Reducing vibration effects on buildings due to earthquake using magneto-rheological dampers

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This research presents vibration control of buildings due to earthquake effect. The model is subjected to the horizontal component of the earthquake, which has a larger effect than the vertical component. Newton's second law of motion is applied to obtain the mathematical model of the structures. Magneto-Rheological (MR) dampers are placed between the stories. Several control algorithms including the decentralized bang-bang controller, the Lyapunov controller, the modulated homogeneous friction controller, the maximum energy dissipation controller, and the clipped-optimal controller are applied with the MR damper. The modified quasi-bang-bang control is proposed in this paper. The MR damper (depending on the control algorithm used) gives a better reduction in the maximum absolute acceleration, also an excellent reduction in the maximum inter-story displacement; also the maximum displacement of the top story is reduced.

يتناول هذا البحث دراسة تخفيض الإهتزازات للمبانى الناتجة عن الزلازل باستخدام خامد MR. لقد تم التعامل مع المركبة الأفقية للزلزال والتى لها التأثير الأكبر. و تم تطبيق قانون نيوتن الثانى للحصول على النموذج الرياضى للمنشأ. و وضعت خوامد MR بين طوابق المبنى. و تم إستخدام طرق عديدة للتحكم فى الإستجابة مع الخامد MR، فمنها خواريزم بانغ- بانغ اللامركزى و خواريزم Lyapunov و خواريزم الإحتكاك المعدل المتجانس و خواريزم أقصى تبديد للطاقة و الـ Clipped-optimal. لقد تم استخدام خواريزم جديد للتحكم مع الخامد MR وهو خواريزم شبه البانغ- بانغ المعدل. وقد تبين أن الخامد MR (معتمدا على طريقة التحكم المستخدمة) يعطى تقليلاً ممتازاً لاستجابة المبنى من حيث التصارع والإزاحة بين الطوابق وإزاحة الطابق العلوى .

Keywords: Magnetorheological damper, Vibration control, Semi-active control, Multi-degree-of-freedom structure, Dynamics

1. Introduction

In recent years, due to developments in design technology and material qualities in civil engineering, the structures become more light and slender. This will cause the structures to be subjected to series structural vibrations when they are located in environments where earthquakes or high winds exist. These vibrations may lead to serious structural damage and potential structural failure. Structural control is one area of current research that looks promising in attaining reduce structural vibrations during loadings such as earthquakes and strong winds. The reduction of structural vibrations occurs by adding a mechanical system that is installed in the structure. The control of structural vibrations can be done by various means such as modifying rigidities, masses, damping, or shape, and by providing passive or active counter forces. Structural control methods that can be used include [1-2]: (passive control systems, active control systems, and semi-active control systems). A passive control system does not require an external power source. However, a passive control system has limited ability because it is not able to adapt to structural changes or varying usage patterns and loading conditions. To overcome these short-comings, active and semi-active control systems can be used. An active control system is one in which an external source powers control actuator(s) that apply forces to the structure in a prescribed manner. These forces can be used to both add and dissipate energy in the structure. Active control strategies for structural systems have been developed as one means by which to minimize the effects of these environmental loads [3-1-4-5]. Since active control relies on external power, which requires routine maintenance and thus may become potentially unstable, semi-active control have been studied by many researchers. Semi-active control systems combine active and passive control systems and attempt to utilize the advantages of both methods to achieve better effects. There has been a great deal of interest in recent years in use of magnetorheological (MR) dampers for semi-active structural control [6]. The advantages of using such devices include low power requirements, high reliability, ensured stability of the control system, and higher force capacities in comparison to other types of damping devices.

In this paper, the modified quasi-bang-bang control algorithm with the MR damper is proposed. Several control algorithms including the decentralized bang-bang controller, the Lyapunov controller, the modulated homogeneous friction controller, the maximum energy dissipation controller, and the clipped-optimal controller are applied with the MR damper. The effect of changing the frequency of excitation on the responses of the building model is studied. Effect of changing building's stiffness on the responses with the MR damper is also considered. Two major earthquake motion records [20], namely the El-Centro record of the 1940 Imperial Valley Earthquake, the Takochi-oki earthquake of the 1968 Hachinohe, were used as inputs in the analyses. This study addresses the use of semi-active magneto-rheological dampers for the seismic response reduction of buildings under seismic loads.

