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PERFORMANCE OF TUNED ACTIVE MASS DAMPER IN CONTROLLING SEISMIC RESPONSE OF BUILDING FRAMES

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ABSTRACT

Control of the seismic response of shear frames with the help of Tuned Active Mass Damper (AMD) is investigated. Two control strategies are adopted for providing the driving force to the AMD.The first one is based on "feed back gain" algorithm which is dependent only on the structural dynamic parameters(close loop system). The second is based on both "feed back gain" and "feed forward gain" algorithms (a combination of open loop and close loop control).The "feed forward gain" is dependent on the characteristics of the ground motion. Both strategies use stochastic control theory and obtain the control law by minimizing a performance index. The control law is derived without time delay. The controlled responses obtained by passive control and active control (using both strategies) are compared for a 10 storey and a 5 storey shear frame subjected to synthetically generated ground motion. The studies are made for two cases of tuning of the AMD namely, (i) to the first natural frequency of the frame and (ii) to the predominant frequency of the ground motion. The results of the study show that active control can provide a substantial reduction in response of the structure and close-open loop system is more effective in controlling the response.

KEYWORDS

Active control; Tuned Mass Damper; Active Mass Damper; Seismic Response; Passive Control; Shear Frame.

INTRODUCTION

For active control of buildings,two types of control mechanisms are widely reported in the literature: (i) pretensioned diagonal tendon bracings and (ii) active mass damper (AMD). The latter is a tuned mass damper(TMD) augmented by active control force. It has received considerable attention because of its simplicity in implementation and has become a topic of considerable interest for many researchers(Chang *et al.*, 1980, Abdel Rohman., 1984, Kobori *et al.*, 1991). The reported work used feedback gain (close-loop) control with or without time delay and the frequency of AMD is generally tuned to the first frequency of the building. There have been also considerable investigations on structural control using active tendon bracings (Chung *et al.*,1988, Abdel Rohman *et al.*,1983, Yang *et al.*,1978). Some of the earlier works on the application of control theory in structural control provide good foundation to the theory of active control of structure (Yao *et al.*,1972, Abdel *et al.*, 1980, 1981, Meirovitch *et al.*,1983).

In the present study,control of the seismic response of shear frame model of tall buildings with the help of AMD is investigated. Two control strategies are adopted for providing the control force to the AMD. First one is based on feedback gain algorithm(close loop system) and the other is based on both feedback gain and feed forward gain algorithm (open- close loop). Response of the controlled structure is obtained for synthetically generated ground acceleration from power spectral density function of ground acceleration. The controlled responses obtained by (i) control using close loop system and (ii) control using open-close loop system are compared. In each case,the AMD is tuned to the first frequency of the frame and to the predominant frequency of ground motion. Moreover, efficiencies in controlling the response by AMD and TMD (acting as a passive control) are compared.

ASSUMPTIONS

The following assumption are made in the study :

(1) Both controlled and uncontrolled responses are within the elastic range.
(2) Time delay effect is neglected i.e instantaneous control is assumed.
(3) Mass of the AMD is assumed to be only a fraction of the mass of the structure.
(4) The dynamic properties of the frame are assumed such that they have same frequencies as those of realistic buildings.

THEORY

A multistorey shear frame with AMD placed on the top storey, is shown in Fig. 1. The equations of motion of the system under ground excitation is given by :

$$M\ddot{X} + C\dot{X} + KX = -MI\ddot{x}_g + G \tag{1}$$

$$m_t\,\ddot{y} + c_t\,(\dot{y} - \dot{x}_n) + (y-x_n) = u - m_t\,\ddot{x}_g \tag{2}$$

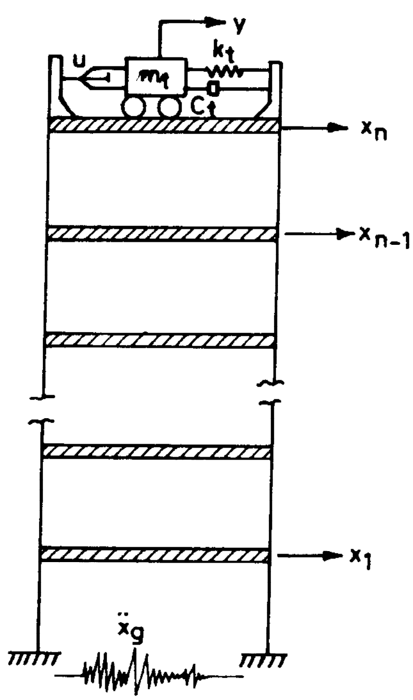

Figure 1 : Shear frame with AMD

in which M,C,K are respectively the mass, damping and stiffness matrices corresponding to the sway degrees of freedom of the frame; m_t, c_t and k_t are respectively the mass, damping and stiffness of AMD; X is the vector of sway displacements of the frame and y is displacement of the mass of AMD; $\ddot{x}_g$ is the ground acceleration; u is the control force; I is a vector unity and G is a vector of size n having all elements as zero except the nth element which is given by

