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Semi-active structural vibration control with magnetorheological damper based on hybrid fuzzy sliding mode controller

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ABSTRACT

Recently, structural vibration control has proved its capacity to save lives and keep structures safe during earthquakes. Furthermore, there is a wealth of research in both numerical and experimental studies. As a result, due to its simplicity and performance in mitigating structural vibrations generated by ground motions, semi-active control played a significant role in the majority of these studies. Nonetheless, the magnetorheological damper is the most often used semi-active device. In particular, the rheological fluid properties have gained adequate attention in earthquake energy dissipation and structural vibrations management, particularly in the civil engineering field. The semi-active control of three scaled excited structures is addressed in this study. A magnetorheological damper operated by a hybrid fuzzy sliding mode controller ensures the proposed control. However, to provide the appropriate current for the damper to operate, this proposed intelligent controller is combined with a clipped optimum algorithm. Otherwise, the numerical simulation results of the seismic excited scaled structure demonstrate the resilience of the suggested controller. As a result, four time-scaled seismic data are applied to the tested structure. Finally, the usefulness of the suggested semi-active control technique in mitigating earthquake structural vibration is demonstrated clearly in the compared controlled and uncontrolled responses.

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1. INTRODUCTION

Recently, the semi-active control technique has grown in importance in the field of civil structural engineering. Several academics conducted numerical and/or experimental analyses on the semi-active method. The semi-active control strategy is seen as a hybrid of the passive and active control systems. In general, the semi-active system's damping system operates like a passive system. In contrast, the regulated forces are generated based on real-time tracking of the structure's responses in loop control. Furthermore, semi-active devices are simple to build and install on structures, are fail-safe and reliable, and can generate the needed forces in real-time excitations without requiring a large external energy source. However, when compared to active devices, these devices have a restricted control capacity. Several investigations and characterizations have been conducted on magnetorheological dampers and electrorheological dampers, two types of semi-active control devices [1]–[4].

Semi-active control systems have been widely deployed in a variety of structures around the world and have been the topic of several examinations and studies over the last several decades. Otherwise, the performance of the semi-active control method is heavily influenced by the controller type rather than the device. As a result, the entire control system was dependent on performance to track the expected response of the regulated system. As a result, numerous controllers were investigated numerically and experimentally. These controllers are classified into two types based on whether a mathematical model is required or not. However, classical controllers require mathematical modeling as well as stability testing [5]. The intelligent controllers class, on the other hand, can easily operate without the need for a mathematical model [6]. Nonetheless, another class that is a blend of the two cited classes is known as the hybrid controller [7].

Significant efforts have been made over the last few decades to develop and propose control algorithms for large-scale semi-active controlled structures subjected to dynamic loads. Furthermore, linear controllers have risen to prominence in the field of structural civil engineering control. Several academics were drawn to the simplicity with which these controllers may be designed, as well as their stability and time convergence in linear instances. A linear-quadratic regulation (LQR) damper was created to mitigate structural vibrations of a three-story scaled stimulated structure. The tested structure was subjected to the El Centro 1940 earthquake, and the simulation results demonstrate the linear controller's effectiveness [8]. Furthermore, the proportional integral derivative (PID) controller was studied experimentally. The controller was created to regulate a two-story scaled building via an active mass damper that was subjected to an earthquake signal. The experimental results achieved using PID controllers were compared to the results obtained with an uncontrolled structure [9].

These linear controllers, on the other hand, are heavily influenced by uncertainties or changes in the external state. Otherwise, the controller mathematical model must be insensitive to disturbance effects in numerous complex instances. In the presence of uncertainty and disturbances, nonlinear controllers are clearly the most robust controllers. Nonetheless, the controller must not only be resilient under a variety of dynamic situations, but it must also exhibit excellent stability, performance, and ease of use. However, in the structural vibrations control under dynamic loading, a sliding mode controller was numerically studied. The controller was created to control an active mass damper for vibration suppression in a three-story scaled building aroused by the Mexico City 1995 earthquake time scale. The boundary layer approach, which replaces the signum function with the saturation function, was utilized to avoid the chattering generated by the signum function [10]. A backstepping controller with a magnetorheological (MR) damper was proposed to regulate a three-story scaled building. The viability of backstepping control was investigated using numerical simulations and tests that compared the results of controlled and uncontrolled structural responses [11].

The majority of civil engineering systems are complex systems with nonlinearities and uncertainties, and the mathematical model characterizing the system is challenging to formulate. Intelligent controllers are the most practical controllers for these circumstances since they do not require a mathematical model to represent the dynamic system. To regulate two numerical examples, a neural network controller trained on the LQR controller was proposed. The first was a simple one-degree-of-freedom construction, and the second was a twelve-story tower. El Centro 1940 earthquake acceleration signal was used to excite the two structures. The effectiveness of the suggested controller, on the other hand, is proved by numerical simulation results of the neural network control vs the original LQR control [12].

