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Controlling vibrations in civil engineering constructions subjected to earthquakes using adaptive sliding mode

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Research Article
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Abstract
A number of academics have taken an interest in semi-active regulation of structural vibrations as of late. Proven to be cost-effective, semi-active control systems ensure that structures are secure against earthquake and wind excitations. This research proposes a semi-active device that dissipates the energy required to excite an earthquake by making use of the properties of magneto-rheological fluids. To control the unwanted vibrations of a structure that is excited by an earthquake, the Magneto-Rheological damper is used. In addition, to manage this semi-active device, a sliding mode controller that is connected to the Clipped optimum algorithm is suggested. Numerical simulation results comparing the controlled and uncontrolled structures demonstrate the efficacy of the newly suggested adaptive controller in controlling structural earthquake vibrations. In any case, an adaptive gain law reinforces the sliding mode controller. An excited three-story scaled structure's evaluation indices show the improvement of the sliding mode controller via the adaptive gain law. This leads us to examine the suggested adaptive sliding mode controller and compare its performance to that of an uncontrolled structure subjected to the excitations of the El Centro 1940 and Boumerdès 2003 earthquakes.

Keywords MR damper · Semi-active control · Earthquake vibration · Adaptive control · Sliding mode control

1 Introduction

The most tragic natural disasters in the world are earthquakes, which cause widespread structural damage, the collapse of buildings and bridges, and, tragically, a large number of casualties among humans. On the other hand, the Huaxian 1556 earthquake in China was the worst earthquake in recorded history, killing an estimated 830,000 people [1]. A 9.1 magnitude earthquake and subsequent tsunami ravaged the Pacific coast of Tohoku, Japan on March 11, 2011, killing over 20,000 people [2]. Two powerful earthquakes struck Algeria. The first was the October 10, 1980, El Asnam earthquake, which had a magnitude of 7.2 and left 300,000 people without homes, 25,000 homes demolished, and 2500 people dead [3]. The second one was the 6.8-magnitude Boumerdès earthquake that occurred on May 21, 2003, which left over 15,000 people homeless and over 2200 dead [4]. Many numerical and experimental investigations on structures subjected to dynamical loads have focused on developing structural control strategies during the last several decades [5]. Yet, by using an external device to dampen the dynamic motion of the structure brought on by earthquakes and wind excitations, structural control provided a substantial extra layer of protection to the structures. There are three tiers of structural control, based on how the external device dissipates dynamic energy: passive, active, and semi-active [6]. Hybrid control is the fourth range that is defined as a mixture of two of the previously mentioned ranges.

Several historical structures were constructed using the concept of seismic base isolation,

which is one of the oldest forms of vibration control known as passive control [7]. So far, a lot of people have put a lot of effort into studying the passive control evolution, and a lot of ground has been covered. A number of researchers were interested in passive control systems because of how easy they were to implement. Hence, these systems are able to manage the vibrations of the building by using its motion. in order to create the necessary forces. They can absorb some of the seismic energy and are inexpensive to install and run on their own power. Nevertheless, these passive systems cannot be adjusted to accommodate different structural conditions or loads. However, in Japan in particular, passive control is used in a number of bridges and constructions. A tower controlled passively using a Tuned Mass damper was first used on the Chiba Port Tower. Analyses of the structural reactions to many earthquakes demonstrated that the Tuned Mass Damper was successful in controlling the 125-meter structure [8]. To manage a steel structure with five stories, it is suggested to use a Tuned Mass Damper that is reinforced with an effective particle damper. Experimental, analytical, and numerical studies were used to evaluate the proposed control under seismic excitation [9]. Nonetheless, the effectiveness of the suggested control was examined by analyzing the structural reactions, and the ideal settings of the Tuned Mass dampers were examined in the context of passive control under seismic record excitations [10].

Other than that, active control technique implementation for exciting structural vibration mitigation has been the center of attention in recent studies. However, for real-time actuator operation, a sizable power source is necessary in this class. To determine the reactions of the controlled structure and communicate that information to the treatment unit, this control relies on a number of sensors. Therefore, an adequate control law determines the necessary control force, and the actuator produces that force. The passive method was shown to be less effective in comparison to this strategy in many investigations.