$$c_t(\dot{y} - \dot{x}_n) + k_t\,(\dot{y} - x_n) - u \tag{3}$$

In order to reduce the number of equation to be solved and to use modal damping for the building, the equations of motion are written in terms of modal coordinates of the building and the displacement of AMD :

$$\bar{M}\,\ddot{Z} + \bar{C}\,\dot{Z} + \bar{K}\,Z = -\,\phi^T M I\,\ddot{x}_g + \phi^T G \tag{4}$$

$$m_t\ddot{y} + c_t\dot{y} + k_t y = -m_t\ddot{x}_g + u - c_t\sum_{i=1}^{m}\phi_{ni}\dot{z}_i - k_t\sum_{i=1}^{m}\phi_{ni}\,z_i \tag{5}$$

in which $\bar{M}$ $\bar{C}$ and $\bar{K}$ are m x m diagonal matrices; $\bar{M} = \phi^T M\phi$ etc.; ϕ is undamped mode shape matrix of size $n \times m$; Z is the vector of generalised co-ordinate and m is the number of mode shapes considered.

For obtaining the control law, state space formulation is used to represent the equilibrium Eqs. 4 and 5 in the form :

$$\dot{V} = AV + Bu + F \tag{6}$$

in which $V^T = [Z\ y\ \dot{Z}\ \dot{y}]$; A is a matrix of size 2 (m+1) $\times$ 2 (m+1) whose elements are functions of $\phi_i,\eta_i,\omega_i,\eta_t,\omega_t$ (ω_i is the ith natural frequency of the building, η_i is the modal damping ratio; η_t and ω_t are the damping ratio and frequency of the AMD); B is the control force coefficient vector and F is the excitation force vector.

The control force is determined by minimizing a performance index which leads to the solution of a Riccati equation (Chang *et al.*,1980).

Close loop system (Feed back gain) :

The Control force is given by

$$u = K^T\,V \tag{7}$$

and, $$K^T = -\frac{B^T P}{r} \tag{8}$$

in which P is determined by solving the following Riccati equation :

$$PA + A^TP - PBr^{-1}\,B^TP + Q = 0 \tag{9}$$

in which Q is 2(m+1) $\times$ 2(m+1) weighting matrix and r is the weighting factor.

Close-open loop system (Feed back - Feed forward gain) :

The control law for close-open loop system is derived with the objective of generating the control force which is a function of both structural response and ground motion (Fig. 2). For this purpose, ground motion is derived from white noise using filters. Filter equations of motion in state-space are augmented to the equations of motion of the structure. As a result, structure-filter system has state vector containing both structural motions and outputs from the filters. The excitation to the system becomes the white noise.

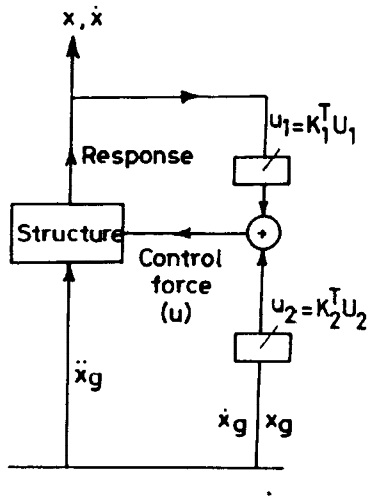

Figure 2 : Close - open loop control

Ground motion as represented by Clough and Penzien (1993) power spectral density function (PSDF) is considered in the present study. The following filter equations of motion represent the transformation of white noise to the desired ground motion :

$$\ddot{x}_g + 2\zeta_g\,\omega_g\dot{x}_g + \omega_g^2\,x_g = -\ddot{s} + w \tag{10}$$

$$\ddot{s} + 2\zeta_s\omega_s\dot{s}_s + \omega_s^2\,s_s = -w \tag{11}$$

x_g is the ground motion which is the output of the second filter and s is the output of the first filter; w is the white noise; ω_g , ζ_g , ω_s and ζ_s are the filter coefficients. The PSDF of ground acceleration $\ddot{x}_g$ as obtained from equations 10 and 11 is given by :

$$S_{\ddot{x}g} = S_0 \frac{\left[1 + (2\rho_s\zeta_s)^2\right]\rho_g^4}{\left[(1-\rho_s^2)^2 + (2\rho_s\zeta_s)^2\right]\left[(1-\rho_g^2)^2 + (2\rho_g\zeta_g)^2\right]} \tag{12}$$

in which S_0 is the PSDF of white noise w; $\rho_s = \omega/\omega_s$ *and* $\rho_g = \omega/\omega_g$

