The Design of a Tuned Mass Damper as a Vibration Absorber

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Abstract

The protection of civil structures, including their material contents and human occupants, is without doubt a world-wide priority of most serious current research. Such protection may range from reliable operation and comfort, on one hand, to serviceability on the other. Examples of such structures which leap to one's mind include buildings, towers, and bridges. In like manner, events which cause the need for such protective measures are environmental like earthquakes and winds, or moving loads like cars and pedestrians in the case of bridges.The earthquake hazard is translated in severe vibrations for the structural systems. In order to handle this world wide problem auxiliary damping devices is added to absorb those vibrations. One of the early used damping devices is the Tuned Mass Damper (TMD) which is a passive system in that it absorbs the structural response without adding an external control signal. In this work a case study of three stories building model excited by a simulated earthquake hazard is investigated versus the response of the same building supplied by a TMD.

Keywords: Structural systems, Passive Dampers, TMD, Earthquake hazard.

تصميم مخمد الكتلة التوليفي كماص للأهتزاز

الخلاصة

أن حماية الهياكل المدنية و بضمنها مكوناتها المادية و مستخدميها من البشر يشكل من دون شك الأولوية في البحث العالمي في الوقت الحاضر. هذه الحماية تتدرج من الأداء الموثوق و المريح, من جهةٍ, الى الناحية الخدمية من جهة أخرى. من امثلة الهياكل التي ترد للذهن هي البنايات و الأبراج و الجسور. وعلى نفس السياق الأحداث التي تُسبّبُ الحاجة إلى مثل هذا الإجراءاتِ الوقائيةِ بيئية مثل الزلازلِ والرياح، أو أحمالَ متحركة مثل السياراتَ والمشاة في حالة الجسورَ. إنّ خطرَ الزلزالَ مُتَرجَمُ في الإهتزازاتِ الحادّة للأنظمةِ الهيكليةِ. لمعالجة هذا الخطر العالمي تُضافُ مخمدات مساعدة لإمْتِصاص تلك الإهتزازاتِ. أحد أوائل أدواتِ الأخماد المستعملةِ هو مخمدالكتلة التوليفي Tuned Mass Damper (TMD) الذي يعد نظام سلبي الفعالية كونه يَمتصُ الأستجابة الهيكليَة بدون الحاجة لإضافة إشارةَ سيطرةٍ خارجيةٍ. في هذا العمل يتم دراسة نموذج بناية مؤلفة من ثلاثة طوابق تتعرض لأضطراب زلزالي تمثيلي ومقارنته بأستجابة نفس البناية بعد تجهيزها ب TMD .

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Introduction

The current design standards or codes of buildings to use high strength materials (less of which would provide the needed structural integrity), welded connections, as well as large cylinder column, light weight concrete slabs supported by open-web steel joists [1]. Ground shaking from earthquakes and their aftershocks can cause buildings and other structures to collapse; trigger fires, flash floods, tsunamis, avalanches and landslides; and disrupt essential services such as power, gas and telephone. As buildings shake, furnishings and stored items can move, break or fall. Aftershocks can cause further damage to already weakened structures. The occurrences of future earthquakes are not predictable, but much of the earthquake-related damage is predictable and preventable. Actually, the flexibility of civil structures owes to the low levels of structural damping and auxiliary damping devices may be introduced, offering a somewhat more predictable, adaptable, and reliable method of imparting additional damping to the system. Mainly, the vibration control techniques have classically been categorized as passive, active, and semi-active control systems. A passive system is activated by the structural motion, the parameters are synthesized through off-line design techniques and no external force or on-line feedback actions are used [2]. On the other hand, active control systems are operating by using external energy supplied by actuators to impart forces on the structure [1]. Semi-active devices for mitigating structural response are defined as

those systems which are incapable of injecting energy into the system, made up of the structure and actuator, but can selectively dissipate, or channel the energy in the system to achieve favorable results [2].

