Influence of Control Strategy in Risk Mitigation of Building Damage Due to Earthquake

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INFLUENCE OF CONTROL STRATEGY IN RISK MITIGATION OF BUILDING DAMAGE DUE TO EARTHQUAKE

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Building structures are prone to damage due to natural disasters, and this challenges structural engineers to design safer and more robust building structures. This study is conducted to prevent these consequences by implementing a control strategy that can enhance a building’s stability and reduce the risk of damage. Therefore, to realize the structural integrity of a building, a hybrid control device is equipped with control strategies to enhance robustness. The control strategy proposed in this study is adaptive nonsingular terminal sliding mode control (ANTSMC). ANTS MC is an integrated controller of radial basis function neural network (RBFNN) and nonsingular terminal sliding mode control (NTSMC), which has a fast dynamic response, finite-time convergence, and the ability to enhance the control performance against a considerable uncertainty. The proposed controller is designed based on the sliding surface and the control law. The building with a two-degree-of-freedom (DOF) system is designed in Matlab/Simulink and validated with the experimental work connected to the LMSTest.Lab software. The performance of this controller is compared with those of the terminal sliding mode control (TSMC) and NTSMC in terms of the displacement response, sliding surface, and the probability of damage. The result showed that the proposed controller, ANTS MC can suppress vibrations up to 46%, and its percentage probability of complete damage is 15% from the uncontrolled structure. Thus, these findings are imperative towards increasing the safety level in building structures and occupants, and reducing damage costs in the event of a disaster.

Keywords
Control strategy. Deep learning. Collapse probability. Building damage. Enhance building safety

1. Introduction

Alleviating the structural building response in the event of an earthquake becomes an increasingly challenging task. The forces of nature threaten human existence, cause financial losses and environmental destruction. Large magnitude earthquakes damage properties and structures, and cause casualties. The earthquake magnitude of greater than 5.0 Mw may cause slight damage to the structures and buildings. The earthquake magnitude of greater than 6.0 Mw causes a lot of damage in a populated area. Moreover, major earthquakes that wreak severe damage occur at 7.0 Mw or higher. The higher moment magnitude with 8.0 Mw above will cause totally destroy to the community near the seismic location (Abu-Faraj et al. 2008). A tool known as HAZUS is used to estimate the existing building stock potential of losses caused by earthquake ground motion. HAZUS estimates the economic, physical, and social impacts of a disaster by using the geographic information system through an agency called the Federal Emergency Management Agency (FEMA). The estimation of the losses estimation is crucial for preparedness plans and rehabilitation strategies of building stocks from earthquake disasters (Duan and Pippin 2008). Besides, the HAZUS damage functions is used to simulate the vulnerability of various types of structural buildings and it provides the information on deriving the building fragility curves for various types of structures consist of the probability of slight, moderate, extensive, and complete structural damage states (Vazurkar and Chaudhari 2016; Peyghaleh et al. 2018).

Robinson et al. (2018) shows empirically derived structural fragility curves of different building types. According to the fragility curves, at 0.4 g, the building made from stone and mud has 98% probability of collapsing. The earthquake effect causes many fatalities based on the 2015 Gorkha earthquake with the recorded magnitude of 7.3 Mw to 8.8 Mw. The curves show that at the magnitude of 8.6 Mw, the number of fatalities was up to 100,000, and at the magnitude of 7.3 Mw, the earthquake caused more than 50,000 fatalities. Giordano et al. (2021) examined the fragility of the structural building made of masonry, RC frame, steel frame and timber frame. This vulnerability
The proposed control strategy had a better response in decreasing the maximum base displacement and structure forces and less energy for the active element than the AMD and TMD (Chesné et al. 2019). In recent years, some proportional-integral-derivative control strategy at smart base-isolate structure to control seismic. The fuzzy rule introducing a new control law for hybrid vibration absorbers referred to as $\alpha$-HMD. $\alpha$-HMD requires smaller active forces and less energy for the active element than the AMD and TMD (Chesné et al. 2019). In recent years, some researchers were interested in the theory of finite time mechanisms. Therefore, TSMC with this characteristic is introduced to overcome the problem caused by sliding mode control which involves in finite time state convergence.

