ROBUST DESIGN OF TMD SYSTEMS FOR THE SEISMIC RESPONSE CONTROL OF ASYMMETRIC SOFT STOREY BUILDING

Nirmalendu Debnath[1] , S.K. Deb[2] and Anjan Dutta[2]

[1] *Post-Graduate Student, Dept. of Civil Engineering , Indian Institute of Technology, Guwahati, India*
[2] *Professor, Dept. of Civil Engineering , Indian Institute of Technology, Guwahati, India*
Email: adutta@iitg.ernet.in

ABSTRACT :

Soft first storey buildings under seismic excitation with huge inter-storey drift at first floor level have been considered for the passive control with coupled tuned mass damper (CTMD) system. The design of tuned mass damper system for the multi degrees of freedom system for the response control under seismic excitation is associated with some efficiency and robustness issues. Robust control strategy is required for the effective reduction of response and damage in the structure. This paper discusses multi-objective optimal design of various tuned mass damper systems of higher robustness and efficiency for torsionally coupled seismically excited soft storey building. Objective functions have been considered as the displacement and acceleration along two translational directions as well as rotational components about the vertical axis. Non dominated sorting genetic algorithm (NSGA) has been used to obtain the design parameters of the CTMD systems.

KEYWORDS: Robustness, Genetic algorithm, Coupled tuned mass damper, Control, Soft storey building.

1. INTRODUCTION

Structural control has received considerable attention from researchers during the past few decades for improving structural functionality and safety against natural hazards like earthquakes and strong wind. Structural control strategy can be subdivided into the passive, active, semi-active and hybrid control strategy. A reasonable amount of research work has been reported in the literature, where tuned mass dampers and other related methodologies were used to control the vibration of structures. The multiple tuned mass damper system with the distributed range of frequencies were proposed by Kangming and Takeru (1992). Yamaguchi and Harnpornchai (1993) studied the fundamental characteristics and performance of multiple tuned mass dampers (MTMDs) with distributed natural frequencies for controlling response of the harmonically forced structures. Masato and Fujino (1994) analytically studied characteristics and efficiency of MTMD-structure system consisting of a large number of small oscillators with natural frequencies distributed around the natural frequency of first mode of the structure. Joshi and Jangid (1997) studied the optimum parameters of the MTMD system for base-excited structure. Jangid and Dutta (1997) discussed about the multiple tuned mass dampers to control torsional response coupled with the lateral response in one direction. Singh *et. al*. 92002) presented an approach for optimum design of tuned mass dampers for response control of torsional building system subjected to bi-directional seismic inputs. Ahlawat and Ramaswamy (2003) discussed multi-objective optimal design of an absorber system for torsionally coupled seismically excited buildings. Desu *et. al*. (2006) have studied on efficient tuned mass damper systems and introduced coupled tuned mass damper. It has been observed from the literature survey that tuned mass dampers have been utilized by many researchers for the response control of the seismically excited structures. However, the TMD design works are mainly based on highly idealized model and also use of evolutionary powerful optimization tool like multi-objective genetic algorithm (GA) is few. Further, the robustness issues in the design of TMD system for MDOF system under seismic excitation are in need of considerable study for the design of TMD system. This paper discusses multi-objective optimal design of various tuned mass damper systems of higher robustness and efficiency for torsionally coupled seismically excited soft storey building.

