Adaptive Sliding Mode Control for Structural Vibration Using Magnetorheological Damper

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***Abstract*—This study presents the design of a new adaptive sliding mode controller to mitigate building vibrations induced by earthquakes, utilizing a semi-active magnetorheological damper (MRD) positioned on the top floor. This damper operates as a passive damper under low-intensity vibrations and transitions to an active damper during high-intensity vibrations, facilitating optimized performance according to vibration severity. The efficiency of the proposed controller was assessed by comparing it with two other robust controllers established in previous studies. This comparison was performed on a prototype three-story structure, subjected to a severe earthquake called El Centro 1940 with an acceleration of 3.9 m/s². The simulation results demonstrated that the proposed controller effectively reduced vibrations significantly. The proposed controller demonstrated enhancement in control effort 660N compared to 751N for first methodology and 722N for second methodology from the literature. The proposed method offers the advantage of reduced design requirements relative to the first and second methods from literatures. Moreover, the proposed method eliminates the necessity for filter adjustments, hence simplifying its implementation. All controllers utilized for comparison are robust and do not require prior knowledge of disturbance bounds. Moreover, the damper was positioned on the top floor in all the procedures analyzed. The results indicate that the proposed controller significantly reduces control effort relative to alternative controllers in addition The proposed method reduces the displacement of the upper floor by 89% compared to other methods, rendering it an effective choice for vibration control and enhancing building reactions to earthquakes.**

Keywords*—Adaptive Sliding Mode Control; Semi-Active Control; Vibration Mitigation Efficiency; Robust Control Comparison; Earthquakes.

I. Introduction

Mitigating structural vibrations induced by seismic events are essential for safeguarding the safety and functionality of buildings, especially hospitals, public facilities, and industrial structures. Several seismic control solutions have been created to mitigate earthquake-induced damage, including passive, active, and semi-active control systems. Passive systems, represented by Tuned Mass Dampers (TMD) [1]-[8], dissipate energy independently but exhibit an issue in not including feedback signals from the building [9]-[12]. Active control technologies, such as Active Tuned Mass Dampers (ATMD), improve performance through control algorithms but necessitate considerable power consumption [13], [14]. Semi-active systems, such as the Magneto-Rheological Dampers (MRD), are a hybrid methodology that combine the benefits of both passive and active systems. They function with minimal power consumption and include the ability to dynamically modulate their damping forces using control algorithms [15]-[18]. These systems operate passively under normal conditions but activate their control mechanisms in strong excitations. The damping force is controlled by modifying the fluid viscosity by electrical or magnetic fields powered by low-energy batteries [19]-[26]. Field investigations from the 2023 Kahramanmaraş earthquake in Türkiye (Mw = 7.6 and Mw = 7.8, (Mw) mean Moment Magnitude) indicated that while many structures were rendered inaccessible to humans, hospitals equipped with dampers remained had less damages, demonstrating the efficacy of these devices in reducing vibrational impacts. This study uses semi-active dampers, which integrate the benefits of both passive and active dampers to enhance vibration reduction efficacy [27]. Many studies in this field aim to design robust and efficient control algorithms for semi-active dampers [28]-[36]. Our present investigation will utilize a three-story prototype structure with a semi-active damper [37]-[39]. A number of previous research focused on single-story structures, while others concentrated on multi-story structures. In research on single-story buildings, Hamidi et al. [40] implemented MRD-based Adaptive Backstepping Sliding Mode Control (ABSMC) system. Although the ABSMC method consumes more energy than the conventional sliding mode control (SMC), but it was necessary to achieve the desired displacement. Also, this method requires prior knowledge of disturbance. A prominent case study involving a three-story prototype building subjected to different scaled simulated earthquakes is used in the all of the following research studies.