2. Dynamic model

The equations of motion can be obtained from Newton's second law of motion or by applying the influence coefficient method.

2.1. Assumption

The following assumptions are considered in the shear model of the building:

- The floors are rigid and the total mass is concentrated at the levels of the floors.
- There is no rotation of the horizontal section at the level of floors.
- The floors are subjected to horizontal ground acceleration.

Consider the n-degree-of-freedom structure (multi-story building), subjected to one dimensional earthquake acceleration, as shown in fig.1 below.

Applying Newton's second law of motion,

$$
\begin{aligned}
& m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - c_2(\dot{x}_2-\dot{x}_1) - k_2(x_2-x_1) \\
&\quad = -m_1\ddot{x}_g - f_1 \\
& m_2\ddot{x}_2 + c_2(\dot{x}_2-\dot{x}_1) + k_2(x_2-x_1) \\
&\quad - c_3(\dot{x}_3-\dot{x}_2) - k_3(x_3-x_2) \\
&\quad = -m_2\ddot{x}_g - f_2 + f_1 \\
& m_{n-1}\ddot{x}_{n-1} + c_{n-1}(\dot{x}_{n-1} - \dot{x}_{n-2}) + \\
& k_{n-1}(x_{n-1} - x_{n-2}) - c_n(\dot{x}_n-\dot{x}_{n-1}) \\
& -k_n(x_n-x_{n-1}) = -m_{n-1}\ddot{x}_g - f_{n-1} + f_{n-2} \\
& m_n\ddot{x}_n + c_n(\dot{x}_n-\dot{x}_{n-1}) + k_n(x_n-x_{n-1}) \\
&\quad = -m_n\ddot{x}_g - f_n .
\end{aligned} \tag{1}
$$

Or in matrix form

$$M_S\ddot{X} + C_S\dot{X} + K_S X = -\Gamma f - M_S \Lambda \ddot{x}_g . \tag{2}$$

Where:

M_s	is the mass matrix, kg,
C_s	is the damping matrix, N.s/m,
K_s	is the stiffness matrix, N/m,
$\ddot{x}_g$	is the one-dimensional horizontal ground acceleration, m/s^2,
Γ	is the matrix representing the position of the control forces
Λ	is the vector of ones, and
f	is the vector of control forces, N.

2.2. State-space representation

The dynamic systems considered in this study are described by ordinary differential equations in which time is the independent variable. By use of vector-matrix notation an nth-order differential equation may be expressed by a first order vector-matrix differential equation [7].

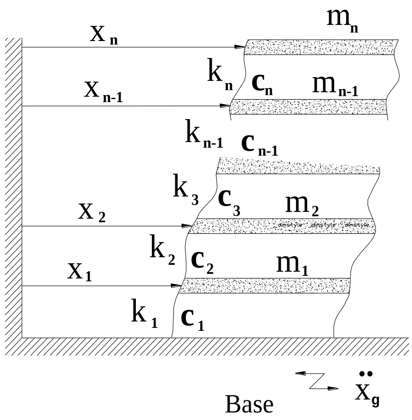

Fig.1. Lumped mass model of the building.

$$\dot{z} = Az + Bf + E\ddot{x}_g, \tag{3}$$

$$yy = Cz + Df\ , \tag{4}$$

$$\mathbf{A}= \begin{bmatrix} 0_{n\times n} & I_{n\times n} \\ -M_s^{-1}K_s & -M_s^{-1}C_s \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} 0_{1\times n} \\ M_s^{-1}\Gamma \end{bmatrix}, \qquad E = -\begin{bmatrix} 0_{1\times n} \\ \Lambda \end{bmatrix}$$

$$\mathrm{C} = \begin{bmatrix} M_s^{-1}K_s & M_s^{-1}C_s \\ I_{n\times n} & 0_{n\times n} \\ 0_{n\times n} & I_{n\times n} \end{bmatrix}, \qquad \mathbf{D} = \begin{bmatrix} M_s^{-1}\Gamma \\ 0_{2n\times n} \end{bmatrix}. \tag{5}$$

where
z is the state vector, ***A, B, C, D*** and ***E*** are state space matrices. $f = [\, f_1\ \ f_2\ \ f_3 \dots f_n \,]^T$, vector of the measured control forces, yy is the measured outputs, and n is the number of degrees of freedom (number of stories).