2. MODELING OF ASYMMETRIC BUILDING

An asymmetric building has been reduced to a system with a master node at each floor level with several other slave nodes at the nodal points of the structure. The asymmetric building has been modeled as 3D shear framed building with three degrees of freedom at each floor level at master node. These are two translations along x and y directions and a rotation about axis normal to the slab surface. The three forces *i.e* F_{jsx}, F_{jsy} and M_{jsz} at slave joints can be constrained with forces F_{jmx}, F_{jmy} and M_{jmz} at master joint by Eq. (2.1). Consequently, the total degrees of freedom in a structure are considerably reduced. The floor slab can be considered as a rigid body for in plane forces and a *planar constraint* is used to treat the floor slabs as rigid diaphragms.
Force and displacement transformations between master and slave nodes can be expressed as

$$\{F_{jm}\} = [T_{ms}]\{F_{js}\} \tag{2.1}$$

Or,

$$\begin{Bmatrix} F_{jmx} \\ F_{jmy} \\ F_{jmz} \\ M_{jmx} \\ M_{jmy} \\ M_{jmz} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ -Y_{ms} & X_{ms} & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} F_{jsx} \\ F_{jsy} \\ F_{jsz} \\ M_{jsx} \\ M_{jsy} \\ M_{jsz} \end{Bmatrix}$$

and

$$\{\delta_{js}\} = [T_{ms}]^T \{\delta_{jm}\}$$

where $\{F_{jm}\}$ and $\{F_{js}\}$ are force vector at master and slave nodes, $\{\delta_{jm}\}$ and $\{\delta_{js}\}$ are displacement vector at master and slave nodes and $[T_{ms}]$ is constrained matrix.

3. COUPLED TUNED MASS DAMPER

An arrangement of tuned mass damper termed as coupled tuned mass damper (CTMD) [9] has been utilized in which a mass is attached to translational springs and viscous dampers in an eccentric manner in such a way that the coupled modes of tuned mass can be utilized to control coupled lateral and torsional vibrations of asymmetric building. A general arrangement of springs-dashpot systems of CTMD has been shown in Fig. 1 The properties of spring-dashpot systems and its eccentricities (L_{x1}, L_{x2}, L_{y1} and L_{y2}) are tuned using genetic algorithm in order to get required amount of response control by producing required modes and frequencies of vibrations in tuned mass.

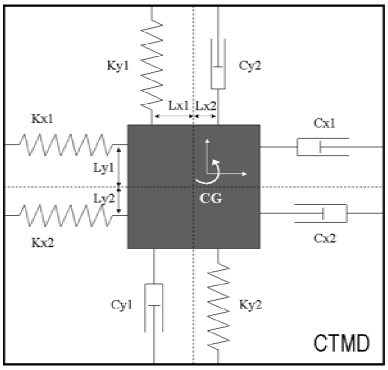

Fig.1. Coupled Tuned Mass Damper (CTMD)

4. IMPLEMENTING GA FOR OPTIMIZATION PROCESS

In order to use Genetic Algorithm (GA) in optimization problems, some parameters of interest in the system to be optimized have to be chosen. These parameters are called design variables. These design variables are represented by some set of strings coded in binary or other codes, which corresponds to the chromosomes of living things. In the present case, an individual design is represented by a binary string of appropriate length incorporating, generally by simple concatenation, the values of all design variables.
Design= $\langle\ y_{p_1}, y_{p_2}, ...y_{p_n}\rangle$ and Chromosome= $\langle 10011100.....001110\rangle$

These strings form the initial population. The variable y_{p_i} is bounded between upper (y_p^u) and lower limits (y_p^l). The decimal value of the design variable can be computed from

$$y_p = y_p^l + \frac{y_p^u - y_p^l}{2^q - 1} \sum_{k=0}^{q} 2^k b_k \tag{4.1}$$

where q is the string length of binary coded design variable. In the present study, fifteen bits have been taken to code each of the design variables. The GA has been adopted to solve a multi-objective optimization problem in the present paper. In a typical multi-objective optimization problem, we get Pareto-optimal solutions or non-dominated solutions. Since none of the solutions in the non-dominated set is absolutely better than any other, any one of them is an acceptable solution. Non-dominated sorting genetic algorithm (NSGA) (Srinivas, and Deb 1993) has been used in the present study in which six objective functions have been considered. It provides a set of Pareto-optimal designs making efficient use of GA's population-based search.