To mitigate motion of flexible structures, passive systems have been used due to their simplicity and reliability, one of the widely used passive energy dissipative devices is the Tuned Mass Damper (TMD), which consists of a small vibratory system (mass, spring and dashpot) placed at the top of the building. The motion of its mass is activated when the natural frequency of the TMD is tuned to be in or near resonance with the predominant frequency of the main structure, such that it oscillates at the same frequency but with a leading phase shift.

Since they were invented in 1909 by Fram, TMDs have proven to be effective to reduce vibrations of not only tall buildings but also of chimneys, bridges and other industrial facilities [3]; as shown in figure (1). One of the pioneering applications of this damper has been in use New York's 278m Citicorp building [4].

Three-Story building Model

In this work the response of three Degree Of Freedom (DOFs) structural system subjected to simulated earthquake vibrations will be analyzed. The equation of motion of the structure model is as follows:

$$M\ddot{d}(t) + C\dot{d}(t) + Kd(t) = D_1 w(t)$$

$$\text{....(1)}$$

Where [5],

$$M = (98.3) \times I_{3\times3} \quad \text{(Kg), is the}$$

mass matrix.

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$C = [175 \; -50 \; 0; \; -50 \; 100 \; -50; 0 \; -50 \; 50]$ N.sec./m, is the damping coefficients matrix.

$K = [12. \; -6.84 \; 0; \; 0 \; -6.84 \; 13.7 \; -6.84; \; 0 \; -6.84 \; 6.84]$ N/m, is the stiffness matrix.

$D_1 = -M$, is the loading effect vector.

$w(t)$ is the external excitation function.

The state-space form of the structural system is:

$$\dot{x}(t) = Ax(t) + Dw(t) \qquad \dots(2)$$

where $x(t) \in R^6$ is the state vector, $A \in R^{6\times6}$ is the system matrix, $D \in R^{6\times1}$ is a disturbance vector. They are given by:

$$x(t) = \begin{bmatrix} d(t) \\ \dot{d}(t) \end{bmatrix}, A = \begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad D = \begin{bmatrix} 0 \\ M^{-1}D_1 \end{bmatrix}$$

$-M^{-1}K = [-1.2208 \quad 0.6958 \quad 0; 0.6958 \; -1.3937 \; 0.6958; \; 0 \; 0.6958 \; -0.6958]*10^4$

$-M^{-1}C = [-1.7803 \; 0.5086 \; 0; 0.5086 \; -1.0173 \quad 0.5086; 0 \; 0.5086 \; -0.5086]$

$M^{-1}D = [-1 \; 0 \; 0; \; 0 \; -1 \; 0; \; 0 \; 0 \; -1]$

In this work the modal frequency of this building is found using Bode plot to be 5.4590Hz (34.3 r/s) as illustrated in figure (2). The corresponding damping ratio is 0.306% for the uncontrolled structure.

The Simulink block diagram of the building is given in figure (3). The simulated earthquake load is presented in figure (4). As illustrated in figure (5) the building suffers from severe excitations especially in the top floor this is due to the low structural damping. The need for auxiliary damping device appears.

Tuned Mass Damper Design

A promising approach to augment the inherent built-in damping of a building is the introduction of a dynamic vibration absorber in the structural system. The dynamic vibration absorber is commonly known as TMD. A dynamic vibration absorber when installed in a structural system of a building imparts indirectly extra damping to the system [5]. It is a device consisting of a mass attached to a building or structure in such a way that it will vibrate at the same frequency as the structure, but with a reverse phase shift. The mass is attached to the structure by a spring-dashpot system and energy is dissipated by the dash-pot as relative motion develops between the mass and the structure.