3. Control algorithms

Two categories of structural control methods are used in this study, they are:
- Passive control methods.
- Semi-active control algorithms

3.1. Passive control methods

3.1.1. Lateral load resisting systems

When designing a building that will be capable of withstanding an earthquake, engineers can choose various structural components, the earthquake resistance of which is now well-understood, and then combine them into what is known as a complete *lateral load resisting system*. These structural components usually include: (shear walls, braced frames, moment resisting frames, and horizontal trusses)

3.1.2. Tuned mass damper

The Tuned Mass Damper (TMD) is a passive control device that can be attached to the structure in order to reduce its responses. The device consists of: (1) - Mass, it is about 1% of the total mass of the building. (2) - Spring, its constant is assumed to tune the TMD to the first mode of the controlled building. (3) - Viscous damper.

3.2. Semi-active control

3.2.1. Introduction

Semi-active devices need power but less than the active devices, the Magneto-Rheological (MR) dampers are employed as semi-active control devices. Fig. 2 shows a schematic of a full-scale 20-ton MR fluid damper. MR fluids consist of micron-sized, magnetically-polarizable particles dispersed in a liquid medium such as mineral or silicone oil. MR fluids are smart, synthetic fluids changing their viscosity from liquid to semi-solid state within milliseconds if a sufficiently strong magnetic field is applied [8]. MR damper exhibits a variable damping coefficient depending on the strength of an accompanying magnetic field. A high magnetic field creates a nearly unyielding damper filled with a semi-solid fluid while no magnetic field produces an ordinary viscous damper [9]. MR fluid devices have been shown to mesh well with application demands and constraints to offer an attractive means of protecting civil infrastructure systems against severe earthquake and wind loading. MR fluids can operate at temperatures from -40 to 150 ºC with only slight variations in yield stress [10].

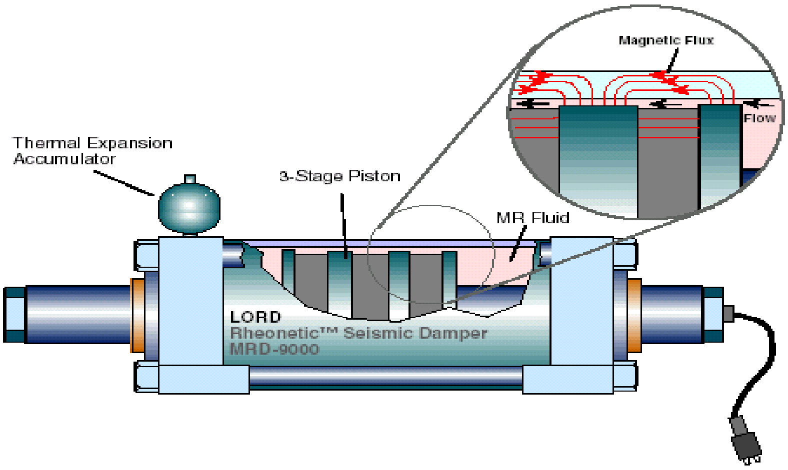

Fig. 2. Schematic of a full-scale 20-ton MR fluid damper [11].

3.2.2. Control algorithms with MR dampers

Several approaches have been proposed in the literature for the control of MR dampers [12].