5.1 Details of objective functions and constraints

Six objective functions and six constraints are used in the present problem for controlling floor displacement and acceleration in both the translational directions and rotational displacement and acceleration along vertical direction. The optimization problem to be solved in the present study involves minimization of objective functions. The six objective functions are given as

$$f_1 = \max\left[\max_t\left\{\frac{|x_t(t)|}{x_{\max}}\right\}\right] \qquad f_2 = \max\left[\max_t\left\{\frac{|y_t(t)|}{y_{\max}}\right\}\right]$$
$$f_3 = \max\left[\max_t\left\{\frac{|\theta_{zi}(t)|}{\theta_{z_{\max}}}\right\}\right] \qquad f_4 = \max\left[\max_t\left\{\frac{|\ddot{x}_t(t)|}{\ddot{x}_{\max}}\right\}\right] \tag{5.1}$$
$$f_5 = \max\left[\max_t\left\{\frac{|\ddot{y}_t(t)|}{\ddot{y}_{\max}}\right\}\right] \qquad f_6 = \max\left[\max_t\left\{\frac{|\ddot{\theta}_{zt}(t)|}{\ddot{\theta}_{z_{\max}}}\right\}\right]$$

where, $x_t(t), y_t(t)$ and $x_{\max}, y_{\max}$ are displacements in x and y directions for the structure with and without control respectively, θ_z and $\theta_{z_{\max}}$ are torsional displacement for the structure with and without control respectively, $\ddot{x}_t(t), \ddot{y}_t(t)$ and $\ddot{x}_{\max}, \ddot{y}_{\max}$ are absolute accelerations in x and y directions for the structure with and without control respectively, $\ddot{\theta}_z$ and $\ddot{\theta}_{z_{\max}}$ are acceleration in θ_z direction for the structure with and without control respectively. Maximum displacement, maximum absolute acceleration in x and y direction and maximum rotation are given by

$$x_{\max} = \max\left[\max_t |x_t(t)|\right]_{unc} \qquad y_{\max} = \max\left[\max_t |y_t(t)|\right]_{unc}$$
$$\theta_{z_{\max}} = \max\left[\max_t |\theta_{tz}(t)|\right]_{unc} \qquad \ddot{x}_{\max} = \max\left[\max_t |\ddot{x}_t(t)|\right]_{unc} \tag{5.2}$$
$$\ddot{y}_{\max} = \max\left[\max_t |\ddot{y}_t(t)|\right]_{unc} \qquad \ddot{\theta}_{z_{\max}} = \max\left[\max_t |\ddot{\theta}_{tz}(t)|\right]_{unc}$$

The following constraints c_i (i = 1 to 6) are used to restrict the search space within the feasible zone of control, where response of the building with control system can occasionally become more than the response of uncontrolled building, particularly during initial generations.

$$c_1 \to 1 - f_1 \ge 0 \qquad c_2 \to 1 - f_2 \ge 0 \qquad c_3 \to 1 - f_3 \ge 0$$
$$c_4 \to 1 - f_4 \ge 0 \qquad c_5 \to 1 - f_5 \ge 0 \qquad c_6 \to 1 - f_6 \ge 0 \tag{5.3}$$

Further the properties of CTMDs like mass, stiffness, damping coefficient and their locations are constrained by upper and lower limits of the design variable.

6. DESIGN OF CTMD SYSTEM UNDER GROUND MOTION

The eight story asymmetric building has been considered for seismic response control using CTMD. Orthogonal components of various ground motion data are used as bi directional seismic input for the building. The mass (*tm*) of CTMD system has been considered as constant (approximately 1% of the total mass of the main system). For the optimization, variables have been considered as follows –

Natural frequency of CTMD in *x* (ω_X) and *y*-direction (ω_Y)

Damping ratio of CTMD in *x*(ζ_X) and *y*-direction (ζ_Y).

