ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA
Revista de la Construcción
Journal of Construction

Research Article

Semi-active structural vibrations control with magneto-rheological damper based on the hybrid fuzzy sliding mode controller

Khaled Zizouni [1],*, Abdelkrim Saidi [2], Leyla Fali [3], Ismail Khalil Bousserhane [4], Mohamed Djermane [5]

[1] ArchiPEL Laboratory, Civil Engineering and Hydraulic Department, TAHRI Mohamed University, Bechar (Algeria), zizouni.khaled@univ-bechar.dz
[2] ArchiPEL Laboratory, Civil Engineering and Hydraulic Department, TAHRI Mohamed University, Bechar (Algeria); saidi.abdelkrim@univ-bechar.dz
[3] FIMAS Laboratory, Civil Engineering and Hydraulic Department, TAHRI Mohamed University, Bechar (Algeria), fali.leyla@univ-bechar.dz
[4] ArchiPEL Laboratory, Electrical Engineering Department, TAHRI Mohamed University, Bechar (Algeria), ismail.bousserhane@univ-bechar.dz
[5] FIMAS Laboratory, Civil Engineering and Hydraulic Department, TAHRI Mohamed University, Bechar (Algeria), djermane.mohamed@univ-bechar.dz
*Correspondence: zizouni.khaled@univ-bechar.dz

Received: 02.10.2021; **Accepted:** 08.01.2023; **Published:** 30.04.2023

Citation: Zizouni, K., Saidi, A., Fali, L., Khalil, I. and Djermane, M. (2023). Semi-active structural vibrations control with Magneto-Rheological damper based on the hybrid fuzzy sliding mode controller. Revista de la Construcción. Journal of Construction, 22(1), 36-50. https://doi.org/10.7764/RDLC.22.1.36.

Abstract: Recently, the semi-active control of structural vibration has demonstrated its ability to preserve human life and keep structures safe during earthquakes. In the civil engineering area, the literature is full of investigation in both numerical and experimental research in which the Magneto-Rheological damper is the most used device. This paper investigates the semi-active control of three scaled excited structures. The proposed control is assured by a Magneto-Rheological damper controlled using a hybrid Fuzzy Sliding Mode controller. Although, a Clipped optimal algorithm is proposed to calculate the required current for the damper operating. Otherwise, the robustness of the suggested controller is proved by the obtained numerical results of the seismic excited scaled structure. Therefore, the tested structure is subjected to four time-scaled earthquake records. Finally, the effectiveness of the proposed semi-active control strategy in mitigating earthquake structural vibration is shown clearly in the compared controlled and uncontrolled responses. The simulation results show that the peak reduction reaches 65% under the 2011 Tōhoku earthquake. In addition, the performance indices prove the robustness of the proposed strategy.

Keywords: Semi-active control, fuzzy sliding mode, MR damper, vibration suppression, earthquake excitation.

1. Introduction

Earthquakes are natural hazards that cause several tragedies and economic losses. Over the past few decades, various approaches to building protection have been proposed as passive seismic isolation (Fali et al., 2022; Wang 2020). Recently, the semi-active control strategy has become more and more critical in civil structural engineering. Several researchers investigated the semi-active strategy in numerical and/or experimental studies. The semi-active control strategy is considered simultaneously compromise the passive and active strategies. In the general case, the damping system of the semi-active system behaves as a passive system. Contrariwise, the controlled forces are generated based on real-time tracking of the responses of the structure in loop control. Furthermore, the semi-active devices are easy to manufacture and install on the structure, fail-safe, reliable, and can generate the desired forces in real-time excitations without requiring a high external energy source. In contrast, these devices are considered as a limited control capacity compared to the active devices. Out of various semi-active monitoring systems, the Magneto-Rheological dampers and the Electro-Rheological dampers are investigated in several studies and characterizations (Savaia et al., 2021).

The usage of semi-active control systems is widespread in various worldwide and has been the subject of several investigations and studies in the past decades. Otherwise, the efficiency of the semi-active control strategy depends on more than just the mechanism choice but in a big part on the controller type. Hence, the whole control system depended on the performance to track the desired response of the controlled system. For this reason, several controllers were the subject of numerical and experimental investigations. These controllers are ranged in two classes according to the need of mathematical model or not to operate. However, the classical controllers are the controllers needing mathematical modeling with verification of stability. On the other hand, the second control class can efficiently operate without needing a mathematical model called the intelligent controllers class (Saeed et al., 2022). Nonetheless, another class which is a combination of the two cited classes is known as the hybrid controller (Phu et al., 2017).

During the last decades, important efforts have been conceived to develop and propose control algorithms for large-scale semi-active controlled structures subjected to dynamic loads. Furthermore, linear controllers have emerged in an important place in the structural civil engineering control area. The simple design of these controllers and their stability and time convergence in linear cases interested several researchers. A linear-quadratic regulation (LQR) was designed to control a Magneto-Rheological (MR) damper to reduce floor’s displacements of a three-story scaled excited structure. The tested structure was excited by the El Centro 1940 earthquake excitation and the simulation results show the effectiveness of the linear controller (Zizouni et al., 2017). Moreover, the Proportional Integral Derivative (PID) controller was the subject of experimental investigation. The controller was conceived to control a two-story scaled framework using an active mass damper subjected to an earthquake signal. The PID controllers' experimental responses were compared with the uncontrolled structure results. (Yu et al., 2014).