As a result, TSMC attracts widespread attention and is known as a nonlinear switching manifold, whereas the state will reach equilibrium in a finite time (Cao et al. 2013). The derivation of TSMC can be found in the study proposed by Liu and Wang (2012). According to Cao et al. (2013), TSMC causes singularity to occur if the initial conditions are not appropriately selected will cause an infinite control law.
Nonsingular terminal sliding mode control (NTSMC) has an advantage in giving a fast dynamic response, finite-time convergence, high control precision and eliminating the paranormal phenomenon in the control input of the system (Xu et al. 2015). NTSMC has been applied in spacecraft, vehicles and rigid manipulators to eliminate singularity problems associated with TSMC (Zhu and Yan 2014; Ning et al. 2018). In 2019, Ba et al. (2019) modified NTSMC with an adaptive time-delay estimation technique. This controller is used to track the position of servomotor-actuated robotic systems. Lastly, the proposed controller successfully verifies the servomotor robot in a real-time 2-DOF different working conditions. The collaboration of the deep learning method with NTSMC enhances the robustness of the system control, which is RBFNN that has good generalization, simple network structure, fast learning, and can improve the control performance against considerable uncertainty of the system (Liu 2013). Deep learning is a subset of machine learning methods based on artificial neural networks. In cases of earthquakes, as Xing et al. (2020) investigated, machine learning able to predict the casualties of an earthquake disaster. The technique proposed by the authors provided accurate prediction and efficient learning, making it suitable for large sample sampling and small sample data fitting. Due to the advantages of RBFNN, this technique is chosen to collaborate with NTSMC. The function of RBFNN in TSMC is to predict the upper bound of an uncertain parameter. The detailed study and the derivation of RBFNN method can be found in the studies by combined RBFNN with TSMC to control robot manipulators. This controller is used to estimate all the system parameters via Gee-Lee matrix and its produce operators. The application of ANTSMC in robot manipulators shows that the proposed controller effectively controls the nonlinear system with robustness even under model changes and parameter uncertainties.

Most of the previous studies applied this controller in the vehicle, robotic and spacecraft systems. However, there has been no empirical evidence on the influence of a control strategy in reducing the building damage risk to date. Padahal this control strategy terdiri daripada characteristic yang bagus dalam vibration control. This paper highlights the design of the newly proposed control strategy, ANTSMC and its impact in preventing the structural building from having damage and collapse by minimize the vibration during earthquake occur. This proposed control strategy integrates the deep learning technique to estimate the desired value in NTSMC. The deep learning technique has the ability to find appropriate value to fit the unknown value in the control strategy used. The proposed controller is also compared to the other controllers to demonstrate its efficiency. Moreover, the building structure representing mass, spring and damper is constructed in Simulink and validated via an experimental setup connected to LMS Test.Lab software. The result from the experimental work has strengthened the building structure that has been built in simulation.

2. System Design

2.1 Building Design

The building structure is represented by the mass, spring and damper system that consists of two DOFs. The controlling device, HMD is installed at the top floor of the building. The building structure and its free body diagram for the system is shown in Figure 1 and Figure 2, respectively. The mathematical model for the building structure are shown as (1), (2) and (3) where \(m_1\) and \(m_2\) denote the mass for each storey, \(k_1\) and \(k_2\) denote the stiffness value and while \(c_1\) and \(c_2\) are damping coefficients for each storey. \(m_d\), \(c_d\) and \(k_d\) are mass, damping and stiffness for HMD. The displacement responses for each floor and the control device are defined as \(x_1\), \(x_2\) and \(x_d\). \(\ddot{x}_g\) is the acceleration of the ground motion.

![Figure 1 Building structure system for the 2-DOF system](image-url)
An actuator is implemented to control HMD, and it is written as;

\[ R_i + K_e (\dot{x}_d - \dot{x}_3) = F_u \]  

(4)

where \( K_f \) is the thrust constant, \( K_i \) is the induced voltage constant, \( R \) is the resistance value, \( F_u \) is the control force generated by the actuator, and \( i \) is current.

2.2 Experimental work

The experimental work is assembled as shown in Figure 3, the assembly is consist of the shaker, amplifier, mobile Signal Conditioning and Data Acquisition System (SCADAS), accelerometer and the 2-DOF building structure. Electrodynamic exciter (S 50350/LS-120), known as shaker, generates vibrations that can be operated either in a horizontal or vertical position. In this case, the vibration of the shaker is set up to a vertical position to reproduce similar seismic movement. The power amplifier received the signal from the input and frontend into the shaker. The voltage or current required by the amplifier depends on the size of the tested system and levels of the target vibration. The accelerometer is used to measure the movement of basement and mass at each floor. The sensitivity of the accelerometer is chosen based on the maximum vibration level. SCADAS is a modular data acquisition device which consists of the frame for housing components containing all the cards, controller and power supply. The power supply includes the battery for autonomous operation, where for this model the duration of battery is around 2.5 hours. The mobile controller card is an ethernet interface linked with the Test.Lab software installed in the personal computer (PC) which consists of two output sources and two encoder inputs. SCADAS is used to capture dynamic signals, measure the accelerometer data and link the PC with Test.Lab software with amplifier. The LMS Test.Lab software was used to control the shaker and received the data from the experimental work. This software is designed as the solution for testing the equipment involved with vibration testing. It also offers quick visualization, easy reporting, and powerful analysis. It produces accurate closed-loop shaker control and has high built-in safety mechanism that reduces the risks of damaged items.