The equation of motion of a TMD is given by:

$$M_T \ddot{d}_T(t) + C_T \dot{d}_T(t) + K_T d_T(t) = E_1 d(t)$$

$$\dots(3)$$

The state-space transform of TMD becomes:

$$\dot{x}_T(t) = A_T x(t) + E_T d(t) \qquad \dots\dots (4)$$

$$A_T = \begin{bmatrix} 0 & 1 \\ -M_T^{-1}K_T & -M_T^{-1}C_T \end{bmatrix}$$

or

$$A_T = \begin{bmatrix} 0 & 1 \\ -\omega_{nT}^2 & -2\zeta_T\omega_{nT} \end{bmatrix} \qquad \dots(5)$$

M_T is the TMD mass which is usually chosen to be 0.25% - 1% of the building total weight [4].

K_T, C_T are the TMD stiffness and the damping of the TMD respectively. ω_{nT}, ζ_T are the undamped natural frequency and the damping ratio of the TMD respectively.

As given earlier the TMD is represented as a second order differential equation, and the design parameters of such equation according to the control theory is the damping ratio ζ_T and the undamped natural frequency ω_{nT}.

In order to absorb the building vibration the TMD is designed such that its natural frequency is close to the building fundamental natural frequency $(\frac{\omega_{nT}}{\omega_{n1}} = 0.98)$. According to Bode plot the fundamental natural frequency is $\omega_{n1} = 34.3\, r/s$ and as shown in figure (2).

Hence, $\omega_{nT} \simeq 34.3\, r/s$. The damping ratio of the TMD depends on the mass ratio μ:

$$\mu = \frac{M_T}{M_b} \qquad \ldots(6)$$

Where, M_b is typically around one third of the building total mass [4]. The damping ratio of the TMD is usually designed such that [1]:

$$\zeta_T = \sqrt{\frac{\mu(1+0.5)}{4(1+\mu)(1+0.5\mu)}} \qquad \ldots(7)$$

According to a study presented in reference [6] the best usually used mass ratio is

$$\mu = 0.02\ (M_b = 98.3\ Kg.\, M_T = 1.966 Kg)$$

which gives the best results, so, according to Eq. (3.8) the resulted damping ratio will be: $\zeta_T = 0.0853$.

So far the TMD design parameters are chosen, hence TMD is designed:

$$A_T = \begin{bmatrix} 0 & 1 \\ -1176.5 & -4.948 \end{bmatrix},$$
$$E_1 = \begin{bmatrix} 0 \\ 8 \end{bmatrix}$$

This TMD system is placed on the top floor to absorb the highest vibration of the building model since the lion share of the destruction happens in the top of the building because it is more flexible.

The block diagram of structural system with the TMD is as given in figure (6).

Since the TMD is placed on the third floor, it is affected by the third floor displacement. When the building is excited by an earthquake hazard the TMD respond to the building rather than to the external excitation, and in this case to the third floor displacement; the TMD vibrates in response but in reverse direction to absorb the structural vibrations.

The resulting building response is given in figure (7). As shown the structural vibration is highly reduced when the TMD is added to the structure meaning that the TMD succeeded to absorb the external

excitation presented by the earthquake.

Conclusions

In this work the problem of structural safety against the earthquake hazard is investigated utilizing the design of a TMD for a three-story building model excited by a simulated earthquake excitation. From the simulation results it is concluded that:

1. When the external simulated earthquake is applied to the building model the largest deflection has been observed in the top floor displacement as expected. The maximum deflection is around 0.028m which is extremely high.

2. The TMD system is passive in nature and dose not depends on a certain control signal of a predesigned controller but it works properly with the structural system and it reduced the structural response to a very accepted extent.

3. All the results are done by simulation but the TMD system as presented in earlier is utilized by many buildings in the real world and it keeps them as safe as possible.