Kavyashree and Rao [41] developed a PID controller combined with a magnetorheological damper (MRD) positioned on the first floor to improve seismic response mitigation. The system was assessed using three common earthquake records: El Centro, Northridge, and Kobe. Their findings indicated a significant decrease in structural displacement, with maximum displacement reduced by roughly 30–40%. Nonetheless, despite its efficacy in specific situations, PID control is significantly constrained by its performance, which is highly dependent on exact model parameters. Under conditions of modeling uncertainties or substantial external disturbances, such as those encountered during intense seismic occurrences, the PID controller may exhibit reduced robustness and fail to maintain consistent performance. This constraint necessitates the development of more adaptable and disturbance-resilient control techniques, such as the proposed ASMC. While Zizouni et al. [42] ped a

Linear Quadratic Regulator (LQR) to govern a scaled structure using MRD to reduce earthquake-induced vibrations. The damper was installed on the first floor, and the system was tested under the impact of the El Centro1940 earthquake. The results showed a significant reduction in displacement up to 40% on the first floor and 30-35% on the upper floors, Despite the controller's desirable performance, it encounters considerable problems, particularly its deficiency in self-adaptability to uncertain system dynamics or variation of external excitations. This constraint may reduce its efficacy in seismic conditions defined by unpredictability, illustrating the necessity for more adaptable and flexible control systems. The proposed Adaptive Sliding Mode Controller (ASMC) aims to address these constraints and attain enhanced reliability under fluctuating operating conditions.

Within the scope of intelligent control, Zizouni et al. [43] proposed a neural network to control MRD for mitigating earthquake-induced vibrations in the three-story building model. The damper was positioned in the first story, and the system was tested in reaction to the 2003 Tohoku and Boumerdès earthquakes. The results indicated an enhancement in minimizing displacement up to 57.64% for the third floor. However, this controller requires a large amount of data and needs long and complex training, especially in complex systems and with prior knowledge of disturbance upper bounds. Saidi et al. [44] proposed ASMC approach integrated with MRD on the first story to mitigate earthquake vibrations. The system was evaluated in response to the El Centro 1940 and Boumerdès 2003 earthquakes. The results demonstrated a significant decrease in third floor displacement of 60.1% during the El Centro 1940 and 50.4% during the Boumerdès earthquake. This ASMC approach may suffer from overestimated gain that grows with time which may lead to high actuating forces. Moreover, the results could be further enhanced by placing the MRD in the top floor instead of the first floor as the authors did. In an additional study conducted by Zizouni et al. [45] MRD was implemented on the first floor with another ASMC method. The structure was subjected to the effects of the El Centro 1940 earthquake. The results indicated a significant decrease in displacement, with a 69.92% reduction on the third floor. Hussain and MohammadRidha [46] proposed Integral Sliding Mode Control using a barrier function (ISMCb), implemented with an MRD located on the top floor of the three-story building. The performance of MRD was evaluated in comparison to ATMD in the context of the Mexico City and El Centro 1940 earthquakes. The results indicated that MRD surpassed ATMD in minimizing displacement, with enhancements of 83.9% compared to open loop during the Mexico City earthquake and 76% compared to open loop during the El Centro 1940 earthquake. ISMCb performance is compared to ASMC approach in [47]. ASMC is redesigned and modified from [45] and implemented with MRD relocated here to be on the third floor instead of the first floor dissipate energy. The test conducted on two distinct earthquake types indicating the significance of MRD floor location. It was shown in [47] that the damper on the top level is more effective than positioning it on the ground floor as was designed previously in [45]. The top-floor displacement decreased by 89.01% as compared to the results of [45] that reduced the displacement by 69%. Another comparison was studied in [47] with ISMCb designed in [46] where both controllers derived MRD on the top floor. The displacement reduction of ASMC was up to 89 % while ISMCb achieved 76%. It is worth noting that both methods under consideration in this study are robust methods that do not require prior knowledge of disturbance bounds, which is a significant advantage when dealing with earthquakes of varying intensity.

These studies demonstrate continual improvements in adaptive control systems designed to mitigate earthquake-induced vibrations. Consequently, in this work, a new (ASMCn) approach developed in [48] is compared to the ASMC results of [47] and ISMCb [46]. The two different robust adaptive control algorithms drive the same MRD to mitigate structural vibrations under two different earthquakes. The main purpose is to see the efficiency of each and the corresponding energy consumption. The advantages of ASMCn over the ASMC and ISMCb are:

1. No filter tuning
2. Comparable displacement reduction with lower control effort by 12.

The structure of this paper is organized as follows: Section 2 introduces the system modeling. Section 3 outlines the design of the Adaptive Sliding Mode Control (ASMC). Section 4 provides a detailed presentation and discussion of the results. Finally, Section 5 presents the conclusion.