The connections between each component are illustrated in Figure 4. The input excitation for moving the shaker is generated by the software and then memorized by SCADAS. The controller card will give the signal to the amplifier and then the amplifier will generate the vibration to the shaker. Three accelerometers are placed in this study to measure the acceleration taken from the base, first floor, and second floor of the building structure. Once
the accelerometer detects the movement, the signal is sent to SCADAS DAC in acceleration value and recorded by the LMS Test.Lab software in the PC. The parameters for the experimental system parameter are shown in Table 1.

![Figure 3 Experimental setup](image)

| Parameter                  | Unit | Value  |
|----------------------------|------|--------|
| Mass (Floor 1 and 2)       | kg   | 764.00 |
| Stiffness (Floor 1 and 2)  | n/m  | 182.9  |
| Damping (Floor 1 and 2)    | n.s/m| 30     |
| Accelerometer sensitivity  | mV/G | 10     |
| Shaker frequency range     | Hz   | 2-4000 |
| Amplifier output power     | VA   | 4200   |
| Field voltage              | V    | 100    |
| Field current              | A    | 6      |
| Signal to noise ratio      | db   | > 80   |

Before running the experiment, it is required to pre-test the closed-loop system by configuring the SelfCheck setting. SelfCheck configuration is used to verify the experimental setup according to the connection, amplifier, and shaker problems. If problems occur, the status in the software window will appear "warning" or "not ok". In this case, the status showing 'Open Channel' appeared. This is because the connection between the accelerometer and data acquisition card output is not stable. The accelerometer channel did not generate a significant result above the background noise level. Other problems that occurred were caused by DAC issues while running the SelfCheck.
configuration. The DAC issue occurs because of the situation by the shaker amplifier that has not enough output to run the full-scale equipment. The explanation of the overall process for the validation of the system is shown in Figure 5.

3. Control Strategies

Consider the building structure as;

\begin{align}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= f(x) + g(x)u + d(x)
\end{align}

(6)

where the system state vector, \( x = [x_1, x_2, x_d]^T \), \( f(x) \) and \( g(x) \neq 0 \) are nonlinear function of \( x \), \( d(x) \) is uncertainties and disturbance and \( u \) is the scalar control input.

3.1 Terminal sliding mode control

The terminal sliding surface is described as (7) where \( \beta \) is a design constant that must be more remarkable than 0, and the value of \( p \) and \( q \) are positive odd integers that meet the condition; \( p > q \).

\begin{align}
s &= x_2 + \beta x_1^{\frac{q}{p}} \\
u &= -g^{-1}(x)[f(x) + \beta \frac{q}{p} x_1^{q/p-1} x_2 + (l_g + \eta)sgn (s)]
\end{align}

(7) (8)

where \( \eta > 0 \).

Stability analysis for TSMC is described as;

\begin{align}
\dot{s} &= \dot{x}_2 + \beta \frac{q}{p} x_1^{q/p-1} \dot{x}_1 \\
&= f(x) + g(x)u + d(x) + \beta \frac{q}{p} x_1^{q/p-1} \dot{x}_1
\end{align}

(9) (10)
Substitute the equation (8) into (10) to obtain;

\[ s\dot{s} = sd(x) - (l_g + \eta)|s| \leq -\eta|s| \quad (12) \]

Based on the equation state in (12), if the value for \( x_2 \neq 0 \) when \( x_1 = 0 \), the singularity occurs. This causes the problem to occur in the reaching phase when the state reaches at \( s = 0 \). This issue is solved by using nonsingular TSMC.