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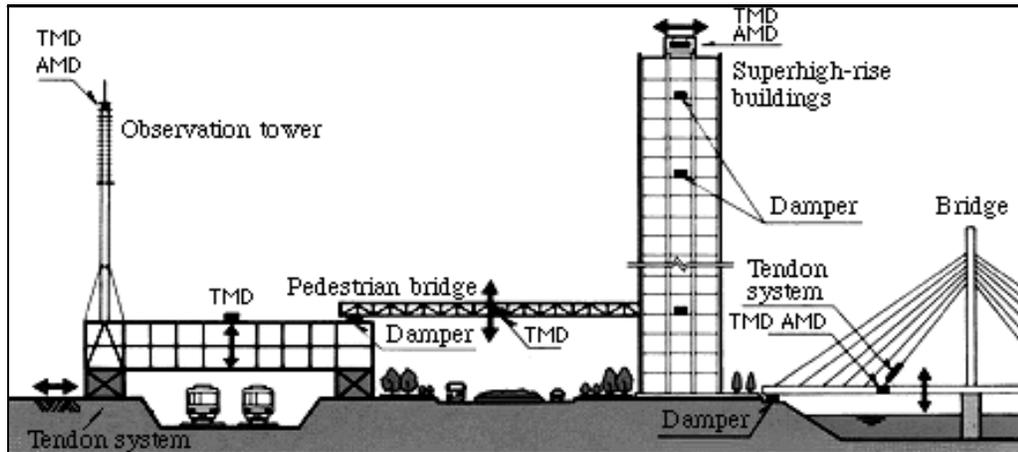
Figure (1) Applicable range of TMDs and AMDs
(*taken from Takenaka Corporation*).
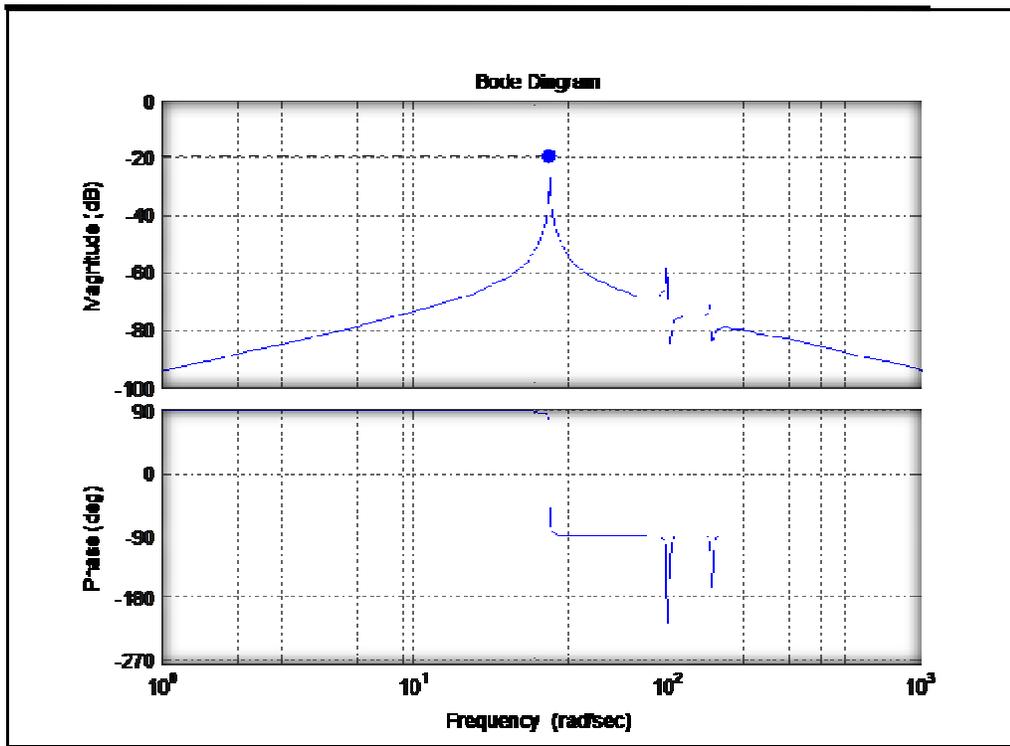