The hybrid controller, on the other hand, integrated two or more controller algorithms in which the advantages are combined, yielding a performed resultant controller. The PID control was built to track the sliding surface of the sliding mode controller in order to control an electromechanical motor experimentally. The proposed hybrid controller shown superior tracking performance, robustness in the face of uncertainties, and chattering problem overcoming in the experimental findings. The suggested PID sliding mode controller demonstrated outstanding stability during the reaching and sliding phases, and the findings demonstrated the effectiveness of this hybrid control when compared to regular PID control [13].

In this article, a hybrid fuzzy sliding mode controller is suggested to control a magnetorheological damper. The current driver is controlled by a clipped optimal algorithm. This semi-active control is designed to reduce undesirable structural vibrations under the Boumerdès 2003 earthquake excitations. The tested structure is a three-story scaled structure, and MATLAB/Simulink was used to generate the findings of the numerical simulation. The effectiveness of the suggested semi-active control is demonstrated by comparing the numerical simulation results of the controlled and uncontrolled structure responses.

2. MAGNETORHEOLOGICAL DAMPER MODELING

Figure 1 depicts a magnetorheological damper, which is one of the most promising semi-active control systems. This apparatus piqued the curiosity of multiple researchers and became the topic of numerous studies and researches. Because of its ease of installation on the structure, normal operation in high gap temperature intervals, and fast response in milliseconds. Several mathematical models characterizing the nonlinear behavior of the magnetorheological damper in the presence of a magnetic field have been presented over the last few decades [14]. Starting with Bingham's simple quasi-static model proposed in 1916 [15], we progress to the augmented Bouc-Wen hysteresis model shown in Figure 2 [16].

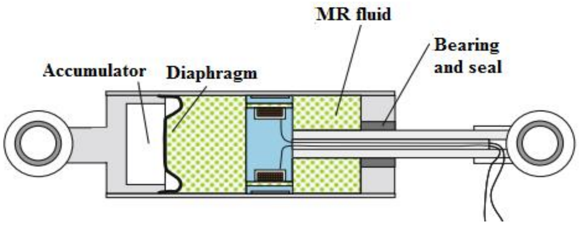

Figure 1. Schematic of the MR damper

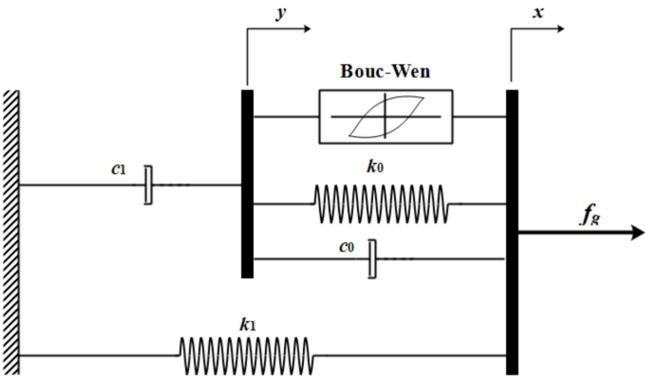

Figure 2. Mechanical model of MR damper

The mathematical model is presented as (1) to (3).

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

$$\dot{y} = \frac{1}{c_0+c_1}[\alpha z + c_0\dot{x} + k_0(x - y)]) \tag{2}$$

$$f_g = c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) + \alpha z) \tag{3}$$

In (1) to (3), x is the displacement of the damper, $\dot{x}$ is the velocity of the damper, f_g is the generated force of the damper, z is the hysteretic component of the damper, k_0 and k_1 are the accumulator stiffness at low and high velocity, c_0 and c_1 are the viscous damping at low and high velocity, γ, β, n, and A are parameters related to the shape loop and the parameters depending on the applied voltage are expressed as (4) to (7),

$$\alpha = \alpha_a + \alpha_b u) \tag{4}$$

$$c_1 = c_{1a} + c_{1b}u \tag{5}$$

$$c_0 = c_{0a} + c_{0b}u \tag{6}$$

$$\dot{u} = -\eta(u - v) \tag{7}$$

where u is the command input phenomenological variable, v is the command voltage applied to damper, and η is the first order filter time constant of the model.

