Semi-Active Control of Mixed Base Isolation System for a 5-Story Building

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Abstract. Earthquakes are disruptions to the movement of the ground resulting from the abrupt release of strain energy in the Earth's crust. The release of energy causes seismic waves, which cause vibrations in civil structures and potentially result in damage. Protecting structures against these unpredictable occurrences, this study employs a novel magnetorheological elastomer (MRE) mixed-base isolation system, integrated with a semi-active fuzzy logic control, to effectively mitigate vibrations in a 5-story building. The design of the isolator, combined with the adaptive control method, dramatically decreases the maximum displacement by 45% and the maximum acceleration by 13% when subjected to a scaled El Centro 1940 seismic wave. This balanced control illustrates the intriguing potential of the proposed system in improving the resilience of buildings and ensuring the comfort of occupants in the face of vibrations caused by earth-quakes.

Keywords: vibration control; fuzzy logic; mixed base isolator; magnetorheological elastomer; semi-active control.

1 Introduction

One of the most effective strategies for mitigating the impacts of seismic vibrations and safeguarding structures against danger is using base isolation techniques. Using passive isolation techniques in seismic engineering has been a familiar and somewhat effective practice [1,2]. However, there are several limitations associated with these systems. One limitation is their fixed frequency response. Passive systems are designed to dampen vibrations within a specific range of frequencies, which means they are effective within that range but less so outside of it, leaving buildings vulnerable to earthquakes with dominant frequencies that fall outside of the tuned range. Additionally, passive isolation systems have limited adaptability, meaning they cannot adjust their properties in real-time to respond to varying seismic intensities or dynamic changes in building response, resulting in insufficient damping during strong earthquakes or unnecessary stiffness during more minor events. To overcome these mentioned limitations of passive isolation systems, semi-active vibration absorbers emerge as a transformative alternative. Semi-active vibration absorbers show great promise as isolators, which

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can outperform other options when their mechanical characteristics are adjusted using a controller [3]. Semi-active isolators minimize vibrations in structures by adjusting their properties, such as stiffness and damping, in real-time. Controllable semi-active isolation systems possess a distinct capability to simultaneously decrease the acceleration and displacement of a structure [4]. Using other semi-active materials in isolation design also has its drawbacks, including slow response times, complex structural designs, and the potential for liquid leaks. However, an isolation system based on MRE offers a potential solution to overcome these challenges. MREs have been receiving considerable attention lately because of their ability to provide tunable rheological properties, quick response to magnetic fields, and ease of integration [5-7].

MRE is a type of intelligent material that changes its mechanical properties when subjected to an external magnetic field. This material consists of elastomers, a polymer known for their elastic properties. These elastomers are later mixed with ferrous particles or additives. When a magnetic field is present, the ferrous particles in the MRE align themselves with the field, which in turn influences the stiffness and damping properties of the elastomer. By adjusting the strength of the magnetic field, it is possible to control the stiffness and damping proper-ties [8,9]. Operating an MRE-based device without a controller can pose limitations. Introducing a controller is essential as it enables performance tuning by effectively reducing the transmission of shock or vibration to the structure in response to input vibrations. Various control strategies have been explored for MRE-based systems, such as optimal control, energy dissipation using discretized on-off control, skyhook techniques, and Lyapunov-based approaches.

The primary objective of this study is to highlight the effectiveness of a novel mixed-base MRE isolator system with fuzzy logic control to mitigate vibrations in a 5-story building. It specifically aims to reduce displacement and acceleration in a simulated seismic event. The theoretical analysis will offer valuable insights into the potential of MRE-based isolation systems to enhance buildings' seismic resilience, providing them with enhanced protection against vibrations caused by earthquakes. The study further validates the effectiveness of fuzzy logic control as a strategy for MRE isolators, emphasizing its adaptability to different seismic intensities and its ability to optimize vibration mitigation. The magnetic circuit of the isolators is also analyzed. A state-space equation is used to create a feedback control loop for the scaled building. The control parameters are fine-tuned by simulating the behavior of a scaled building under control.

2 Structural design of MRE vibration isolator

2.1 MRE Vibration Isolator Structure

The structural design of an MRE vibration isolator in this work involves several key components, each has an essential role in its overall performance. The electromagnetic coil generates a magnetic field when an electric current is applied. This field interacts with the MRE core, consisting of four vertical laminated MRE, four steel and one horizontal MRE, each 3mm, 3mm and 10mm thick respectively. the horizontal MRE core, protective shell, and upper and bottom plates contribute to the isolator's load-bearing capacity, as depicted in Figure 1.

