


Adaptive backstepping sliding mode control design for vibration suppression of earth-quake building supported by magneto-rheological damper

Journal of Low Frequency Noise,
Vibration and Active Control
2021, Vol. 0(0) 1–16
© The Author(s) 2021
DOI: 10.1177/14613484211064659
journals.sagepub.com/home/lfn


Amjad J Humaidi¹ , Musaab E Sadiq², Ahmed I Abdulkareem¹, Ibaheem K Ibraheem^{3,4} 
and Ahmad Taher Azar^{5,6}

Abstract

In this study, the design of adaptive backstepping sliding mode control (ABSMC) has been developed for vibration suppression of earth-quake building supported by magneto-rheological (MR) damper. The control and adaptive laws developed based on ABSMC methodology has been established according to stability analysis based on Lyapunov theorem. A Single degree of freedom (SDOF) building system has been considered and the earthquake acceleration data used in performance analysis of the proposed controller is based on El Centro Imperial Valley Earthquake. The ABSMC has been compared to classical sliding mode control in terms of vibration suppression in the controlled system subjected to earthquake. The performance of proposed controller has been assessed via computer simulation, which showed its effectiveness to stabilize the building against earthquake vibration and the boundness of estimated stiffness and viscosity coefficients.

Keywords

Earthquake, vibration, structural building, adaptive control, backstepping control, sliding mode control

Introduction

Earthquakes are responsible for the destruction and severe damage to buildings and structures because of their peak accelerations.¹ They are one of the most destructive natural hazards that cause great loss of life (10,000 people die each year due to earthquakes). In Algeria, for example, the EL-Asnam earthquake of 10 October 1980 with a magnitude of 7.2 destroyed at least 25,000 housing units and made 300,000 people homeless, while the main shock had killed about 2500 peoples.² Over the past few decades, safety of structural systems against earthquake motions is one of the most important challenges in the life cycle of a building. Therefore, the control of structural vibration mitigation has attracted several researchers from theoretical and experimental side.³

A passive control system consists of devices attached to a structure without requiring an external power source to operate with limited control performance. This technology is dedicated to reinforce or modify the stiffness and damping of building structure. On the other hand, the active control system requires large external power source. They show better performance

¹Control and System Engineering Department, Baghdad, Iraq

²General Company for Grain Processing, Ministry of Trade, Baghdad, Iraq

³Department of Computer Engineering Techniques, Al-Rasheed University College, Baghdad, Iraq

⁴Department of Electrical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq

⁵College of Computer & Information Sciences (CCIS), Prince Sultan University, Saudi Arabia

⁶Faculty of Computers and Artificial Intelligence, Benha University, Egypt

Corresponding author:

Amjad J Humaidi, Control and Engineering Department, University of Technology, Al-sina Street, Baghdad 10001, Iraq.

Email: amjad.j.humaidi@uotechnology.edu.iq



Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (<https://creativecommons.org/licenses/by/4.0/>) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (<https://us.sagepub.com/en-us/nam/open-access-at-sage>).

than passive systems, but on the price of reliability and cost. Semi-active control systems are class of active control systems with small external energy requirements which can in real-time tracked the motion of structure to develop the control forces guarantying the structure stability. Recently, many control algorithms and semi-active devices have been investigated for earthquake hazard mitigation especially magneto-rheological (MR) dampers due to their numerous advantages. The MR dampers are smart devices with synthetic fluids changing their viscosity from liquid to semi-solid state in milliseconds if an electric or magnetic field is applied, low-power requirements, mechanical simplicity, low cost, high dynamic range, and very fast excellent control effect responses.²

The control strategies applied to control MR dampers for structural vibration mitigation are ranged in two classes. The first one is the classical category which requires a mathematical model based on Lyapunov stability.³ The second one is the intelligent category which does not require a mathematical model of the system.⁴ Another category called a hybrid control is the combination of the tow precedents categories.⁵

Many researchers have presented different control strategies to address the vibration control problem in structures suffering from earthquakes. The following researches interviews the recent control strategies designed to mitigate the impact of vibration on earth-quakeed systems.

Zizouni et al. proposed a robust Linear Quadratic Regulator (LQR) for semi-active control of three-story structure supported by MR damper. The control design is devoted to both suppressing the seismic vibration and minimizing the input energy of the MR damper.² In Ref. 1, Çetin et al. designed an adaptive controller for vibration suppression of structural system against earthquake excitation and wind loading based on a semi-active MR damper. The unmeasurable internal state variables are estimated using nonlinear observer. Royel et al. developed a nonlinear control design based on second-order sliding mode control to inhibit the external earthquakes or dynamic loadings for smart structures, which is integrated with MR fluid damper.⁶ In Ref. 7, Zizouni et al. neural network controller to mitigate the vibrations of 3-story scaled structure. The control methodology is based on linear quadratic (LQ) control for actuating the MR damper. A clipped optimal algorithm is combined with the proposed controller to adapt the control voltage fed to the MR damper. In Ref. 8, Guclu has combined robust sliding mode control (SMC) and proportional integral derivative controller for active-seismic control of multi-degree-of-freedom structural system against earthquakes to suppress the building vibrations. Khalatbarisoltani et al. proposed reinforcement learning-based controller for active structural control systems subjected to seismic uncertainties. The control methodology is based on online tuning the gain-scheduling PD fuzzy controller. A state predictor is combined with proposed controller to solve the time delay problem.⁹ Chen and Lai have combined a transfer system with a modern control strategy for shaking tables in order to mimicking the responses of high-rise buildings subjected to earthquakes. Three nonlinear controllers and three linear controllers are designed and synthesized to verify the feasibility and applicability of the proposed strategy.¹⁰ In Ref. 11, Afkham and Ehteram have deigned sliding mode control for nonlinear-modeled buildings in the presence of earthquakes. The proposed controller could significantly reduce the floor displacements of building under earthquakes. Schlacher et al. presented a class of a hybrid control systems for earth-quakeed high-raised buildings based on passive base isolation supported by active damper. The control law has been designed to solve the disturbance decoupling problem by approximation. The stability of controlled system has proven based on Liypunov theory and dissipative systems to yield robust control against seismic vibration.¹² Chang and Sung presented a neuro-control algorithm based on structural modal energy for a 3-story nonlinear building supplied with active mass damper to suppress the earthquake vibration. The control algorithm showed more effectiveness in reducing the structural response and modal energy as compared to non-controlled response and a multilayer perceptron.¹³ In Ref. 14, Shan et al. proposed model reference adaptive control to reduce the effect of earthquake to excited structures. The adaptive control law is developed based on backstepping theory and the stability of controlled system was analyzed considering a little prior knowledge of structural model and parametric effects due to actuator saturation and the switching delay. In Ref. 15, Alli and Yakut have designed fuzzy sliding-mode control (FSMC) for seismic isolation of 8-story shear building excited by earthquake. The FSMC could remove the chattering effect without losing the robustness against parametric uncertainties, modeling inaccuracies and varying dynamic loads. In Ref. 16, A. Rayegani and G. Nouri have investigated the performance of MR damper to prevent seismic pounding in isolated buildings with different gap distances. For each gap distance, the fuzzy logic control of MR damper has been optimized to prevent pounding and to improve the behavior of structure as compared to isolated pounded building. In Ref. 17, Li et al. presented an adaptive model reference sliding model control design to suppress the vibrations of a multi-degree-of freedom nonlinear structure supported with active-mass damper subjected to earthquake excitation. A modified unscented Kalman filter is developed to adaptively identify the unknown states and parameters necessary for control forces. Yao et al. have applied a semi-active control based on MR damper to a vehicle suspension system. Firstly, MR damper has been designed and tested in flow mode and a Bouc-Wen model was adopted to characterize the performance of designed damper. The coefficients of the damper have been optimized numerically and experimentally. The semi-active control strategy together with MR damper has been applied to vibration

control of suspension vehicle.¹⁸ In Ref. 19, Saidi A et al. proposed an adaptive sliding mode control for vibration mitigation of scaled three-story building structure supported by MR damper fixed at ground floor. A comparison study has been conducted between controlled and uncontrolled structures subjected to the same excitation of earthquake. In Ref. 20, Yuksel H. and Nurkan Y. have presented adaptive backstepping control design for vibration suppression of uncertain nine-story building structure. The building is supported by tuned mass damper established on the top floor. The stability of controlled building model is guaranteed and the effectiveness of controller has been verified. In Ref. 21, Fali L et al. presented sliding mode control design based on adaptive gain law for controlling the vibration of three-story scaled structure subjected to earthquake excitation. The structure is equipped with semi-active device (MR damper) which is fed by required force control to suppress unwanted vibrations of shaking structure. A Clipped optimal algorithm is applied for commanding the current driver.