These parameters are defined as [16]: $c_{0a} = 21\ \mathrm{N \cdot s/cm}$; $c_{0b} = 3.5\ \mathrm{N \cdot s/cm}$; $k_1 = 5\ \mathrm{N/cm}$; $k_0 = 46.9\ \mathrm{N/cm}$; $\alpha_a = 140\ \mathrm{N/cm}$; $\alpha_b = 695\ N/cm$; $c_{1a} = 283\ N \cdot s/cm$; $c_{1b} = 2.95\ N \cdot s/cm$; $A = 301$;

$\gamma = 363\ cm^{-2}$; $n = 2$; $\beta = 363\ cm^{-2}$; $\eta = 190\ s^{-1}$; $x_0 = 14.3\ cm$. The MR damper augmented Bouc-Wen model is simulated under a sinusoidal excitation of 2.5Hz frequency and amplitude of 1.5 cm with different voltage levels (0, 0.5, 1 and 1.25 V). As a result, Figure 3 shows the mechanical model for the MR damper's hysteresis behavior.

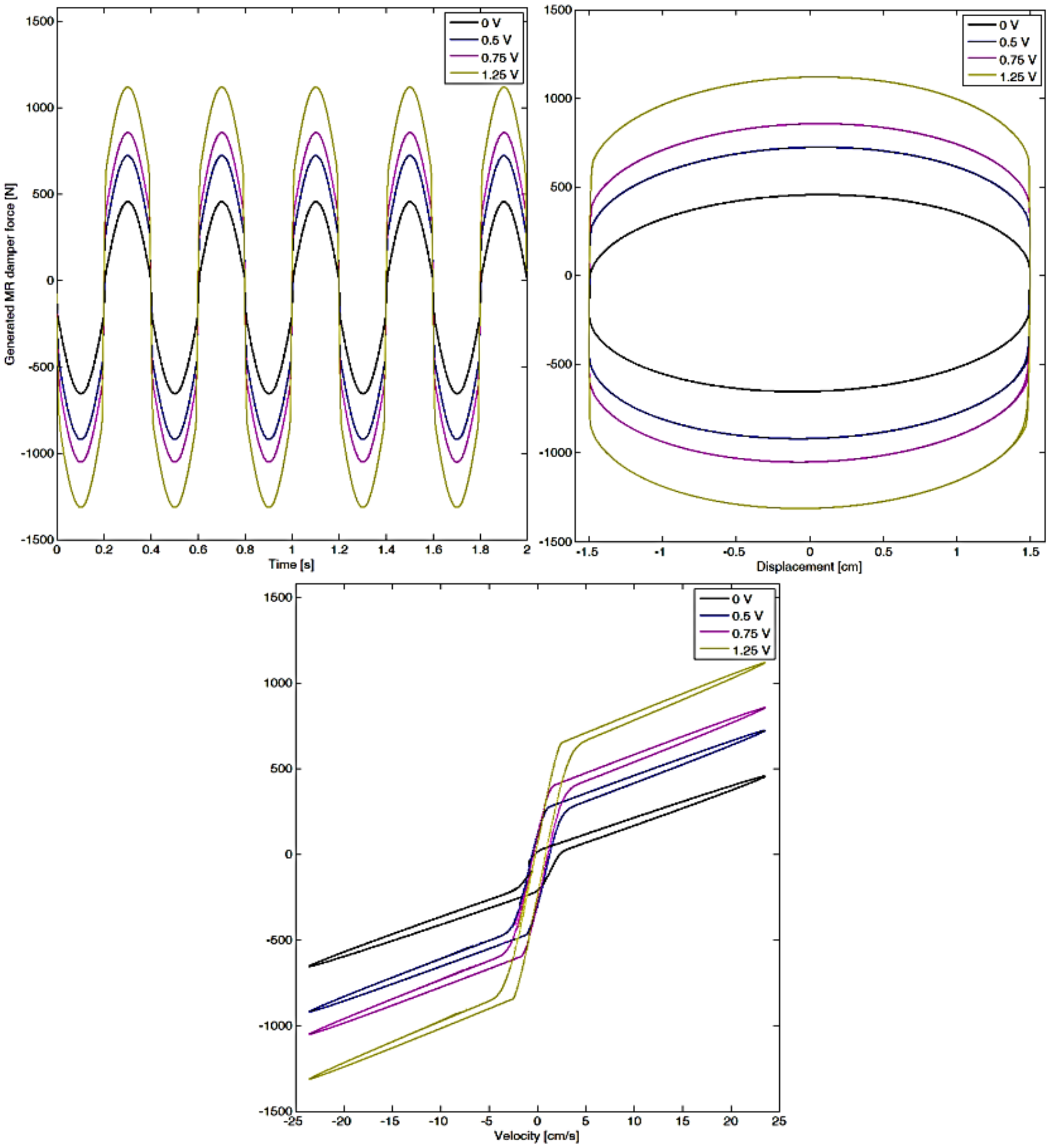

Figure 3. Force-time, force-displacement, and force-velocity relationships for the MR damper with different voltage levels

The semi-active device needs a magnetic field to generate the desired force of control. Thus, the control system needs another algorithm to calculate this required applied voltage. Despite the existence of many different current driver algorithms, the clipped optimal algorithm proposed to drive the desired current to the magnetorheological damper governed by (8).

$$v = v_{max} H\{(f_d - f_g) f_g\} \tag{8}$$

$H\{.\}$ designed the Heaviside step function, v_{max} the maximum applied voltage, f_g and f_d are the force generated by the magnetorheological damper and the force calculated by the hybrid controller.