One of the defects of these linear controllers is that they are strongly affected by uncertainties or external condition variations. Otherwise, in several complex cases, the controller mathematical model must have insensitivity to the disturbance effects. Nonlinear controllers are considered the most robust controllers in the presence of uncertainty and disturbances. Nonetheless, the controller must be robust under various dynamic conditions and present high stability, performance, and ease of use. However, a sliding mode controller was numerically investigated under dynamic loading in the structural vibrations control. The controller was designed to control an active mass damper to suppress the vibration of a model of a three-floor structure excited with the Mexico City 1995 earthquake time scale. The chattering caused by the signum function was avoided using the boundary layer method, replacing the signum function with the saturation function (Fali et al., 2018). A Backstepping controller was proposed to reduce a three-story frame vibration response with an MR damper. The feasibility of Backstepping control was explored by numerical simulations and experiments in which the results of the controlled and uncontrolled structure responses were exposed (Zapateiro et al., 2009).

Most systems in the civil engineering area are considered complex systems with nonlinearities and uncertainties where the mathematical model describing the system is difficult to formulate. Without needing a mathematical concept to represent the dynamic system, intelligent controllers are the most practical controllers for these cases. A neural network controller trained on the LQR controller was proposed to control two numerical examples. The first example was a simple single-degree-of-freedom structure; the second one was a twelve-story building. The two structures were excited with El Centro 1940 earthquake acceleration signal. However, the effectiveness of the proposed controller is demonstrated via computational simulation results of the neural network control compared to the original LQR control (Blachowski & Pnevmatikos, 2018).

Although, the hybrid controller combines two or more controller algorithms in which the advantages are combined, giving a performed resulting controller. The PID control was designed to track the sliding mode controller's sliding surface to control an electromechanical motor experimentally. The experimental results have shown a good tracking performance, robustness in the presence of uncertainties, and a chattering problem overcoming the proposed hybrid controller. The proposed PID sliding mode controller evinced remarkable stability during the reaching and sliding phases, and the results compared to the traditional PID control proved the effectiveness of this hybrid control (Eker, 2006).

This paper proposes a hybrid fuzzy sliding mode algorithm to control a Magneto-Rheological damper. The current driver is adjusted with a Clipped optimal scheme. However, this semi-active control is designed to reduce undesirable structural vibrations under the 1990 Manjil, the 1995 Kobe, the 2003 Boumerdès, and the 2011 Tōhoku earthquakes excitation. The tested structure is a three-story scaled structure, and the numerical simulation results are executed using MATLAB/Simulink. The proposed control strategy's benefit is confirmed by comparing the numerical simulation outcomes of the hybrid controlled and without-control structure responses.

2. The MR damper modeling

The Magneto-Rheological damper in Figure 1 is one of the most full of promise semi-active control mechanisms. This device interested some researchers and was the subject of different studies and research (Ghaffari et al., 2015; Zhang et al., 2020). Owing to its simple installation on the structure, which usually operates in high gap temperature intervals, it fast responds in milliseconds. During the last decades, the nonlinear behavior in the magnetic field applied to the Magneto-Rheological damper was investigated, and many mathematical models were proposed (Ismail et al., 2009). Starting from the simple quasi-static model proposed by Bingham in 1916 (Bingham, 1916), arriving at the augmented Bouc-Wen hysteresis model illustrated in Figure 2 (Spencer et al., 1997).

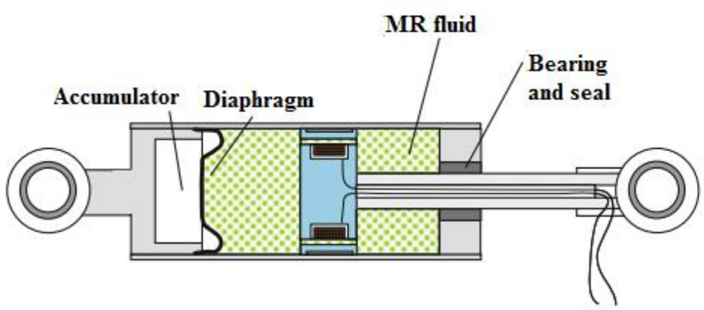

Figure 1. Magneto-Rheological damper schematic.

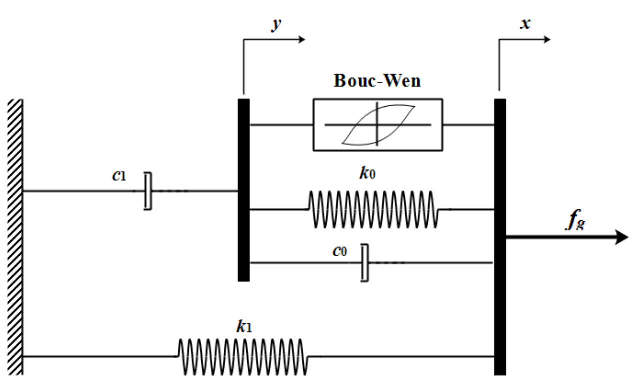

Figure 2. Magneto-Rheological damper Mechanical model.

The mathematical model is presented as

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

$$\dot{y} = \frac{1}{c_0+c_1}[\alpha z + c_0\dot{x} + k_0(x-y)] \quad (2)$$
$$f_g = c_0(\dot{x}-\dot{y}) + k_0(x-y) + k_1(x-x_0) + \alpha z \quad (3)$$

Where x and $\dot{x}$, are the damper's displacement and velocity, f_g and z are respectively the predicted force and the evolutionary variable response of the damper, k_0 and k_1 are the accumulator stiffness at velocity limits, c_0 and c_1 are the viscous damping at velocity limits, γ, β, n, and A are the model parameters and the parameters depending on the applied voltage are expressed as

$$\alpha = \alpha_a + \alpha_b u \quad (4)$$
$$c_1 = c_{1a} + c_{1b} u \quad (5)$$
$$c_0 = c_{0a} + c_{0b} u \quad (6)$$
$$\dot{u} = -\eta(u - v) \quad (7)$$

Where u, v are the filter's output variable, the circuit applied voltage and η is the time constant of the model filter.