3.2.2.1. Control based on Lyapunov stability Theory Leitmann [13] applied Lyapunov's direct approach for the design of a semi-active controller. In this approach, a Lyapunov function is chosen of the form

$$V(z) = \frac{1}{2}\|z\|_P{}^2, \tag{6}$$

where $\|\mathbf{z}\|_P$ is the *P*-norm of the states defined by,

$$\|z\|_P = [z^T Pz]^{1/2}, \tag{7}$$

and P is a real, symmetric, positive definite matrix. In the case of a linear system, to ensure $\dot{V}(z)$ is negative definite, the matrix P is found using the Lyapunov equation,

$$A^T P + PA = -Q_P. \tag{8}$$

For a positive definite matrix Q_p, the derivative of the Lyapunov function for a solution of eq. (3) is:

$$\dot{V} = -\frac{1}{2}z^T Q_P z + z^T PBf + z^T PE\,\ddot{x}_g. \tag{9}$$

Thus, the control law which will minimize $\dot{V}$ is:

$$V_i = V_{max} H((-Z^T)PB_i f_i), \tag{10}$$

where $H(.)$ is the Heaviside step function, f_i is the measured force produced by the *i*th MR damper and B_i is the *i*th column of the **B** matrix in eq. (3). Notice that this algorithm is classified as a bang-bang controller, and is dependent on the sign of the measured control force and the states of the system. However, one challenge in the use of the Lyapunov algorithm is in the selection of an appropriate Q_p matrix.

3.2.2.2. Decentralized bang-bang control McClamroch and Gavin [14] used a similar approach to develop the decentralized bang-bang control law. In this approach, the Lyapunov function was chosen to represent the total vibratory energy in the structure (kinetic plus potential energy), as in:

$$V = \frac{1}{2}x^T K_S x + \frac{1}{2}(\dot{x} + \Lambda\dot{x}_g)^T M_S(\dot{x} + \Lambda\dot{x}_g). \tag{11}$$

Using a similar approach to that in Lyapunov design, the resulting control law that will minimize $\dot{V}$ is:

$$V_i = V_{max} H(-(\dot{X} + \Lambda\dot{X}_g)^T \Gamma_i\, f_i). \tag{12}$$

The pseudo velocity, $\dot{X}_g$ is obtained by integrating the absolute acceleration (Spencer et al. [15]) using:

$$H(s) = \frac{39.5s}{39.5s^2 + 8.89s + 1} . \tag{13}$$

3.2.2.3. Clipped-optimal control One algorithm that has been shown to be effective with the MR damper is the clipped-optimal control approach proposed by Dyke et al. [16-8]. The clipped-optimal control approach is to design a linear optimal controller *Kc*(*s*) that calculates a vector of desired control forces, $f_c = [f_{c1}\ f_{c2}\ ....\ f_{cn}]^T$ based on the measured structural responses *yy* and the measured control forces vector *f* applied to the structure.

$$f_c = L^{-1}\left\{ - K_c(s)\ L\left\{\left\{ \begin{matrix} yy \\ f \end{matrix} \right\}\right\}\right\}, \tag{14}$$

where $L\{.\}$ is the Laplace transform. The control law is as follow:

$$V_i = V_{max} H((f_{c\,i} - f_i) f_i) . \tag{15}$$

3.2.2.4. Modulated homogeneous friction This algorithm originally developed for use with variable friction devices was modified for MR dampers by Jansen and Dyke [12]. The control law is

$$V_i = V_{max} H(f_{ni} - |f_i|), \tag{16}$$

where $f_{ni} = g_{ni}\ |\Delta_i\ (t\text{-}s)|$, $s = \{min\ x \geq 0 : \Delta_i\ (t\text{-}x) = 0\}$ and $\Delta_i\ (t\text{-}s)$ and is the most recent local extrema in the deformation of the ith device. The proportionality constant g_{ni} has units of stiffness (N/m), and its optimal value is dependent on the amplitude of the ground excitation.