3. THE FUZZY SLIDING MODE CONTROLLER

Recently, the nonlinear controllers of dynamic systems modeling uncertainties and external disturbances with condition variations have gained considerable attention. However, the sliding mode controller (SMC) is one of the robust and popular nonlinear controllers widely used in civil engineering structural control. The main objective of the sliding mode controller is to force the system error's to reach the sliding surface and keep it moving on to the desired state.

Let suppose the dynamic system presented as (9),

$$\dot{x} = f(x.t) + b(x,t)u \tag{9}$$

where x is the stat vector, $f(x,t)$ and $b(x,t)$ are the smooth vector fields and u is the system input which the control force.

The control objective is that the tracking error $e(t)$ should converge to zero and reach the sliding surface defined by (10),

$$S(t) = G^T e \tag{10}$$

where G is the sliding surface switching vector. The stability of the system (9) is satisfied using the Lyapunov stability theorem as (11).

$$S \cdot \dot{S} < 0 \tag{11}$$

The solution is given by the two components,

$$u = u_{eq} + u_s \tag{12}$$

where u_{eq} is the equivalent solution and u_s is the switch solution given by (13) and (14),

$$u_{eq}(x,t) = -\big(S(t)b(x,t)\big)^{-1} S(t)f(x,t) \tag{13}$$

$$u_s = M \cdot \operatorname{sgn}(S) \tag{14}$$

where M is the control gain and $sgn(\cdot)$ is the signum function,

$$\operatorname{sgn}(S) = \begin{cases} -1 & \text{if } \ S < 0 \\ 0 & \text{if } \ S = 0 \\ 1 & \text{if } \ S > 0 \end{cases} \tag{15}$$

Otherwise, the function defined in (15) caused the Chattering problem, an oscillation with a finite frequency and amplitude. This problem affected the stability of the whole system in the presence of unwanted frequency signals in the output responses [17]. However, to overcome this drawback, several techniques and solutions were proposed and investigated. In where the basic criterion is ensured a sufficient width of the boundary layer guarantying the attractiveness of the controller on it. One of the techniques chattering suppress is the combined fuzzy logic sliding mode control. This hybrid controller combined the advantages of the two controllers and offered better performance and stability in structural vibration control. It is commonly known that the disadvantage of the sliding mode control is the chattering phenomenon induced by the infinite frequency of the signum function. The widely used solution to this problem based on the boundary layer around the switch surface idea and (15) is given by (16) and (17),

$$u_s = M \cdot \operatorname{sat}\left({S}/{\xi}\right) \tag{16}$$

$$\operatorname{sat}\left({S}/{\xi}\right) = \begin{cases} {S}/{\xi} & \left|{S}/{\xi}\right| \le \xi \\ \operatorname{sgn}\left({S}/{\xi}\right) & \left|{S}/{\xi}\right| > \xi \end{cases} \tag{17}$$

where the constant factor ξ defines the boundary layer thickness and sat(·) is the saturation function.

However, there exists a design conflict between the requirement on control performances and accuracy and the smoothness of the control signals thus the chattering suppression. For this reason, the boundary layer width should be chosen in order to obtain a good compromise between sliding mode robustness and chattering elimination or reduction. In general, to have a good tracking performance we can use a small boundary layer thickness, but this choice will increase the chattering problem. In the other hand, introducing a greater boundary layer thickness alleviates the chattering phenomenon and can provide a smoother control signal.

In this study, a fuzzy sliding surface is presented to perform the sliding mode controller and overcome the chattering problem, where a fuzzy system mechanism replace (16). This approach proves that a fuzzy controller is an extension of an SMC with if-then rules constructed as [18].

Rule 1: If S is BN, then u_s is bigger.
Rule 2: If S is MN, then u_s is big.
Rule 3: If S is ZE, then u_s is medium.
Rule 4: If S is MP, then u_s is small.
Rule 5: If S is BP, then u_s is smaller.

BN is big negative, MN is medium negative, ZE is zero, MP is medium positive, and BP is big positive. In Figure 4, membership functions for the output variable are illustrated. The defuzzied output u_s for a fuzzy input S is shown clearly in Figure 5.