In [11], researchers looked at the possibility of controlling an eleven-story building with a particle swarm optimization method and a fuzzy logic controller for the active mass damper. Through numerical simulations conducted under several seismic excitation records, the effectiveness of the suggested regulation was shown. The effects of soil-structure interaction were taken into account when investigating a 40-story building that had an active tuned mass damper and had been subjected to various earthquake experiments. A combination of the proportional integral derivative controller and linear quadratic regulation ensured active control, while particle swarm optimization was used to improve the tuned mass damper settings. Furthermore, the suggested regulation reduced the tall building's peak displacements, both with and without taking the effects of soil-structure interaction into account [12].

Because of its simplicity and durability, the semi-active control method is now receiving a lot of interest for its ability to decrease structural vibrations generated by earthquake or wind excitations. These gadgets are easier to use, more environmentally friendly, and do not need a large amount of electricity from an external source. In a perfect world, this setup would guarantee both the responsiveness of the active control system and the dependability of the passive one. Earthquake applications in civil engineering have made use of a wide range of semi-active devices. However, because of their simplicity and robustness, magneto-rheological and electro-rheological dampers are the most commonly employed devices in semi-active control.

In their study, Zahrai and Salehi [13] compared the semi-active control

performance of two different building models: one with nine stories and the other with twenty. In order to regulate the current driver, the MR damper was managed by a linear optimal controller that was connected to a clipped optimum algorithm [13]. To manage the vibrations of a three-story building that was scaled down, an active control system that included MR dampers was suggested. However, in order to manage the MR damper and the device's current, a linear quadratic regulator was developed. The results of the numerical simulations comparing the managed and uncontrolled structures under the time scaled record of the El Centro 1940 earthquake demonstrated the effectiveness of the suggested semi-active control system [14].

The potential of hybrid control systems lies in their ability to integrate the greatest features of active and passive control systems. Several structural control vibration reduction applications involved this system. We study the vibration control of a one-degree-of-freedom structure using a hybrid mass-liquid damper that consists of a passive liquid damper coupled to a tuned mass damper. For optimal performance in the face of harmonic and earthquake excitations, the research zeroed in on the suggested hybrid control system's design parameters [15]. A hybrid control system that combines a base isolation system with an active mass damper that is controlled via a feedback loop that is linear and quadratic in nature was presented. Numerical simulations of a 6-story building jolted by the El Centro, Northridge, and Loma Prieta earthquakes demonstrated the efficacy of the suggested hybrid control system [16]. A dependable control rule is the key component of active or semi-active control separation from both a theoretical and experimental perspective. However, this control law calculated the necessary control forces to dampen the vibration's structure while maintaining stability and resilience in the face of a wide range of external dynamic situations. This is why there have been studies comparing and evaluating different control laws, and the results may be grouped into two categories. The classical models are the first kind; they use a mathematical model based on the Lyapunov stability principle, regardless of whether the underlying law is linear or not.

In any case, intelligent models that do not need a mathematical model with shown stability constitute the second category. The control laws have been the subject of investigation by several scholars in the last few years. Protecting the classical linear quadratic regulator's performance control from outside disturbances is the goal of designing a robust linear quadratic regulator [17]. On the other hand, vibration cancellation examines the behavior of a flexible beam with the use of a linear quadratic Gaussian controller. Two kinds of uncertainty may be handled by the executed controller: modeling uncertainties and measurement noise [18]. An active mass damper is used to manage the vibration of a three-story scaled structure by use of a nonlinear sliding mode controller. To avoid the chattering issue, the suggested nonlinear controller has a saturation function. The proposed control was proven reliable by the numerical simulation results of the tested three-story structure subjected to a time-scaled Mexico City earthquake [19]. The alternative is a neural network controller-based intelligent control for nonlinear dynamic systems. A supervised learning algorithm trains the remaining neurons, while the controller's design allows the input and hidden layer neurons to adapt through self-organized learning [20]. On the other hand, a hybrid controller takes the best features of two different types of controllers and combines them into one. This makes it a third kind of controller. Additionally, to manage an Active Tuned Mass damper, a hybrid controller that incorporates both the Proportional Integral Derivative (PID) and a