Finite-time analysis for the system is derived based on the following equation;

\[ \int_{s=s(0)}^{s=s(t_r)} ds = \int_{0}^{t_r} \pm ndt \quad (13) \]

\[ s(t_r) - s(0) = \pm nt_r \quad (14) \]

\[ t_r = \frac{s(0)}{n} \quad (15) \]

Suppose that after time \( t_r \), the attaining time which is the time of switching trajectory reach at sliding surface, \( t_s \) from \( x_1(t_r) \neq 0 \) to \( x_1(t_r + t_s) = 0 \). In this phase \( s = 0 \),

\[ x_2 + \frac{1}{p} x_1^{q/p} = 0 \quad (16) \]

\[ \dot{x}_1 = -\frac{1}{p} x_1^{q/p} \quad (17) \]

Then, the equation in (17) is integrated to obtain equation (18) written as;

\[ \int_{x_1(t_r)}^{0} x_1^{q/p} dx_1 = -\int_{t_r}^{t_s+t_r} \beta dt \]

\[ -\frac{p}{p-q} x_1^{1-q/p}(t_r) = -\beta t_s \quad (19) \]

\[ t_s = \frac{p}{\beta(p-q)} |x_1(t_r)|^{1-q/p} \quad (20) \]

### 3.2 Nonsingular terminal sliding mode control

Terminal sliding mode control type nonsingular has an advantage in giving a fast dynamic response, finite-time convergence, high control precision, and can eliminate the abnormal phenomena in the control input of the system.

\[ s = x_1 + \frac{1}{p} x_2^{p/q} \quad (21) \]

\[ u = -g^{-1}(x)[f(x) + \beta \frac{q}{p} x_2^{2-p/q} + (l_g + \eta) + sgn(s)] \quad (22) \]

Where \( \beta > 0 \), \( p \) and \( q \) are both positive odd numbers, \( 1 < p/q < 2 \), \( \eta \) is greater than zero and \( l_g \) is estimated using adaptive law.

Analysis of stability for NTSMC is written as;
\[ \dot{s} = \dot{x}_1 + \frac{1}{\beta q} p x_2^q \dot{x}_2 \tag{23} \]

\[ = x_2 + \frac{1}{\beta q} p x_2^q \left( f(x) + g(x)u + d(x) \right) \tag{24} \]

Substitute equation (22) into (24) to obtain;

\[ = \frac{1}{\beta q} p x_2^{q-1} \left( d(x) - (l_g + \eta) \right) \tag{25} \]

\[ s\dot{s} = \frac{1}{\beta q} p x_2^{q-1} \left( sd(x) - (l_g + \eta) |s| \right) \tag{26} \]

\[ s\dot{s} \leq -\frac{1}{\beta q} p \eta x_2^{q-1} |s| \tag{27} \]

When \( x_2 \neq 0 \), \( x_2^{p-1} > 0 \) as to \( p \) and \( q \) are positive integers. This result in the equation (28) and it can be concluded that the condition for Lyanpunov is satisfied in the case of \( x_2 \neq 0 \).

\[ -\frac{1}{\beta q} p \eta x_2^{p-1} > 0 \tag{28} \]

The condition when \( x_2 = 0 \) is studied by substituting equation (28) into (29) written as;

\[ \dot{x}_2 = g(x) - \beta q x_2^{q-2} u - (l_g + \eta) sgn(s) \tag{29} \]

\[ \dot{x}_2 = g(x) - (l_g + \eta) sgn(s) \tag{30} \]

Since we have \( s > 0 \), \( \dot{x}_2 \leq -\eta \) and when \( s < 0 \), \( \dot{x}_2 \geq \eta \), therefore the switching line \( s = 0 \) can be reach in finite time. The sliding mode \( s = 0 \) can be obtained from anywhere with the condition of switching trajectories in finite time.

### 3.3 Adaptive nonsingular terminal sliding mode control

The deep learning method, RBFNN, has the capability to approximate the uncertainties of unknown bound with universal error. Therefore, this technique is used in this study to estimate the value of the upper bound of an uncertain parameter, \( l_g \). The structure of RBFNN is shown in Figure 6, which consists of three layers. The first layer is the input for RBFNN determined by equating the number of input variables in the process data. Five neurons in the hidden layer are the connective weight between hidden and output neurons determined using rule-of-thumb method. It is crucial to find the correct number of neurons in the hidden layer because too few neurons will result in underfitting. Underfitting occurs when a number of neurons in the hidden layer are difficult to detect the signals in a complicated data set. Meanwhile, too many neurons in the hidden layer can cause overfitting and this problem may occur when neural networks have so much information processing capacity. The steps on designing ANTSMC in this study are as follow;

1. Simplify the system into \( \dot{x}_1 \) and \( \dot{x}_2 \)
2. Design sliding variables
3. Design NTSMC with an unknown parameter for ANTSMC, RBFNN
4. Perform stability analysis by satisfied Lyapunov condition
5. Perform analysis on attaining time
6. Construct in Simulink and apply to the system
\[ l_g = w^T \varphi_i(x) + \vartheta_i \]

\[ \varphi_i(x) = \exp \left( -\frac{||x - m_i||^2}{\sigma_i^2} \right) \]

\[ \hat{\vartheta} = |s| M \varphi_i(x) \]