The Variable Structure Control with Sliding Mode Control (SMC) was developed by Emelyanov and his team assistances in the early 1950's. The SMC methodology is an effective tools which it aims to design a controller for a nonlinear, complex, high order and time varying systems in the presence of certain or uncertain parameters variations and external disturbances.^{22,23} The main advantage of the SMC that it is low sensitive for system parameters variations and disturbances which restricted the necessity of exact modeling.²⁰ The SMC replaces the dynamics of a system by application of a discontinuous control signal that forces the system to slide along a stable manifold known as sliding surface.^{24,25}

The SMC introduces control law which can be distributed into two main parts (equivalent part and switching part). The equivalent part deals with dynamic of the system and sliding surface such as to conduct the trajectory of the states toward the sliding surface. The switching part of control signal is responsible for driving states trajectory to equilibrium point by maintaining the dynamics of the system onto the sliding surface.^{26,27} In the control action of the SMC, there is undesired phenomena known as chattering, which is caused by the high frequency oscillation of the sliding variable around the sliding surface, and it is one problem in using sliding mode technique.²⁷

The backstepping control procedure depends on the concept of simplifying the complex nonlinear system by decomposing it into lower orders subsystems.^{28,29} This is based on the fact that in each equation of the system mathematical model and subsystem, one of the coordinates acts as a virtual, and this coordinate has to appear in an affine way in each equation.³⁰ It is a nonlinear control method based on the Lyapunov theorem with advantage of design flexibility because of the recursive use of Lyapunov functions.³¹ The combination of sliding mode control and backstepping control can simplify the design of backstepping controller, also enhanced the robustness of the controller and the overall system to the undesired external disturbances.³² In addition, it has been shown that the chattering effect in using SMC is considerably reduced by fusing both SMC and backstepping control.

In the practical applications, the problem with the presence of uncertainty, external disturbances or unwanted vibration is that their bounds cannot be determined precisely. The adaptive control technique is used to adapt the parameters of controller such as to cope with these uncertainties, disturbances or vibration such as to keep the controlled systems within stability margins.^{33–36}

One critical problem with building systems subjected to earthquakes is that their parameters such as spring and viscosity coefficients encounter evitable variations under earthquake vibration. Therefore, one solution to fix this problem is to propose an adaptive control. In order to have the robustness power of sliding mode control and the effectiveness of backstepping control theory, the Adaptive Backstepping Sliding Mode Control (ABSMC) has been proposed for vibration suppression of building supported by MR damper. This is a new control design, which has not been addressed previously. The present work proposed three nonlinear controllers, represented by SMC, BSMC, and ABSMC, to control and guarantee the stability of Earth-quake building with the assistance of MR damper. The contributions of this study can be highlighted as follows:

1. To solve the problem of vibration control in building, supported by MR damper and subjected to earthquake, by developing new algorithms based on SMC, BSMC, and ABSMC.
2. To prove the asymptotic stability of controlled building in the presence seismic vibration for the three proposed controllers (SMC, BSMC, and ABSMC) such that all errors finally converges to their corresponding zero equilibrium conditions.
3. To show the boundness of estimated viscosity and stiffness coefficients of adaptively-controlled building system.
4. To show the superiority of ABSMC performance as compared to SMC in terms of vibration suppression.

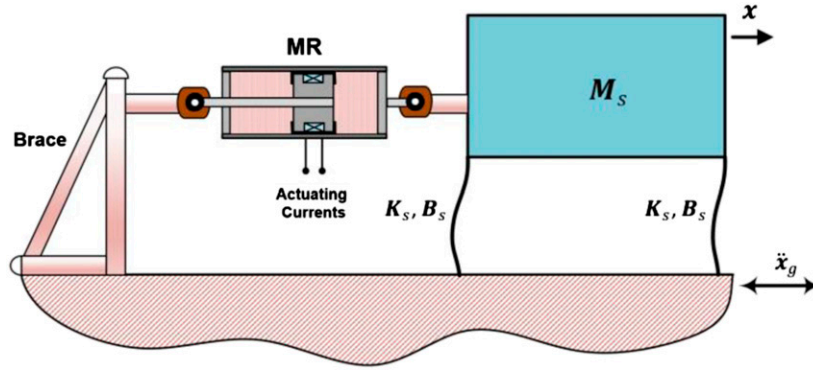


Figure 1. Schematic representation of Earth-quaked building supported by MR damper. Note: MR: magneto-rheological.

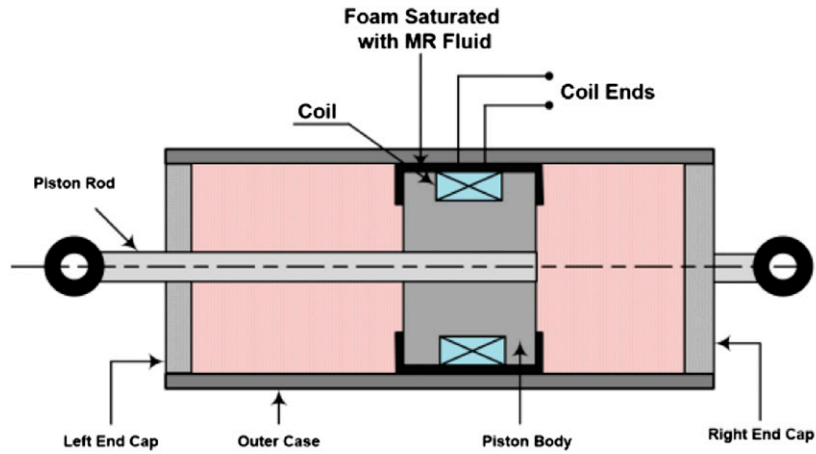


Figure 2. Schematic representation of MR damper.

Dynamic model

In this study, the used building structure model is equipped with an MR damper located between the ground and a brace as shown in Figure 1. It has been shown that the control force in this floor is more effective than the control force of MR damper located in the upper floors.³⁷ This structure is seismically subjected to acceleration \ddot{x}_g .

The general equation of dynamic motion for the structural system shown in Figure 1 can be described by

$$M_s \ddot{x} + B_s \dot{x} + K_s x = M_s \ddot{x}_g + f_{MR} \quad (1)$$

where x , \dot{x} , and \ddot{x} are displacement, acceleration, and velocity of floor relative to the base, respectively. The parameter M_s denotes the mass of structure, while the parameters K_s and B_s characterize the stiffness and damping of structure due to earthquake, respectively. The variable \ddot{x}_g represents the acceleration generated by the earthquake. The input f_{MR} denotes the force, which is generated by MR damper.

In order to represent equation (1) into state variable form, the state variable x_1 is assigned to displacement and x_2 is designated to the velocity of structure floor. Therefore, equation (1) can be rewritten as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{B_s}{M_s} x_2 - \frac{K_s}{M_s} x_1 + \frac{1}{M_s} f_{MR} + \ddot{x}_g \end{aligned} \quad (2)$$

where v represents the control force (control signal) and \ddot{x}_g is the earthquake data function.