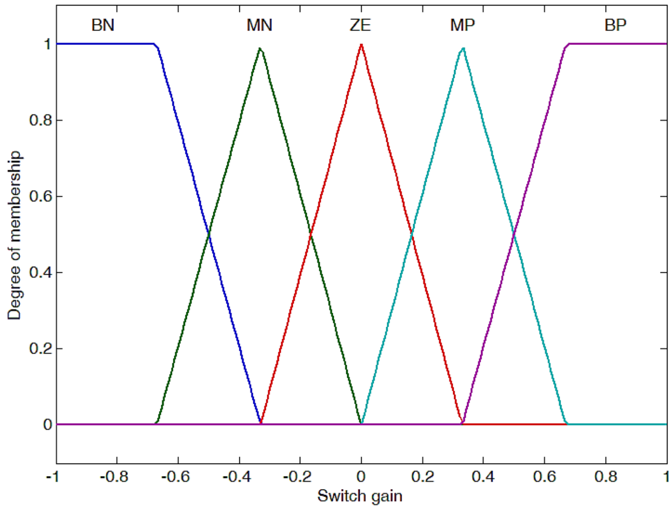

Figure 4. Membership functions for the input variable

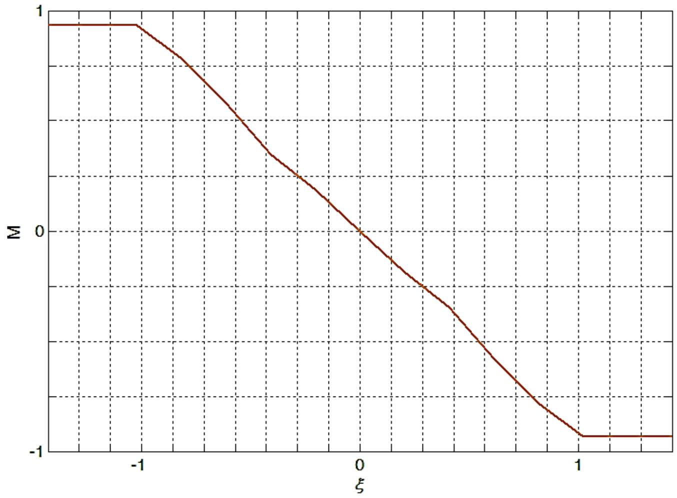

Figure 5. The switch control action of the fuzzy sliding mode controller

This is to control the structural vibrations and reduce the displacements of the switch part of the control force given by the fuzzy logic controller output and the equivalent part of control given by the sliding mode controller output is appended to assure the required force of control. Therefore, the proposed hybrid control is shown in Figure 6.

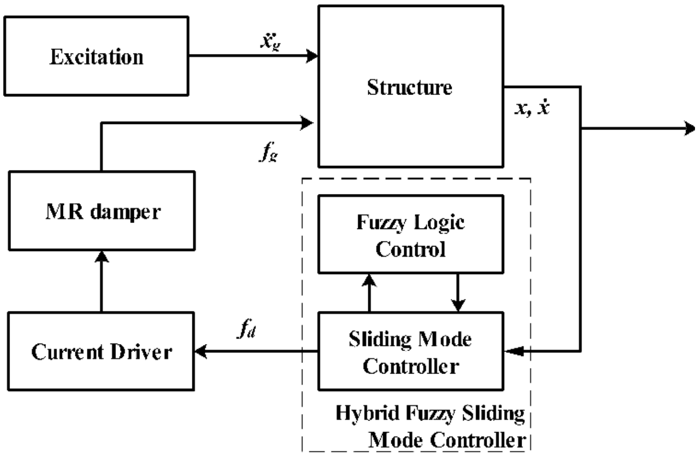

Figure 6. Block diagram of the proposed semi-active fuzzy sliding mode control strategy

4. NUMERICAL SIMULATION

The numerical simulation example of three scaled structures with an MR damper installed on the first floor is presented in Figure 4. The mathematical presentation of the building structure subjected to the horizontal component of the 1990 Manjil, the 1995 Kobe, the 2003 Boumerdès, and the 2011 Tohoku earthquakes excitations $\ddot{x}_g$ shown in Figure 7 is written as (18).

$$M_s\ddot{x} + C_s\dot{x} + K_s x = M_s\Lambda\ddot{x}_g + \Gamma f_g \tag{18}$$

In (18), x is the displacement vectors of the floor, $\dot{x}$ is the velocity, and $\ddot{x}$, is the acceleration; f_g is the generated MR damper control force, Γ and Λ are respectively the MR damper's position vector and the earthquake acceleration effect vector's defined as (19) and (20).

$$\Gamma = [-1 \quad 0 \quad 0]^T \tag{19}$$

$$\Lambda = [1 \quad 1 \quad 1]^T \tag{20}$$

The specifications of the four North-South earthquake records are listed in Table 1. However, in the numerical simulation, the earthquakes are time scaled.

