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An Adaptive Controller Design for ATMD System Used in Structures Under the Effect of Unknown Nonlinear Effects

Bilinmeyen Doğrusal Olmayan Etkilerin Etkisi Altındaki Yapılarda Kullanılan ATMD Sistemleri için Uyarlanabilir Bir Kontrolör Tasarımı

Rafet Can Ümütlü [1]* , Hasan Öztürk [2] , Barış Bıdıklı [3]

[1] Dokuz Eylül Üniversitesi Fen Bilimleri Enstitüsü Mekatronik Mühendisliği Bölümü, İzmir, Türkiye
[2] Dokuz Eylül Üniversitesi Mühendislik Fakültesi Makina Mühendisliği Bölümü, İzmir, Türkiye
[3] İzmir Katip Çelebi Üniversitesi Mühendislik ve Mimarlık Fakültesi Mekatronik Mühendisliği Bölümü, İzmir, Türkiye
Sorumlu Yazar / Corresponding Author *: rafet.umutlu@deu.edu.tr

Abstract

Active tuned mass damper (ATMD) devices are favored in many applications to reduce vibrations induced by earthquakes in multi-story structures. In the literature, the Lyapunov-based controller design for ATMD systems is a popular topic of research. The building structures have been modeled linearly in the majority of studies so far in the literature. As a result, the controls in these researches are linear as well. Only a few studies have considered the nonlinear dynamics of multi-story structures, however, in these works, linear control schemes employing various linearization approaches are provided. Nonlinear behavior is the inherent behavior of multi-story buildings with ATMD systems. As a consequence, studying nonlinear dynamics while designing a nonlinear controller is regarded to be a more realistic approach. Furthermore, numerous unpredictable external factors should be considered during control design to guarantee that the control systems are able to operate securely in any environment. In order to create a more realistic approach, the linear model of the multi-story structure is reconfigured in this work by adding nonlinear ambiguous functions to it. It was assumed in this study that the structural parameters were unknown at the time of controller design. Adaptive compensation rules replace all system parameters of the system necessary in control design. Theoretically, Lyapunov-based arguments are used to show that the developed controller can keep the structure stable while attaining the main control aim. Matlab-Simulink is used to analyze the performance of the developed controllers.

Keywords: Nonlinear control, Vibration control, Lyapunov based control, Robust Control, ATMD Systems

Öz

Aktif ayarlı kütle sönümleyici (ATMD) cihazları, çok katlı yapılarda depremlerin neden olduğu titreşimleri azaltmak için birçok uygulamada tercih edilmektedir. Literatürde ATMD sistemleri için Lyapunov tabanlı kontrolör tasarımı popüler bir araştırma konusudur. Literatürde bugüne kadar yapılan çalışmaların çoğunda bina yapıları doğrusal olarak modellenmiştir ve bu araştırmalardaki kontroller de doğrusaldır. Çok katlı yapıların doğrusal olmayan dinamikleri sadece birkaç çalışmada ele alınmıştır, ancak bu çalışmalarda çeşitli doğrusallaştırma yaklaşımlarını ile birlikte doğrusal kontrol stratejileri kullanılmıştır. Doğrusal olmayan davranış, ATMD sistemlerine sahip çok katlı binaların doğal davranışıdır. Sonuç olarak, doğrusal olmayan bir kontrolör tasarlarken doğrusal olmayan dinamikleri incelemek daha gerçekçi bir yaklaşım olarak görülmektedir. Ayrıca, kontrol sistemlerinin güvenli bir şekilde çalışabilmesini garanti etmek için kontrol tasarımı sırasında çok sayıda öngörülemeyen dış faktör dikkate alınmalıdır. Daha gerçekçi bir yaklaşım oluşturmak için çok katlı yapının lineer modeli bu çalışmada lineer olmayan belirsiz fonksiyonlar eklenerek yeniden yapılandırılmıştır. Bu çalışmada, kontrolör tasarımı sırasında yapısal parametrelerin bilinmediği varsayılmıştır. Uyarlanabilir kompanzasyon kuralları, kontrol tasarımında gerekli olan sistemin tüm sistem parametrelerinin yerini alır. Teorik olarak, Lyapunov tabanlı argümanlar, geliştirilen kontrolörün ana kontrol amacına ulaşırken yapının stabilitesini koruyabileceğini göstermek için kullanılır. Matlab-Simulink, geliştirilen kontrolörlerin performansını analiz etmek için kullanılmıştır.

