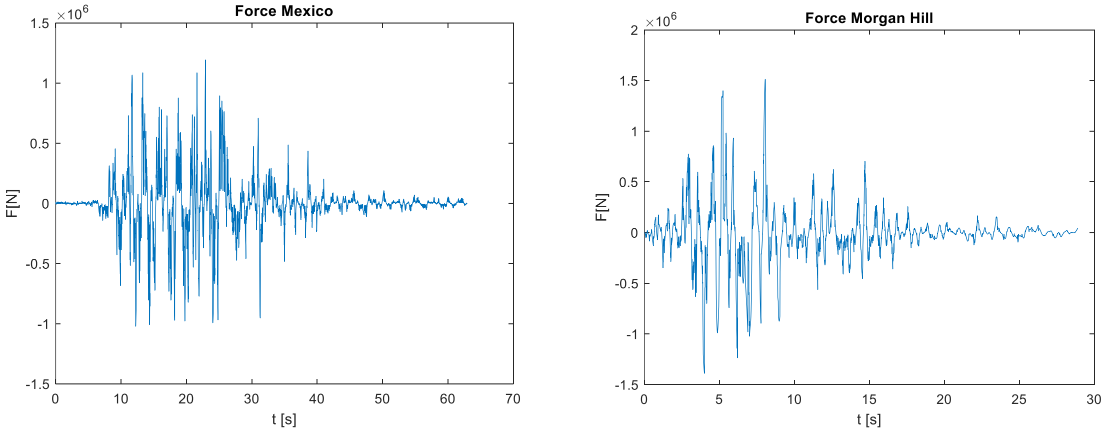


Figure 7: Force generated for each seismic record.

6 CONCLUSIONS

- Using fuzzy logic, the control forces are optimized to minimize the displacement and velocity induced by the seismic excitations. This methodology enables real-time modifications to the control forces, adapting to the fluctuating seismic conditions, leading to enhanced safety and performance of the structure. Incorporating fuzzy logic control for magnetorheological dampers in seismic design has the potential to greatly enhance the structural performance during earthquakes and provide a more efficient approach to mitigate the effects of seismic loads.

- The reduction in the system shows the effectiveness of the controller regulating the behavior of the system. By using the controller, the system has been able to achieve improved performance while ensuring that the maximum responses remain within acceptable limits. This is a clear indication that the controller has been successful in maintaining the stability of the system by limiting its response to external disturbances. As a result, the system can function reliably and predictably, and its performance can be optimized to meet the desired requirements.

- The ability of the damper to produce the necessary forces that keep a structure stable and balanced is dependent on the voltage, which serves as the driving force. Without the correct voltage, the damper would not be able to effectively regulate the structure, leading to potential instability and structural damage. Therefore, it is crucial to ensure that the right voltage is applied to the damper to guarantee its proper function and the safety of the structure.

- Effective control techniques are essential for optimizing the performance of dampers in various applications. When the structure faced with a maximum response with no control, it is necessary to apply the maximum voltage to the controller and implement advanced control algorithms to minimize displacement and velocity.

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