Substituting for $\ddot{x}_g$ in Eqs. 4 and 5 using Eqs. 10 and 11, following state space equation for the structure filter system is formed :

$$\dot{U} = DU + \bar{B}u + Jw \tag{13}$$

in which $U^T = (Z\ y\ x_g\ s\ \dot{Z}\ \dot{y}\ \ \dot{x}_g\ \dot{s})$; D is a matrix of size $2(m+3) \times 2(m+3)$ whose elements are functions of structures modal characteristics and filter coefficients; $\bar{\mathbf{B}}$ is the control force coefficient vector and J is the white noise coefficient vector whose all elements are zero except for the last one which is equal to -1.

The control force is, as before, given by

$$u = K^T U \tag{14}$$

K^T is obtained after solving the Riccati equation as shown by Eqs. 8 and 9. u may be written as :

$$u = u_1 + u_2 = K_1^T U_1 + K_2^T U_2 \tag{15}$$

in which $U_1^T = (Z \; y \; \dot{Z} \; \dot{y})$ and $U_2^T = (x_g \; s \; \dot{x}_g \; \dot{s})$

K_1^T and K_2^T are respectively called the close loop and open loop control, Fig. 2.
After substituting for u, Eqs. 6 and 13 are converted into first order differential equations with state vectors V and U respectively. For Eqn. 6, the excitation force vector is generated by simulating $\ddot{x}_g$ from PSDF given by Eqn. 12, For Eqn. 13, excitation w is generated from white noise PSDF, S_0. Eqn. 6 and 13 are numerically solved by fourth order Runga Kutta method. The responses of the frame are determined from modal co-ordinates Z using modal transformation relationship.

DISCUSSION OF RESULTS

Controlled and uncontrolled responses of a 5 storey and a 10 storey shear frame are determined for ground motion represented by Clough and Penzien PSDF as given by Eq.12. The parameters of Eq.12 are taken as $\omega_s = 2\pi$ rad/see, $\omega_g = 0.1\ \omega_s$, $\zeta_g = \zeta_s = 0.4$, peak frequency of PSDF is 5.61 rad/sec. and So is determined for standard deviation of ground acceleration equal to 0.61 m/sec.sq. Modal damping of frame is 0.02, height of storey (H) = 4.0 m, bay width (B) = 6.1 m, for both building frames; EI for 10 storey building is 2.0 x 10^7 N/m^2; EI for 5-storey building is 1.64 x 10^7 N/m^2. Floor masses $m_1 = m_2 = \ldots.. = m_8$ = 4022 Kg and $m_9 = m_{10}$ = 2060 Kg for 10 storey building ; for 5-storey building m_1 = 1341 Kg, m_2 = 1444 Kg, m_3 = 1547 Kg, m_4 = 1856 Kg and m_5 = 2063 Kg. The first three frequencies for 10 storey frame are 5.03,14.85,24.02 (rad/sec.) and for 5-storey frame, they are 12.91, 35.38, 56.03 (rad/sec).

Mass of AMD is taken as 0.01 times the total mass of the frame. The stiffness of the frame is adjusted to tune it to different specified frequencies. The damping C is determined based on the damping ratio of 0.072. For close loop control, Q matrix is a diagonal matrix with unit values at the diagonal elements corresponding to displacement and velocity of the modal co-ordinates of the structure. For close- open loop control diagonal elements corresponding to x_g and $\dot{x}_g$ are additionally set to unity. Three values of weighting factor r are considered namely, r = 1, 10^{-4} and 10^{-6}.