These parameters are defined as (Spencer et al., 1997)
$c_{0a} = 21\ N\cdot s/cm$; $c_{0b} = 3.5\ N\cdot s/cm$; $k_1 = 5\ N/cm$ $k_0 = 46.9\ N/cm$; $\alpha_a = 140\ N/cm$; $\alpha_b = 695\ N/cm$; $c_{1a} = 283\ N\cdot s/cm$; $c_{1b} = 2.95\ N\cdot s/cm$; $A = 301$; $\gamma = 363\ cm^{-2}$; $\beta = 363\ cm^{-2}$; $\eta = 190\ s^{-1}$; $n = 2$; $x_0 = 14.3\ cm$
The MR damper augmented Bouc-Wen model is simulated under a sinusoidal excitation of 2.5Hz frequency and amplitude of 1.5cm with different voltage levels (0, 0.5, 1 and 1.25V). Thus, the hysteresis comportment of the MR damper mechanical model is presented in Figure 3.

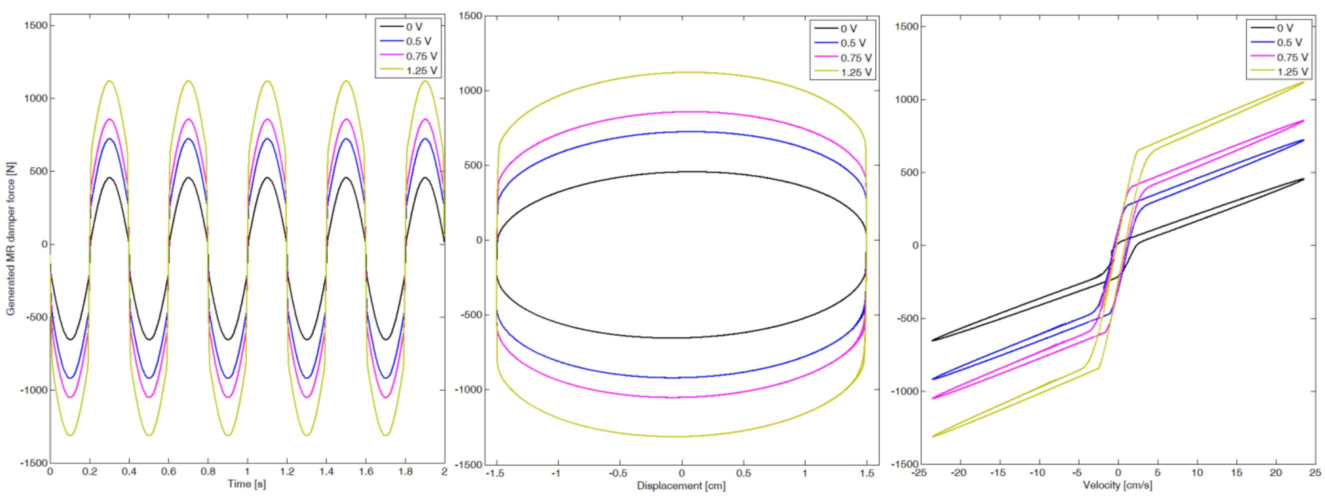

Figure 3. Force-time, force-displacement and force-velocity relationships for the MR damper with different voltage levels.

Whereas 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 approach proposed to drive the desired current to the magnetorheological device governed by

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

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

3. Research significance

Advanced control techniques are widely used in civil engineering areas to perform structural responses against earthquake or wind excitations. Several active technique devices are cited and investigated in numerical or experimental studies literature. However, the main key to the active strategy's success is the best control law choice and design. Recently, nonlinear controllers of dynamic systems modeling uncertainties and external disturbances with condition variations have gained considerable attention. Moreover, the sliding mode controller (SMC) is a robust and popular nonlinear controller widely used in civil engineering structural control. The main objective of this controller is to force the system error to reach the equilibrium state and keep it moving on all the time. At the same time, this controller stability is strongly affected by the discontinuous control signal known as Chattering caused by the high-frequency oscillation. The chattering phenomenon is brought on also by unmodeled dynamics or discrete time implementation, leading to instability and negative control accuracy.

The Chattering suppression is the subject of several investigations and studies where various solutions were proposed. The asymptotic observed-based is already used to suppress any chattering in several papers (Zhang & Li 2016). On the other hand, the gain adaptation is used to adjust the boundary layer thickness and suppress the finite oscillation (Fali et al., 2019; Zizouni et al. 2022; Saidi et al., 2019). Hybridization is one of the robust solutions in which the advantages of two controllers are combined. The main idea of this work is to replace the switching part of the sliding mode control law with an intelligent control law based on the smoothing technics of the switch. The new hybrid fuzzy sliding mode can overcome the chattering phenomena and offer stability to the control law and the whole system. A case study is developed by numerical simulation to investigate the stability of the system and the effectiveness of the suggested semi-active control strategy to reduce structural vibration.

The widely used dampers are Magneto-Rheological dampers (semi-active), Active mass dampers (active) and Tuned mass dampers (passive). Several studies are investigating and comparing these widely used dampers in the literature. Passive dampers do not need any power, automation, or maintenance and are already used in several buildings worldwide and have been trusted by engineers. Otherwise, the active dampers are generally the automation of passive dampers already existing in the building. These dampers can provide remarkable control force offering the best performance in vibration suppression, especially for strong earthquakes, while they need high power and regular maintenance.