II. System Modeling

A. Mathematical Model of a Building

The mathematical model of a building is given [14], [15].

$$M\,\ddot{x}(t) + C\,\dot{x}(t) + K\,x(t) = M\,\Lambda\,\ddot{x}_g - \Gamma\,f_{mrd} \tag{1}$$

Where $x, \dot{x}, and\ \ddot{x}$ represent the displacement, velocity, and acceleration vectors of the structure, respectively. $x = [x_1, x_2, x_3, \dots, x_n]^T$, where n represents the number of floors, and in this study, n = 3. $C, K\ and\ M \in R^{n*n}$ represent the damping, stiffness, and mass matrices, respectively. $\ddot{x}_g$ represents the unknown seismic acceleration. $\Lambda \in R^{n*1}$ is a unit vector, f_{mrd} denotes the force generated by the dampers, and $\Gamma \in R^{n*1}$ indicates the position of each damper. This study will focus on a single damper located on the top floor:

$$\Gamma = [0, 0, 0, 0, 0, 1]^T \tag{2}$$

The state equation representation for (1) is as follows:

$$\dot{z} = Az + B\,f_{mrd}(t) + D\ddot{x}_g \tag{3}$$

Where, $B\ and\ D$ are $\in R^{2n*1}$, $A \in R^{2n*2n}$, f_{mrd} is represent the damper force and $z = [z_1, z_2, z_3, \dots, z_n]^T$ represent displacement and $\dot{z}$ represented velocity. The matrices are represented as follows:

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, B = \begin{bmatrix} 0 \\ -M^{-1}\Gamma \end{bmatrix}, D = \begin{bmatrix} 0 \\ \Lambda \end{bmatrix} \tag{4}$$

Where

$$M = \begin{bmatrix} m_1 & 0 & \dots & 0 \\ 0 & m_2 & \dots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & m_n \end{bmatrix},$$

$$C = \begin{bmatrix} c_1 + c_2 & c_2 & \dots & 0 & 0 \\ -c_2 & c_2 + c_3 & \dots & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & \vdots & c_{n-1} + c_n & -c_n \\ 0 & 0 & \vdots & -c_n & c_n \end{bmatrix}, \text{ and}$$

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

Where $m_1, m_2, \dots, and\ m_n$ indicate floors' masses; $k_1, k_2, \dots, and\ k_n$ indicate floors' stiffness coefficients; $c_1, c_2, \dots, and\ c_n$ indicate floors' damping coefficients The mathematical model of the structure subjected to seismic forces The system's schematic, including the building, damper, and control system, is shown in Fig. 1 [40].

In this paper, the building model is a prototype and the earthquake excitation signal is scaled accordingly, as described in [44]. The earthquake used is El Centro 1940 earthquakes [49] which is assumed bounded in this work:

$$|\ddot{x}_g| \leq \delta \quad (5)$$

Where δ is the bound for the unknown earthquake. In the next subsection, the MRD model that is used in this work is presented.

B. Dynamic Model for MRD

The MRD is a semi-active damper that contains a hydraulic cylinder divided by a piston head. The cylinder contains a viscous fluid capable of crossing tiny orifices. The cylinder's two sides are linked by an external valve that controls the device's operation. The semi-active stiffness control device modifies the system dynamics by modifying the structural stiffness. Moreover, it is powered by a small battery, requiring less than 50 Watts of energy. The MRD reacts in milliseconds and works within a temperature range of -40°C to +150°C [40], [44]. MRD is commonly used for seismic control owing to its simplicity of installation and maintenance, along with its compact sizes, supporting installation on any floor of the structure. The MRD illustrated in Fig. 2 [44].