Linear Quadratic Regulator is suggested. Consequently, using four earthquake records, the hybrid control is assessed for its ability to reduce seismic structural vibrations in a ten-story stimulated building [21].
In order to lessen the effects of seismic vibrations on structures, this work aims to provide a semi-active control system that makes use of MR dampers. However, in order to determine the necessary force control for the MR damper, a sliding mode controller suggests a nonlinear law of control. A gain adaption rule is implanted to conduct the nonlinear controller. Nevertheless, a Clipped optimum technique is now being used to direct the driver. Nevertheless, numerical simulation results comparing the reactions of the controlled and uncontrolled structures are used to assess the suggested semi-active control. El Centro in 1940 and the Boumerdès in 2003 are two time-scaled earthquake records that were used to excite the tested structure, which is a three-story scaled building.
The remaining sections of the article are structured as follows: Section presents the model of the tested scaled structure subjected to earthquake excitation. Section 2 therefore provides a synopsis of the MR damper medialization. Section 3 designs the driving algorithm and nonlinear controller with an adaptation rule. Section 5 therefore focuses on the numerical example for evaluating the proposed semi-active control's efficiency. Presenting the conclusions and comments taken from the investigation, the current study came to a close.

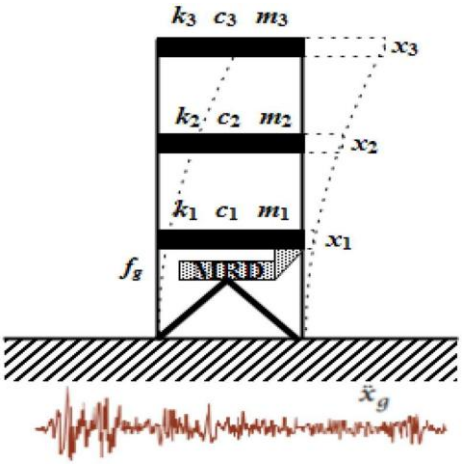


Fig. 1 Diagram of scaled structure model with the MR damper implan- tation

The MR damper is placed between the ground and the first floor and the governing equation of motion can be written

$$M_s\ \ddot{x} + C_s\ \dot{x} + K_s\ x = M_s \Lambda \ddot{x}_g + \Gamma\ f_g \quad (1)$$

where $\ddot{x}$, $\dot{x}$ and x are respectively acceleration, velocity and displacement vector of the floor's relative to the base, M_s, C_s and K_s are respectively mass, damping and stiffness matrix of the scaled structure with 3 × 3 dimensions, $\ddot{x}_g$ is the ground motion acceleration, $\Gamma = -1\ 0\ 0\ ^T$ is the vec- tor describing the MR damper's position, $\Lambda = 1\ 1\ 1\ ^T$ is the earthquake acceleration effect vector's and f_g is the control force generated by the MR damper.

In the state-space the system of Eq. (1) can be presented as

$$\dot{z} = Az + Bf_g + E\ddot{x}_g$$
$$y = Cz + Df_g + G\ \ddot{x}_g \quad (2)$$

where $z = x\ \dot{x}^{\ T}$ is (6 × 1) dimensional state vector, y is a measured output vector. The matrices $A^{6\times6}$, $B^{6\times1}$ and $E^{6\times1}$, $C^{6\times6}D^{6\times1}$ and $G^{6\times1}$ are the state space spaces matri- ces which can be expressed as

2 MR damper model

Figure 2 shows an MR damper, which is one of the most prospective devices for semi-active structural control vibrations caused by seismic excitations. The device's stated benefits, such as reversibility and stability under earthquake or wind stresses, are the reason for this. On the other hand, controlling structural vibrations was made very difficult by the MR damper's highly nonlinear dynamic behavior [22]. One kind of fluid that may be controlled to alter its rheological behavior when exposed to a magnetic field is the magneto-rheological fluid, which can be used in MR dampers. Milliseconds are all it takes for the magneto-rheological fluid to go from liquid to semi-solid to solid, which in turn alters the force exerted by the damper. Multiple investigations and behavioral modeling of the magneto-rheological fluid have been conducted since its discovery [23]. It was Bingham's basic plastic model of magneto-rheological fluid dynamics that was first proposed [24]. However, the Bingham model was generated by the three constants Her- schel–Bulkley fluid model in which the nonlinear flow of the rheological fluid is considered [25]. However, other academics were intrigued by the Bingham model's simplicity, which led to its extension to a typical linear model in serial [26]. On the other hand, the hysteretic behavior of the magneto-rheological fluid was not considered in the construction of these models. Alternatively, Bouc put out a model that accounted for this conduct; moving forward, Wen expanded on this model and dubbed it the Bouc-Wen model. It has