Figure (2) Bode Plot of the three stories building.
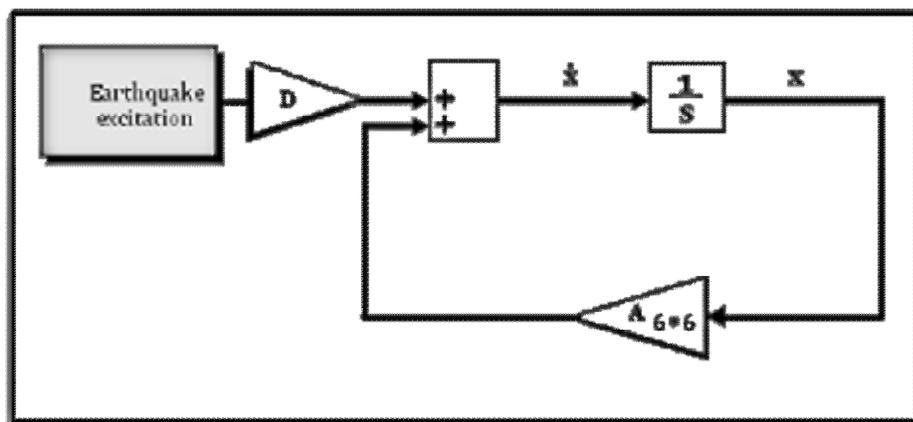
Figure (3) A Simulink block diagram of the structural system.
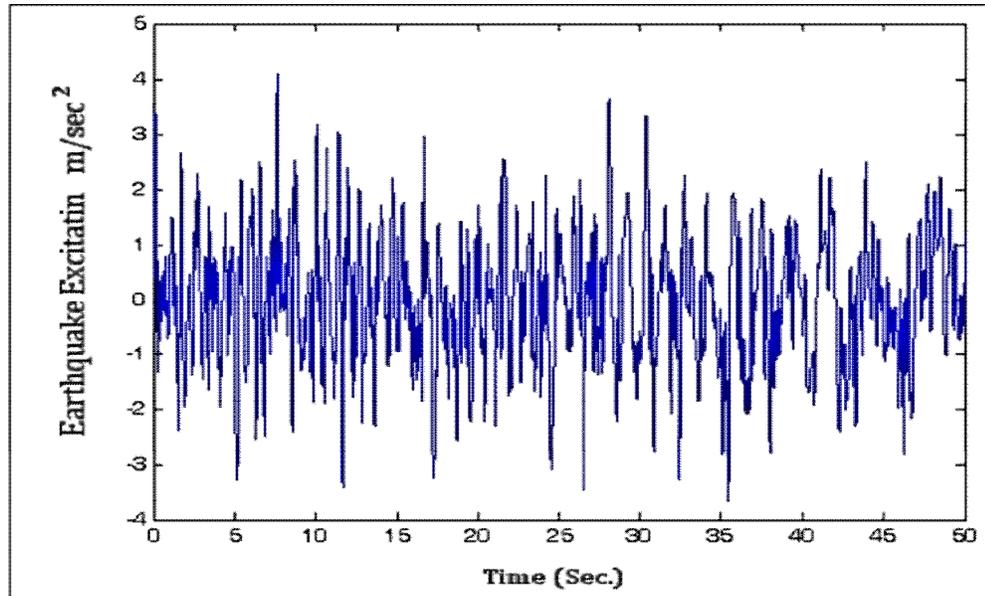
Figure (4) A Simulated earthquake excitation.