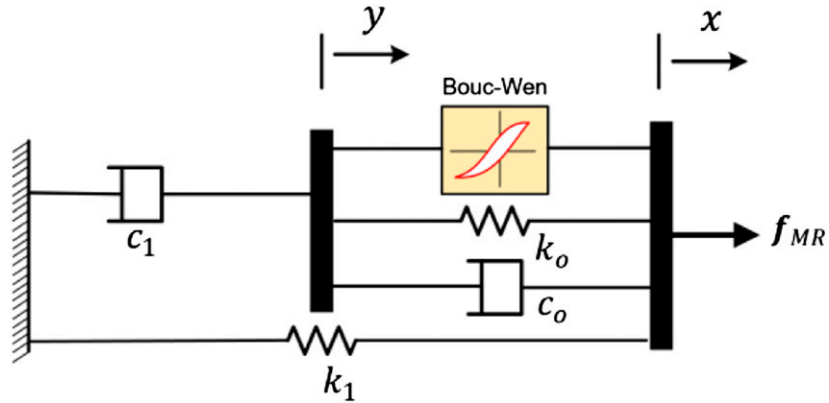


Figure 3. Modified Bouc-Wen model of MR damper.

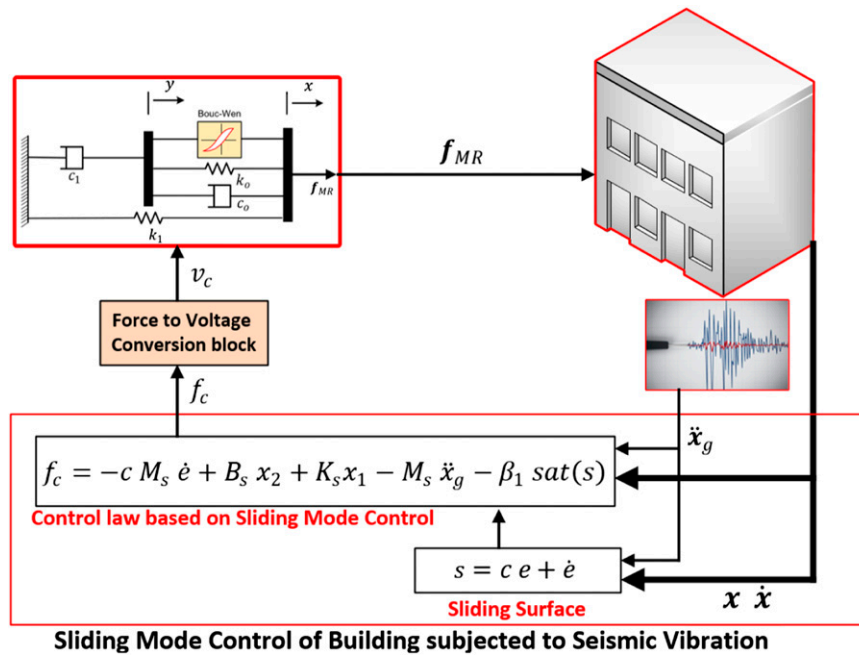


Figure 4. Schematic diagram of sliding mode controlled building subjected to seismic vibration.

The schematic representation of the MR damper is described in Figure 2. The MR damper consists of conventional damper, whose viscosity is electrically controlled via actuating coil. This coil is excited by an external voltage which is part of controlled signal for this system. The MR damper nonlinear behavior was firstly developed and extended by Bingham model.³⁸ Then, other researchers has proposed other models of MR damper based on differential equation, which are verified and validated based on experimental setup.³⁹⁻⁴¹

The dynamic properties of this MR device are augmented by Bouc-Wen model, which is shown in Figure 3. Based on Figure 3, the dynamic equations which characterize MR device can be described by^{42,43}

$$f_{MR} = c_1 \dot{y} + k_1(x - x_o) \tag{3}$$

$$c_1 \dot{y} = c_o(\dot{x} - \dot{y}) + k_o(x - y) + az \tag{4}$$

$$\dot{z} = -\gamma z |\dot{x} - \dot{y}| |z|^{n-1} - \beta (\dot{x} - \dot{y}) |z|^n + A (\dot{x} - \dot{y}) \quad (5)$$

where, f_{MR} denotes the output force. The variables x and \dot{x} represent displacement and velocity of the damper, respectively, the evolutionary variable z represent the hysteresis behavior of the output force according to the displacement and velocity of the damper. The coefficients k_0 and c_0 denotes the accumulator stiffness and viscous damping at low velocity, while c_1 and k_1 describe the damping and stiffness at high velocities. The parameters g , b , n , and A characterize the shape and scale of the hysteresis loop. The parameters of the MR damper depending on the applied voltage v are⁴⁴

$$\alpha = \alpha_a + \alpha_b u, \quad c_o = c_{oa} + c_{ob} u, \quad c_1 = c_{1a} + c_{1b} u \quad (6)$$

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

where v represents the command voltage applied to the control circuit, u denotes the phenomenological variable covering the dynamic of the system, and η represent time-response constant. The coefficients α_a , α_b , c_{oa} , c_{ob} , c_{1a} , and c_{1b} constitutes the elements of damping coefficients α , c_o and c_1 .

It is worthy to mention that MR devices can change the stiffness of their fluid up to 100 Hz and can operate over a wide range of the ambient temperature, usually from -40°C to $+150^\circ\text{C}$. They have a large yield shear stress routinely between 50–100 kPa for applied magnetic fields of 150–250 kA/m. MR fluids react to external stimulus in a few milliseconds and can be readily controlled by standby batteries with a voltage in range of 12–24 V.

Adaptive backstepping sliding mode control

In this section, the control and adaptive laws are developed based on adaptive backstepping SMC methodology. Firstly, sliding mode control design has to be conducted and then the adaptive backstepping SMC will be established accordingly. In the control design, the actual force f_{MR} is replaced by the notation f_c to indicate the control force, which has to be controlled by control algorithm.

Sliding mode control

Let e be the difference between the actual state x_1 and the desired displacement x_{1d}

$$e = x_1 - x_{1d} \quad (8)$$

In our case, x_{1d} must equal to zero, then $e = x_1$. Therefore, the first and second derivative of error equation gives

$$\begin{aligned} \dot{e} &= \dot{x}_1 = x_2 \\ \ddot{e} &= \dot{x}_2 = -\frac{B_s}{M_s} x_2 - \frac{K_s}{M} x_1 + \frac{1}{M_s} f_c + \ddot{x}_g \end{aligned} \quad (9)$$

The sliding surface s can be defined as

$$s = ce + \dot{e} \quad (10)$$

Taking the first time derivative of equation (10) to have

$$\dot{s} = c\dot{e} + \ddot{e} = c\dot{e} + \dot{x}_2 \quad (11)$$

Using equations (9) and (11) becomes

$$\dot{s} = c\dot{e} - \frac{B_s}{M_s} x_2 - \frac{K_s}{M_s} x_1 + \frac{1}{M_s} f_c + \ddot{x}_g \quad (12)$$

where c is a scalar design parameter. In the SMC technique, the control law (f_c) is defined by

$$f_c = f_{eq} + f_{sw} \quad (13)$$

where f_{eq} and f_{sw} are the equivalent and switching control parts, which are described respectively by

$$f_{eq} = -cM_s\dot{e} + B_sx_2 + K_sx_1 - M_s\ddot{x}_g \quad (14)$$

$$f_{sw} = -\beta_1 \text{sign}(s) \quad (15)$$

where β_1 is a scalar design gain. In order to reach ($\dot{s} = 0, s = 0$), the control law f_c will be deduced

$$f_c = -cM_s\dot{e} + B_sx_2 + K_sx_1 - M_s\ddot{x}_g - \beta_1 M_s \text{sign}(s) \quad (16)$$

Figure 4 shows the schematic diagram of sliding mode controlled building subjected to Seismic Vibration. The figure illustrates the connection of controller with MR damper to be generated the desired force for mitigating the earth vibration.