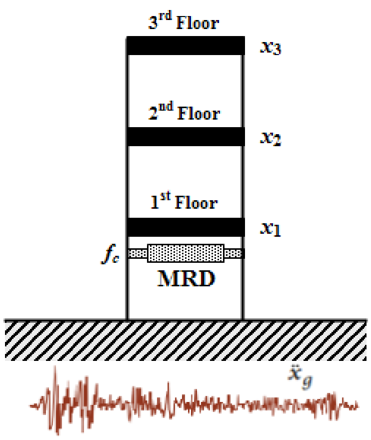

Figure 7. The three-story scaled structure model

Table 1. Specifications of the earthquakes N-S components used in the numerical example

Earthquake	Location	Station	Magnitude	PGD (cm/s)	PGV (cm/s^2)	PGA (g)
Manjil 1990	Iran	Ab Bar	7.4 Mw	21.34	12.84	0.53
Kobe 1996	Japan	Nishi-Akashi	6.9 Mw	7.05	4.04	0.50
Boumerdès 2003	Algeria	Dar El-Beida	6.8 Mw	3.27	4.53	0.35
Tohoku 2011	Japan	Oshika	9.1 Mw	12.75	14.85	2.58

However, M_s, C_s, and K_s are the mass, damping, and stiffness matrix of the structure defined as [6]. The numerical simulation results of the structure responses are cared out using MATLAB/Simulink. The proposed hybrid fuzzy sliding mode controller is evaluated and assessed. Moreover, the semi-active strategy performance is proven by the compared displacement responses of the controlled and uncontrolled structure.

$$[M_s] = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} Kg$$

$$[K_s] = \begin{bmatrix} 12 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \times 10^5 \; N/m$$

$$[C_s] = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} N \cdot sec$$

Thus, the compared time history displacement responses of the uncontrolled and hybrid-controlled structures of the first to the third floors under the 1990 Manjil, the 1995 Kobe, the 2003 Boumerdès, and the 2011 Tohoku earthquakes excitations are presented respectively in Figures 8 to 11. Moreover, the peak floors displacement comparison of the controlled and uncontrolled cases under the four earthquakes are depicted in Figure 12.

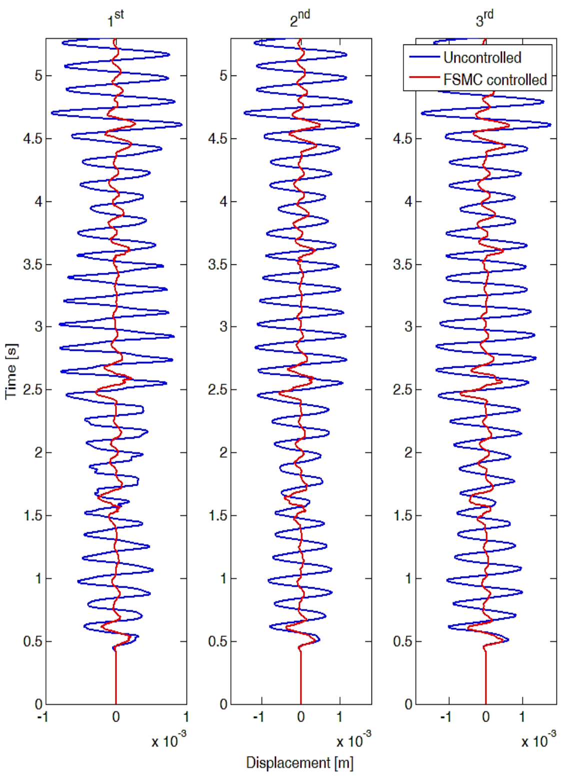

Figure 8. Time history of floors displacement under the 1990 Manjil earthquake excitation

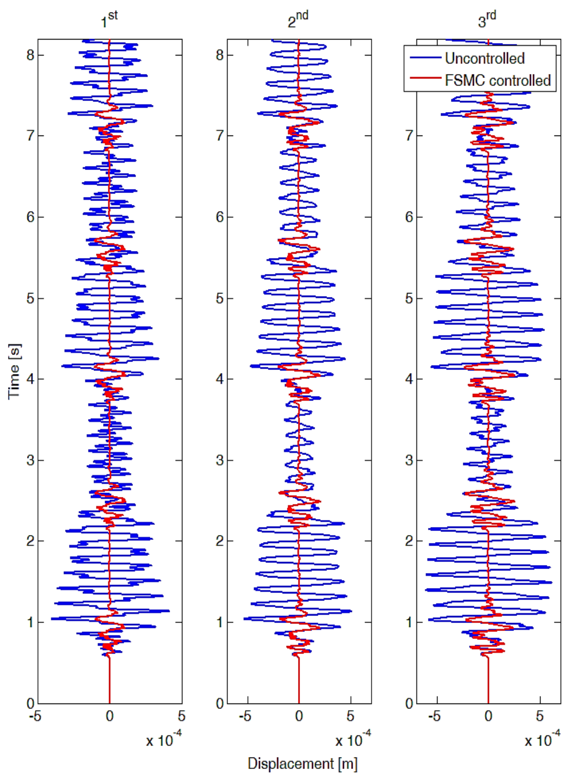

Figure 9. Time history of floors displacement under the 1995 Kobe earthquake excitation