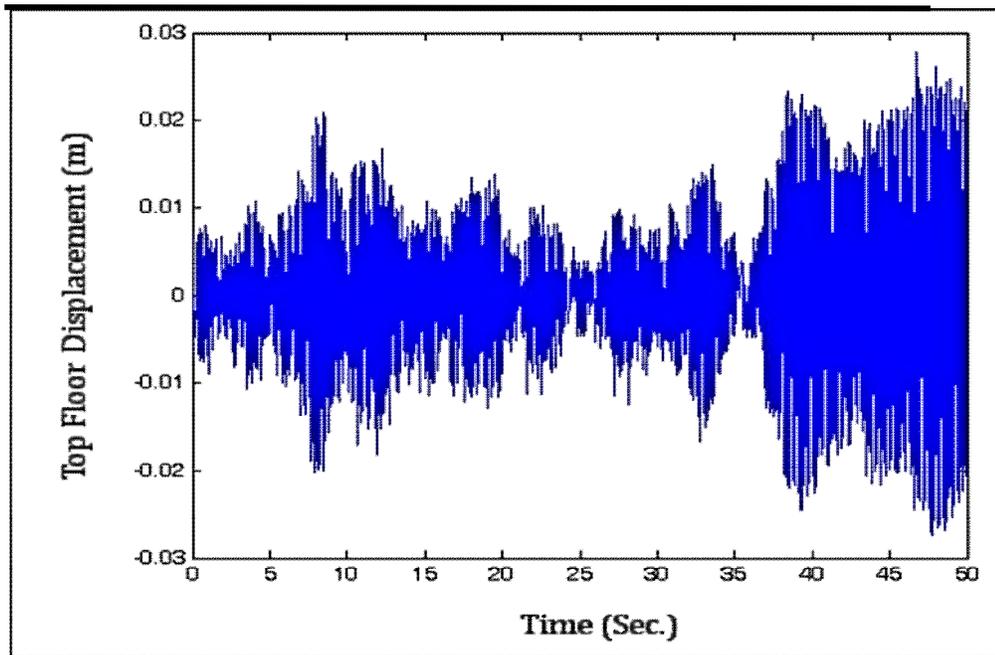
Figure (5) Displacement of the Top floor of the building.
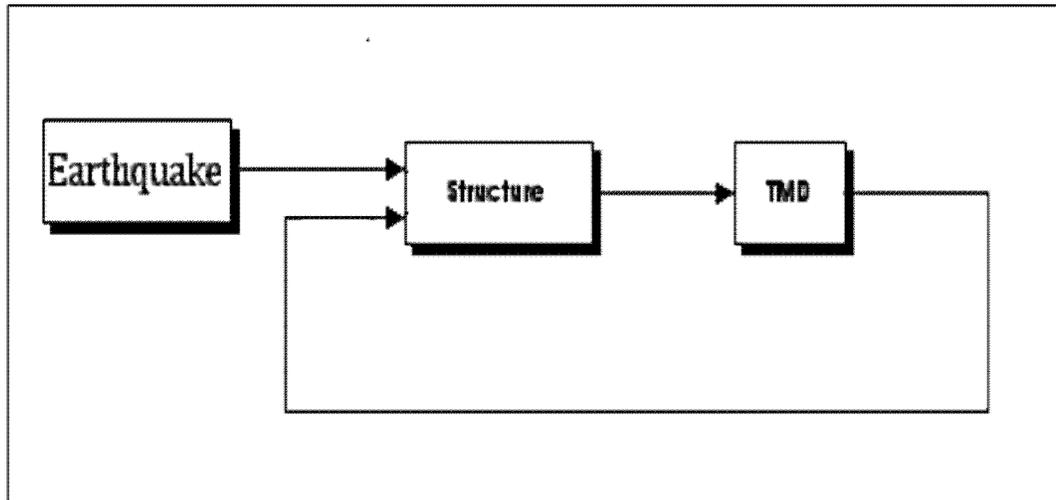
Figure (6) Simulink block diagram of the building model with TMD.