In practical realization of MR-based controlled building structures, the MR coils requires current actuating signal to generate force. Therefore, a driver is required to convert the desired voltage (control signal) into desired current and hence to desired force. Other optimal algorithm is required to control the voltage-to-current converter (driver) via Heavy step function.^{19,21,33}

Stability analysis

The candidate Lyapunov Function (L.F.) can be defined as

$$V_s = \frac{1}{2}s^2 \quad (17)$$

The time derivative of L.F. gives

$$\dot{V}_s = s \left[c\dot{e} - \frac{B_s}{M_s}x_2 - \frac{K_s}{M_s}x_1 + \frac{1}{M_s}f_c + \ddot{x}_g \right] \quad (18)$$

Based on equations (17) and (19) becomes

$$\dot{V}_s = s(-M_s\beta_1 \text{sign}(s)) \quad (19)$$

or

$$\dot{V}_s = -M_s\beta_1 |s| \quad (20)$$

The \dot{V}_s is negative definite so that the sliding variable will reach the sliding surface in finite-time. Consequently, during the sliding mode, the state will reach asymptotically to the origin. In order to reduce the effect of the chattering phenomenon, the signum function is replaced by the saturation function. The last control law

$$f_c = -cM_s\dot{e} + B_sx_2 + K_sx_1 - M_s\ddot{x}_g - \beta_1 \text{sat}(s) \quad (21)$$

Backstepping sliding mode control

In order to derive the ABSMC control law, the BSMC has to be derived as a first step to design the ABSMC controller. In what follows, the algorithm of BSMC is explained in steps:

Step 1. The tracking error and its derivative is given respectively as

$$e_1 = x_1 - x_{1d} \quad (22)$$

Since $x_{1d} = 0$, then $e_1 = x_1$. The time derivative of e_1 gives

$$\dot{e}_1 = \dot{x}_1 = x_2 \quad (23)$$

Let x_{2v} is the virtual control and defined as

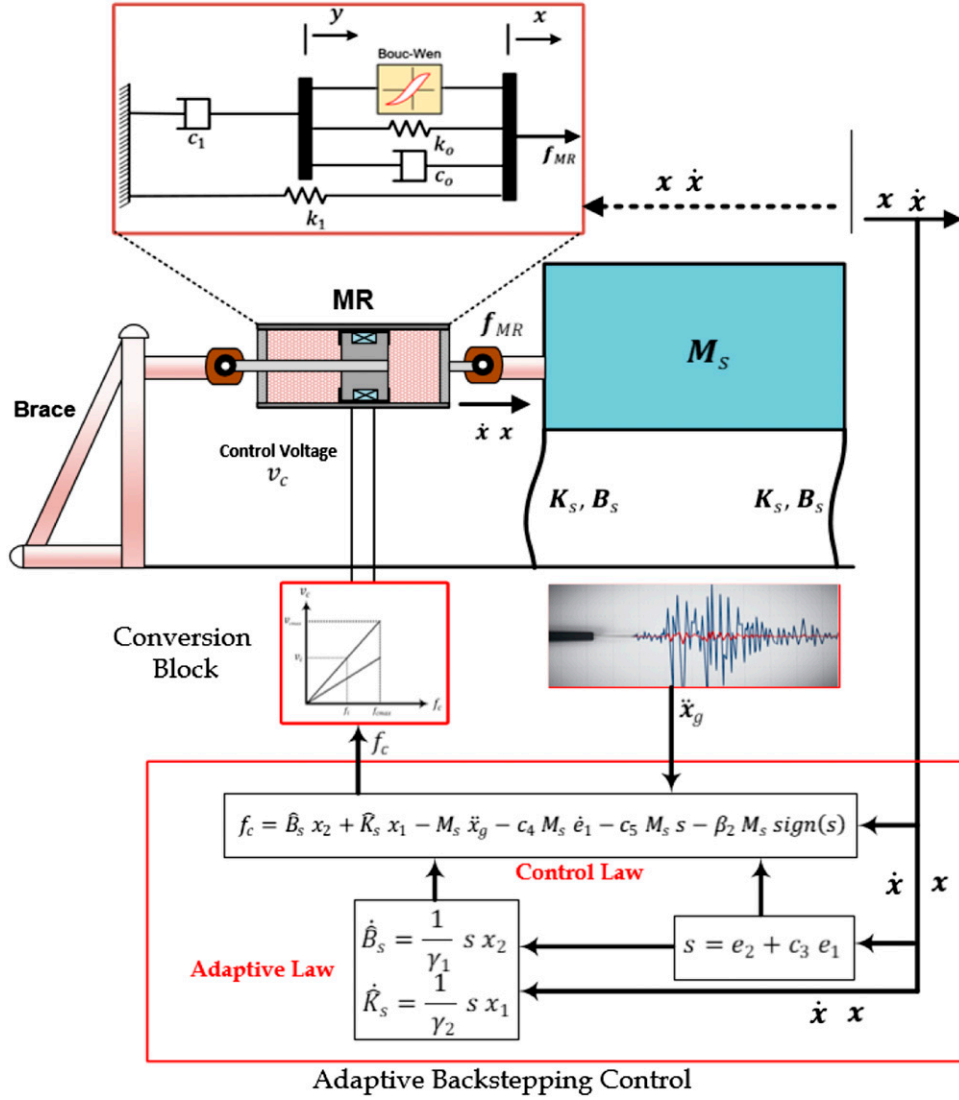


Figure 5. Suppression of seismic vibration based on adaptive backstepping control algorithm for earth-quake structure supported by MR damper.

$$x_{2v} = a(e_1) = -c_1 e_1 \quad (24)$$

where c_1 is a positive constant. The candidate L.F. is chosen as

$$V_1 = \frac{1}{2} e_1^2 \quad (25)$$

Taking the time derivative of L.F. and using equation (23) to have

$$\dot{V}_1 = e_1 \dot{e}_1 = e_1 x_2 \quad (26)$$

If the variable x_2 is assigned as virtual control x_{2v} , as defined by equation (24), then equation (26) becomes

$$\dot{V}_1 = -c_1 e_1^2 \quad (27)$$

This indicates that $\dot{V}_1 < 0, \forall e_1 \neq 0$.

Step 2. The deviation of the virtual control x_{2v} from its actual control variable x_2 can be defined as

$$e_2 = x_2 - x_{2v}$$

or

$$e_2 = x_2 - \alpha(e_1) \quad (28)$$

Then, using equations (28) and (23) to have

$$\dot{e}_1 = \alpha(e_1) + e_2$$

After that the dynamics of e_2 is given by

$$\dot{e}_2 = \dot{x}_2 - \dot{\alpha}(e_1) \quad (29)$$

Based on equation (24), the time derivative of $\alpha(e_1)$ is given by $\dot{\alpha} = -c_1 \dot{e}_1$. Then, equation (29) can be written as

$$\dot{e}_2 = -\frac{B_s}{M_s}x_2 - \frac{K_s}{M}x_1 + \frac{1}{M_s}f_c + \ddot{x}_g + c_1 \dot{e}_1 \quad (30)$$

The second L.F. candidate and its time derivative are respectively given by

$$V_2 = V_1 + \frac{1}{2}e_2^2 \quad (31)$$

$$\dot{V}_2 = \dot{V}_1 + e_2 \dot{e}_2 \quad (32)$$

Using equation (30) and (27), one can have

$$\dot{V}_2 = -c_1 e_1^2 + e_2 \left(-\frac{B_s}{M_s}x_2 - \frac{K_s}{M_s}x_1 + \frac{1}{M_s}f_c + \ddot{x}_g - c_1 \dot{e}_1 \right)$$

In order to have $\dot{V}_2 < 0$, the control force f_c is set to be

$$f_c = \left(B_s x_2 + K_s x_1 - M_s \ddot{x}_g + c_1 M_s \dot{e}_1 - c_2 M_s e_2 \right)$$

Then

$$\dot{V}_2 = -c_1 e_1^2 - c_2 e_2^2 \quad (33)$$

If c_2 is a positive constant, then $\dot{V}_2 \leq 0$. One can conclude that the control law can guarantee the negative definiteness of \dot{V}_2 and hence it proves the asymptotic stability of the system.