Anahtar Kelimeler: Doğrusal olmayan kontrol, Titreşim kontrolü, Lyapunov tabanlı kontrol, Robust Kontrol, ATMD Sistemleri

1. Introduction

With the developing world and increasing population, the demand for high-rise buildings is increasing in many earthquake regions. In parallel with this, the demand for earthquake protection systems to protect buildings and people in the face of earthquakes is rapidly increasing. Earthquake-induced vibrations can be reduced by passive and active vibration control methods. There has been an increasing number of studies on this subject in recent years.

Passive control methods were used to damping vibration before control systems developed to this day. Vibration isolation using rubber bearings is one of the most popular methods of passive vibration control. In case of earthquake input, seismic isolation devices such as those consisting of rubber and steel plates have been used .Base isolators are flexible isolation devices, placed between the building structure and the foundation for reducing seismic wave propagation into the structure [1]. The addition of this device will increase the flexibility of the structure, hence, the structural time period. For that reason, isolators reduce the propagation of high frequency signal from ground to the structure. They are one of the popular technique applied widely in bridges [2]. Another passive control method is tuned mass damper (TMD). It is based on simple idea of transferring the kinetic energy of the vibrating structure to a properly tuned and specially designed single degree of freedom oscillator [3–6].

TMD system, which is moved with the help of an actuator, is called an ATMD system [7]. The ATMD, which is usually placed on the last floor of the building, moves with the designed controller signal, generating a vibration response and reducing the overall vibration response of the building [1]. Since multi-degree of freedom systems generate vibration in various vibration modes, ATMD systems have a very high performance in reducing the vibration of such structures [8]. ATMD systems are used in conjunction with various control strategies to mittigate the vibration in structures. As an example of these control strategies; Fuzzy logic control [2,9,10], PID control [11–13], Siliding mode control [14–16] and various lyapunov based controllers [14,17–20] can be given.

A lyapunov based adaptive controller has been designed for earthquake-induced vibrations of multi-storey buildings with ATMD system placed on the last floor of the building. In previous studies in the literature, linear controllers were designed for linear structures or structures containing nonlinear parameters were linearized and a control design was made. Structures physically exhibit nonlinear behavior. Because of this situation, it is thought that designing a non-linear controller considering these nonlinear dynamics is a more realistic and

applicable approach. Band-limited white noise has been added to the system equation of the structure as a f_n function. This function is used in this study, taking into account the nonlinear parameters, measurement noise, and uncertain dynamics. A completely robust control strategy is proposed to provide robustness against these uncertain and nonlinear dynamics of the structure. The controller designed with a robust adaptive structure can be applied to different buildings with different structures. The designed controller also compensates for the unknown system parameters with the term compensation and overcomes the system nonlinearities owing to its nonlinear structure.

2. Material and Method

2.1. Structure Model and Controller Design

The nine-story building structure is selected the use in this study as a model. The ATMD system is placed on the top floor, as seen in Figure 1. m_i, k_i and b_i represent to mass, stiffness and damping coefficients of stories of the structure, respectively. In addition to m_d, k_d and b_d represent to mass, stiffness and damping coefficients of ATMD systems, respectively.