The nonlinear model of MRD which described by the modified Bouc–Wen model, this model was presented by [42], [50]. The applied force proposed by this model is governed by the following equations:

$$f_{mrd} = c_1 \dot{y} + k_0 (x - y) + k_1 (x - x_1) \alpha \xi \quad (6)$$

$$\dot{y} = \frac{1}{c_0 + c_1} (c_0 \dot{x} + k_0 (x - y) + \alpha \xi) \quad (7)$$

$$\dot{\xi} = -\Upsilon |\dot{x} - \dot{y}| \xi |\xi|^{r-1} - \beta (\dot{x} - \dot{y}) |\xi|^r + a (\dot{x} - \dot{y}) \quad (8)$$

Where, x and $\dot{x}$, are taken from the floor where the damper is mounted respectively, f_{mrd}, ξ, k_0 and k_1 are generated force, hysteretic component, accumulator stiffness respectively at low and high velocity. Υ, β, r and a are parameters giving the shape and scale of the hysteresis loop. c_0 and c_1 are the viscous damping at low and high velocity respectively, which depend on control voltage as seen in Eqs (9), (10) (11) and (12) respectively:

$$\alpha = \alpha_a + \alpha_b \mu \quad (9)$$

$$c_1 = c_{1a} + c_{1b} \mu \quad (10)$$

$$c_0 = c_{0a} + c_{0b} \mu \quad (11)$$

$$\dot{\mu} = -F_t (\mu - v_c) \quad (12)$$

In Eq. (12), F_t represents time response factor, μ is a phenomenological variable enveloping the system, and v_c is the command voltage applied to the damper's control circuit. The resulting provided control voltage of MRD is shown below [1], [9], [17]:

$$v_c = v_{max} H[(u - f_{mrd}).f_{mrd}] \quad (13)$$

Where v_{max} is the maximum applied voltage and the range from 0 to 2.25volt, u is the controller signal (control algorithm), and f_{mrd} the force created by MRD. $H(.)$ represents a Heaviside step function.

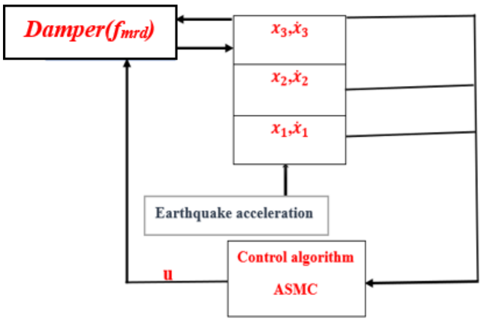


Fig. 1. Schematic representation for structure exposed to seismic vibrations [44]

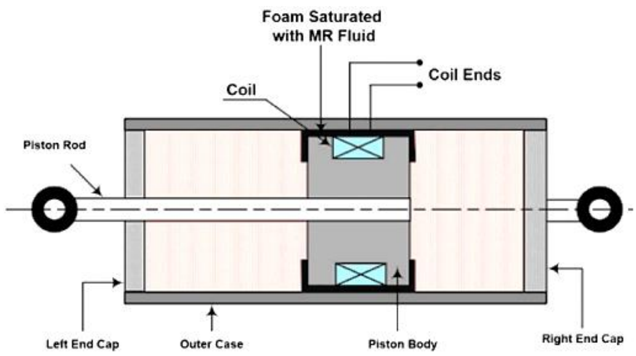


Fig. 2. Cross-section of the MR damper body [44]