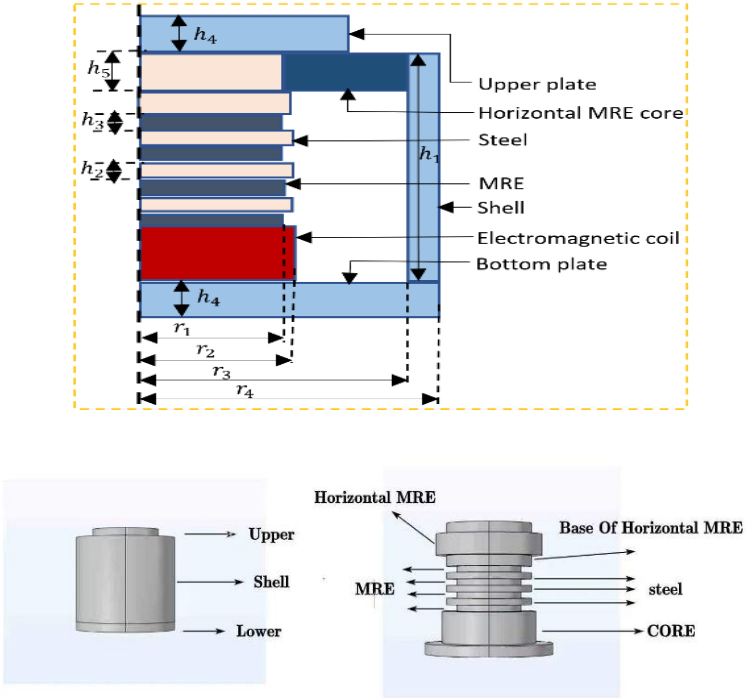


Fig. 1. Schematic and 3D model of vibration isolator

2.2 Electromagnetic Circuit Design of MRE Isolator

Designing the magnetic circuit for a magnetorheological isolator is vital to creating an efficient and effective device. The magnetic circuit is essential in generating the magnetic field required to alter the rheological properties of the MRE within the Isolator. To properly design an isolator magnetic circuit, the concept of Ohm's law for magnetic circuits is applied.

$$\sum \mathrm{NI} = \sum \Phi R_T, \qquad R_T = \frac{L}{\mu \mathrm{A}} \tag{1}$$

The formula includes the magnetic flux (Φ), the total resistance (R_T) in the magnetic circuit, which is determined by the magnetic path length (L), the permeability of the material (μ), and the cross-sectional area (A). The magnetic resistance at each part of the magnetic circuit in equation (1) is calculated using the formulae in equation (2) and the results depicted in table 1.

$$\begin{cases} R_1 = \dfrac{h_4}{\mu_0 \mu_1 \pi r_1} + \dfrac{1}{\mu_0 \mu_1 2\pi - h_4} \ln\left[\dfrac{r_4}{r_1}\right] \\ R_2 = \dfrac{h_1}{\mu_0 \mu_2 \pi (r_4^2 - r_3^2)} \\ R_3 = \dfrac{h_4}{\mu_0 \mu_3 \pi r_3^2} \\ R_4 = \dfrac{4h_3}{\mu_0 \mu_4 \pi r_1^2} + \dfrac{4h_2}{\mu_0 \mu_5 \pi r_2^2} \\ R_5 = \dfrac{h_5}{\mu_0 \mu_2 \pi r_1^2} + \dfrac{h_5}{\mu_0 \mu_4 \pi (r_3^2 - r_1^2)} \end{cases} \tag{2}$$

$$h_1 = 54mm, h_2 = h_3 = 3mm, h_4 = h_5 = 10mm$$

$$r_1 = 15mm, r_2 = 18mm, r_3 = 25mm, r_4 = 30mm$$

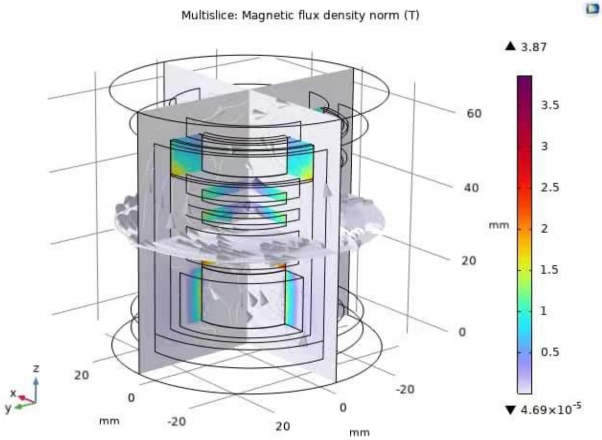
$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{N/A^2}, \mu_1 = \mu_2 = \mu_3 = 200, \mu_4 = 3.34$$