In these types of rigid structures vibration suppression is realized based on the fact that damping the vibration of the top floor during an earthquake is enough for damping the vibration of the whole building. In such applications, damping systems placed on the top floor of the building are used to reduce the vibration of the building. Therefore, a control system can be designed by focusing on the displacement of the last floor of the building. In other words, the control problem can mathematically be started from the following equation.

Equations of motion of a nine-story building under earthquake excitation with the ATMD are given below;

$$m_i\ddot{y}_i + b_i(\dot{y}_i - \dot{y}_{i-1})$$
$$-b_{i+1}(\dot{y}_{i+1} - \dot{y}_i)$$
$$+k_i(y_i - y_{i-1}) \qquad (1)$$
$$-k_{i+1}(y_{i+1} - y_i) = 0$$
for $i = (1 - 8)$

$$m_9\ddot{y}_9 + b_9(\dot{y}_9 - \dot{y}_8) - b_d(\dot{y}_d - \dot{y}_9)$$
$$+ k_9(y_9 - y_8) \qquad (2)$$
$$- k_d(y_d - y_9)$$
$$+ f_n = u_f$$

$$m_d\ddot{y}_d + b_d(\dot{y}_d - \dot{y}_9) + k_d(y_d - y_9) \qquad (3)$$
$$= -u_f$$

In Eq. (1), For the case where i = 1, y_0 and $\dot{y}_0$ represents the displacement and velocity of ground motion.

In Eq. (2) f_n represents to nonlinearity, noise and other uncertainties. In Eq. (2) and Eq. (3),u_f symbolize the force applied to the control mass to mitigate the vibration of the building.
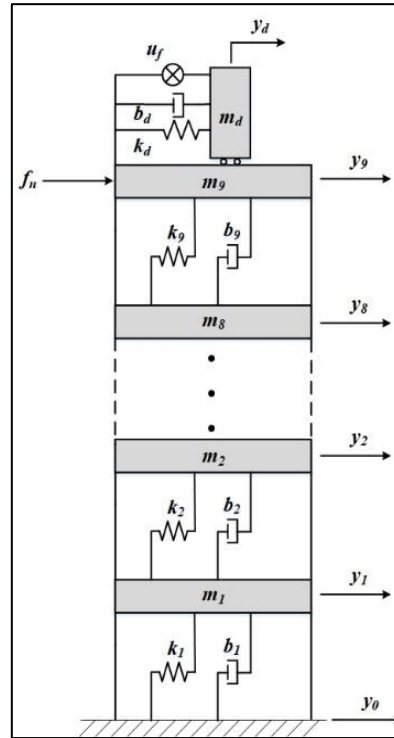
Figure 1. Building structure model under earthquake excitation ATMD systems on the top floor.

The Eq. (2) can be rearranged as

$$m_9\ddot{y}_9 + f_m(\dot{y}_8, \dot{y}_9, \dot{y}_d, y_8, y_9, y_d)$$
$$+ f_n = u_f \qquad (4)$$

where f_m represents a remaining function, which includes system states and system

parameters. In Eq. (5), it is aimed to assign the state to be controlled in Eq. (4) to a variable and make it proper for the control design.

$$x = y_9 \qquad (5)$$

The auxiliary error term $e \in \mathbb{R}$ is defined as

$$e \triangleq u_v - \dot{y}_9 \qquad (6)$$

Time Derivative of Eq. (6) multiplied by m_9

$$m_9 \dot{e} = m_9 \dot{u}_v - m_9 \ddot{y}_9 \qquad (7)$$

Design virtual controller

$$u_v \triangleq -g_1 x \qquad (8)$$

where $g_1 \in \mathbb{R}^+$ denotes the positive constant control gain.