III. Adaptive Sliding Mode Control Design

The mathematical modelling of systems for controller design often results in discrepancies between the theoretical model and actual systems due to inherent uncertainties, unmodeled dynamics, and many other factors. Adaptive control is regarded as an effective method for regulating linear and nonlinear systems influenced by uncertainties and disturbances since it facilitates real-time adjustments of controllers to maintain desired performance levels. Adaptive approaches are especially suitable for robust control, as they allow accurate parameter adjustment in dynamic situations where system parameters are either unknown or variable over time. The combination of adaptive control approaches with sliding mode control (SMC) algorithms has resulted in the formulation of adaptive sliding mode control (ASMC), categorized as a variable structure control methodology. ASMC is notably acknowledged for its enhanced capability to manage uncertainties and disturbances, rendering it more efficient than conventional sliding mode control (CSMC). In CSMC design, explicitly accounting for uncertainty and disturbance bounds is essential to ensure sliding motion along the sliding manifold [49], [51]-[56]. However, including these constraints in the control design often leads to excessively elevated control gains, significantly increased control signals. Researchers have worked on creating a flexible, adaptive control gain that is unaffected by uncertainty and disturbance bounds [40], [44], [57], [58]. instead of depending on a fixed gain. This method aims to reduce control effort and undesirable chattering [48].

To illustrate the concept of ASMC, consider the following nonlinear control system:

$$\dot{x} = f(x) + bu\,, b \neq 0 \quad \forall x \tag{14}$$

Where $x \in \mathrm{R}^n$ the state is vector, $f(x,t) \in R^{n\times n} and\ b(x,t) \in R^{n\times m}$ are nonlinear functions furthermore, $f(x,t)$ contains unmeasured perturbations, and $u \in R^m$ is the control law. The sliding variable s is illustrated in the equation below:

$$s = Gx \tag{15}$$

Where, $G = [g_1\ g_2\ \dots g_n\ ]$ to be designed.

The control signal is:

$$u = -k\ sign\big(s(x,t)\big) \tag{16}$$

The reachability of the sliding manifold is guaranteed using the following Lyapunov function:

$$V(s) = \frac{1}{2}\ s^2 \tag{17}$$

$$\dot{V}(s) = s\ \dot{s} \tag{18}$$

The dynamic of sliding variable is:

$$\dot{s} = \frac{\partial s}{\partial x}\dot{x} + \frac{\partial s}{\partial t} = \frac{\partial s}{\partial x}(f(x) + bu) + \frac{\partial s}{\partial t} \tag{19}$$

$$\dot{s} = \left(\frac{\partial s}{\partial t} + \frac{\partial s}{\partial x}\ f(x)\right) + \left(\frac{\partial s}{\partial x}\ b\right)u \tag{20}$$

Where $\left(\frac{\partial s}{\partial t} + \frac{\partial s}{\partial x}\ f(x)\right) = \psi_1(x.t)$ and $\left(\frac{\partial s}{\partial x}\ b\right) = \psi_2(x.t)$

ψ_1 and ψ_2 are bounded functions but their upper bounds are unknown,

$$|\psi_1| \leq \psi_{1M} \text{ and } 0 < \psi_{2m} \leq \psi_2 \leq \psi_{2M} \tag{21}$$

$$\dot{s} = \psi_1(x.t) + \psi_2(x.t)\cdot u \tag{22}$$

From Eq.(22) and Eq.(18) we get:

$$\dot{V}(s) = s\ \dot{s} = s(\psi_1(x.t) + \psi_2(x.t)\cdot u) \tag{23}$$

$$\dot{V}(s) < |s|(\ |\psi_1| - |\psi_2|\cdot k) \tag{24}$$

To ensure the reachability condition, the derivative of Lyapunov function has to be negative definite, for that choose the control gain as follows:

$$k \geq \left|\frac{\psi_{1M}}{\psi_{2m}}\right| \tag{25}$$

The control gain k is constant and contains a significant value to surpass the upper bound of perturbations that the system may encounter, increasing the chattering phenomenon. The upper bounds of uncertainties and perturbations are required for determining its value. All these issues must be addressed, and our solution is to employ the ASMC methodologies. The following subsections describe ASMC technique.

A. ASMCn

ASMC presented in this section is designed for system in (3) this method is implemented for the first time to regulate vibrations in the building. The following control law will be used in this system:

$$u = -k(t)\ sign\big(s(x,t)\big) \tag{26}$$

And the adaptive gain law will be derived based on the methodology outlined below [48]:

$$\dot{k} = \begin{cases} \bar{k}\ |s(x,t)|\ sign(|s(x,t)| - \varepsilon)\,, & if\ k(t) > \mu \\ \mu & if\ k(t) \leq \mu \end{cases} \tag{27}$$

Where, $\bar{k} > 0, \mu > 0$ and ε value must be small and positive and $k > \mu$ for all $t > 0$. We followed the specified parameters when choosing the values of both $\bar{k}$ and (ε). The gain $\bar{k}$ shouldn't exceed the controller's constraints saturation limit of control, whereas a smaller value of (ε) enhances tracking accuracy.