Adaptive backstepping sliding mode control

In this study, it is assumed that an uncertainty in parameters of vibrated system will arise due to an earthquake. In particular, two uncertainties will be addressed for this application; one uncertainty which concerned to the viscous damping coefficient B_s and the other with the stiffness coefficient K_s of the building system; that is

$$\widehat{B}_s = B_s + \tilde{B}_s, \quad \widehat{K}_s = K_s + \tilde{K}_s \quad (34)$$

where \widehat{B}_s is the estimated value of B_s coefficient, \widehat{K}_s represents the estimated value of the K_s coefficient, B_s and K_s represent the nominal values of damping and stiffness coefficients, respectively. The objective is how to design ABSMC to suppress the vibration of building subjected to earthquake with assistance of MR damper. The candidate L.F. can be defined as

$$V_4 = V_3 + \frac{1}{2}\gamma_1 \tilde{B}_s^2 + \frac{1}{2}\gamma_2 \tilde{K}_s^2 \quad (35)$$

where γ_1, γ_2 are the adaptation gains. The time derivative of last equation gives

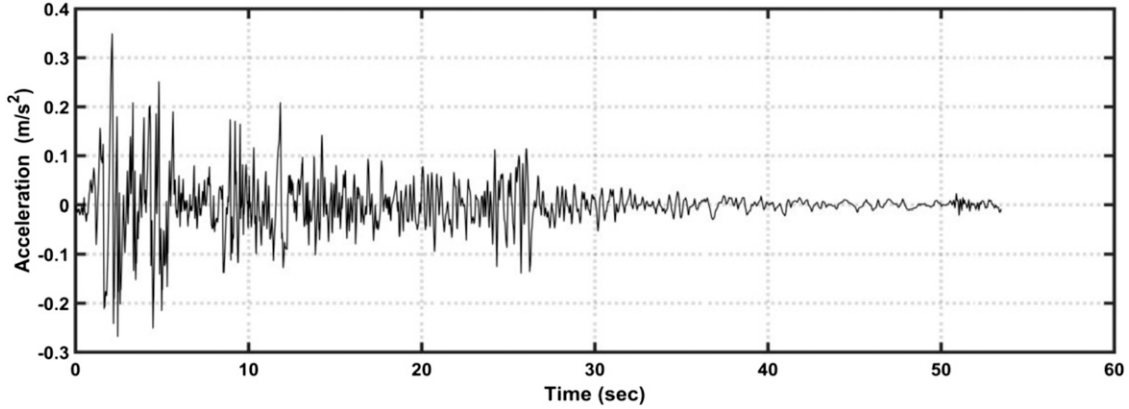


Figure 6. El Centro 1940 Imperial Valley earthquake.

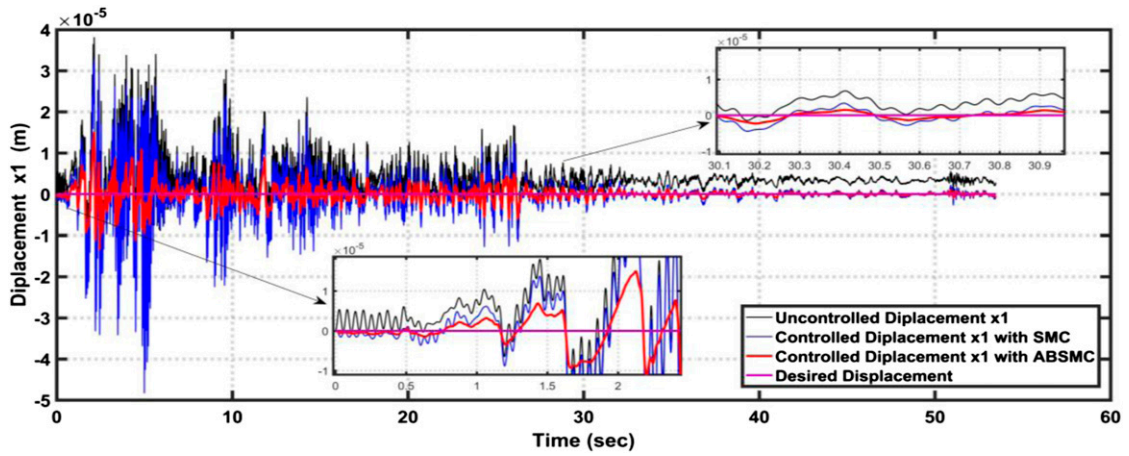


Figure 7. Displacement responses of the earth-quake building Based on SMC and ABSMC. Note: ABSMC: adaptive backstepping sliding mode control; SMC: sliding mode control.

$$\dot{V}_4 = \dot{V}_3 + \gamma_1 \tilde{B}_s \hat{B}_s + \gamma_2 \tilde{K}_s \hat{K}_s$$

Assuming low variation in coefficients K_s and B_s , then $\hat{K}_s = \tilde{K}_s$ and $\hat{B}_s = \tilde{B}_s$

$$\dot{V}_4 = -c_1 e_1^2 - c_2 e_2^2 - s \left(\frac{B_s}{M_s} x_2 + \frac{K_s}{M_s} x_1 - \frac{1}{M_s} f_c - \ddot{x}_g - c_4 \dot{e}_1 \right) + \gamma_1 \tilde{B}_s \hat{B}_s + \gamma_2 \tilde{K}_s \hat{K}_s \quad (36)$$

The control law (f_c) can be deduced as follows

$$f_c = \hat{B}_s x_2 + \hat{K}_s x_1 - M_s \ddot{x}_g - c_4 M_s \dot{e}_1 - c_5 M_s s - \beta_2 M_s \text{sign}(s) \quad (37)$$

Using the control law in equation (37), one can get

$$\begin{aligned} \dot{V}_4 = & -c_1 e_1^2 - c_2 e_2^2 - c_3 s^2 - \beta_2 s \text{sign}(s) + \gamma_1 \tilde{B}_s \hat{B}_s + \gamma_2 \tilde{K}_s \hat{K}_s \\ & - s \left(B_s - \hat{B}_s \right) x_2 - \left(K_s - \hat{K}_s \right) x_1 \end{aligned} \quad (38)$$

Using equations (34) and (38) can be rewritten as

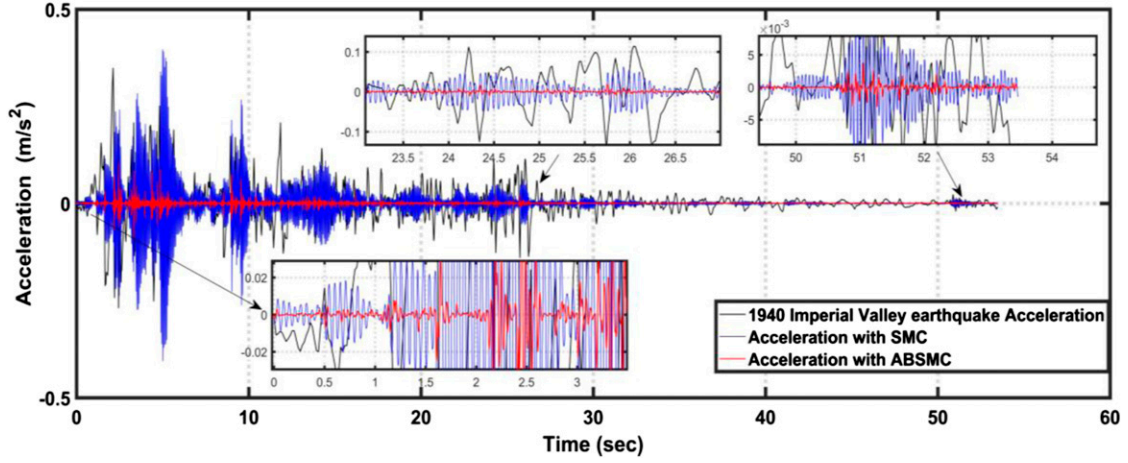


Figure 8. Acceleration responses of the earth-quaked building based on SMC and ABSMC. Note: ABSMC: adaptive backstepping sliding mode control; SMC: sliding mode control.