$$a = a_a + a_b u \quad (12)$$

$$c_1 = c_{1a} + c_{1b} u \quad (13)$$

$$c_0 = c_{0a} + c_{0b} u \quad (14)$$

$$\dot{u} = -\eta(u - v) \quad (15)$$

where x and $\dot{x}$, are respectively displacement and velocity of the device, f_g and z are respectively the generated force by the device and the hysteretic component of the device, 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 of the shape loop, u and v are the command input phenomenological variable and the command voltage applied to device, η is a time constant of the first order filter of the Bouc–Wen model and y is the displacement of the damping c_1.

The parameters are defined as c_{0a} = 21 N s/cm; c_{0b} = 3.5 N s/cm; k_1 = 5 N/cm; k_0 = 46.9 N/cm; a_a = 140 N/cm; a_b = 695 N/cm; c_{1a} = 283 N s/cm; c_{1b} = 2.95 N s/cm; A = 301; γ = 363 cm^{-2}; β = 363 cm^{-2}; η = 190 s^{-1}; n = 2; x_0 = 14.3 cm

The hysteresis behavior of the MR damper under a sinusoidal displacement of 1.5 cm amplitude and 2.5 Hz fre- quency with a constant voltage levels of 0 V, 0.5 V, 0.75 V and 1.25 V respectively are depicted in Figs. 3, 4 and 5. However, the Fig. 3 presented the generated force of the MR damper function of time. Moreover, the generated force of the device function of its displacement is depicted in Fig. 4. Whereas, the generated force of the damper-velocity hysteresis loop is presented in Fig. 5.

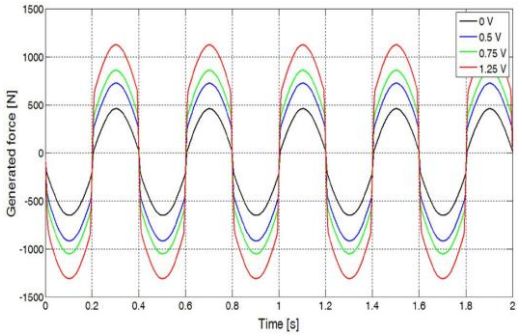


Fig. 2 Generated force of the simulated Bouc–Wen model under sinu- soidal excitation

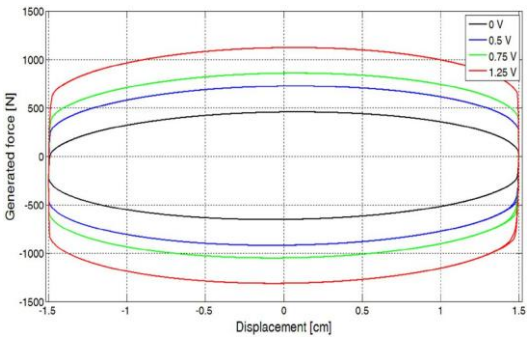


Fig. 3 Force-displacement hysteresis loop of the simulated Bouc–Wen model under sinusoidal excitation

simplify the control design by separating the system's motion into lower-dimensional systems. The chattering issue, which involves oscillations of limited amplitude and frequency, so impacts the sliding mode controller's resilience.

An assortment of chattering suppression techniques, including as the observer-based technique, the state-dependent gain approach, and the boundary layer method, have been implemented for sliding mode control in recent times [31]. Sliding mode control used a two-step discontinuous control signal to drive the system's dynamics to the desired value. The first step is the reaching phase, during which the system's trajectory is guided to the sliding surface by the control. The second part of the process is the sliding phase, during which the system's trajectory slides across the surface and continues to slide [32]. Now, we'll have a look at the system of nonlinear dynamics given by

$$\dot{x} = f(x, t) + g(x, t)u \quad (16)$$

where x is the state vector, u is the desired control, $f(x)$ and $g(x)$ are smooth uncertain functions with $g(x) /= 0$.