The concept of this methodology is presented in Fig. 3, observe that $k(t)$ increases gradually when $|s| > ε$. $k(t)$ continues to increase until it reaches a stage where the gain $k(t)$ is equal to the perturbation at time t_1 according to Eq. (28). After that from the time interval t_1 to t_2, the $k(t)$ continues to increase, and at time t_2, $|s| = \varepsilon$. Therefore, $k(t)$ stops increasing, which means that k-dynamics equals to zero ($\dot{k} = 0$).

$$k(t_1) = \left|\frac{\psi_1(t_1)}{\psi_2(t_1)}\right| \tag{28}$$

Afterward $|\ s\ | < \varepsilon$, $\dot{k}$ becomes negative, causing $k(t)$ to decrease at $t = t_3$ such as:

$$k(t_3) = \left|\frac{\psi_1(t_3)}{\psi_2(t_3)}\right| \tag{29}$$

Thus, the gain $k(t)$ only increases when necessary to guide $s(t)$ to (ε) region.

After $t = t_3$, the gain k is insufficient to mitigate disturbances so the process thereafter recommences. The gain $k(t_i)$ is uniformly bounded for t_i as shown in Eq. (30) by some value k^{**} as proved in lemma (2) in [48]:

$$k(t_i) = \left|\frac{\psi_1(t_i)}{\psi_2(t_i)}\right| \leq \frac{\psi_{1M}}{\psi_{2m}} = k^{**} \tag{30}$$

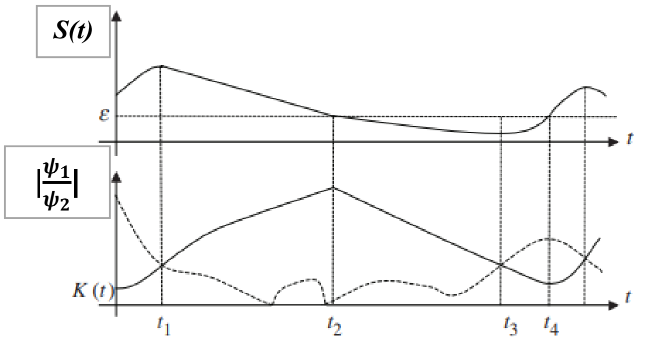


Fig. 3. Describing the behavior of $s(t)$ (top) and $k(t)$ (bottom) with time [48]

B. Eliminating Chattering

Chattering is a serious issue since it causes damage to system. Therefore, the discontinues $sign\ (s\ )$ is replaced by the saturation function by creating small boundary layer. The saturation function represented bellow [59], [60]:

$$sat(s) = \begin{cases} sign(s), & if|s| > \varphi \\ \frac{s}{\varphi}, & if\ |s| \le \varphi \end{cases} \tag{31}$$

Where $\varphi$is the boundary layer width, φ should be less than the value of (ε), so it falls near zero (s=0). The replacement of the sign with saturation decreases chattering; however, the price of having a smooth control function is a less in robustness, which consequently leads to reduced accuracy.

IV. Numerical Simulation

This study employs a scaled model of a three-story building as a case study. Table I illustrates the structural parameters, while Table II outlines the specifications of the employed prototype MR damper and Table III shows the control parameters. The damper is positioned on the top floor, and simulations were performed using MATLAB/Simulink (versionR2018a) with a step size of 0.001second. An ASMCn was developed to regulate the damper. This section presents the simulation results for evaluating the performance of the proposed controller ASMCn in comparison to other methods from the literature. One is newly employed and the other ASMC taken from the literature, in mitigating seismic effects compared to the uncontrolled case (Open-loop). The controlled responses of the first, second, and third floors are presented in Fig. 5 and Fig. 6, respectively, under the influence of the El Centro earthquake shown in Fig. 4, compared to the uncontrolled response. The results showed that both methodologies ASMCn and ASMC achieved a significant improvement in reducing displacement compared to the open-loop condition, and the extent of this improvement was very similar between the two methods. However, in terms of energy consumption, the proposed method achieved a reduction of 8.66% compared to the other adaptive control method, as shown in Fig. 6.