The time derivative of Eq. (8) is used in Eq. (7). The Eq. (7) is rearranged utilizing Eq. (4) and is obtained Eq. (9).

$$m_9 \dot{e} = -m_9 g_1 \dot{y}_9 - u_f + f_m + f_n. \qquad (9)$$

$(f_m - m_9 g_1 \dot{y}_9)$ terms are defined as

$$(f_m - m_9 g_1 \dot{y}_9) \triangleq \mathbf{C\phi} \qquad (10)$$

where $\mathbf{C} \in \mathbb{R}^{1\times6}$ represents the vector of uncertain coefficients, $\mathbf{\phi}(\dot{y}_8, \dot{y}_9, \dot{y}_d, y_8, y_9, y_d) \in \mathbb{R}^{6\times1}$ represents the certain vector of base functions. Rearranging Eq. (9) by using Eq. (10)

$$m_9 \dot{e} = -u_f + \mathbf{C\phi} + f_n \qquad (11)$$

Uncertain coefficients vector $\mathbf{C}$ is adaptively compensated using compensator error $\tilde{\mathbf{c}} \in \mathbb{R}^{1\times6}$ and compensator vector $\hat{\mathbf{C}} \in \mathbb{R}^{1\times6}$ defined as

$$\tilde{\mathbf{C}} = \mathbf{C} - \hat{\mathbf{C}} \qquad (12)$$

Design the controller

$$u_f = \hat{\mathbf{C}}\mathbf{\phi} + \rho_b tanh(e) + g_2 e. \qquad (13)$$

where $g_2 \in \mathbb{R}^+$ denotes the positive constant control gain. and $\rho_b \in \mathbb{R}^+$ denotes the positive bounding constant of the modeling error and ρ_b is selected as

$$|f_n| \le \rho_b. \qquad (14)$$

Lyapunov function is defined as

$$V \triangleq \frac{1}{2}y_9^2 + \frac{1}{2}m_9 e^2 + \frac{1}{2}\tilde{\mathbf{C}}^T\tilde{\mathbf{C}}. \qquad (15)$$

Time derivative of Eq. (15)

$$\dot{V} = -g_1 y_9^2 - g_2 e^2 + \tilde{\mathbf{C}}^T\left(\dot{\hat{\mathbf{C}}} + \mathbf{\phi}^T e\right) \\ + e[f_n - \rho_b tanh(e)] \qquad (16)$$

The adaptive compensation rules are determined from Eq. (17)

$$\dot{\hat{\mathbf{C}}} = -\mathbf{\phi}^T r \qquad (17)$$

In Eq. (16), $\dot{V}$ is nonpositive and that provides the Lyapunov stability criterion.

$$\dot{V} \le -\beta\|\mathbf{z}\|^2 \qquad (18)$$

where $\mathbf{z} \in \mathbb{R}^2$ is a vector defined as

$$\mathbf{z} \triangleq [x \quad e]^T \qquad (19)$$

and $\beta \in \mathbb{R}^+$ denotes a positive constant selected as

$$\beta = \min\{g_1, g_2\} \qquad (20)$$

From Eq. (15) and the bound of its time derivative Eq. (18), it is seen that $\mathbf{z}(t) \in \mathcal{L}_\infty$. Boundedness of this term guarantees the boundedness of x and e. From its design in Eq. (8), it is seen that boundedness of x guarantees the boundedness of u_v. Boundedness of the virtual control input can be utilized along with the boundedness of e and its definition in Eq. (6) to show that $\dot{y}_9 \in \mathcal{L}_\infty$. Boundedness of $\dot{y}_9$ is utilized along with Eq. (5) and can be utilized with the time derivative of Eq. (7) to show that $\dot{u}_v \in \mathcal{L}_\infty$. Boundedness of $\dot{u}_v$ can be used with the time derivative of Eq. (6) to show that $\dot{e} \in \mathcal{L}_\infty$. Boundedness of $\dot{y}_9$ and $\dot{e}$ guarantees the boundedness of $\dot{\mathbf{z}}(t)$. All of the remaining signals under the closed-loop operation can be shown via standard signal chasing arguments.