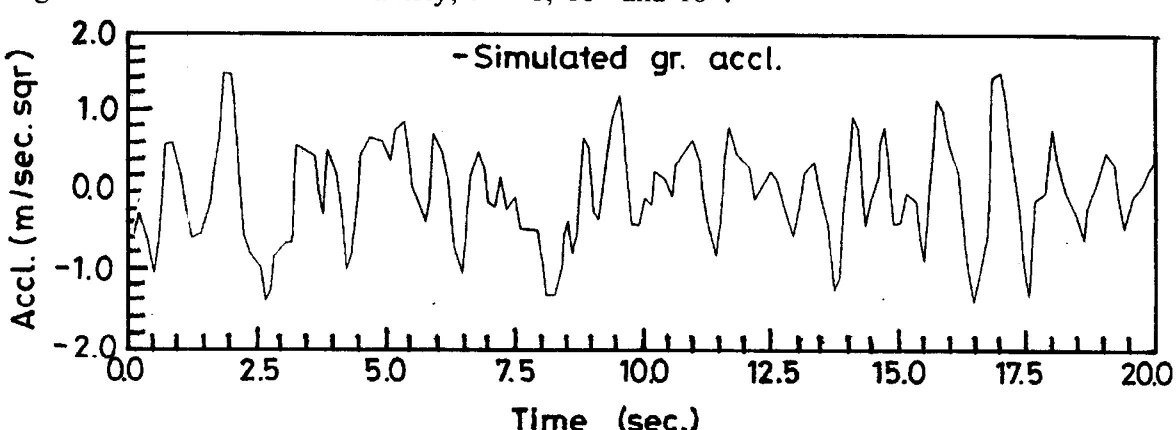

Figure 3 : Simulated Ground Acceleration

Figure 3. shows the sample time history of the acceleration of the ground motion, generated from the PSDF and used in the study. Tables 1 and 2 compare between the controlled and uncontrolled responses of the

top storey of 10 storey and 5 storey frames respectively. In the tables UC refers to uncontrolled response ; CP refers to passively controlled response; CC refers to controlled response for close loop system and CCO refers to controlled response for close-open loop system.

Table 1: Comparison of responses & control force for 10 storey frame (AMD tuned to first frequency)

Quantities		UC	CP	Closed-loop (CC) r1	Closed-loop (CC) r2	Closed-loop (CC) r3	Open-close loop (CCO) r1	Open-close loop (CCO) r2	Open-close loop (CCO) r3
x (m)	Peak	.438	.288	0.288	0.196	0.101	0.285	0.180	0.0892
	rms	.172	.105	0.1048	0.0683	0.038	0.103	0.0624	0.0327
u (kN)	Peak	-	-	.00289	5.025	28.685	.00365	7.079	37.027
	rms	-	-	.00114	2.057	10.396	.00135	2.494	12.554

Table 2: Comparison of responses & control force for 5 storey frame (AMD tuned to first frequency)

Quantities		UC	CP	Closed-loop (CC) r1	Closed-loop (CC) r2	Closed-loop (CC) r3	Open-close loop (CCO) r1	Open-close loop (CCO) r2	Open-close loop (CCO) r3
x (m)	Peak	.039	.033	0.0326	0.0249	0.0213	.0316	.0247	.01851
	rms	.014	.011	.0174	.00880	.0077	.0107	.00833	.00660
u (kN)	Peak	-	-	.00044	1.276	9.9090	.00032	.6790	3.8290
	rms	-	-	.00014	0.409	3.6100	.00011	0.228	1.3870

Note :
$r = 1$ (r_1); $r=10^{-4}$ (r_2); $r=10^{-6}$ (r_3); x = displacement response; u = control force.

For 10 storey frame, there is about 60% reduction in peak and 40% reduction in rms response for passive control. The reduction in response for active control increases as weighting factor 'r' is reduced. For $r = 10^{-6}$, reduction in peak response is about 76% and reduction in rms response is about 80% for close loop system. The corresponding reductions for close-open loop system are 80% and 85%. When controlled responses between close loop and close-open loop systems are compared for $r = 10^{-6}$, there is about 12% reduction in response for close-open loop system but, there is a corresponding increase in control force by about 20%.

For 5 storey frame, there is less reduction of controlled responses compared to 10 storey building. However,close-open loop system provides about 15% less response than that obtained for close loop system (when r = 10^{-6}). It is interesting to note that the required control force for close-open loop system is about 60% less than that for close loop system. This shows the effectiveness of using close-open loop system. A typical plot of controlled and uncontrolled response of the 5 storey frame is shown in Fig.4.