3.2.2.5. Maximum energy dissipation This algorithm considers a Lyapunov function that represents the relative vibratory energy in the structure (i.e., without including the velocity of the ground in the kinetic energy term) [12]. The control law for the abovementioned algorithm is as follows:

$$V_i = V_{max} H(-\dot{x}^T \Lambda_i f_i) . \tag{17}$$

3.2.2.6. Quasi-bang-bang control The quasi-bang-bang control algorithm for the application of the MR dampers uses two distinct control laws depending on whether the building is moving towards or away from its static equilibrium, or rest, position [17].
The control algorithm is as follow:

$$V_i = \begin{cases} V_{max} & \text{(if moving away from center)} \\ 0 & \text{(if moving towards center)} \end{cases} . \tag{18}$$

3.2.2.7. Modified quasi-bang-bang control This is a new control algorithm proposed in this research; the algorithm is similar to the quasi-bang-bang control. The control algorithm is as follow:

$$V_i = \begin{cases} \alpha V_{max} & (\text{If sign}(x) = 1 \text{ and sign}(\dot{x}) = 1) \\ \beta V_{max} & (\text{If sign}(x) = -1 \text{ and sign}(\dot{x}) = -1). \\ V_{max} & \text{(Otherwise)} \end{cases} \tag{19}$$

Where the values of α and β are between 0 and 1.

4. Three story building model with single MR damper

In the first example, a three-story building model with a single MR damper is considered. The MR damper is rigidly connected between the ground and the first floor of the building. Fig. 3 shows a diagram of the building with the MR damper. The system used in this example is a simple model of the scaled three-story test structure, described in [18-3], which has been used in previous studies at the Structural Dynamics and Control/ Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre Dame.

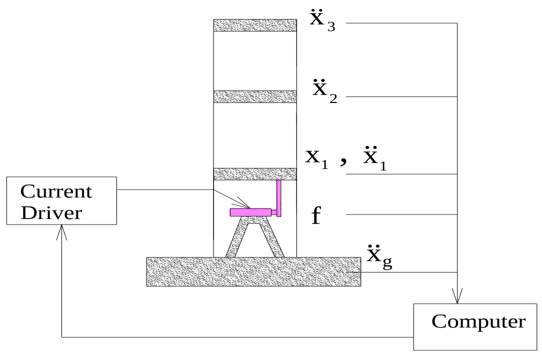

Fig. 3. Diagram of MR damper implementation.

The building parameters are as follow:

$$M_S = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix},$$

$$C_S = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix},$$

$$K_S = 10^5 \times \begin{bmatrix} 12.0 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix}. \qquad (20)$$

Dyke et al. [19] obtained the responses of this model for the uncontrolled, passive-off, passive-on and the clipped optimal control cases only. The purpose of this example is to compare the results of the proposed program used in this study with the results obtained in [19], and to use extra control algorithms. The results of the uncontrolled, passive-off, passive-on systems are similar to those in [19], but the clipped optimal control gives better results (the algorithm depends on a variable which is obtained by iteration).

Table 1 below gives the peak responses of the building, when subjected to the north south component of the 1940 El-Centro earthquake [20]. Since the system under consideration is a scaled model, the earthquake is produced at five times the recorded rate [19]. The uncontrolled case means that no MR dampers are implemented with the structure. The passive-off and passive-on means that the driving volt is set to zero and to the maximum value respectively. Both the passive-off and passive-on cases are capable of reducing the structure responses.

Two controllers (**A** and **B**) are designed based on Lyapunov stability method. For controller A the matrix **Q** is given as **Q** = [ones (1,6); zeros (5, 6)].

For controller **B**, **Q** = [zeros (3, 6); eye(3) *zeros* (3,3)] and *eye*(3) $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$.

Lyapunov controller **B** gives the best reduction in both the inter-story drift (*Dn*) and the maximum story displacement (*Xn*), but gives a lower reduction in the absolute acceleration (*An*).

Quasi-bang-bang controller gives the same reduction in the maximum displacement as the Lyapunov controller **B**, but with a higher reduction in the maximum acceleration.

Modified quasi-bang-bang gives the same reduction in the displacement as the Lyapunov controller **B** and the quasi-bang-bang system, but with a reduction in the maximum absolute acceleration, more than the two algorithms. For the Modified quasi-bang-bang control $\alpha = 0$ and $\beta = 0.11$.

Decentralized bang-bang control gives the highest reduction in acceleration, but cannot be able to reduce the displacement over the passive on case. Clipped-optimal control algorithm gives a high reduction in both the inter-story drift and the maximum story displacement; also gives a good reduction in the maximum absolute acceleration.