The following equation guarantees that $\mathbf{z}(t) \in \mathcal{L}_2$, integration of Eq. (18) that can be obtained as follows is utilized

$$\int_0^\infty \|\mathbf{z}(\sigma)\|^2 d\sigma \le \frac{V(0)}{\beta} \qquad (21)$$

Boundedness of $\dot{\mathbf{z}}(t)$ can be utilized with $\mathbf{z}(t) \in \mathcal{L}_2 \cap \mathcal{L}_\infty$ and Barbalat's Lemma [21] to prove semi-global asymptotic stability of $\mathbf{z}(t)$ that guarantees the main purpose of the control design in the sense that

$$x, e \rightarrow 0 \text{ as } t \rightarrow \infty. \tag{22}$$

2.2. Simulation Studies

In this section, the Lyapunov based adaptive controller applied to the ATMD system that is placed on the top floor of nine story structure. The numerical values of structural coefficients [20] given in Table 1.

The determined structure is exposed to the Kocaeli earthquake in Turkey on 17 August 1999. Acceleration, velocity and displacement of ground motion is shown in the Figure 2.[22,23]

Table 1.   Parameters of the building model and the ATMD

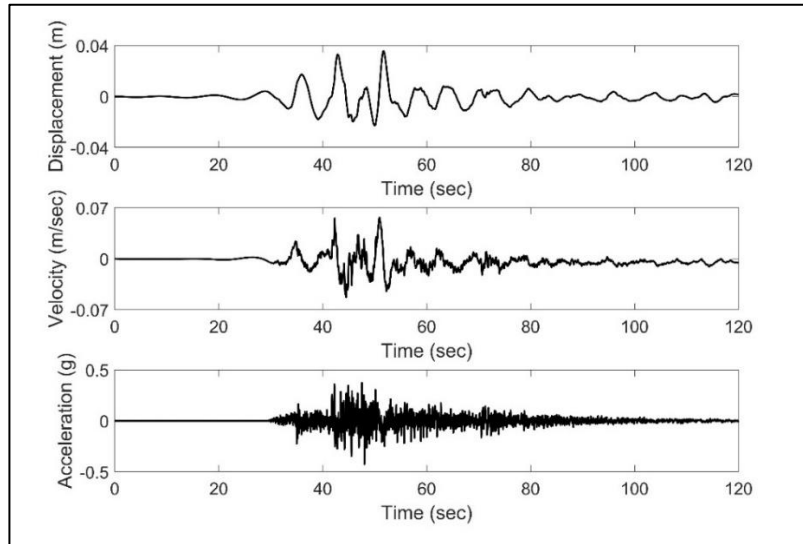| Parameter	Value $x10^3$ (kg)	Parameter	Value $x10^3$ (N/m)	Parameter	Value $x10^3$ (Ns/m)
m_1	450	k_1	18.05	b_1	26.17
m_2	345	k_2	340	b_2	490
m_3	345	k_3	326	b_3	467
m_4	345	k_4	285	b_4	410
m_5	345	k_5	269	b_5	386
m_6	345	k_6	243	b_6	348
m_7	345	k_7	207	b_7	298
m_8	345	k_8	169	b_8	243
m_9	345	k_9	137	b_9	196
m_d	69	k_d	0.3365	b_d	152.39

Figure 2. Acceleration, velocity and displacement data of Kocaeli Earthquake

One of the most significant benefits of Lyapunov-based control design techniques is that the theoretical limits of control gains that preserve overall system stability can be found in the stability analysis. Control gains can then be chosen from stated rules through trial and error,

as long as the system's overall stability is assured. According to the stability analysis described in the article, choosing positive defined control gains is sufficient to guarantee the stability of the system.