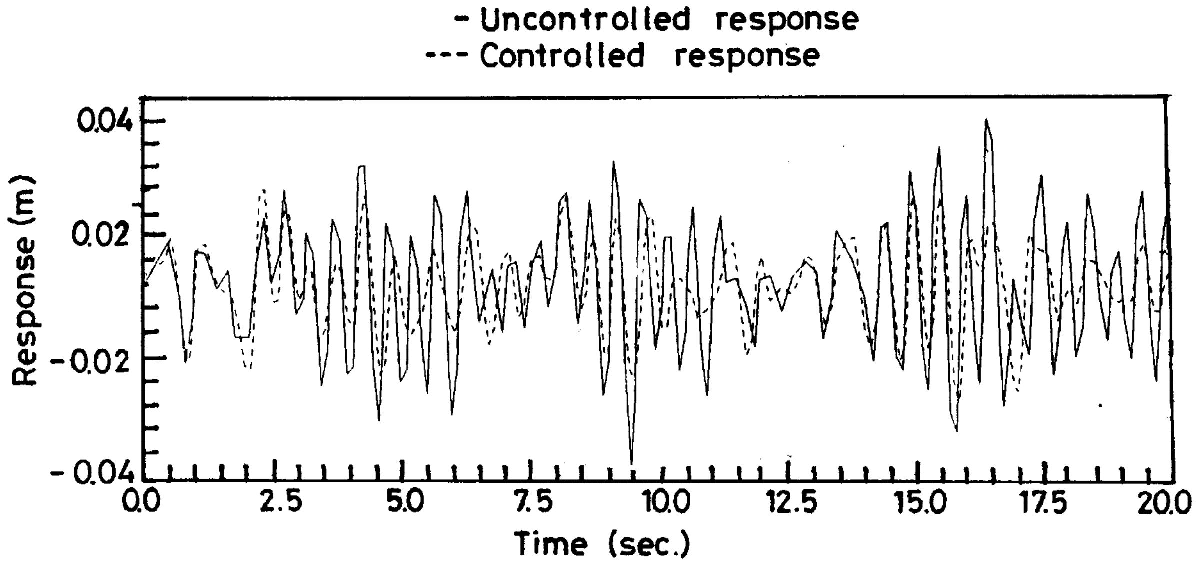

Figure 4 : Uncontrolled and Controlled (close loop) response for 5 storeyed frame, r = 10^{-4}

Tables 3 and 4 compare between the controlled responses for different tuning frequencies. Passively controlled response becomes less when AMD is tuned to the first frequency of the building. The increase in passively controlled response is about 10-20% when AMD is tuned to the predominant frequency. However, active control provides better reduction in response when AMD is tuned to the predominant frequency of ground acceleration (for 5 storey frame). Also, required control force is less for this case.

Table-3 Comparison of response & control force for 10-storey frame (AMD tuned to different frequencies and r= 10^{-4})

Quantities		Tuned to ω_1			Tuned to ω_p		
		CP	CC	CCO	CP	CC	CCO
x in (m)	peak	0.288	0.196	0.180	0.2899	0.216	0.197
	rms	0.105	0.0683	0.0624	0.117	0.0746	0.067
u in (KN)	peak	-	5.025	7.079	-	6.021	7.454
	rms	-	2.057	2.494	-	2.524	2.881

Table-4 Comparison of response & control force for 5-storey frame (AMD tuned to different frequencies and r= 10^{-4})

Quantities		Tuned to ω_1			Tuned to ω_p		
		CP	CC	CCO	CP	CC	CCO
x in (m)	peak	.0326	.02498	.0247	.0386	.0239	.0222
	rms	.0107	.0088	.0083	.0134	.0087	.0085
u in (KN)	peak	-	1.276	.679	-	1.207	1.128
	rms	-	.409	.228	-	.434	.421

Note :
ω_1 = first frequency; ω_p = predominant frequency of ground acceleration

CONCLUSIONS

Control of the seismic response of multi storey shear frame is achieved by passive control with TMD and by active control with AMD. For active control,both close loop and close-open loop systems are used. For the latter, a formulation is presented to obtain the control force which is dependent on both structural response and ground motions. The formulation incorporates random ground motion as represented by Clough and Penzien double filter PSDF. The comparison between controlled and uncontrolled responses are made for different cases of studies. The numerical results lead to the following conclusions:

i) Active control leads to more reduction in response compared to the passive control; reduction in response increases as the weighting factor 'r' decreases.

ii) Close-open loop system provides a better control of response than the close loop system. For 5-storey building,it becomes evident as there is also a substantial reduction in the control force.

iii) For passive control,tuning of the mass-damper to the first frequency of the frame is the best. However for active control, tuning of AMD to the predominant frequency of ground motion may prove to be better under certain cases (such as the case of 5-storey frame)

iv) Close-open loop system appears to be more effective for less flexible system.

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