For the last dampers, the semi-active offers considerable control force higher than the passive and less than the active but needs little energy to operate (few batteries). These dampers are preferred because of their simple installation, low maintenance cost, rapidity of response, and possible passive operation in magnetic field absence. Magneto-Rheological dampers can also provide more considerable control forces in slower course regions (Savaia et al., 2021). Magneto-Rheological fluids operate as Newtonian fluids in the absence of the magnetic field. The magnetic saturation of the particles governs the performance of magnetorheological fluids, and their elastic limit is, therefore, more significant than ten times the magnetic saturation. Moreover, the elastic limit obtained by magnetorheological fluids is approximately fifty times higher than an electrorheological fluid. (Jolly et al., 1999; Spaggiari 2013).

4. Basic theory of the fuzzy sliding mode controller

Let suppose the dynamic system presented as follow

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

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 approaching and converging the tracking error $e(t)$ to zero, thus reaching the sliding surface defined by

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

Where G is the sliding surface switching vector
Using the Lyapunov stability principle, the stability of the system (9) is guaranteed by

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

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

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

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

Where M is the switch gain and sgn(·) is the signum function

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

Otherwise, the function defined in (15) caused an oscillation with finite oscillation and amplitude known as the Chattering phenomenon. This problem affected the stability of the whole system in the presence of unwanted frequency signals in the output responses (Bartolini, 1989). However, several techniques and solutions were proposed and investigated to overcome this drawback. Where the essential criterion is ensured, sufficient boundary layer wideness guarantees the system's attractiveness. One of the Chattering suppresses techniques 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 control approach 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 the equation (15) is given by

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

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

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

However, a design conflict exists between the control performance requirement, accuracy, and the control signal's smoothness, thus the Chattering suppression. For this reason, the boundary layer width should be chosen to obtain a good compromise between sliding mode robustness and Chattering elimination or reduction. In general, we can use a small boundary layer thickness to have a good tracking performance, but this choice will increase the Chattering problem. Conversely, 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 developed to perform the sliding mode controller and overcome the chattering problem, where a fuzzy system method adopts the expression of the equation (16). This method demonstrates that a fuzzy controller is an extended version of an SMC with If-Then rules constructed (Bousserhane et al., 2006)

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

Where BN is a big negative, MN is medium negative, ZE is zero, MP is medium positive, and BP is a big positive. In Figure 4, membership functions for the output variable are illustrated. The fuzzified output u_s for a fuzzy input S is shown clearly in Figure 5. In order to control the vibrations and reduce the system displacements, 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 are appended to assure the required force of control. Therefore, the designed hybrid control is presented in Figure 6.