The control design in Eq. (13) is applied from the actuator input and the control gains are selected as follows via trial and error method

$$g_1 = 360, \ g_2 = 4700, \rho_b = 1 \qquad (23)$$

3. Results

Uncontrolled system, TMD control system and ATMD control system were examined. Figure 3 shows the vibration of the ninth floor during the earthquake for these three different situations. The TMD system reduces the vibration response compared to an uncontrolled situation, but it has been observed that the amplitude of the vibration and the time taken to reduce the

vibration is much higher than the ATMD system. The root mean square (RMS) and peak values of three different cases are given in Table 2. In RMS values, TMD showed 51.44% vibration reduction compared to uncontrolled condition, while ATMD achieved 56.76% improvement in vibration response compared to TMD. According to peak values, ATMD system reached a 25% better result than TMD controller. It is seen that the designed controller is used together with ATMD systems to significantly reduce vibrations caused by earthquakes in structures containing nonlinear parameters.

As can be seen in Figure 4, the controller mass displacement remained within a reasonable range. Figure 5 shows the variation of the force required to be applied to the controller mass during the earthquake to dampen vibrations caused by the earthquake.
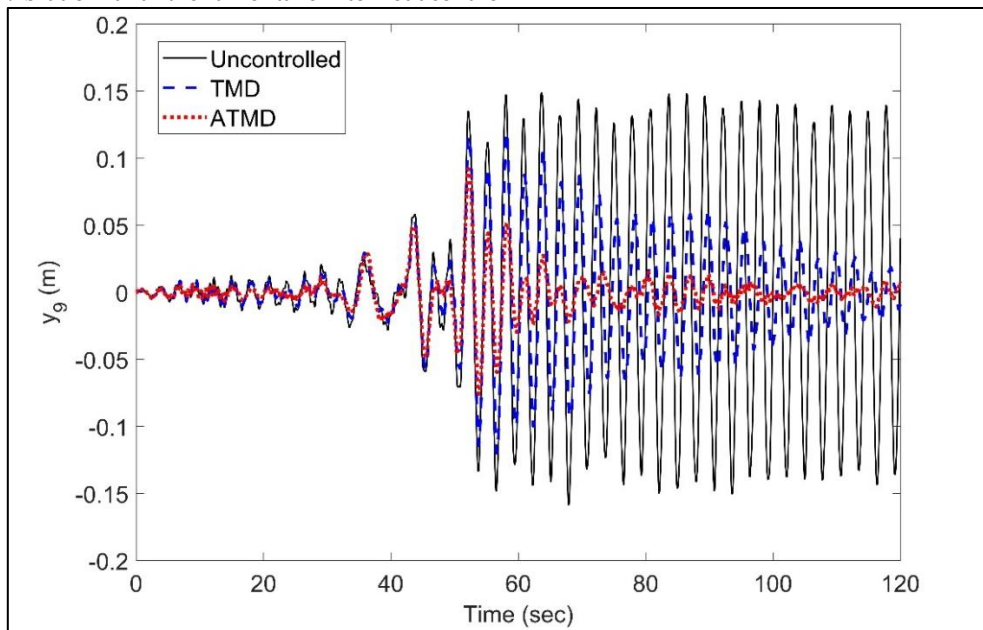