$$R_{KX} = \frac{K_{X1}}{K_{X2}} \quad \& \quad K_{X1} + K_{X2} = K_X \;; \qquad R_{KY} = \frac{K_{Y1}}{K_{Y2}} \quad \& \quad K_{Y1} + K_{Y2} = K_Y$$

$$R_{CX} = \frac{C_{X1}}{C_{X2}} \quad \& \quad C_{X1} + C_{X2} = C_X \;; \qquad R_{CY} = \frac{C_{Y1}}{C_{Y2}} \quad \& \quad C_{Y1} + C_{Y2} = C_Y$$

Mass centroid of CTMD in x and y direction.
Distance of x-directional 1st and 2nd spring and dashpot from the centre line (L_{Y1}) and (L_{Y2}).
Distance of y-directional 1st and 2nd spring and dashpot from the centre line (L_{X1}) and (L_{X2}).
Hence there are 14 number of variable in the design of single CTMD.

Table 1. Details of design variables for single CTMD

Variables	**Upper and lower limits**
Natural frequencies in two directions $(\omega_X, \ \omega_Y)$	0-50 rad/s
Damping ratios in two directions (ζ_X, ζ_Y)	0-1
Stiffness ratios in two directions (R_{KX}, R_{KY})	0.01-100
Damping coefficient ratios in two directions (R_{CX}, R_{CY})	0.01-100
X- ordinate of CTMD position in m	(-4.286) -5.714
Y- ordinate of CTMD position in m	(-5.214) -3.786
Springs & dashpots distance w.r.t CG of TMD $(L_{X1}, L_{X2}, L_{Y1}, L_{Y2})$	0-0.5m

8. Multiple CTMD Systems and their performance

For the optimization, implementation variables have been considered as follows –
For the MCTMD system, a distributed range of frequencies have been developed with the multiple CTMD. Consider N numbers of individual CTMD are forming the MCTMD system. The total mass (tm) of the MCTMD system has been kept constant (approximately 1% of the building mass). Now the natural frequency in x-direction of the ith CTMD can be expressed as follows –

$$\omega_{X\,i} = \omega_{TX}[1 + (i - \frac{N+1}{2})\frac{\beta_X}{N-1}] \quad i = 1,\, 2,\, 3.\dots\dots N$$

Average of the natural frequencies of the all the CTMD in x-direction $\omega_{TX} = \frac{1}{N}\sum_{i=1}^{N}\omega_{X\,i}$

Band width of distributed frequency range $\beta_X = \frac{\omega_{XN} - \omega_{X1}}{\omega_{TX}}$

Similarly for the y -direction

$$\omega_{Y\,i} = \omega_{TY}[1 + (i - \frac{N+1}{2})\frac{\beta_Y}{N-1}]$$

$$\omega_{TY} = \frac{1}{N}\sum_{i=1}^{N}\omega_{Y\,i} \qquad \text{where, } i = 1,2,3\dots\dots N$$

$$\beta_Y = \frac{\omega_{YN} - \omega_{Y1}}{\omega_{TY}}$$

Further, introducing mass ratio as a new variable, which is the ratio of the ith CTMD mass (tmi) to the 1st CTMD mass ($tm1$) and designated as $Rtmi$.

$$Rtmi = \frac{tmi}{tm1}$$

For i=1, $Rtm1$=1 and the total multiple CTMD mass, $tm = tm1 + \sum_{i=2}^{N} Rtmi\ .\ tm1$

$$\text{or,} \quad tm1 = \frac{tm}{1 + \sum_{i=2}^{N} Rtmi}$$

Hence, all the masses of the MCTMD system can be computed with the help of $(N\text{-}1)$ number of mass ratios.