Table 1. Magnetic resistances in the circuit

Component	R_1	R_2	R_3	R_4	R_5
Resistance ($10^6\ A/Wb$)	0.100	0.248	0.020	4.092	1.952

$$\Phi = B_4 A_4 \quad F = NI = B_4 A_4 R_T = 2719.75 Amp - turns \tag{3}$$

Combining equations 1 – 3, and the magnetic saturation strength of MRE use is 0.6T, the number of coil turns N is calculated to be 1430 considering the 5% magnetic leakage phenomenon, and the maximum current value used in the coil is 2A. This study uses Comsol software to conduct magnetic field analysis on the vibration isolator. The electromagnetic field simulation results, as depicted in Figure 2, show the magnetic field intensity in the isolator when the applied current is 2A.



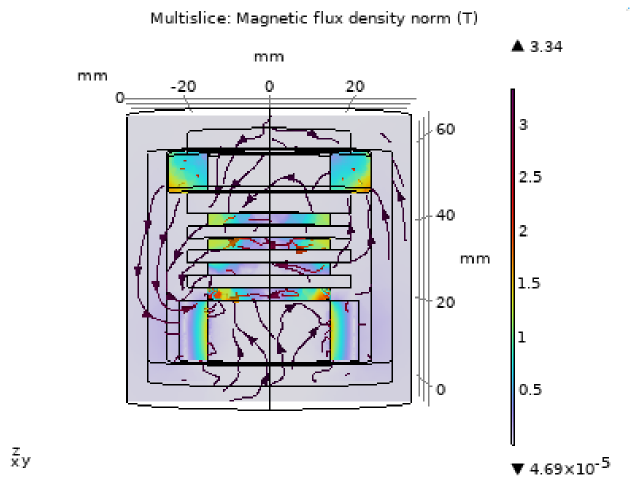


Fig. 2. Electromagnetic analysis of 2D and 3D magnetic flux density

3 Isolated building modelling and control system

3.1 Isolated Building Modelling

The equation of motion of controlled base isolated five degrees of freedom building subjected to a horizontal earthquake excitation (El Centro 1940) wave can be expressed as;

$$
\begin{aligned}
&m_1\ddot{x}_1 + c_2(\dot{x}_1 - \dot{x}_2) + k_2(x_1 - x_1) + c_1 x_1 + k_t(\mathrm{I})x_1 = -m_1\ddot{x}_g \\
&m_2\ddot{x}_2 - c_2(\dot{x}_1 - \dot{x}_2) - k_2(x_1 - x_1) + c_3(\dot{x}_2 - \dot{x}_3) + k_3(x_2 - x_3) = -m_2\ddot{x}_g \\
&m_3\ddot{x}_3 - c_3(\dot{x}_2 - \dot{x}_3) - k_3(x_2 - x_3) + c_4(\dot{x}_3 - \dot{x}_4) + k_4(x_3 - x_4) = -m_3\ddot{x}_g \\
&m_4\ddot{x}_4 - c_4(\dot{x}_3 - \dot{x}_4) - k_4(x_3 - x_4) + c_5(\dot{x}_4 - \dot{x}_5) + k_5(x_4 - x_5) = -m_4\ddot{x}_g \\
&m_5\ddot{x}_5 - c_5(\dot{x}_4 - \dot{x}_5) - k_5(x_4 - x_5) = -m_5\ddot{x}_g \\
&\mathrm{M}\ddot{x} + C\dot{x} + KX = -\mathrm{M}\ddot{x}_g
\end{aligned}
\tag{4}
$$