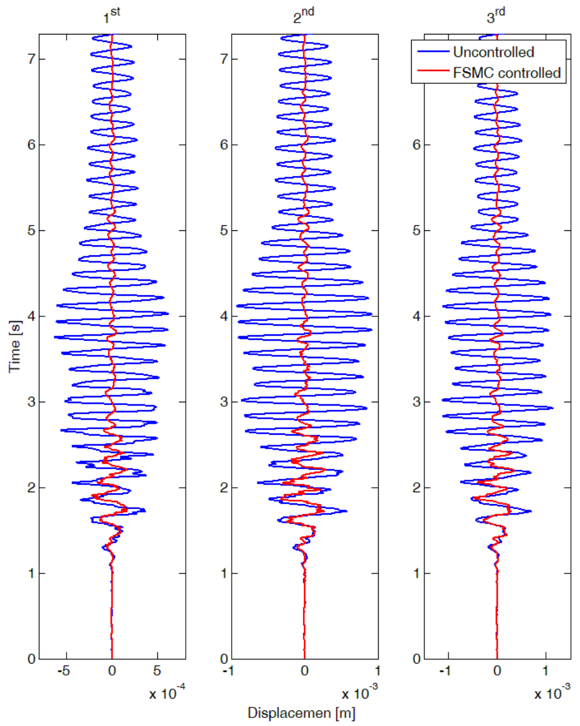

Figure 10. Time history of floors displacement under the 2003 Boumerdès earthquake excitation

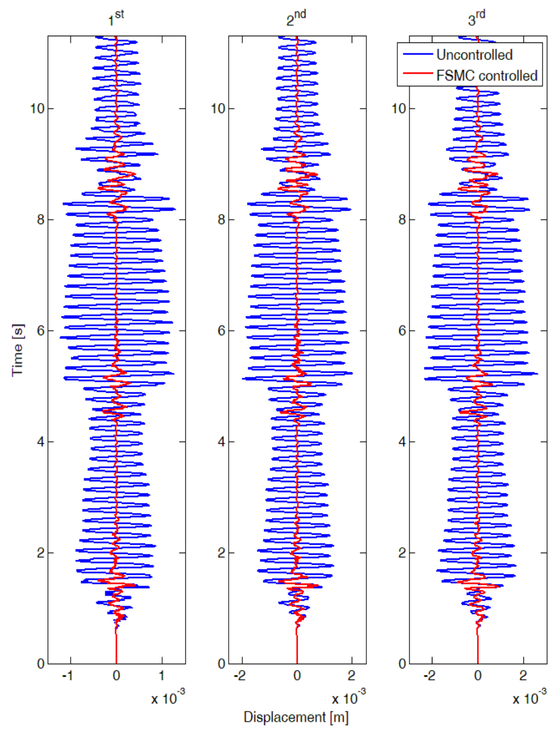

Figure 11. Time history of floors displacement under the 2011 Tohoku earthquake excitation