Figure 3. Displacement of nineth story of building for three different case

Table 2. Statistical values of last story displacement

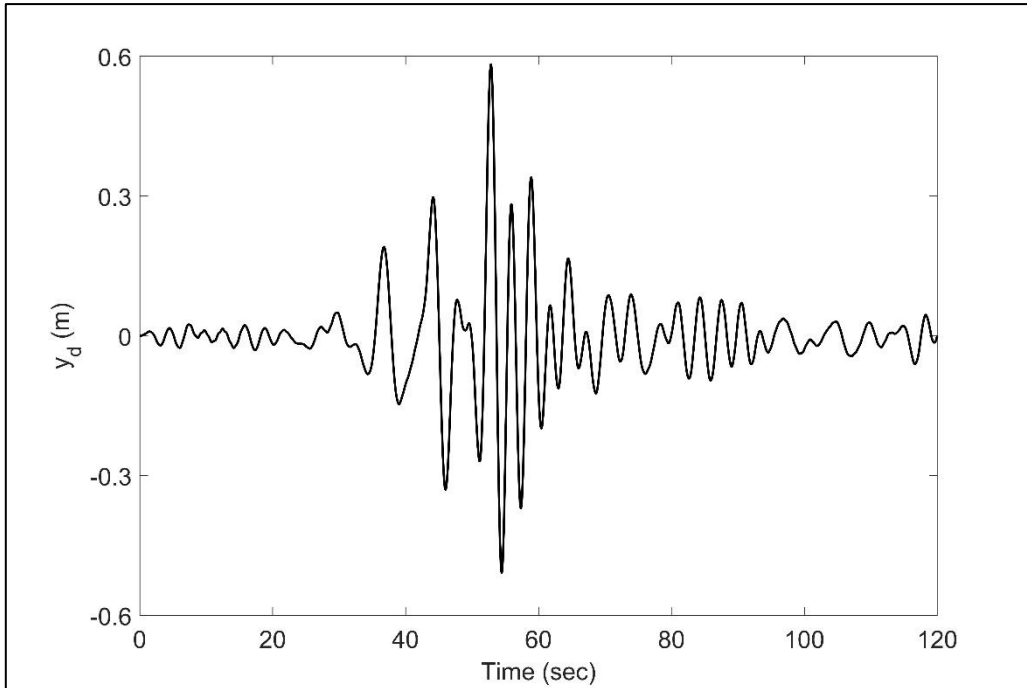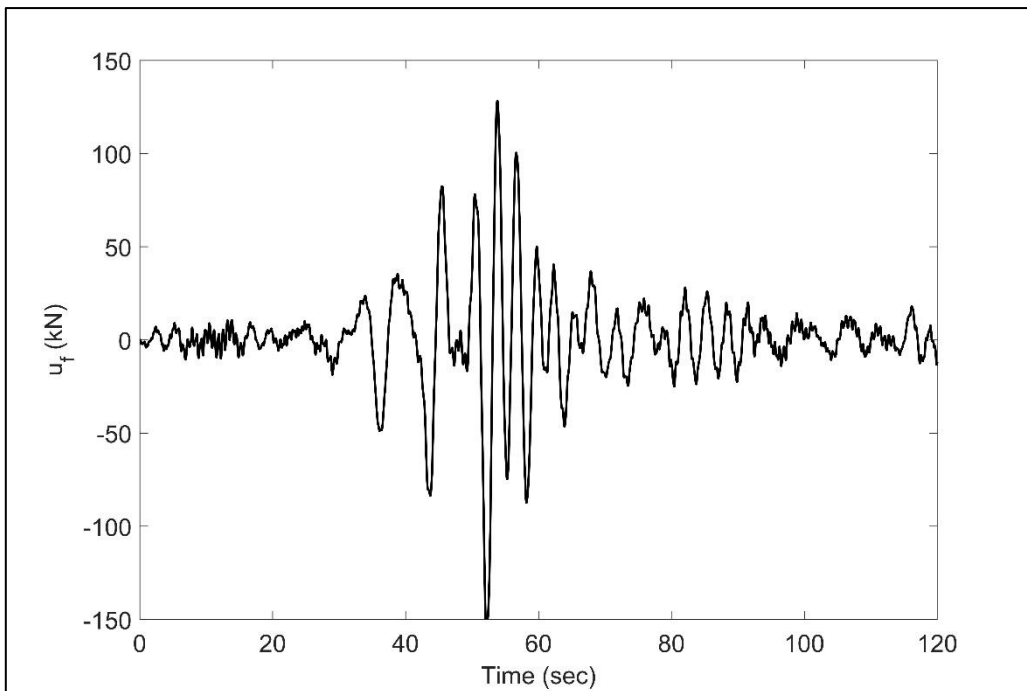|	Uncontrolled (m)	TMD (m)	ATMD (m)
RMS	0.0745	0.0370	0.0160
Peak	0.1587	0.1199	0.0920