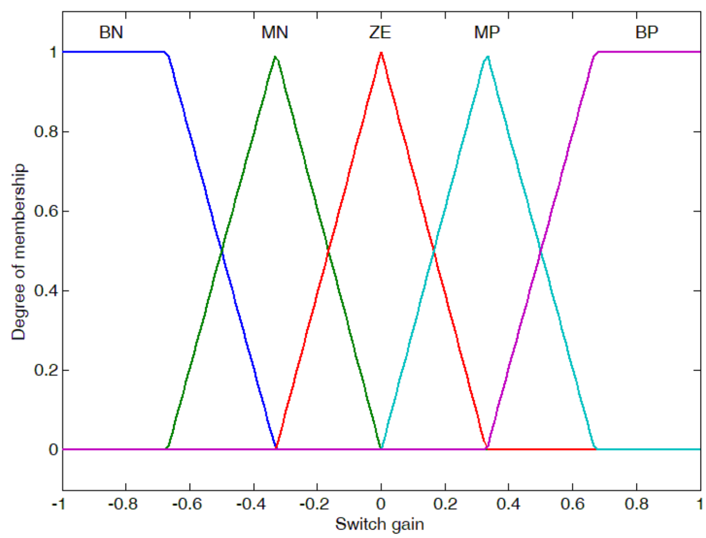

Figure 4. Membership functions for the input variable

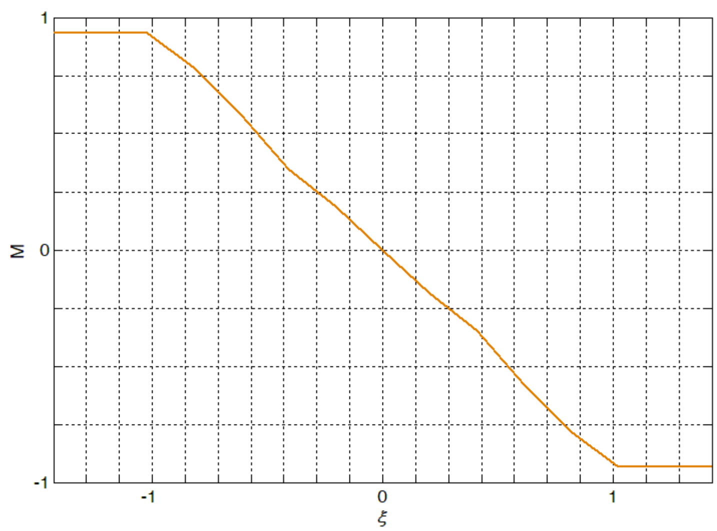

Figure 5. The switch control action of the fuzzy sliding mode approach

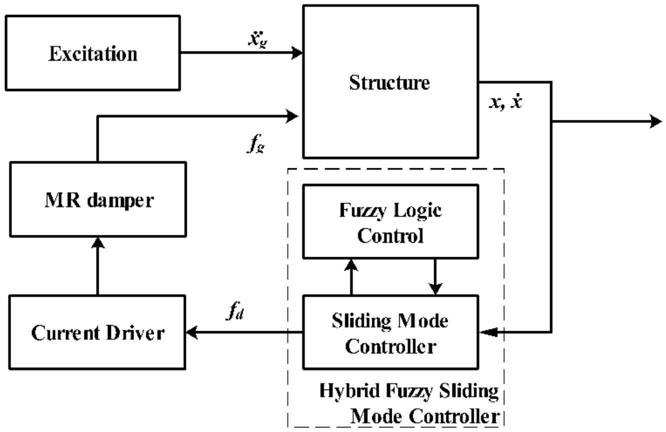

Figure 6. Block schema of the proposed semi-active hybrid control strategy

5. Numerical investigation

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

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

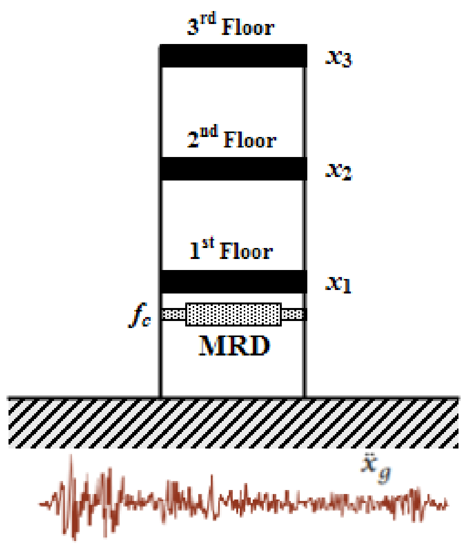

Figure 7. The three story scaled structure model

Where $\ddot{x}$, $\dot{x}$ and x are the acceleration, velocity and displacement floor's vectors, 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 defined as

$$\Gamma = \begin{Bmatrix} -1 \\ 0 \\ 0 \end{Bmatrix} \tag{19}$$

$$\Lambda = \begin{Bmatrix} 1 \\ 1 \\ 1 \end{Bmatrix} \tag{20}$$

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

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

Earthquakes	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
Tōhoku 2011	Japan	Oshika	9.1 Mw	12.75	14.85	2.58

However, M_s, C_s and K_s are the structure's mass, damping and stiffness matrices defined as (Zizouni et al., 2017)

$$[M_s] = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} Kg \tag{21}$$

$$[K_s] = \begin{bmatrix} 12 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \times 10^5\, N/m \tag{22}$$

$$[C_s] = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} N \cdot sec/m \tag{23}$$

6. Numerical example validation

The numerical simulation analysis of the structure responses are carried out using MATLAB/Simulink. The proposed hybrid fuzzy sliding mode controller is evaluated and assessed. Moreover, the semi-active strategy performance is demonstrated by comparing the displacement responses of controlled structure to those without any control.

Thus, the compared time history displacement responses of the structure without control to those of the hybrid controlled structure of the first, second, and top floors under the 1990 Manjil, the 1995 Kobe, the 2003 Boumerdès, and the 2011 Tōhoku earthquakes excitations are presented, respectively in Figures 8, 9, 10 and 11. Moreover, the peak floor displacement comparisons of the controlled and uncontrolled cases under the four earthquakes are depicted in Figure 12.

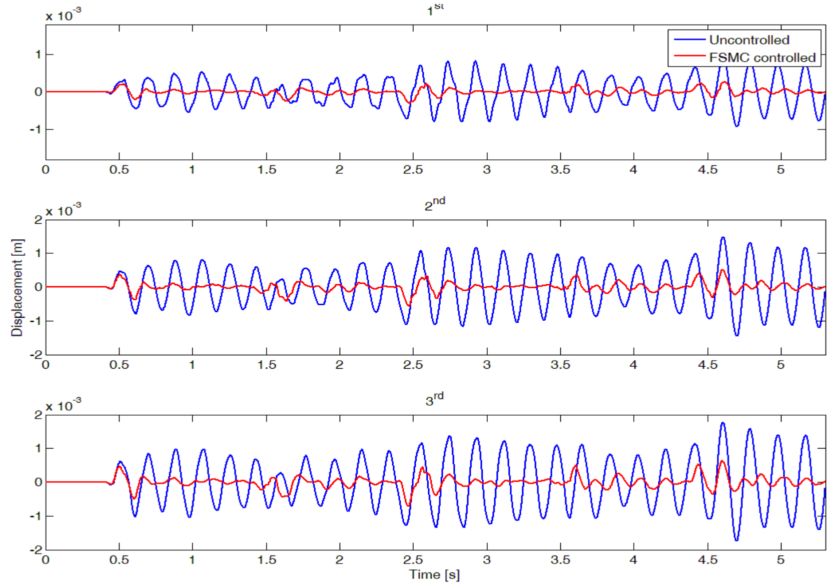

Figure 8. Time history of floors displacement under the 1990 Manjil earthquake excitation