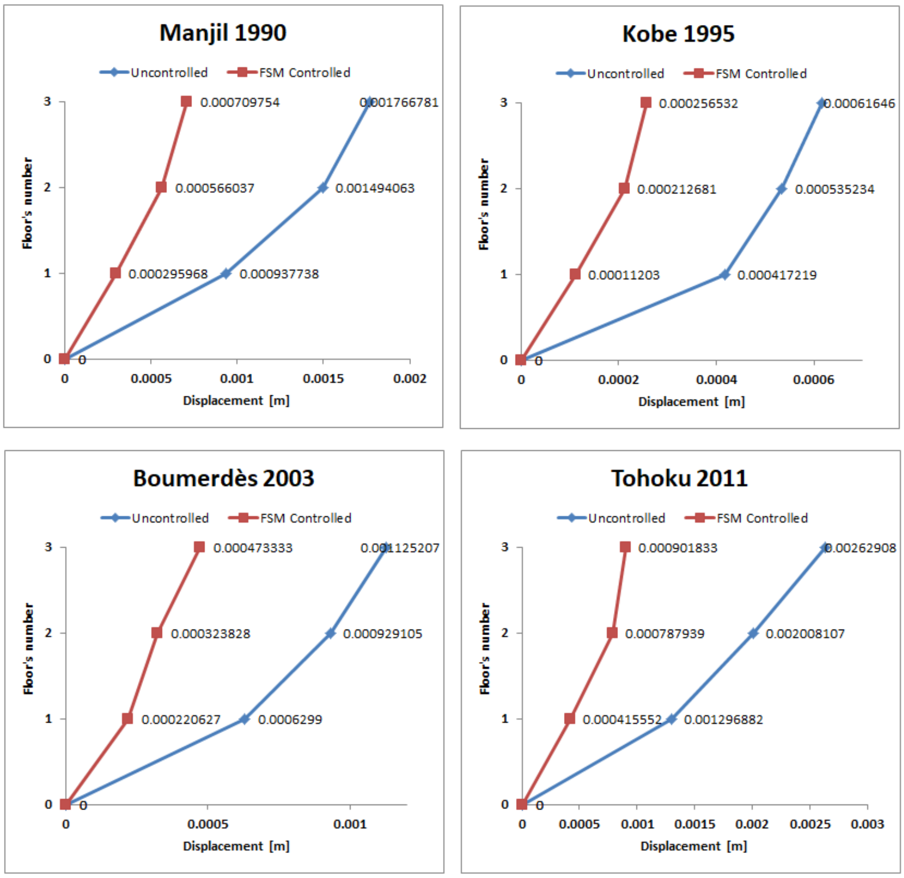

Figure 12. The peak floors displacement under the different earthquakes excitations

The effectivity of the suggested hybrid semi-active control strategy is evaluated using the peak floor displacement reduction. The peak floor displacement reduction values are calculated under each earthquake load and listed in Table 2. Thereby, under the 1990 Manjil, the 1995 Kobe, the 2003 Boumerdès, and the 2011 Tohoku earthquakes, the peak reduction of each floor given in Table 2 shows the robustness of the semi-active control strategy.

Table 2. Peak floors' displacement reduction under the different earthquakes excitations

Earthquakes	Peak reduction of floors		
	1^{st}	2^{nd}	3^{rd}
Manjil 1990	68.44%	62.11%	59.83%
Kobe 1995	73.15%	60.26%	58.39%
Boumerdès 2003	64.97%	65.15%	57.93%
Tohoku 2011	67.96%	60.76%	65.70%

Table 3 proved the effectiveness of the MR damper controlled using a hybrid fuzzy sliding mode controller. The calculated evaluation indices proved the performance of the suggested hybrid controller to perform the structural vibrations control under earthquake excitations. J_1, J_2, J_3, and J_4 are respectively the peak inter-story drift ratio, the level acceleration, the level base shear, and the normed inter-story drift ratio. J_5, J_6, and J_7 are respectively the normed acceleration, the normed base shear, and the peak control force. Moreover, the indices J_8 and J_9 are the control device stroke and the normed control power.

Table 3. Indices of evaluation under the different earthquakes excitations

Earthquakes	J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8	J_9
Manjil 1990	0.798	0.991	0.098	0.501	0.506	0.056	0.030	0.403	0.0013
Kobe 1995	0.431	1.072	0.101	0.421	1.019	0.088	0.029	0.403	0.0015
Boumerdès 2003	0.503	1.141	0.102	0.545	1.028	0.083	0.024	0.444	0.0019
Tohoku 2011	0.575	1.127	0.100	0.615	1.063	0.100	0.130	0.447	0.0002

5. CONCLUSION

The hybrid fuzzy sliding mode controller based on the fuzzification of the switching term of the sliding mode controller is investigated to control structural vibrations of an excited scaled structure. The effectiveness of the controller is measured through consideration of the evaluation indices under the 1990 Manjil, the 1995 Kobe, the 2003 Boumerdès, and the 2011 Tohoku earthquakes. The compared numerical simulation results of the uncontrolled and the controlled structure are shown also as the performance of the proposed semi-active control strategy. Thus, the following can be concluded: i) the hybridization of the sliding mode controller using a fuzzy logic controller offered more stability and robustness to the classical controller without affecting the robustness of the control; ii) the numerical simulation comparison results of the two cases uncontrolled structure and hybrid semi-active controlled structure shows clearly the reduction in the displacement responses in the three floors under the four earthquakes; iii) the proposed strategy ensures efficiency of peak reduction in each floor of the structure. The peak reduction attains 73% on the first floor and 65% on the second and third ones; iv) the value of the indices J1, J2, J3, J4, J5, and J6 proves the effectivity of the suggested control strategy to perform the structure responses; v) the performance of the semi-active device behavior is evaluated and justified by the three indices value J7, J8, and J9 under each of the 1990 Manjil, the 1995 Kobe, the 2003 Boumerdès and the 2011 Tohoku excitations; and vi) according to the outcomes of this study, the semi-active MR damper controlled using a fuzzy sliding mode controller coupled to the clipped optimal algorithm is a suitable solution to reduce structural vibrations in earthquake excited civil engineering structures.

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