Where,

\[ M = \frac{1}{\beta q} \frac{p}{\beta q} \frac{p}{q} - 1 \geq 0 \]

### 3.4 Controls of Structure System

The measurement for the sliding variable is obtained by using the mathematical model described by equations (7) and (21). The values of \( p \) and \( q \) must be positive odd numbers. After applying all the assumption values, the best performance response is obtained when the values are set to 5 and 3. The terminal sliding variables, \( s \) and control design, \( u \) for each controller used are;

\[ s_{TSMC} = x_2 + x_1^{3/5} \]

\[ s_{NTSMC} = x_1 + x_2^{5/3} \]

\[ s_{ANTS} = x_1 + x_2^{5/3} \]

**Theorem 1.**

After applying the control law in (39) into the building structure (1), suppose that the sliding variable in (36) and (37) will converge to zero in finite time, and the proposed controller can guarantee robustness and stability of the system. The controller design for the building structure is derived as;

\[ u_{TSMC} = k_d x_1 + c_d \dot{x}_1 - M_{f} \beta \frac{q}{p} \frac{2}{x_1^{2/3}} \dot{x}_2 - M_{f} (\xi + \eta) \text{sgn}(s) \]

\[ u_{NTSMC} = k_d x_2 + c_d \dot{x}_2 - M_{f} \beta \frac{q}{p} \frac{2}{x_2^{2/3}} \dot{x}_1 - M (\xi + \eta) + \text{sgn}(s) \]
Proof 1.

The proof for Theorem 1 is obtained through stability analysis of this controller. Consider that the Lyapunov function candidate is $\dot{V} = \frac{1}{2} s^2$. Then the derivative of $V$ along the trajectory is

$$\dot{V} = s \ddot{s}$$  \hspace{1cm} (40)

$$\ddot{s} = \ddot{x}_1 + \frac{1}{p} \frac{p}{q} \dot{x}_2$$  \hspace{1cm} (41)

$$\ddot{s} = x_2 + \frac{1}{p} \frac{p}{q} \dot{x}_2^2 \left[ - \frac{k_f}{M_r} x_1 - \frac{c_f}{M_r} + \frac{1}{M} (u - f_d) \right]$$  \hspace{1cm} (42)

Substitute equation (39) into (42), resulting in equation (44) as shown below;

$$\ddot{s} = x_2 + \frac{1}{p} \frac{p}{q} \dot{x}_2^2 \left[ - \frac{k_f}{M_r} x_1 - \frac{c_f}{M_r} + \frac{f_d}{M_r} + \left( \frac{k_f}{M_r} x_1 + c_f \right) \frac{x_2^2}{p} - \left( \xi + \eta \right) \text{sgn}(s) \right]$$  \hspace{1cm} (44)

$$\ddot{s} = x_2 + \frac{1}{p} \frac{p}{q} \dot{x}_2^2 \left[ \frac{f_d}{M_r} - \frac{\xi}{p} x_2^2 \right] - (\xi + \eta) \text{sgn}(s)$$  \hspace{1cm} (45)

$$\ddot{s} = -(\xi + \eta) \text{sgn}(s) - \frac{f_d}{M}$$  \hspace{1cm} (46)

The sliding surface estimation error is written as;

$$\dot{s}_e = s - \dot{s} = \ddot{x}_2$$  \hspace{1cm} (47)

This yields equation (48), where $\xi$ is the adaptive law value.

$$\dot{V} = s \ddot{s} = (s - \ddot{x}_2) (\ddot{x}_2 + (\xi + \eta) \text{sgn}(\ddot{x}))$$  \hspace{1cm} (48)

$$\dot{V} = (s - \ddot{x}_2) (\ddot{x}_2 - (\xi + \eta) \text{sgn}(\ddot{x}))$$  \hspace{1cm} (49)

Solve the equation above and obtain the equation as follows;

$$\dot{V} = -\frac{f_d}{M} s + \frac{f_d}{M} \ddot{x}_2 - (\xi + \eta) \text{sgn}(|\ddot{x}|) + \ddot{x}_2 (\xi + \eta) \text{sgn}(\ddot{x})$$  \hspace{1cm} (50)