Fig. 4 shows the maximum responses due to sinusoidal input of acceleration. It is shown that the responses (displacement and acceleration) reach their peak values when the frequency of excitation is close to the first natural frequency of the building (5.46 Hz).

It is also shown that the damping is effective to reduce both the displacement and the acceleration when the building is near to resonance. Also when the frequency of excitation is close to the second natural frequency of the building (15.8 Hz), the acceleration reaches a maximum value but the displacement remains at a lower value.

Table 1
Peak responses of the three-story building model due to El-Centro earthquake

Control strategy	Xn (m)	Dn (m)	An (m/s^2)	F (N)
Uncontrolled	0.0055 0.0083 0.0097	0.0055 0.0031 0.0020	8.720 10.620 14.020	_
Passive-off	0.0021 0.0036 0.0045	0.0021 0.0016 0.0010	4.216 4.832 7.176	259.2
Passive-on	0.0008 0.0020 0.0031	0.0008 0.0017 0.0011	2.914 4.976 7.710	992.8
Lyapunov controller (A)	0.0009 0.0021 0.0031	0.0009 0.0017 0.0010	6.356 5.373 7.183	1023
Lyapunov controller (B)	0.0013 0.0018 0.0023	0.0013 0.0012 0.0011	5.613 7.326 7.709	993.3
Quasi-bang-bang control	0.0013 0.0016 0.0023	0.0013 0.0014 0.0010	5.288 7.294 7.040	1007.5
Modified quasi-bang-bang control	0.0013 0.0017 0.0023	0.0013 0.0014 0.0010	4.907 6.746 6.837	1035
Decentralized bang-bang control	0.0015 0.0025 0.0032	0.0015 0.0013 0.0008	3.776 4.310 5.416	923
Modulated homogeneous friction	0.0019 0.0029 0.0038	0.0019 0.0013 0.0010	5.330 5.916 6.790	503 gn=115000
Maximum energy	0.0008 0.0020 0.0031	0.0008 0.0017 0.0011	3.150 5.023 7.731	992.5
Clipped-optimal control	0.0014 0.0021 0.0026	0.0014 0.0014 0.0008	6.000 4.551 5.553	918 r = 1e-8

This means that, if a building with a natural frequency (first natural frequency) lower than the dominant frequency of the earthquake (by studying the history of earthquakes at the region on which the building is to be constructed) is designed, the displacement response of the building will be at a lower value with no additional damping, but a little amount of damping still needed in order to reduce the acceleration in the second mode (fig. 4-b).

5. Eight-story building with multiple MR dampers

An eight story building is considered in this example as an actual large scale building. The characteristics of the building are the same for each story: floor mass = 345.6 metric tons, elastic stiffness =3.404 × 10^8 kN/m and internal damping coefficient = 100 tons/s. A Tuned Mass Damper (TMD) is installed on the top of the building. The properties of the TMD are: mass = 29.63 tons, damping = 25 tons/s and stiffness = 957.2 kN/m. The natural frequency of the TMD is 5.68 rad/s, which is 98% of the first natural frequency of the building. The characteristics of the building are taken from [21]. For this example four MR dampers are used, each capable of producing a force of 900 kN. This number of MR dampers and their position (between each two adjacent floors from the first until the fourth floor) where obtained by