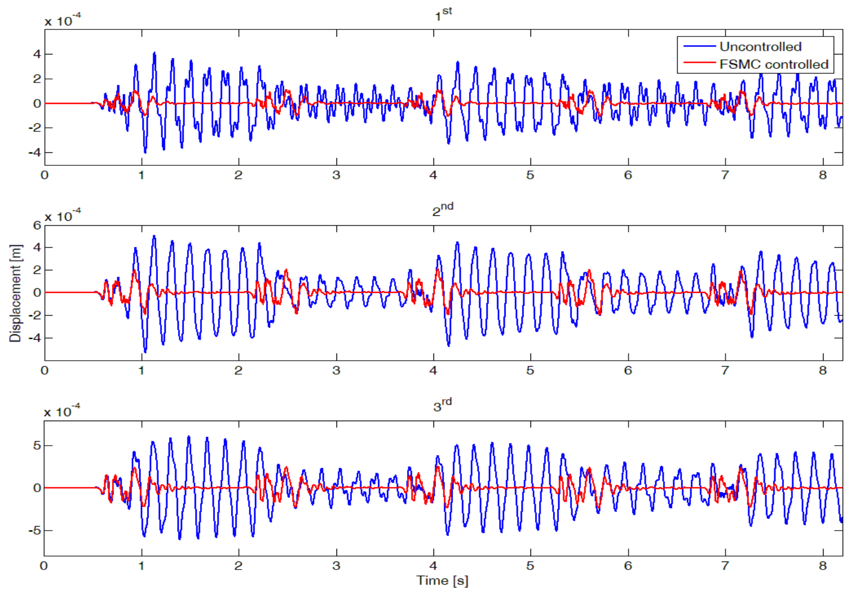

Figure 9. Time history of floors displacement under the 1995 Kobe earthquake excitation

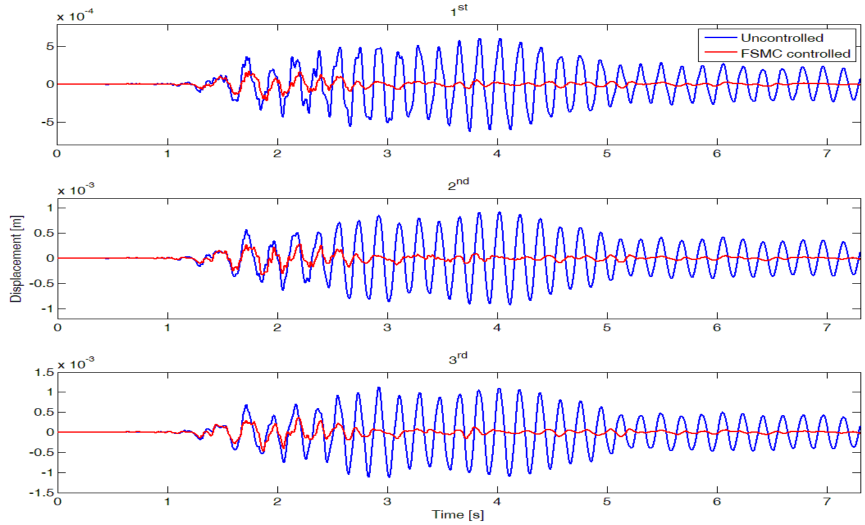

Figure 10. Time history of floors displacement under the 2003 Boumerdès earthquake excitation

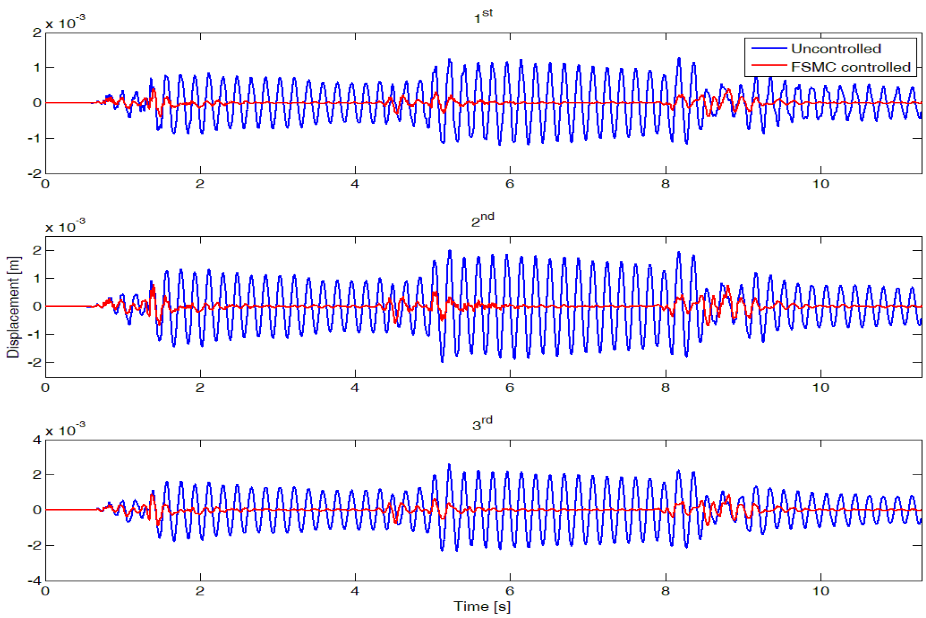

Figure 11. Time history of floors displacement under the 2011 Tōhoku earthquake excitation

The reliability of the proposed 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 presented in Table 2 show the success of the semi-active control strategy to suppress undesired structural vibrations.