Where $\frac{f_d}{M} \leq \xi$, \hspace{1cm} (51)
\[ \dot{V} = \dot{s} \dot{\xi} + \dot{\xi}_2 - (\xi + \eta) s \text{sgn}|\dot{s}| + \dot{\xi}_2 (\xi + \eta) \]  
\[ \dot{V}(t) = \dot{s} \dot{s} = \leq -\eta |\dot{s}| \]  
That is,
\[ \dot{V} \leq -\eta |s| < 0 \text{ for } s \neq 0 \]

According to equation (53), the Lyapunov controller stability of ANTSMC for the building structure can be evaluated. In this study the value of \( \eta \) is 0.01, and the sliding surface is taken with the value of \( 2 \times 10^5 \) resulted - \( 0.02 \times 10^5 \). Therefore, the value obtained is below than 0, thus, proving that the stability of the controller, NTSMC manifold converges to zero in finite time. On the other hand, if (37) is reached, the output tracking error of the building structure will converge to zero in finite time and prove the robustness and the stability of the system. This completes the proof for Theorem 1.

This study uses two inputs, one output, and five hidden neurons. The block diagram consists of an adaptive NTSM with the building structure is shown in Figure 7, where \( x_f \) is the desired value for the system output, \( e \) is error, \( s \) is sliding mode, \( u \) is the control input, and the output feedback is displacement and velocity of the building structure.

**Figure 7** Block diagram of the system with the adaptive NTSMC

## 4. Result and Discussion

### 4.1 System validation

The building structure model constructed in Matlab are validated via an experimental setup measured by the LMS.Test lab software. The acceleration results were measured using the accelerometer as shown in Figure 8 (a), (b) and (c) for ground input, second floor and first floor with the range of 0.78 m/s\(^2\), 0.01 m/s\(^2\), and 0.1 m/s\(^2\), respectively.
The results of the experimental work and simulation are compiled in Figure 9. As can be seen from these figures, the results of both methods have the same minimum and maximum values. The acceleration ranges for the first and second storeys are ±0.01 m/s² and ±0.1 m/s², respectively.
Figure 9 Comparison of the simulation and experimental results (a) ground input (b) second floor (c) first floor

4.2 Implementation of the control strategy

The building structure is equipped with HMD together with the implementation of the control strategy. The actual parameter for the building structure is used to evaluate the effectiveness of the controller in real life as shown in Table 2. Two input excitations are given as disturbances to study the robustness of the control strategy towards the system taken from the real earthquake occurred in El Centro in 1960 with the magnitude of 6.9 M\textsubscript{w} and Southern Sumatra on 12 September 2007 with the magnitude of 8.4 M\textsubscript{w}.
| Number of floors | Mass (10^3 kg) | Stiffness (10^5 N/m) | Damping (10^5 N.s/m) |
|------------------|----------------|---------------------|---------------------|
| First and second | 320            | 930                 | 15.69               |
| HMD              | 44             | 36.7                | 0.71                |

The results obtained for the building structure with both excitations are shown in Figure 10 for the second and first floors, respectively. The result shows that the implementation of control strategies has successfully suppressed the earthquake-induced vibrations. The maximum vibration occurred at 2.17 s causing the reduction percentage measured at the second floor with respect to the uncontrolled system generated by each controller to be 46% for ANTSMC, 36% for NTSMC, and 10% for TSMC. The reduction percentage generated by the first floor is 40% for ANTSMC, 38% for NTSMC, and 7.5% for TSMC. This shows that the ANTSMC has the highest reduction percentage compared to the other controllers.

The second excitation taken from Southern Sumatra with the duration of acceleration is longer compared to the El Centro earthquake which is 320.725 s. The results obtained are shown in Figure 11 for both floors of the building. The maximum vibration recorded for the second and first floors are $1.3 \times 10^{-3}$ m and $0.78 \times 10^{-3}$ m, respectively. Based on these maximum displacement values, the percentage of vibration reduction from the uncontrolled structure for each control strategy is 42% by NTSMC, 38% by NTSMC, and 19% by TSMC. After the implementation of control strategies, it was shown that ANTSMC has the superior performance in suppressing the building vibration.

![Figure 10](image1.png)

(a) Comparison of the displacement responses for the building structure at the (a) second floor (b) first floor for the El Centro excitation
The sliding surface measured by the El Centro excitation for each controller is shown in Figure 12. The sliding surface design should reflect the required specification when the sliding mode is established. The figures show that the state trajectories are moving towards the sliding surface that was set to 0 to maintain the position of the system during an earthquake. This has fulfilled the system with a required response to obtain a stable condition. The same time was setting for each controller and resulting the state trajectory generated by the ANTSMC has a faster response to reach the desired sliding surface compared to NTSMC and TSMC.