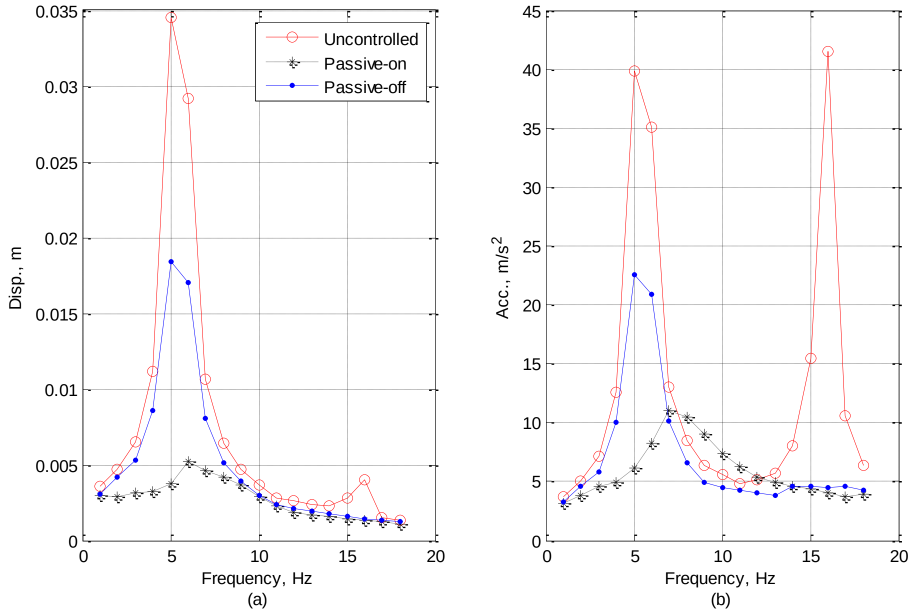

Fig. 4. Maximum responses due to sinusoidal input.

iteration on the passive on case, to give the best reduction in all responses. The total control force is about 13% of the total weight of the building. The MR damper used herein is obtained from Dyke [22].

Considering El-Centro as an input, the best reduction in acceleration (27 %) can be obtained by the clipped-optimal control algorithm applied with the MR damper. Lyapunov controller gives the best reduction in the maximum inter-story drift (47.2 %), also the maximum displacement of the stories (*Xn*) is reduced (39.8 %). But the maximum absolute acceleration is higher than that in the clipped-optimal controller (20.4 % reduction).

Under the horizontal component of Takochi-oki earthquake [20], the best reduction in the maximum displacement (34.3 %) and the maximum drift (42.2 %) were achieved by the maximum energy dissipation algorithm. However the Lyapunov controller gives similar values for the maximum inter-story drift. The best reduction in the maximum absolute acceleration (38.3 %) is obtained by the clipped-optimal controller.

By adding TMD at the roof of the building, the results give a better reduction in the maximum displacement, the maximum inter-story displacement, and the maximum absolute acceleration. The best reduction in the maximum displacement is achieved by the passive on system (51.1 % & 36.1 %), for El-Centro and Takochi-oki respectively. The best reduction in the absolute acceleration is obtained by the decentralized bang-bang control (27.3 %), for El Centro earthquake as an input, and by the passive-off (47.1 %), for the Takochi-oki earthquake.

By adding braces between each two adjacent floors, this will result in an increase in the building stiffness. In this example it is assumed that the bracing system is to double the stiffness of the building. It is indicated that the bracing system is able to give a high reduction in both the maximum displacement and the maximum inter-story displacement. But the maximum absolute acceleration is increased. The best reduction in the maximum displacement is obtained by the passive-on system (60.6 %) with El-Centro, and by the maximum energy dissipation system (59.8 %) with the Takochi-oki earthquake. The best reduction in acceleration is obtained by the clipped-optimal controller (3.7%) for El-Centro, and by the passive-off system (53.1 %) with the Takochi-oki earthquake. Herein it is noticed that as the building stiffness increased, the control systems are not able to reduce the maximum responses as with the flexible building. So, it is concluded that the control systems are more efficient in reducing the maximum responses, with buildings which have a lower stiffness (flexible buildings).

6. Conclusions

The major contributions provided by this research are:

- It is preferable to construct a structure with lower natural frequency which is away from the frequency of excitation. However as the frequency of excitation become closer to the lower frequency of the structure the control algorithm becomes very effective. Also, it was seen that the control system is more effective for flexible structures.
- MR dampers are able to reduce the responses of buildings, when suspended between the lower floors. The best reduction in acceleration (27 %) can be obtained by the clipped-optimal control algorithm applied with the MR damper. Lyapunov controller gives the best reduction in the maximum inter-story drift (47.2 %) (in case of eight-story building with El-Centro as an input).
- TMD is capable of giving an appropriate reduction in the responses.

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