$$tmi = \frac{tm\ .\ Rtmi}{1+\sum_{i=2}^{N} Rtmi} \quad i=2,3,4.........N$$

For each of the CTMD, two numbers of damping ratio variables ($\zeta_{X\ i}, \zeta_{Y\ i}$) have been used as variables and hence for *N* numbers of MCTMD *2N* numbers of damping ratios are used as variables. Further, each (i^{th}) CTMD is having two numbers of variables *(*X_i*,*Y_i*)* in form of x & y co-ordinate positions. Finally, each CTMD is having eight numbers of distinct variables combining the spring stiffness ratios (R_{KXi}, R_{KYi}) in two directions, damping coefficient ratios (R_{CXi}, R_{CYi}) in the two directions, distance of springs & dashpots from the CG of CTMD ($L_{X1i}, L_{X2i}, L_{Y1i}, L_{Y2i}$). The spring stiffness ratios and damping coefficient ratios will compute the stiffness in each of the spring and damping coefficients in each of the dashpots respectively.

Table 2. Details of design variables for multiple CTMD

Overall variables	**Upper and lower limits**
Average Natural frequencies (ω_{TX}, ω_{TY})	0-50 rad/s
Band width factors of distributed frequencies (β_X, β_Y)	0-2
(*N-1*) numbers mass ratios (*Rtm2, Rtm3…RtmN*)	0.05-20
Damping ratios in two directions (ζ_{Xi}, ζ_{Yi})	0-1
Stiffness ratios in two directions (R_{KXi}, R_{KYi})	0.01-100
Damping coefficient ratios in two directions (R_{CXi}, R_{CYi})	0.01-100
X- ordinate of CTMD position (X_i) in m	(-4.286) -5.714
Y- ordinate of CTMD position (Y_i) in m	(-5.214)-3.786
Spring & dashpot distance w.r.t. CG of CTMD ($L_{X1i}, L_{X2i}, L_{Y1i}, L_{Y2i}$)	0-0.5m

9. Performance evaluation

The eight storied asymmetric building has been considered to be consisting of rigid diaphragms, which are connected with the axially inextensible columns. The mass of each storey has been assumed to be lumped at the C.G. of the floor diaphragms. The performance of the designed tuned mass damper for the multi degrees of freedom structures subjected to ground excitation is assessed in terms of control level achievable, stability of the system as well as robustness. The robustness can be described as the performance of a designed CTMD system under other seismic excitations. The stability of the secondary system can be assessed by the range of stroke length of the TMD system.

9.1 Performance of ground motion based designed MCTMD

From the pareto optimal solutions of optimal designs, minimum values of the six numbers objective functions are evaluated for different excitations. Root mean square (RMS) of these minimum objective function values is a parameter of control level. This can be computed as –

RMS of minimum objective functions = $\left[\frac{1}{6}\sum_{i=1}^{6}(f_i)^2_{\min}\right]^{\frac{1}{2}}$ where, f_i is representing the objective functions. The RMS of minimum values of objective functions are shown in Fig. 2. Thus it is seen that MCTMD provides better control than single CTMD under all different excitations.