The general presentation of the sliding surface is defined

$$\sigma = Se \quad (17)$$

$$e = x - x_d \quad (18)$$

where $S^{1\times6}$ is the sliding surface coefficient matrix of switch- ing, e is the tracking error of the system and x_d is the desired response. The sliding surface is governed by

$$\sigma(x) = 0$$
$$\dot{\sigma} = \frac{\partial \sigma}{\partial x}\dot{x} = \frac{\partial \sigma}{\partial}(f(x,t) + g(x,t)u) = 0$$

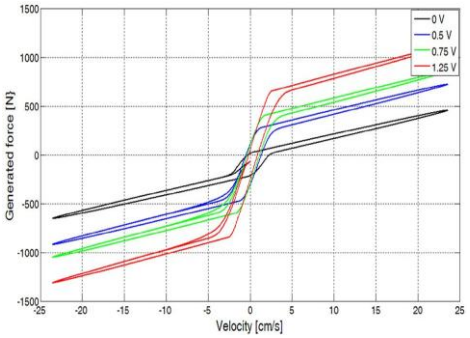


Fig. 4 Force-velocity hysteresis loop of the simulated Bouc–Wen model under sinusoidal excitation

3 Semi active control algorithm

One of the interesting nonlinear controller in semi-active controlled devices is the sliding mode controller (SMC) especially in civil engineering area. This control was early appeared in the 1960s from Emel'yanov and Barbashin works

$$u_{eq}(x, t) = -(\sigma(x)g(x, t))^{-1}\sigma(x) f(x, t) \quad (23)$$

where M is the control gain and sgn(·) is the signum function defined as sgn(σ) =

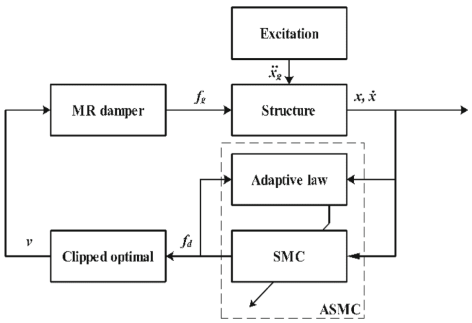


Fig. 5 Block diagram of the semi-active control system

$$\begin{cases} -1 & \text{if } \sigma < 0 \\ 0 & \text{if } \sigma = 0 \\ 1 & \text{if } \sigma > 0 \end{cases} \quad (24)$$

Hence, the boundary layer approach is one of the most popular ways to lessen the chattering effects. Building a protective barrier over the surface of a discontinuity without compromising the controller's resilience is the key idea. Outside of this boundary layer, nevertheless, the control rule is very much like the sliding mode law. Alternatively, Eq. (23) is provided by and continuous control is guaranteed within the boundary layer [33].

$$u_d = M \cdot \text{sat}\left(\frac{\sigma}{\xi}\right) \quad (25)$$

where ξ is the boundary layer thickness and sat(·) is the sat- uration function defined by make possible the adjustment of the control gain accurately with the uncertainties/disturbances variation.

20)

This solution can be presented in the state space as

$$u_{eq}(x, t) = -(S \cdot B)^{-1} S Az + E \ddot{x}_g \quad (21)$$

To enforce the sliding mode ($\sigma = 0$) the component-wise control law have to satisfy the following condition

$$u^{+}(x, t)\ \sigma > 0$$

[29, 30]. Due to its strong robustness and easy implemen- tation this controller is considered as one of the robust

$$\dot{\sigma}(x) \cdot \sigma(x) < 0 u = u^{-}(x, t)\ \sigma < 0 \quad (22)$$

controllers used in complex high-order nonlinear dynamic
Thus, to ensure that σ and $\dot{\sigma}$ are of opposite signs the problems. Whereas, the sliding mode controller is low sensi- tivity controller to the parameter variations and disturbances of the system in addition to that the sliding mode controller expression for the control variable u_d is written as