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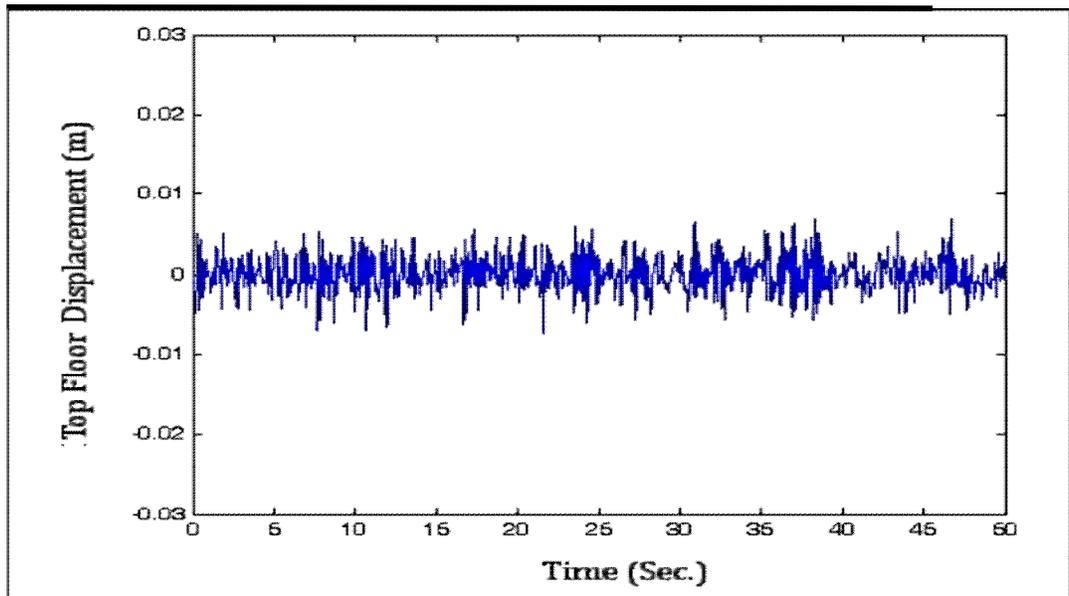
Figure (7) Top floor displacement of the structure with the TMD.
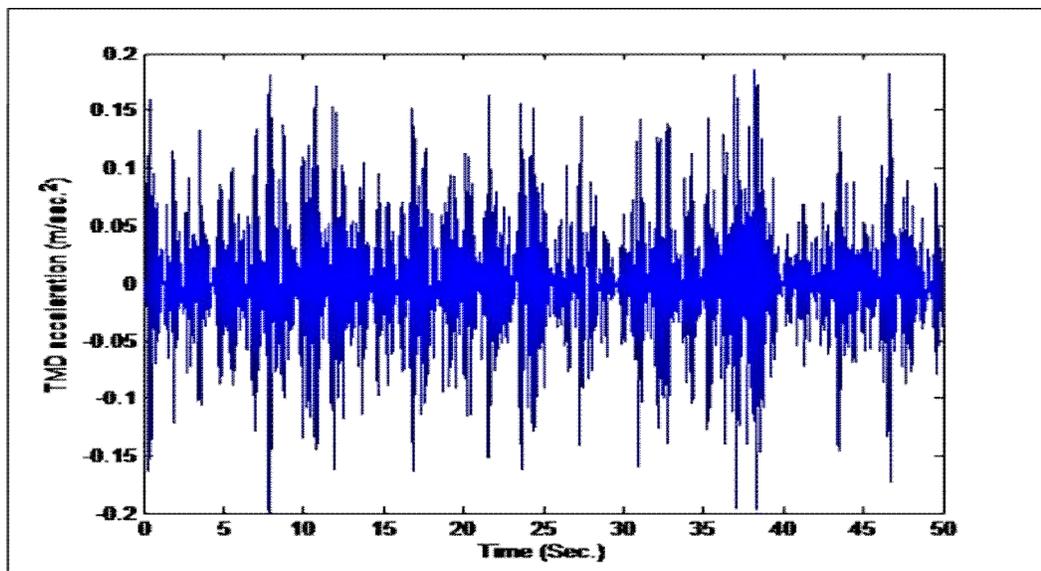
Figure (8) The TMD acceleration applied to the structural system.