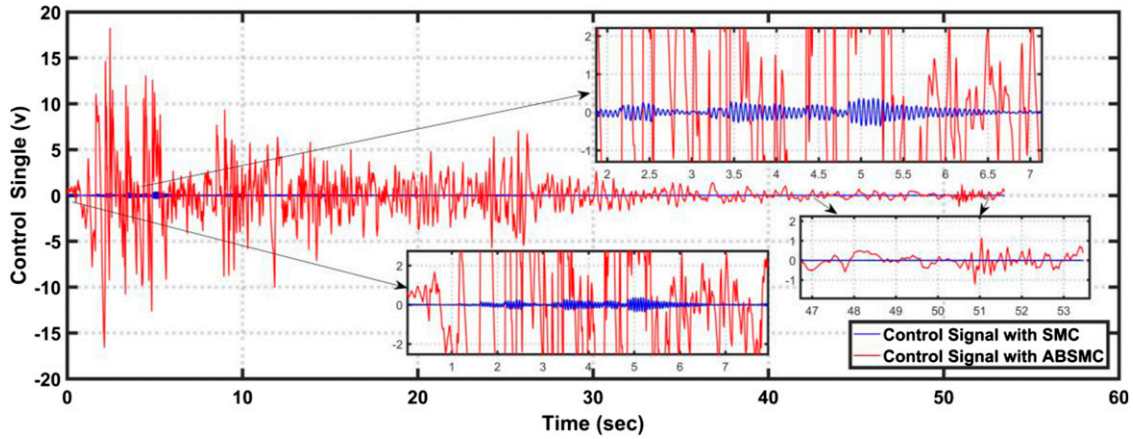


Figure 9. Control signal generated from SMC and ABSMC. Note: ABSMC: adaptive backstepping sliding mode control; SMC: sliding mode control.

$$\dot{V}_3 = -c_1 e_1^2 - c_2 e_2^2 - c_3 s^2 - \beta_2 |s| + \tilde{B}_s \left(\gamma_1 \dot{\tilde{B}}_s - s x_2 \right) + \tilde{K}_s \left(\gamma_2 \dot{\tilde{K}}_s - s x_1 \right) \quad (39)$$

In order to guarantee negative definiteness of \dot{V}_4 function, the last terms have to be set to zero. This results in the following adaptive laws

$$\dot{\tilde{B}}_s = \frac{1}{\gamma_1} s x_2 \quad (40)$$

$$\dot{\tilde{K}}_s = \frac{1}{\gamma_2} s x_1 \quad (41)$$

Since $\dot{V}_4 \leq 0$, the system is negative definite and hence, the proposed ABSMC can guarantee the stability of the building subjected to earthquake and supported by MR damper.

The control force developed due to either classical or adaptive backstepping control design cannot directly actuate the MR damper; since this device requires a voltage signal to be operated. Figure 5 shows the controlled earth-quaked structure based on adaptive backstepping control algorithm.

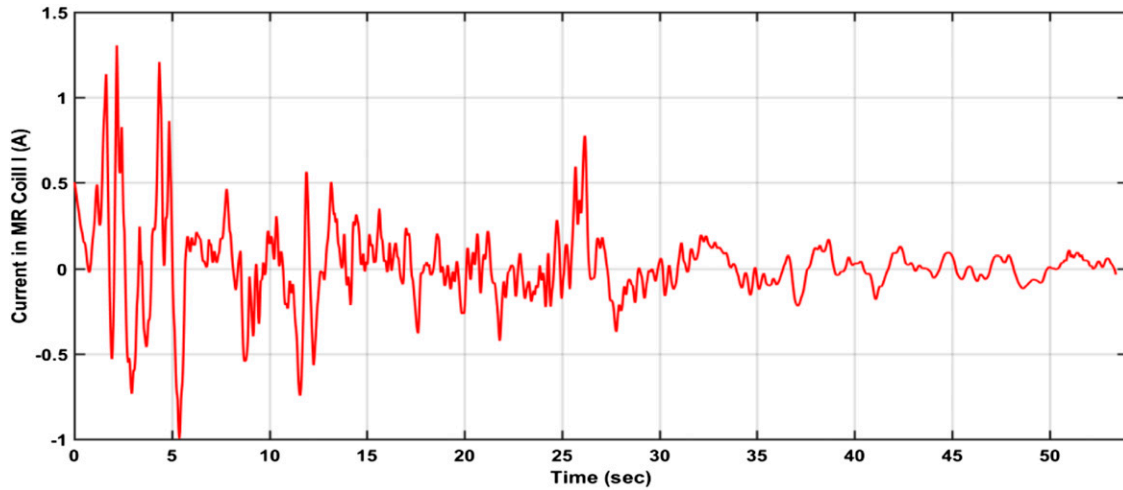


Figure 10. The current passing through the coil of MR Damper.

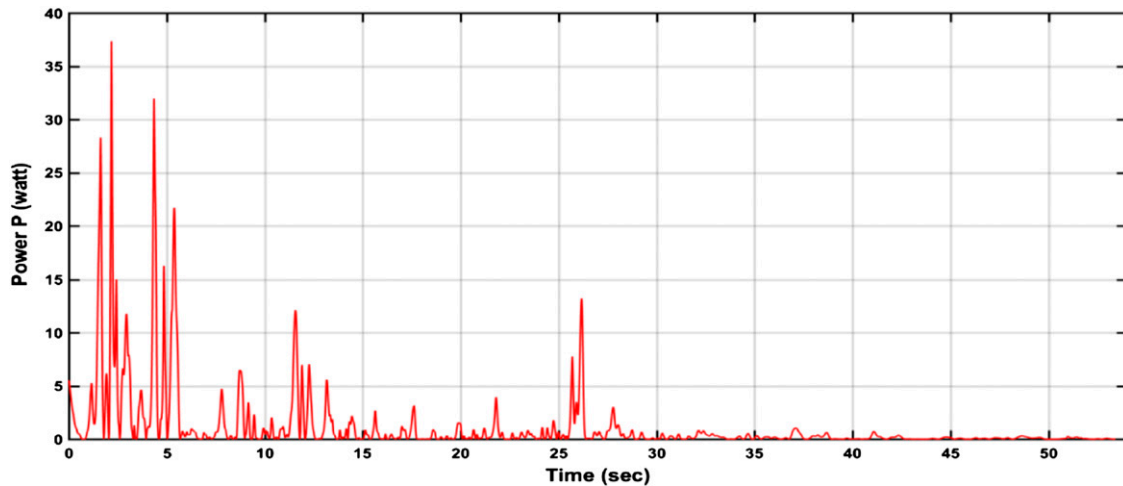


Figure 11. The power dissipated through the coil of MR Damper.

Computer simulation

In this section, the effectiveness of backstepping sliding mode control and adaptive backstepping sliding mode controllers are assessed and compared to each other. The design Parameters for SMC are set to $c = 10$, $k = 1$, while the design parameters for ABSMC have the settings: $c_1 = 100$, $c_2 = 1$, $c_3 = 10$, $c_5 = 100$ and $k = 100$. The adaptive rate parameters of adaptive law are set to the values $\gamma_1 = \gamma_1 = 1$. The system parameters are $M_s = 93.3 \text{ Kg}$, $C_s = 175 \text{ N} \cdot \text{s/m}$, $K_s = 12 \times 10^5 \text{ N/m}$.²

The data used in this study are related to earthquake happened in May 1940 at Imperial Valley (Brawley).⁴⁵ Total damage has been estimated at about \$6 million. The magnitude was 7.1. The behavior of earthquake has been recorded and displayed in Figure 6.

The dynamic responses of displacement of building system under earthquake based on sliding mode control and ABSMC is shown in Figure 7. As compared to uncontrolled system, it is evident from the figure that the SMC and ABSMC could reduce the effect of earthquake vibration with the presence of MR damper. However, the figure shows that the ABSMC could give less magnitude of vibration for controlled and earth-quaked building than that based on SMC.