$$u_d = M \cdot \text{sgn}(\sigma) \quad (26)$$

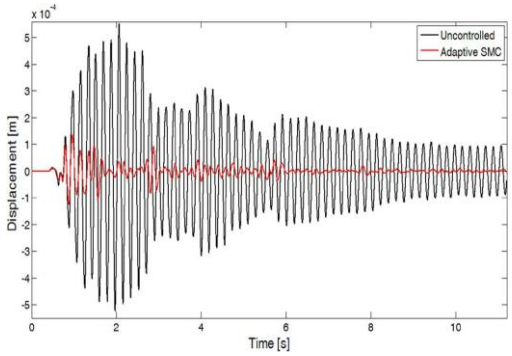


Fig. 6 Displacement responses of 1st floor under the 1940 El Centro earthquake

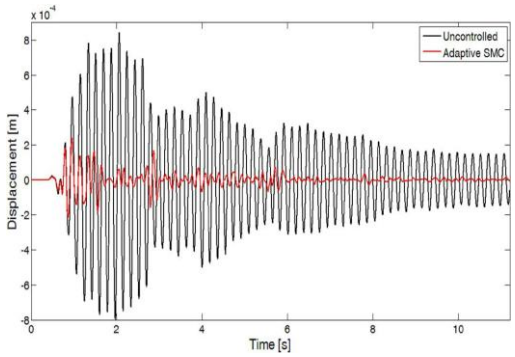


Fig. 7 Displacement responses of 2nd floor under the 1940 El Centro earthquake

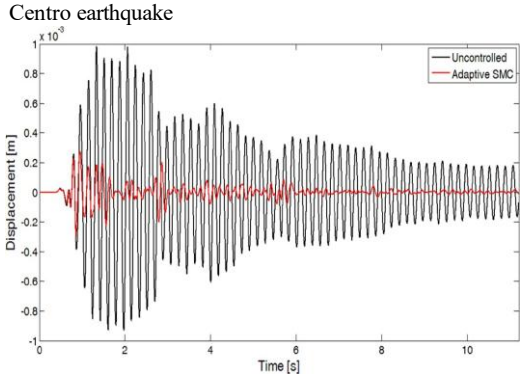


Fig. 8 Displacement responses of 3rd floor under the 1940 El

Centro earthquake

15 illustrate the relationship between the applied voltage to the MRD driver and the temporal responses of the adaptive switching gain during the 1940 El Centro earthquake excitation. Switching gain grows and shrinks with respect to the sliding surface (i.e., the error tracking), as shown by the findings. Fig. 16 shows the results of comparing the adaptive SMC

damping force generated by the MR damper with the traditional SMC under conditions of random displacement and input current from the 1940 El Centro earthquake. The picture shown

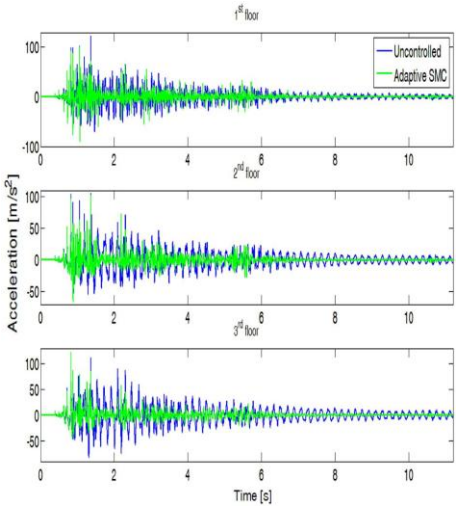


Fig. 9 Acceleration responses of the 1st, 2nd and 3rd floor under the 1940 El Centro earthquake

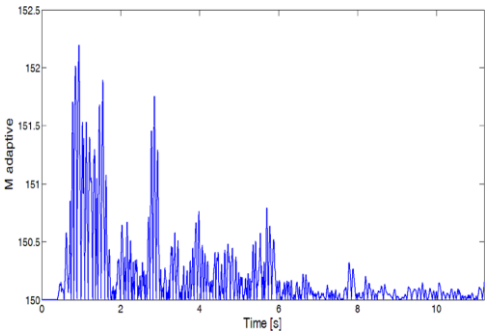


Fig. 10 Adaptive switching gain time record under the 1940 El Centro earthquake

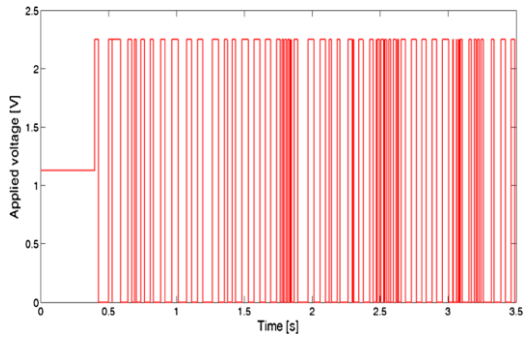


Fig. 11 Command voltages applied to MR damper driver under the 1940 El Centro earthquake