To enhance the reliability of the results, an additional comparison was made between the proposed method and another control method taken from the literature, belonging to the same category of sliding mode control, known as ISMCb. This comparison was conducted using the same prototype structure, the same El Centro earthquake, and the same damper at the same location.

A statistical index Rd_r is used to measure the reduction percentage in displacement compared to the open-loop condition. This rate is calculated based on the specific floor displacement as follows [45]:

$$Rd_r = \frac{|x_i^{max}| - max|x_i|}{|x_i^{max}|} \tag{32}$$

Where Rd is the displacement reduction ratio, x_i is the peak floor displacement, x_i^{max} is the uncontrolled floor peak displacement. The integral sliding control method showed an improvement in reducing displacement of (33) in the three floors by 76.91%, 76.26%, and 76% respectively, while the improvement rates for the proposed method were 81%, 88%, and 89% respectively. As for energy consumption, the proposed method showed good performance, achieving a 12.11% improvement compared to ISMCb. All the statistics are mentioned in Table IV.

TABLE I. System Parameters [49]

Parameter	Value
Mass matrix (M) Kg	$\begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix}$
Damping matrix (C) $N.s$/m	$\begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix}$
Stiffness matrix (K) N/m	$10^5\begin{bmatrix} 12 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix}$

TABLE II. MRD Parameters [49]

Parameter	Value
c_{0a}, c_{0b}	21 $N.s/cm$,3.5 $N.s/cm$
k_0, a	46.9 N/cm, 301
c_{1a}, c_1	283 $N.s/cm$, 2.95 $N.s/$cm
R	2
α_a ,α_b	140 N/cm, 695 $N/$cm
γ ,β	363 cm^{-2}, 363 cm^{-2}
η , x_0	190s^{-1}, 14.3 cm
v_{max}	2.25 v

TABLE III. Control Parameter

Parameter	Value
G	[0 0 0 0 0 1]
μ	3
ε	0.005
φ	0.003
$\bar{k}$	45

TABLE IV. Comparation between Proposed Method and Published Work Under Elecentro 1940 Earthquake

Floor	Index	ISMCb [46]	ASMC [47]	ASMCn
1		76.91 %	81.82 %	81.82 %
2	Rd%	76.27 %	88.18 %	88. 18 %
3		76 %	89 %	89 %
1		0.00127	0.001	0.0010
2	$Max\ \vert x\vert$	0.00197	0.0013	0.0013
3		0.00233	0.00132	0.0013
Over all	$Max\ f_{mrd}(N)$	751	722.6	660

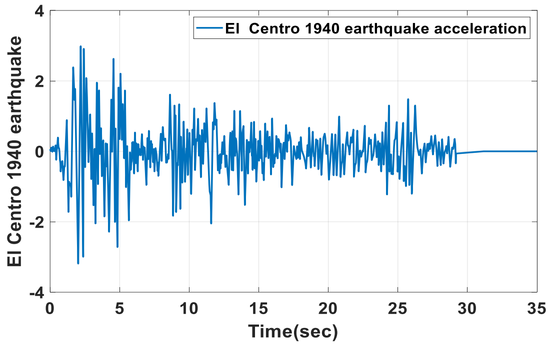
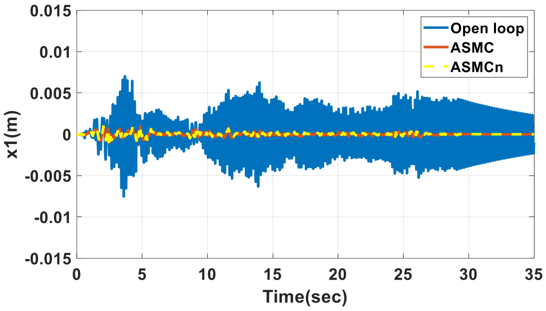
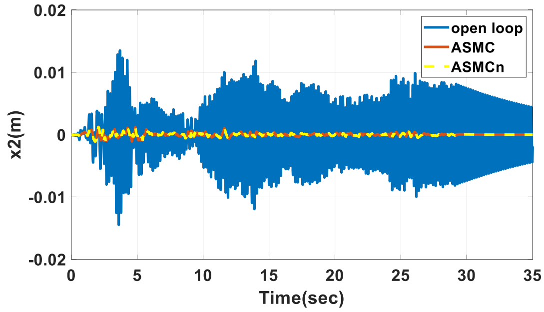