Figure 4. Displacement of ATMD mass

Figure 5. Controller force applied to the ATMD for vibration attenuation of structure

Fig. 6(a), 6(b), 6(c), 6(d), 6(e), and 6(f) shows the adaptive compensations of the uncertain parameters $\hat{C}_1, \hat{C}_2, \hat{C}_3, \hat{C}_4, \hat{C}_5$ and $\hat{C}_6$, respectively. The term compensation is used to achieve the control objective. The numerical values of these terms are irrelevant provided they change within a limited range. The variation of compensation parameters in a limited range while vibration control is taking place during an earthquake as shown in Figure 6.
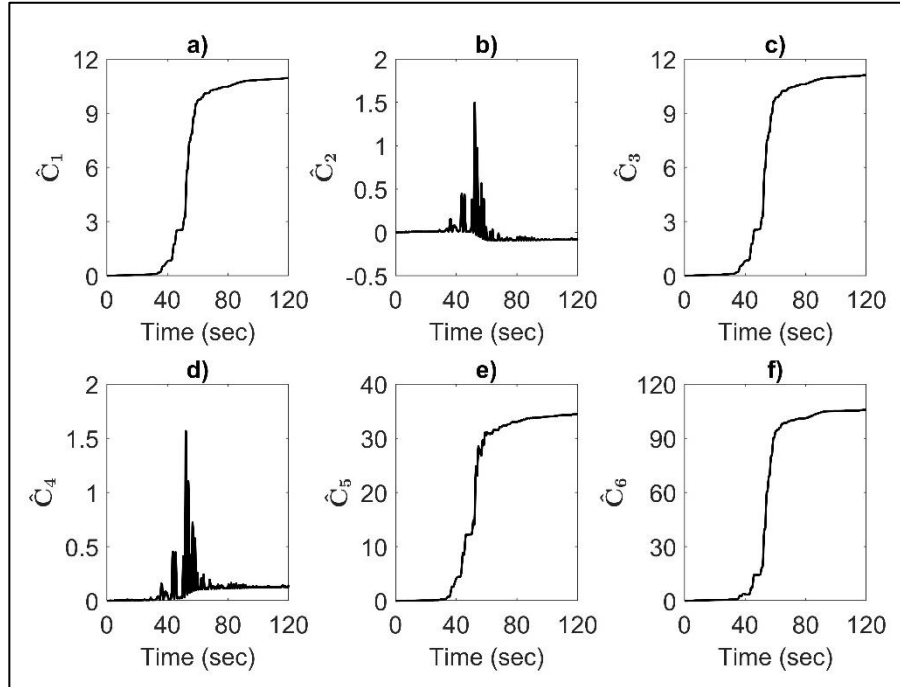

Figure 6. Changing values of compensation parameters during the earthquake

4. Conclusions

In this study, a Lyapunov based adaptive controller is designed to reduce the vibration of a nine-story building under earthquake effect. In order to get a more realistic approach, the linear model of the multi-story building has been rearranged by adding nonlinear function f_n. This function represents the nonlinear parameters, measurement noise, and uncertain dynamics in the mathematical model. Band limited white noise is used instead of defined nonlinear uncertain function in this study. The main purpose of controller design is to reduce vibrations of building structure stories under earthquake excitation with ATMD placed on the top floor. A completely robust control strategy is proposed to ensure the robustness of the designed structure against uncertain and nonlinear dynamics. The designed controller can compensate coefficient of the remaining function that is includes system parameters independently of the system model. Top floor displacements have been compared for three different situations, uncontrolled, TMD and ATMD, and the damping effect of the ATMD system driven by the designed controller is quite successful. It is theoretically proved by using Lyapunov-based arguments that the designed controller can maintain the stability of the structure while achieving this main control goal.

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