The results are summarized in Figure 13 for both excitations measured at the first and second floor taken at the maximum vibration of the building structure which occurred at 2.17 s for the El Centro and 108.6 s for the Southern Sumatra excitations. According to both figures, the second floor generated a higher sway during the seismic activity than the first floor. However, when control strategies were applied, the vibrations were suppressed.
This study considers the ductile reinforced concrete building and the building collapse probability is measured according to the graph damage of probability for the low-rise building under the 3-DOF system according to the guideline given by FAMA and IDA. Based on the probability of the building collapse for both excitations, it is clear that the implementation of the proposed controller which is the adaptive NTSMC in the 2-DOF structure has reduced the percentage of the building from collapse. From Figure 14 (a), the percentage of the building to have slight damage is 98%, and after the implementation of the controller, the probability is reduced to 50%. Moreover, the probability percentage of the building to have complete damage is reduced from 0.8% to 0.2%. From Figure 14 (b), the probability of the building to have slight damage is 100% which is reduced to 98%. For complete damage, the probability is reduced from 15% to 0.8%. This controller shows a high percentage reduction when applied to the system that is triggered by the El Centro earthquake rather than by the Southern Sumatra earthquake since the magnitude of the El Centro earthquake is lower than the magnitude of the Southern Sumatra earthquake. However, both responses show impressive results in reducing the probability of the building collapse.

5. Conclusion

This study was aimed at investigating the influence of implementing the control strategy, namely ANTSMC to the 2-DOF structure in enhancing the building’s structural and decreasing the risk of the building from damage. The system was validated by the experimental work for the 2-DOF structure and acceleration responses were measured by the LMS Test.Lab software. The result for the building system response was compared to the simulation result in Simulink. ANTSMC was designed to enhance the performance of the building structure by suppressing the vibration during an earthquake. The effectiveness of the controller was compared with TSMC and NTSMC. The
stability of ANTSMC was demonstrated as the building structure reached its equilibrium faster and maintained its position as the desired response stated. Moreover, the proposed control strategy reduced the probability of damage to the building structure. The probability percentage of the building to have slight damage with the implementation of ANTSMC was reduced until 50% compared to an uncontrolled building with a probability of 98% to have a slight damage. The lower percentage in having the probability of the building experiencing damage shows the significant impact of the implementation of control strategy in the building structure.

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Conflict of interest

All authors declare that they have no conflicts of interest.

References

Abu-Faraj ZO, Hamdan TF, Wehbi MR, et al (2008) The study of postural stability in an earthquake-simulated environment yields a retained cognitive learning outcome. J Biomed Pharm Eng 2:14–21

Alam J, Hussan M, Sarraz A (2017) Seismic Fragility Assessment of RC Building using Nonlinear Static Pushover Analysis. 26:7

Allen RM, Melgar D (2019) Earthquake early warning: Advances, scientific challenges, and societal needs. Annu Rev Earth Planet Sci 47:361–388

Ansal A, Kurtuluş A, Tönük G (2010) Seismic microzonation and earthquake damage scenarios for urban areas. Soil Dyn Earthq Eng 30:1319–1328. https://doi.org/10.1016/j.soildyn.2010.06.004

Ba DX, Yeom H, Bae J (2019) A direct robust nonsingular terminal sliding mode controller based on an adaptive time-delay estimator for servomotor rigid robots. Mechatronics 59:82–94. https://doi.org/10.1016/j.mechatronics.2019.03.007

Bayrak OF, Bikçe M, Erdem MM (2021) Failures of structures during the January 24, 2020, Sivrice (Elazığ) Earthquake in Turkey. Nat Hazards 1–27. https://doi.org/10.1007/s11069-021-04764-z

Cao L, Chen X, Sheng T (2013) Fault tolerant small satellite attitude control using adaptive non-singular terminal sliding mode

Chesné S, Collette C (2018) Experimental validation of fail-safe hybrid mass damper. J Vib Control 24:3935–4406. https://doi.org/10.1177/1077546317724949

Chesné S, Inquieté G, Cranga P, et al (2019) Innovative Hybrid Mass Damper for Dual-Loop Controller. Mech Syst Signal Process 115:514–523. https://doi.org/10.1016/j.ymssp.2018.06.023

Cremen G, Velazquez O, Orihuela B, Galasso C (2021) Predicting approximate seismic responses in multistory buildings from real-time earthquake source information, for earthquake early warning applications. Bull Earthq Eng 1–21. https://doi.org/10.1007/s10518-021-01088-y