The performance comparison between SMC and ABSMC are evaluated in terms of Root Mean Square (RMS) of displacement. It has been shown that the RMS value of displacement for uncontrolled system under earthquake is equal to

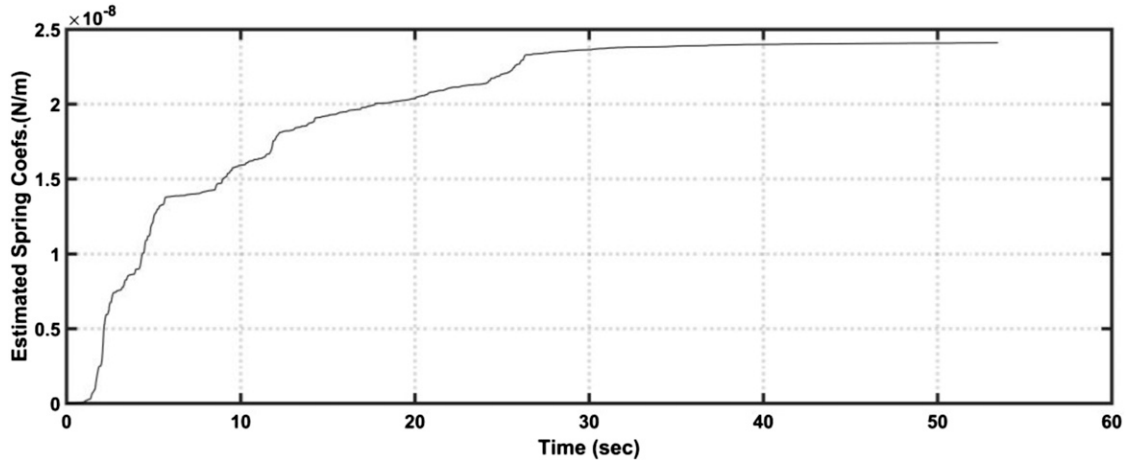


Figure 12. Estimated value of stiffness coefficient by adaptive law.

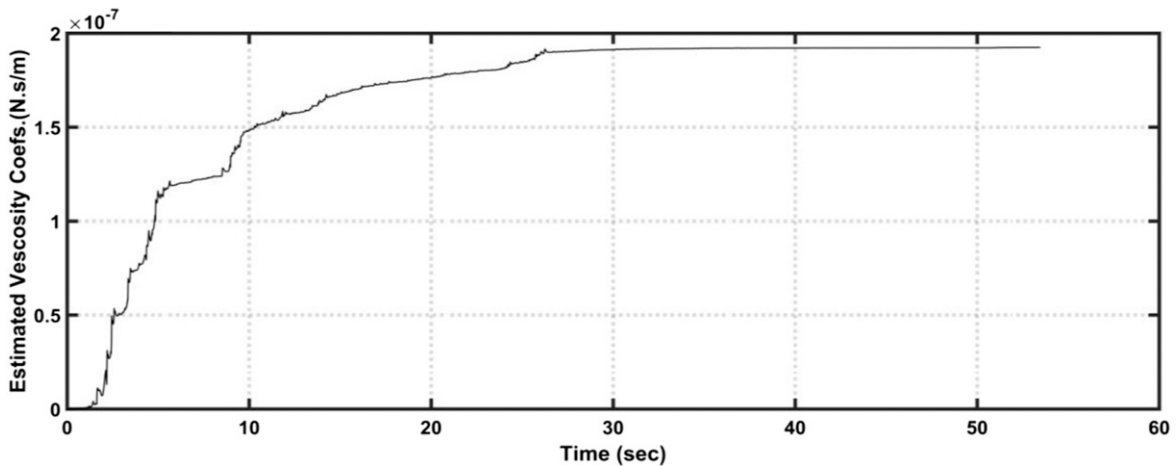


Figure 13. Estimated value of viscosity coefficient by adaptive law.

16.5347×10^{-6} , while the RMS value of displacement resulting from SMC is equal to 6.231×10^{-6} and the RMS value of displacement over the duration of earthquake for ABSMC is equal to 2.0244×10^{-6} . This indicates that the ABSMC has better ability to suppress the magnitude of vibration due to earthquake.

The acceleration generated due to adaptive backstepping sliding mode control and the conventional sliding mode control is shown in Figure 8. It is clear that the acceleration generated by ABSMC is less than that generated by the SMC. This indicates that vibration suppression due to ABSMC is better than SMC.

Figure 9 shows the generated control signal based on SMC and ABSMC. It is clear from the figure that the control effort produced by SMC is less than that based on ABSMC and this is price has to be paid by the ABSMC for better vibration suppression.

In this study, the value of resistance and inductance are taken as $R = 21.9 \Omega$ and $L = 6.6 \text{ H}$, respectively.⁴⁶ Based on impedance of MR circuit, characterized by its resistance and reactance, and the control voltage indicated in Figure 9, the current flows through the circuit is shown in Figure 10 according to Ohm's law. Based on these values and the control voltage indicated in Figure 9, the envelope of current is illustrated in Figure 10. Figure 11 shows the instantaneous power consumption over the time of earthquake period. The average of power has been evaluated to be 5.73 W.

Under seismic vibration due to earthquake, the mass of structure remains unchanged, but the structure's stiffness and damping will encounter a change or variation. This change in stiffness and damping characteristics of the building requires an adaptive control design to account and compensate these uncertainties. The cooperation of developed adaptive law and

control law of ABSMC will cope with such variation in parameters. In this study, the maximum allowable change in building stiffness and damping is assumed to take 5% of their nominal values. The estimated values of stiffness and viscosity coefficients are depicted in Figures 12 and 13, respectively.

It is clear from the figures that the adaptive law could give bounded estimated uncertain parameters which lead to stability of controlled system. However, if these estimated parameters go unbounded in magnitude, this may lead to instability problems of adaptive controlled building system.

Conclusion

In this paper, design of ABSMC has been presented to mitigate the vibration of building subjected to earthquake. The design of control algorithm has been developed according to Lyapunov-based stability analysis such to guarantee the asymptotically stability. The efficacy of proposed ABSMC has been confirmed based on numerical simulation. Based on simulated results, an improvement of 62.32% in vibration suppression has been obtained with SMC as compared to uncontrolled building, while the ABSMC could give 87.76% and 67.5% improvement in vibration suppression as compared to uncontrolled and SMC-based building, respectively. However, the power absorbed by MR circuit in case of SMC is 73.3% less than that based on ABSMC; this is the price to be paid by latter controller for suppression improvement. In addition, the proposed adaptive controller could give bounded estimated values for stiffness and viscosity coefficients. The present work can be extended to include building of multiple stories. Other control strategies can be pursued to conduct a comparison study in performance with proposed controller.^{47–49}

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iDs

Amjad J Humaidi  <https://orcid.org/0000-0002-9071-1329>

Ibaheem K Ibraheem  <https://orcid.org/0000-0001-7009-3634>

References

1. Çetin S, Zergeroglu E, Sivrioglu S, et al. Adaptive control of structures with MR Damper. In: 18th IEEE International Conference on Control Applications Part of 2009 IEEE Multi-conference on Systems and Control. Saint Petersburg, Russia, 8–10 July, 2009.
2. Zizouni K, Bousserhane IK, Hamouine A, et al. MR Damper-LQR control for earthquake vibration mitigation. *Int J Civ Eng Technol* 2017; 8(11): 201–207.
3. Andrey P and Leonid F. Stability notions and Lyapunov functions for sliding mode control systems. *J Franklin Inst* 2014; 351: 1831–1865.
4. Kobersy I, Finaev V, Beloglazov D, et al. Design features and research on the neuro-like learning control system of a vehicle. *Int J Neural Networks Adv Appl* 2014; 1: 73–80.
5. Azadi E, Egtesad M, Fazelzadeh SA, et al. Vibration suppression of smart nonlinear flexible appendages of a rotating satellite by using hybrid adaptive sliding mode/Lyapunov control. *J Vibr Control* 2012; 19(7): 975–991.
6. Royel SA, Movassaghi Z, Kwok N, et al. Smart structures using MR dampers with second order sliding mode control. In: International conference on control: Automation and information sciences (ICCAIS), Saigon, Vietnam, 26–29 November 2012, pp. 170–175. IEEE.
7. Zizouni K, Fali L, Sadek Y, et al. Neural network control for earthquake structural vibration reduction using MRD. *Front Struct Civ Eng* 2018; 13: 1171–1182.
8. Guclu R. Sliding mode and PID control of a structural system against earthquake. *Math Comput Modell* 2006; 44: 210–217.
9. Khalatbarisoltani A, Soleymani M, and Khodadadi M. Online control of an active seismic system via reinforcement learning. *Struct Control Health Monit* 2018; 26(3): 1–18.
10. Chen PC and Lai CT. Advanced control strategy for floor response replication of high-rise buildings subjected to earthquakes. *J Earthquake Eng* 2020; 1–25. DOI: [10.1080/13632469.2020.1713927](https://doi.org/10.1080/13632469.2020.1713927).