In the equation (4),

$$
M = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ & & \ddots & \\ 0 & 0 & 0 & m_n \end{bmatrix}
\qquad
C = \begin{bmatrix} c_0 + c_1; -c_1; & & & \\ & -c_1; c_1 + c_2; -c_2; & & \\ & \ddots & \ddots & \ddots \\ & & & -c_{n-1}; c_{n-1} + kc_n; -c_n \\ & & -c_n; & c_n \end{bmatrix}
$$

$$K = \begin{bmatrix} k_0 + k_1; -k_1; & & & & \\ & -k_1; k_1 + k_2; -k_2; & & & \\ & \ddots & \ddots & \ddots & \\ & & & -k_{n-1}; k_{n-1} + k_n; -k_n & \\ & & & -k_n; & k_n \end{bmatrix}$$

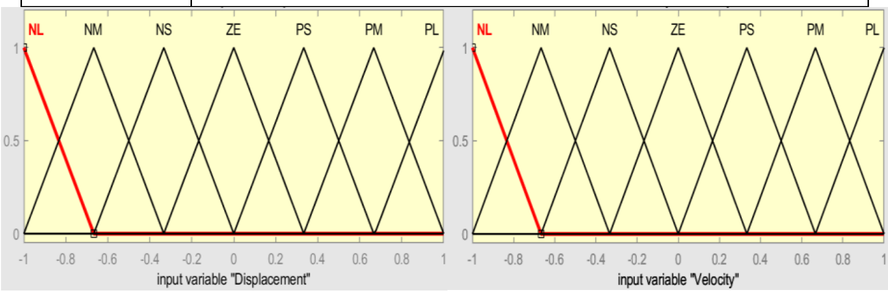
Floors mass is represented by m_i, x_i represents the displacement of the floors from the ground. The damping and stiffness coefficients are denoted as c_i and k_i respectively, the isolators have current-dependent damping and stiffness coefficients $C_t(I)$ and $k_t(I)$ respectively, $\ddot{x}_g$ is the ground acceleration, representing the horizontal movement of the ground during an earthquake.

3.2 Fuzzy Logic Control

The study uses IF-THEN rules to establish a connection between the input and output. The linguistic parameters shown in Table 2 are transformed into numerical values by defuzzification. The input parameters for the system design are the displacement, which measures the deviation of each floor from its equilibrium position, and the velocity, which measures the rate of change of building relative displacement. Both input parameters have fuzzy domains of [-1, 1]. The output parameter is the voltage supplied to the isolator, which has a domain of [0, 1]. Triangular membership functions are utilized for both the input and output parameters, as shown in Figure 3.

Table 2. Semi-active fuzzy rules

	Velocity						
Displacement	NB	NM	NS	ZO	PS	PM	PL
NB	PL	PM	PM	PS	PS	ZO	NM
NM	PM	PS	PS	ZO	PM	NM	NM
NS	PS	PS	ZO	PM	NM	NM	NM
ZE	ZE	ZE	PM	PS	PM	NM	NM
PS	PS	PM	NM	NM	NM	NM	NM
PM	NM	NM	NM	NM	NM	NM	NB
PL	NB	NM	NM	NM	NM	NB	NB



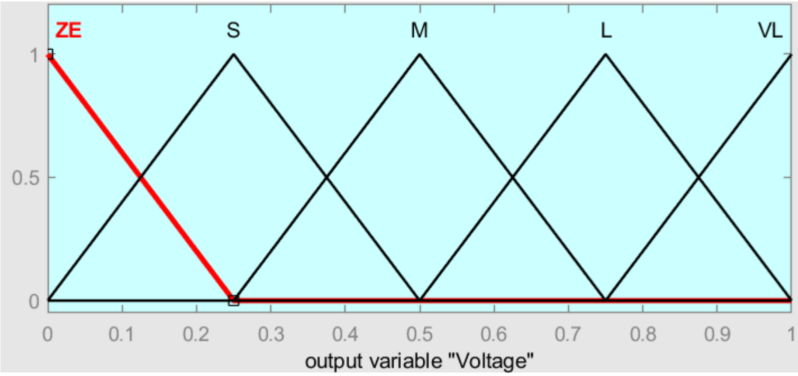


Fig. 3. Input and output variable membership functions

3.3 Simulation Results and Analysis

The analysis was carried out on scaled El Centro 1940 seismic wave of magnitude of 7 as an input comparing the effect of semi-active isolator fuzzy logic control and uncontrolled scenarios on displacement and acceleration of the floors, utilizing parameters in Table 3.