demonstrate the displacement responses of the regulated structure and the uncontrolled structure, respectively, during the Boumerdès 2003 earthquake excitation. Figure 20 shows that, in comparison to the uncontrolled structure, the adaptive sliding mode control effectively reduced the accelerations of the floor during the Boumerdès earthquake excitation of 2003. Fig. 21 shows the temporal responses of the adaptive switching gain during Boumerdès earthquake excitation 2003, while Fig. 22 shows the applied voltage to the MRD driver. The values of the sliding surface clearly have an effect on the switching gain, which can go up or down. Figure 23 shows the comparison between the traditional sliding mode control and the adaptive sliding mode control-calculated produced force of the MR damper during the Boumerdès 2003 earthquake.

Fig. 18 Displacement responses of 2nd floor under the 2003 Boumerdès earthquake

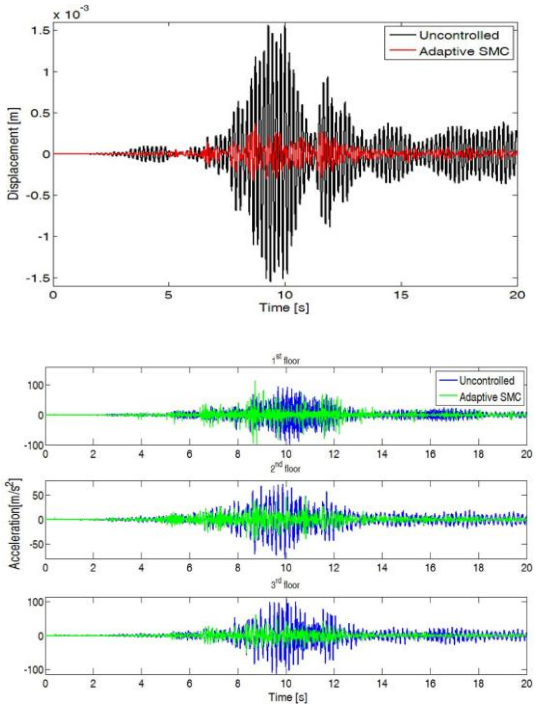


Fig. 12 Displacement responses of 3rd floor under the 2003 Boumerdès earthquake

Fig. 13 Acceleration responses of the 1st, 2nd and 3rd floor under the 2003 Boumerdès earthquakethe reducing story drift ratio in J1. Nonetheless, the J2 index evaluated the floor acceleration level reduction. Whereas, the earthquake maximum shear base reduction is calculated using J3 where is esteemed by 10% under the 1940 El Centro earthquake and 32% under the 2003 Boumerdès earthquake. Otherwise, the J4 index shown the peak control force reduc- tion using the normed inter story drift ratio.

4 Conclusions

Numerical results validate the effectiveness of the suggested semi-active approach for controlling the MR damper, which is based on an adaptive sliding mode controller in conjunction with the Clipped optimum algorithm. Additionally, the suggested control has the capacity and resilience to lessen the seismically stimulated structure's reactions, as shown by the numerical simulation findings. Alternatively, the adaptive rule that is a part of the sliding mode control system helps to keep the system's response on the sliding surface without estimating the border of uncertainties or disturbances. The results show that the adaptive sliding mode control works as expected on a numerical simulation. The suggested semi-active control was also shown to be effective in reducing unwanted structural vibrations, as shown by the computed evaluation indices. On the other hand, civil engineering structures that are subject to earthquakes can benefit from the suggested semi-active control system, which uses a clipped optimal current algorithm in conjunction with an adaptive sliding mode controller to control a damper in the MR system.

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