11. Afkham B and Ehteram S. Nonlinear control of buildings subjected to earthquakes by using sliding mode controller (SMC). *Mod Appl Sci* 2010; 4(12): 170–176.
12. Schlacher K, Kugi A, and Irschik H. Nonlinear control of earthquake excited high raised buildings by approximate disturbance decoupling. *Acta Mech* 1997; 125: 49–62.
13. Chang S and Sung D. Modal-energy-based neuro-controller for seismic response reduction of a nonlinear building structure. *Appl Sci* 2019; 9: 1443.
14. Shan J, Ouyang Y and Shi W. Adaptive control of earthquake-excited nonlinear structures with real-time tracking on prescribed performance criteria. *Struct Control Health Monit* 2018; 25: 1–21.
15. Alli H and Yakut O. Fuzzy sliding-mode control of structures. *Eng Struct* 2005; 27: 277–284.
16. Rayegani A and Nouri G. Application of smart dampers for prevention of seismic pounding in isolated structures subjected to near-fault earthquakes. *J Earthquake Eng* 2020: 1–16. DOI: [10.1080/13632469.2020.1822230](https://doi.org/10.1080/13632469.2020.1822230).
17. Li L, Wang N, and Qin H. Adaptive model reference sliding mode control of structural nonlinear vibration. *Shock Vibr* 2019; 2019: 1–13.
18. Yao GZ, Yap FF, Chen G, et al. MR damper and its application for semi-active control of vehicle suspension system. *Mechatronics* 2002; 12(7): 963–973.
19. Saidi A, Zizouni K, Kadri B, et al. Adaptive sliding mode control for semi-active structural vibration control. *Stud Inf Control* 2019; 28(4): 371–380. DOI: [10.24846/v28i4y201901](https://doi.org/10.24846/v28i4y201901).
20. Yuksel H and Nurkan Y. Adaptive Backstepping control with estimation for the vibration isolation of buildings. *J Vibr Control* 2012; 18(13): 1996–2005.
21. Fali L, Djermame M, Zizouni K, et al. Adaptive sliding mode vibrations control for civil engineering earthquake excited structures. *Int J Dyn Control* 2019; 7(3): 955–965. DOI: [10.1007/s40435-019-00559-0](https://doi.org/10.1007/s40435-019-00559-0).
22. Utkin VI. *Sliding mode control: mathematical tools, design and applications*. Columbus, OH: The Ohio State University, 2015.
23. Mohammad AM and AL-Samarraie SA. Robust controller design for flexible joint based on back-stepping approach. *IJCCCE* 2020; 20(2): 58–73.
24. Humaidi AJ and Akram HH. PMLSM position control based on continuous projection adaptive sliding mode controller. *Syst Sci Control Eng* 2018; 6(3): 242–252.
25. Shibly A, Hamzah M, and Al-Nadawi YK. Vehicle ABS control system design via integral sliding mode. *Int J Autom Control* 2016; 10(4): 356–374.
26. Al-Dujaili AQ, Falah A, Humaidi AJ, et al. Optimal super-twisting sliding mode control design of robot manipulator: design and comparison study. *Int J Adv Rob Syst* 2020; 17(6): 1–17.
27. Falah A, Humaidi AJ, Al-Dujaili A, et al. Robust super-twisting sliding control of PAM-actuated manipulator based on perturbation observer. *Cogent Eng* 2021; 7(1): 1–30.
28. Humaidi AJ and Hameed M. Development of a new adaptive backstepping control design for a non-strict and under-actuated system based on a PSO Tuner. *Information* 2019; 10: 38.
29. Ai Q, Zhu C, Zuo J, et al. Disturbance-estimated adaptive backstepping sliding mode control of a pneumatic muscles-driven ankle rehabilitation robot. *Sensors* 2017; 18: 66.
30. Humaidi AJ, Kadhim SK and Gataa AS. Development of a novel optimal backstepping control algorithm of magnetic impeller-bearing system for artificial heart ventricle pump. *Cybern Syst* 2020; 51(4): 521–541.
31. Petit F, Daasch A and Albu-Schäffer A. Backstepping control of variable stiffness robots. *IEEE Trans Control Syst Technol* 2015; 23: 2195–2202.
32. Mohd Basri MA. *Design and application of an adaptive backstepping sliding mode controller for a six-DOF quadrotoraerial robot*. Cambridge, England: Cambridge University Press, 2018.
33. Humaidi AJ and Hameed AH. Robustness enhancement of MRAC using modification techniques for speed control of three phase induction motor. *J Electr Syst* 2017; 13(4): 723–741.
34. Humaidi AJ and Hameed AH. Design and comparative study of advanced adaptive control schemes for position control of electronic throttle valve. *Information* 2019; 10(2): 65.
35. Humaidi AJ, Hameed MR, and Hameed AH. Design of block-backstepping controller to ball and arc system based on zero dynamic theory. *J Eng Sci Technol* 2018; 13(7): 2084–2105.
36. Ye D. Design and simulation of adaptive backstepping sliding mode control of manipulator based on MATLAB. *Rev de la Fac de Ing* 2017; 32(11): 235–240.
37. Jansen LM and Dyke SJ. Semi-active control strategies for MR dampers: a comparative study. *J Eng Mech* 2000; 126(8): 795–803.
38. Pohoryles DA and Duffour P. Adaptive control of structures under dynamic excitation using magnetorheological dampers: an improved clipped-optimal control algorithm. *J Vibr Control* 2015; 21(13): 2569–2582.
39. Bingham EC. An investigation of the laws of plastic flow. *Bulletin of the Bureau of Standards* 1916; 13(2): 309–353.

40. Gamota DR and Filisko FE. Dynamic mechanical studies of electrorheological materials: moderate frequencies. *J Rheol* 1991; 35(3): 399–425.
41. Ismail M, Ikhouane F, and Rodellar J. The hysteresis Bouc-Wen model, a survey. *Arch Comput Methods Eng* 2009; 16(2): 161–188.
42. Spencer BF, Jr, Dyke SJ, Sain MK, et al. Phenomenological Model for Magnetorheological Dampers. *J Eng Mech* 1997; 123(3): 230–238.
43. Dyke SJ, Spencer BF, Jr, Sain MK, et al. Modeling and control of magnetorheological dampers for seismic response reduction. *Smart Mater Struct* 1996; 5: 565–575.
44. Dyke SJ. Seismic protection of a benchmark building using Magnetorheological dampers. In: Proceedings of the Second world conference on structural control, Kyoto, Japan, June 28–July 1 1998, pp. 1455–1462.
45. McVerry GH. Frequency domain identification of structural models from Earthquake records. PhD thesis. Pasadena, CA: California Institute of Technology, 1979.
46. Yang G, Jung HJ, Spencer BF, et al. Dynamic modeling of large-scale magneto-rheological damper systems for civil engineering applications. *J Eng Mech* 2004; 130(9): 1–12.
47. Humaidi AJ, Ibraheem KI, Azar AT, et al. A new adaptive synergetic control design for single link robot arm actuated by pneumatic muscles. *Entropy* 2020; 22(7): 723.
48. Tahir TA and Al-Samarraie SA. The application of extremum seeking algorithms in pid tuning for continuous stirred tank reactor. *Int Rev Autom Control* 2021; 14(1): 28–38.
49. Humaidi AJ, Hameed AH and Hameed MR. Robust adaptive speed control for DC motor using novel weighted E-modified MRAC. In: 2017 IEEE International Conference on Power, Control, Signals and Instrumentation, Engineering (ICPCSI), 2017, pp. 313–319.