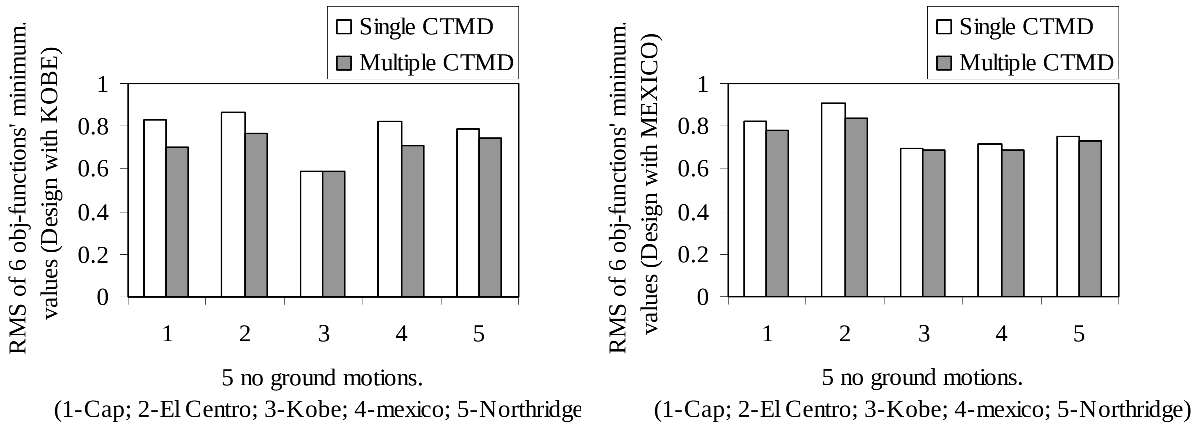

Fig.2 RMS of 6 no objective functions' minimum values for single and multiple CTMD

An asymmetric building shows the predominant influence of torsion, which effects the building badly. Torsion controlling objective function's minimum values for both the case of single and multiple CTMD systems have been shown in Fig. 3. It is observed very clearly that MCTMD system is performing very well in terms of torsional control.

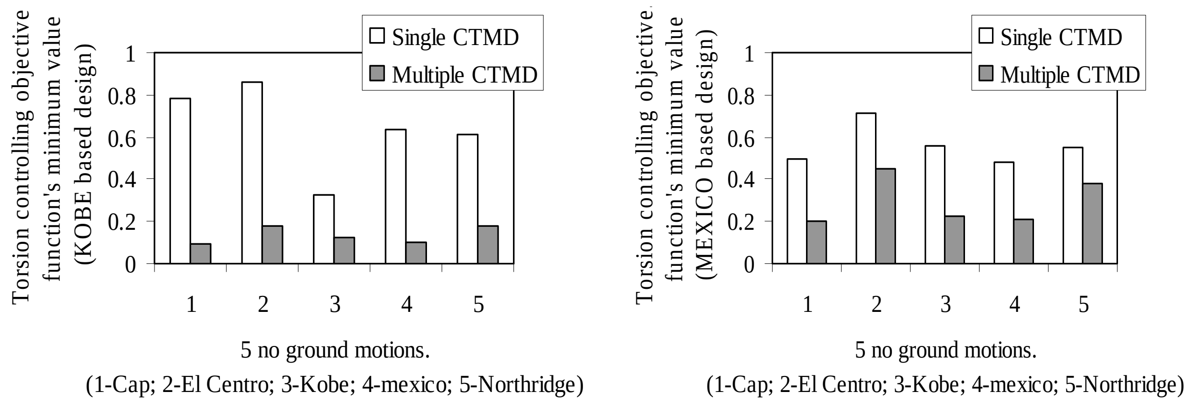

Fig.3 Torsion control objective function's minimum values for single and multiple CTMD

The average stroke length for both single and multiple CTMD systems has been shown in Fig. 4. Stoke length range is observed to be quite lower for MCTMD system in comparison to those from a single CTMD.