Table 3. Simulation parameters

Floor Mass [kg]	Stiffness coefficient [kN/m]	Damping coefficient [kNs/m]
$m_b = 6700$	$k_b = 323$	$c_b = 7.45$
$m_1 = 5897$	$k_1 = 33732$	$c_1 = 67$
$m_2 = 5897$	$k_2 = 29093$	$c_2 = 58$
$m_3 = 5897$	$k_3 = 28624$	$c_3 = 57$
$m_4 = 5897$	$k_4 = 24954$	$c_4 = 50$
$m_5 = 5897$	$k_5 = 19059$	$c_5 = 38$

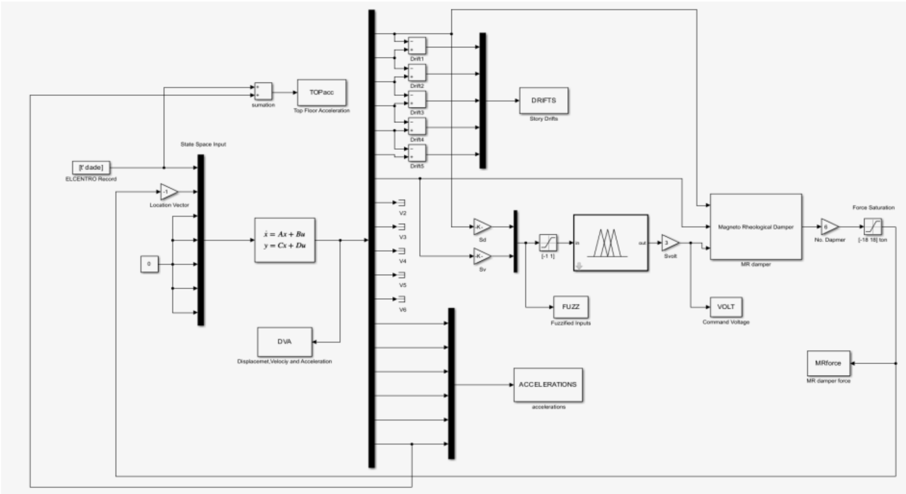
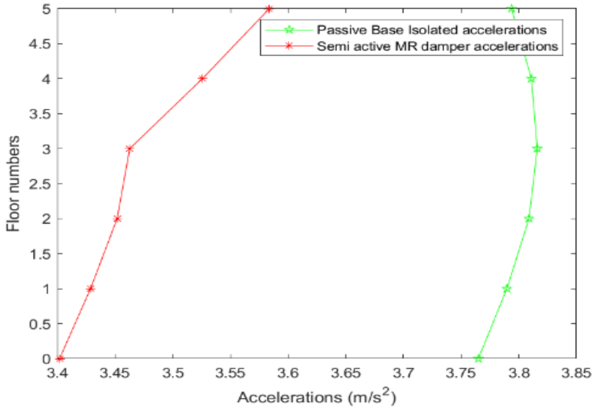


Fig. 4. Simulink model of semi-active MRE mixed base Isolator

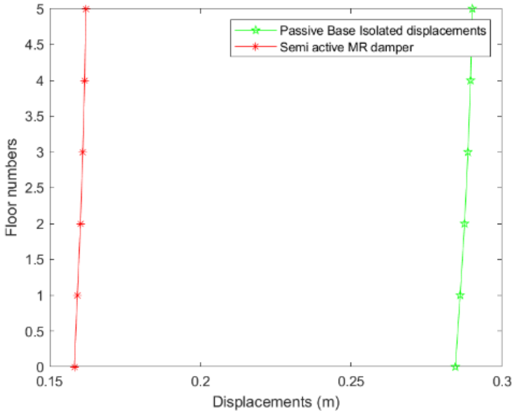
A SIMULINK model and MATLAB code are used to implement the state-space equations of the building simulation, as shown in Figure 4. An analysis of displacements and accelerations of the first and top floors is used to evaluate the effectiveness of the controlled MRE isolator. As depicted in Figure 5 – 6 and table 4, implementing the fuzzy logic controller significantly reduced peak displacement on both the first and top floors. The decrease corresponded to 45% and 42% for the respective floors. On the other hand, the controller also reduced the maximum acceleration on both floors. There was a 9% decrease on the first floor, while the top floor experienced a reduction of 13% (from 3.79 to 3.29), when combined with a fuzzy controller, the isolator successfully achieved a well-balanced distribution of vibration control benefits between the two floors.