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

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

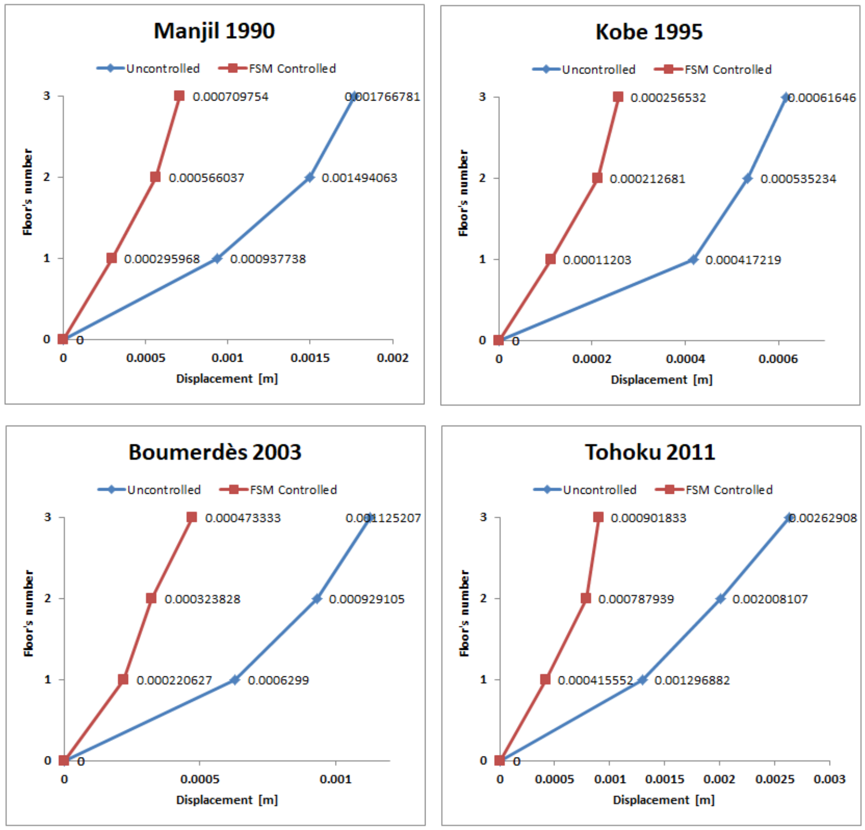

Figure 12. The peak floors displacement under the different earthquakes excitations

Using the peak floor displacement attenuation, the suggested hybrid semi-active control strategy's efficacy is assessed. The decrease in the peak displacement value of each floor is calculated under each earthquake load and listed in Table 2. Thereby, under the 1990 Manjil, the 1995 Kobe, the 2003 Boumerdès, and the 2011 Tōhoku earthquakes, the peak reduction of each floor presented in Table 2 show the performance of the semi-active control strategy.

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
Tōhoku 2011	0.575	1.127	0.100	0.615	1.063	0.100	0.130	0.447	0.0002

Whereas, to prove the proposed fuzzy sliding mode controller robustness in structural vibration control, the hybrid controller is applied to the same system three-scaled structure using an active mass damper. The active mass damper characteristics are illustrated in (Zizouni et al., 2020) and the structures is subjected again to the 2003 Boumerdès earthquake. As a result, Table 4 illustrates the compared peak displacement response of each structure floors between controlled using a magnetorheological damper (MRD) to controlled using an active mass damper.

Table 4. Peak floor's displacement reduction using different control strategies under the 2003 Boumerdès earthquake.

Control strategy	Peak reduction of floors		
	1st	2nd	3rd
MRD	64.97%	65.15%	57.93%
AMD	70.06%	71.13%	64.52%

From the obtained numerical simulation results the peak reduction of the floor displacement reaches 73.15% in the second floor under the 1995 Kobe earthquake. In addition, the peak displacement reduction reaches in the third floor of the structure 59.83%, 58.39%, 57.93% and 65.70% respectively under the 1990 Manjil, 1995 Kobe, 2003 Boumerdès and 2011 Tōhoku earthquakes. These results prove the success of the proposed control to ensure the stability of the dynamic system.

Accordingly, the system responses under the fuzzy sliding mode controller subjected to an earthquake excitation is evaluated using six indices J_1–J_6. Thus, the calculated indices prove the system stability and robustness using the proposed hybrid controller. Moreover, the indices J_7–J_9 prove the performance of the hybrid controller to command the Magnetorheological damper.

In addition, the proposed controller proves its effectiveness and accuracy in controlling civil engineering structures using active mass dampers. Table 4 shows the peak displacement values between the active and semi-active control strategies. The results indicate little difference between the active and semi-active strategies due to the force level generated by the two modes. Therefore, using an active mass damper, the hybrid controller affirms its stability and reliability in active vibration structural control.

7. Conclusions and comments

The hybrid fuzzy sliding mode controller based on the fuzzification of the switching term of the sliding mode controller is investigated to suppress structural vibrations of an excited scaled structure. The effectiveness of the controller is verified through the calculation of the evaluation indices under the 1990 Manjil, 1995 Kobe, 2003 Boumerdès, and 2011 Tōhoku earthquakes. The compared numerical simulation results of the uncontrolled and the controlled structure is also shown the performance of the suggested semi-active control strategy. Thus, the following can be concluded:

1. The hybridization of the sliding mode controller using a fuzzy logic controller offered more stability and potency to the classical controller without affecting the robustness of the control.
2. The numerical simulation comparison responses of the two cases, uncontrolled structure, and hybrid semi-active controlled structure, show clearly the reduction in the displacement responses in the three floors under the four earthquakes.
3. The proposed strategy ensures the efficiency of peak reduction on each structure floor. The peak reduction attains 73% on the first floor and 65% on the second and third floors.
4. The value of the indices J_1, J_2, J_3, J_4, J_5, and J_6 proves the proposed control strategy's effectiveness in performing the structure responses.
5. The robustness of the semi-active device behavior is approved and justified by the three indices value J_7, J_8, and J_9 under each of the 1990 Manjil, 1995 Kobe, 2003 Boumerdès, and 2011 Tōhoku excitations.
6. 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.