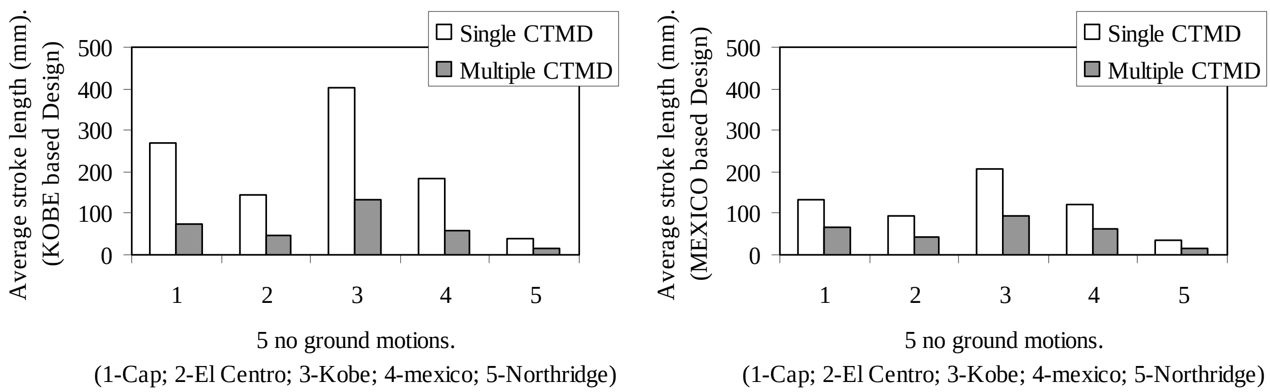

Fig.4 Average stroke length for single and multiple CTMD systems under various motions

Robustness of optimal designs under other excitation has been expressed in form of a ratio in percentage. This performance has been studied for single and multiple CTMD designed under Kobe and Mexico motions separately. The results are shown in the Table 3. In both the cases, multiple CTMD system is showing better robustness under the other seismic excitations.

Table 3. Robustness of single and multiple (3 no) CTMD systems under seismic excitations.

	Cap	El Centro	Kobe	Mexico	Northridge
Single CTMD (Designed under Kobe)	*31%*	*12%*	*100%*	*14%*	*7%*
Multiple CTMD (Designed under Kobe)	*57%*	*32%*	*100%*	*34%*	*13%*
Single CTMD (Designed under Mexico)	*9%*	*12%*	*22%*	*100%*	*26%*
Multiple CTMD (Design under Mexico)	*23%*	*39%*	*39%*	*100%*	*30%*

10. CONCLUSION

The robustness problems in the tuned mass damper system have been discussed by considering coupled tuned mass damper (CTMD). The robustness could be improved by using MCTMD for seismic response control of soft storey building structure. Multiple use of CTMD is clearly showing better performance. Mass has been kept as approximately 1% of the total mass of the building system. Multiple TMD system provides better performance in the passive control in comparison to single TMD system. This has been demonstrated for an irregular building.

REFERENCES

Kangming, Xu., Takeru, I.. (1992). Dynamic characteristics of multiple substructures with closely spaced frequencies. *Earthquake Engg Struct Dyn.* **21**, 1059-1070.

Yamaguchi, H. and Harnpornchai, N. (1993). Fundamental characteristics of multiple tuned mass dampers for suppressing harmonically forced oscillations. *Earthquake Engg Struct Dyn.* **22**, 51-61.

Masato, A. and Fujino, Y.(1994). Dynamic characteristics of multiple tuned mass dampers and some design formulas. *Earthquake Engg Struct Dyn.* **23**, 813-835.

Joshi, A.S. and Jangid, R.S. (1997). Optimum parameters of multiple tuned mass dampers for base excited damped systems. *Journal of Sound and vibration* **202:5**, 657-667.

Jangid R.S and Dutta T.K. (1997). Performance of multiple tuned mass dampers system for torsionally coupled system. *Earthquake Engg Struct Dyn* **26**, 307-317.

Singh, M.P., Singh, S. and Moreschi, L.M. (2002). Tuned mass dampers for response control of torsional buildings. *Earthquake Engg Struct Dyn* **31**, 749-769.

Ahlawat, A.S. and Ramaswamy, A. (2003). Multi-objective optimal absorber system for torsionally coupled seismically excited structures. *Engineering Structures* **25**, 941-950.

Desu, N.B., S. K. Deb, S.K. and Anjan Dutta, A.(2006). Coupled tuned mass dampers for control of coupled vibrations in asymmetric buildings. *Journal of Structural Control Health Monitoring* **13**, 897-916.

Srinivas, N. and Deb K. (1993) Multiobjective. Optimization using non-dominated sorting in genetic algorithms. *Technical Report, Department of Mechanical Engineering, Indian Institute of Technology, Kanpur, India*.