Table 4. Displacement and acceleration simulation results

Floor	Uncontrolled Displacement (m)	Controlled Displacement (m)	Uncontrolled Acceleration (m/s^2)	Controlled Acceleration (m/s^2)
First floor	0.284	0.157	3.789	3.421
Top floor	0.292	0.162	3.797	3.293

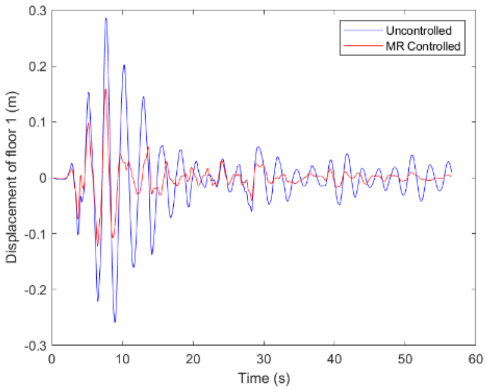


(a)Accelerations

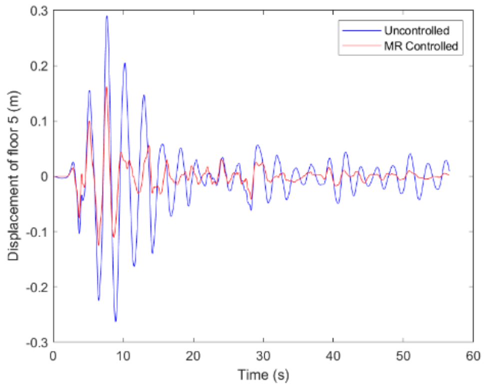


(b) Displacements

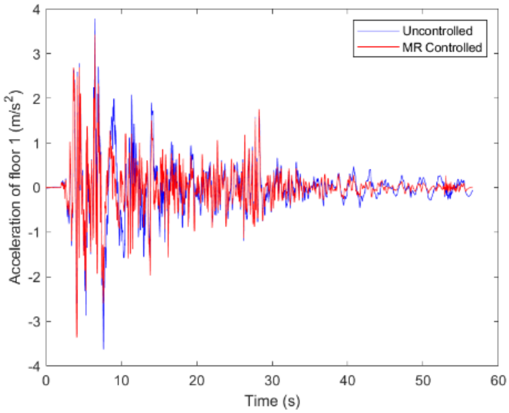
Fig. 5. Floors (a) Accelerations and (b) Displacements in Passive and semi-active mode



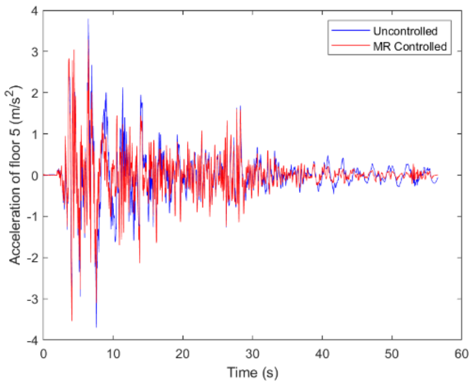
(a)first floor displacement



(b) fifth floor displacement



(c) first floor acceleration



(d) fifth floor acceleration

Fig. 6. Structure Controlled and Uncontrolled

4 Conclusion

The outcomes of this study demonstrate the effectiveness of a novel mixed-base MRE isolator system with fuzzy logic control in mitigating vibrations in a 5-story building. Through extensive analysis and evaluation, it was observed that the system successfully minimized the maximum displacement and acceleration of both the first floor and the top floor. The maximum displacement of the first floor decreased by 45%, from 0.284 to 0.157, while the top floor experienced a decrease of 42%, from 0.292 to 0.162. Additionally, the maximum acceleration of the first floor decreased from 3.789 to 3.421, representing a 9% decrease, and the top floor acceleration decreased from 3.797 to 3.293, representing a 13% decrease during a simulated seismic event demonstrating its capacity to enhance the resilience of structures against earthquake-induced vibrations. The fuzzy logic controller, in combination with the mixed-base MRE isolators, resulted in a comprehensive control performance that successfully addressed displacement and acceleration concerns. However, it is essential to conduct additional optimization and experiments to validate the controller and enhance its performance in different scenarios, thus ensuring its practical feasibility.

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