Author contributions: All authors contributed to the paper's preparation. KZ and IKB proposed de hybrid chattering suppress solution. KZ and LF simulated the model and carried out the results. LF and AS structured and wrote the paper. MD supervised and oriented the study.

Funding: The authors affirm that there is no funding for this work.

Conflicts of interest: The authors affirm that none of them has any conflicts of interest.

References

Bartolini G. (1989). Chattering Phenomena in Discontinuous Control Systems. International Journal of Systems Science, 20(12), 2471-2481.

Bingham E. C. (1916). An Investigation of the Laws of Plastic Flow. U.S. Bureau of Standards Bulletin, 13, 309-353.

Blachowski B., & Pnevmatikos N. (2018). Neural Network Based Vibration Control of Seismically Excited Civil Structures. Periodica Polytechnica Civil Engineering, 62(3), 620-628.

Bousserhane I. K., Hazzab A., Rahli M., Mazari B., & Kamli M. (2006). Fuzzy Sliding Mode Based on Indirect Field Orientation for Induction Motor Drive. 32nd Annual Conference on IEEE Industrial Electronics, Paris, France.

Eker I. (2006). Sliding Mode Control with PID Sliding Surface and Experimental Application to an Electromechanical Plant. ISA Transactions, 45(1), 109-118.

Fali L., Djermane M., Zizouni K., & Sadek Y. (2019). Adaptive sliding mode vibrations control for civil engineering earthquake excited structures. International Journal of Dynamics and Control. 7(3), 955-965.

Fali L., Sadek Y., Djermane M., & Zizouni K. (2018). Nonlinear Vibrations Control of Structure under Dynamic loads. The 4th Student Symposium on Application Engineering of Mechanics SSAEM'4, Bechar, Algeria.

Fali L., Zizouni K., Saidi A., Ghomri T., Bousserhane I. K., & Djermane M. (2022). Structural Vibration Control in Excited Structures: History and Prospects. Journal of Vibration Engineering & Technology. (Article in press).

Ghaffari A., Hashemabadi S. H., & Ashtiani M. (2015). A review on the simulation and modeling of magnetorheological fluids. Journal of Intelligent Material Systems and Structures, 26(8), 881-904.

Ismail M., Ikhouane F., & Rodellar J. (2009). The Hysteresis Bouc-Wen Model, a Survey. Archives of Computational Methods in Engineering, 16, 161-188.

Jolly M.R., Bender J.W., Carlson J.D. (1999). Properties and Applications of Commercial Magnetorheological Fluids. Journal of Intelligent Material Systems and Structures. 10(1), 5-13.

Phu D. X., Choi S. M., & Choi S. B. (2017). A New Adaptive Hybrid Controller for Vibration Control of a Vehicle Seat Suspension Featuring MR Damper. Journal of Vibration and Control, 23(20), 3392-3413.

Saeed M.U., Sun Z., & Elias S. (2022) Research developments in adaptive intelligent vibration control of smart civil structures. Journal of Low Frequency Noise, Vibration and Active Control. 41(1), 292-329.

Saidi A., Zizouni K., Kadri B., Fali, L., & Bousserhane I.K. (2019). Adaptive sliding mode control for semi-active structural vibration control. Studies in Informatics and Control, 28(4), 371-380.

Savaia G., Panzani G., Corno M., Cecconi J., & Savaresi, S. M. (2021). Hammerstein–Wiener modelling of a magneto-rheological damper considering the magnetization dynamics. Control Engineering Practice, 112, 104829.

Spaggiari A. (2013). Properties and applications of Magnetorheological fluids. Frattura ed Integrità Strutturale, 7(23), 57-61.

Spencer B. F., Dyke S. J., Sain M. K., & Carlson J. D. (1997). Phenomenological model for Magnetorheological Dampers. Journal of Engineering Mechanics, 123(3), 230-238.

Wang J. (2020). A seismic-shielding structure based on phononic crystal. Revista de la Construcción, 19(3), 272-287.

Yu W., Thenozhi S., & Li X. (2014). Stable Active Vibration Control System for Building Structures using PD/PID Control. 19th World Congress of the International Federation of Automatic Control Volumes. Cape Town, South Africa, 47(3), 4760-4765.

Zapateiro M., Karimi H. R., Luo N., Phillips B. M., & Spencer B. F. (2009). Semiactive Backstepping Control for Vibration Reduction in a Structure with Magnetorheological Damper Subject to Seismic Motions. Journal of Intelligent Material Systems and Structures, 20(17), 2037-2053.

Zhang, X., & Li, Z. (2016). Sliding-Mode Observer-Based Mechanical Parameter Estimation for Permanent Magnet Synchronous Motor. IEEE Transactions on Power Electronics. 31(8), 5732-5745.

Zhang Y., Li D., Cui H., & Yang, J. (2020). A new modified model for the rheological properties of magnetorheological fluids based on different magnetic field. Journal of Magnetism and Magnetic Materials, 500, 166377.

Zizouni K., Bousserhane I. K., Hamouine A., & Fali L. (2017). MR Damper-LQR Control for Earthquake Vibration Mitigation. International Journal of Civil Engineering and Technology, 8(11), 201-207.

Zizouni K., Fali L., Bousserhane I.K., Sadek Y. (2020). Active mass damper vibrations control under earthquake loads. International Journal of Advances in Mechanical and Civil Engineering. 7(2), 26-30.

Zizouni K., Saidi A., Fali L., Bousserhane I.K., & Djermane, M. (2022). Adaptive sliding-mode control for improved vibration mitigation in civil engineering structures. Mechanical Sciences, 13(2), 899-908.