D’Ayala D, Ansal A (2012) Non linear push over assessment of heritage buildings in Istanbul to define seismic risk. Bull Earthq Eng 10:285–306. https://doi.org/10.1007/s10518-011-9311-1

Djedoui N, Ounis A, Pinelli JP, Abdeddaim M (2017) Hybrid Control Systems For Rigid Buildings Structures Under Strong Earthquakes. Asian J Civ Eng 18:893–909

Duan X, Pappin JW (2008) A Procedure For Establishing Fragility Functions For Seismic Loss Estimate Of Existing Buildings Based On Nonlinear Pushover Analysis. 14th World Conf Earthq Eng

Federal Emergency Management Agency (FEMA) (2003) HAZUS-MH MR4 Multi-Hazard Loss Estimation Methodology – Earthquake Model: Technical Manual. Department of Homeland Security

Giordano N, De Luca F, Sextos A, et al (2021) Empirical seismic fragility models for Nepalese school buildings. Nat Hazards 105:339–362. https://doi.org/10.1007/s11069-020-04312-1

Gkimprisis A, Tubaldi E, Douglas J (2020) Evaluating alternative approaches for the seismic design of structures. Bull Earthq Eng 18:4331–4361. https://doi.org/10.1007/s10518-020-00858-4

Gupta HK, Sabnis KA, Durah R, et al (2020) Himalayan Earthquakes and Developing an Earthquake Resilient Society. J Geol Soc India 96:433–446. https://doi.org/10.1007/s12594-020-1581-2

Liu J (2013) Radial Basis Function (RBF) Neural Network Control for Mechanical Systems https://doi.org/10.1007/978-3-642-34816-7
Liu J, Wang X (2012) Advanced Sliding Mode Control for Mechanical Systems: Design, Analysis and MATLAB Simulation. Springer Science & Business Media https://doi: 10.1007/978-3-642-20907-9

Martins L, Silva V (2020) Development of a fragility and vulnerability model for global seismic risk analyses. Bull Earthq Eng 1–27

Mitchell R, Kim Y, El-Korchi T, Cha YJ (2013) Wavelet-neuro-fuzzy control of hybrid building-active tuned mass damper system under seismic excitations. JVC/Journal Vib Control 19:1881–1894. https://doi.org/10.1177/1077546312450730

Ning D, Sun S, Du H, et al (2018) Control of a multiple-DOF vehicle seat suspension with roll and vertical vibration. J Sound Vib 435:170–191. https://doi.org/10.1016/j.jsv.2018.08.005

Peyghaleh E, Mahmoudabadi V, Martin JR, et al (2018) Impact of local site conditions on portfolio earthquake loss estimation for different building types. Nat Hazards 94:121–150. https://doi.org/10.1007/s11069-018-3377-x

Robinson TR, Rosser NJ, Densmore AL, et al (2018) Use of scenario ensembles for deriving seismic risk. Proc Natl Acad Sci 115:E9532–E9541. https://doi.org/10.1073/pnas.1807433115

Thenozhi S, Yu W (2013) Advances in modeling and vibration control of building structures. Annu Rev Control 37:346–364. https://doi.org/10.1016/j.arcontrol.2013.09.012

Vamvatsikos D, Cornell CA (2002) Incremental dynamic analysis. Earthq Eng Struct Dyn 31:491–514. https://doi.org/10.1002/eqe.141

Xing H, Junyi S, Jin H (2020) The casualty prediction of earthquake disaster based on Extreme Learning Machine method. Nat Hazards 102:873–886. https://doi.org/10.1007/s11069-020-03937-6

Xu W, Jiang Y, Mu C, Yue H (2015) Nonsingular terminal sliding mode control for the speed regulation of permanent magnet synchronous motor with parameter uncertainties. doi: 10.1109/IECON.2015.7392393.

Vazurkar UY, Chaudhari DJ (2016) Development of Fragility Curves for RC Buildings. Int J Eng Res 5:591–594. https://doi.org/10.17950/ijer/v5i3/016

Zamani A-A, Tavakoli S, Etedali S, Sadeghi J (2018) Online tuning of fractional order fuzzy PID controller in smart seismic isolated structures. Bull Earthq Eng 16:3153–3170. https://doi.org/10.1007/s10518-017-0294-4

Zhu Z, Yan Y (2014) Space-based line-of-sight tracking control of GEO target using nonsingular terminal sliding mode. Adv Sp Res 54:1064–1076. https://doi.org/10.1016/j.asr.2014.05.013