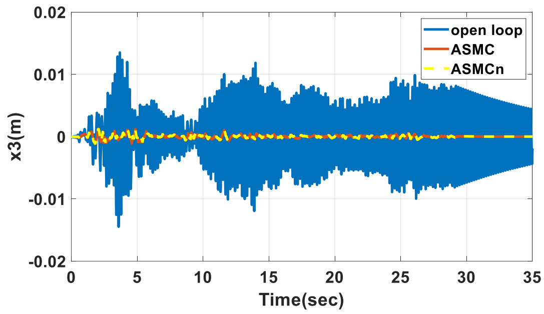
Fig. 4. Time- scaled El Centro 1940 earthquake



(a) First floor



(b) Second floor



(c) Third floor

Fig. 5. Displacements (a, b, c) for the three floors in the open-loop and control-loop cases using methods ASMC [25] and ASMC*

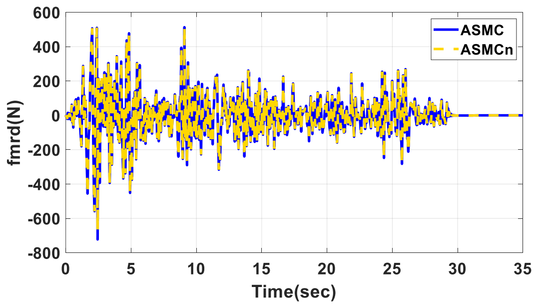


Fig. 6. The control force generated by damper with ASMC [47] and ASMCn

V. CONCLUSION

This study presents an adaptive sliding mode control designed to reduce the vibrations of a building during seismic events. The proposed methodology was evaluated on a prototype three-story building, equipped with an MR damper on the top floor, and the structure was exposed to the scaled El Centro earthquake. The efficacy of the proposed control was validated via numerical simulations, whereby it was compared to two SMC approaches from previous studies: one is adaptive control and the other utilizing Integral SMC with a Barrier function (ISMCb). The results demonstrated the efficiency of the proposed control method in improving the dynamic performance of the structure subjected to seismic events. It has demonstrated a clear ability to achieve significant reductions in displacements compared to the uncontrolled case, while maintaining lower control effort levels compared to other methods in the literature. A decrease in the maximum control effort of approximately 12.11% was recorded compared to the ISMCb method, and 8.66% compared to the ASMC method.

This research presented two different methods for the construction of adaptive sliding mode controllers. Both approaches allow the implementation of sliding mode control laws with gain adaptation, without prior knowledge of the bounds of uncertainties or disturbances, while ensuring that the adaptive gain values are not overestimated. The first approach ASMC depends on the evaluation of perturbations using the equivalent control concept, which necessitates the use of a low-pass filter. The second adaptive control law ASMCn does not estimate the boundary of perturbations and establishes a real sliding mode.

It is worth noting that neither of the two methods ASMCn and ASMC provide a strict guarantee for the persistence of the sliding variable near zero within the ε region. This is due to the effect of perturbation that takes it out of this region temporarily until the gain increases to take it back inside again. Therefore, it is proposed, as a future work, to use ASMC based on the barrier function. This methodology provides an invariant set that maintains the sliding variable inside it, contributing to enhancing the robustness level of the system under external disturbances.

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