Optimization of Tuned Mass Damper Parameters Using Evolutionary Operation Algorithm

B. Islam
Graduate Student, Bangladesh University of Engineering and Technology, Bangladesh

R. Ahsan
Professor, Bangladesh University of Engineering and Technology, Bangladesh

15 WCEE
LISBOA 2012

SUMMARY:
Optimum parameters of Tuned Mass Dampers (TMD) are determined in this paper to minimize dynamic response of a multi-storied building system. The response of the structural system is simulated under lateral excitation. To optimize dynamic parameters of the TMD system for minimum top deflection of the structure, a numerical global optimization algorithm called Evolutionary Operation (EVOP) is used. This optimization tool possesses high probability of locating global minimum efficiently. The study proposes a design methodology of a TMD system based on EVOP algorithm. Also a comparison has been made with two other optimization approaches. The study shows the effectiveness of present approach in optimization leading to a more feasible selection of TMD parameters.

Keywords: Tuned Mass Damper, Optimization, Evolutionary Operation

1. INTRODUCTION

In the history of structural engineering a number of vibration control technique have been proposed and adopted so far to reduce structural response due to lateral excitations. Methodologies developed and used in order to improve structural performance and minimize structural damage mainly are vibration isolation, control of excitation forces, vibration absorber etc. In case of vibration absorbers Tuned Mass Damper (TMD), Active Mass Damper (AMD), Hybrid Mass Damper (HBD) has been studied to control the behaviour of tall structure subjected to excitations. Among these systems still TMD is popular because of its easy principle and several successful applications in real practice. A TMD is a system with a tuned mass, spring and damping elements which assists to increase the damping of the primary structure and hence aids in reducing vibration and keeping it within the desirable limit.

Frahm (1909) first proposed the basic form of TMD which did not possess any damping property by itself. So the effectiveness of the system was dependent upon the matching of its natural frequency and that of the excitation force. After that Ormondroyd and Den Hartog (1928) introduced internal damping in TMD. Optimum choices of damper parameters were not considered until Den Hartog (1947) proposed closed form expressions of frequency ratio and damping ratio of the TMD for an undamped single degree of freedom system. Later damping in the main system was included through several researches performed by Bishop and Welboum (1952), Snowdon (1959), Falcon et al. (1967), Ioi and Ikeda (1978). With time a number of studies and their extensions were made by Warburton and Ayorinde (1980), Thompson (1981), Warburton (1982), Villaverde et al. (1985, 1993 and 1995), Sadek et al. (1997) to obtain optimum TMD parameters considering different conditions. Rana and Soong (1998) simplified the design of TMD to control a single mode of a MDOF system. In addition they also inspected the prospect of controlling multiple structural modes with multi-tuned mass dampers (MTMD). Lin et al. (2001) applied an extended random decrement method to reduce dynamic responses of a MDOF system subjected to seismic load. Lee et al. (2006) proposed an optimal design theory for buildings associated with TMDs at different storey level and power spectral density (PSD) function of environmental disturbances. Optimal design parameters were expressed in terms of damping coefficients and spring constants through minimization of performance index of structural response. A numerical approach was also developed to search optimal design parameters of MTMDs. Bakre and Jangid (2007) developed explicit mathematic expressions for optimum TMD parameters using numerical searching technique. Rudinger (2007) included nonlinear viscous damping elements to TMD and analyzed the effect. Unlike previous studies related to TMD optimization where TMD mass ratio was a preselected parameter, Marano et al. (2010) optimized TMD mass ratio along with other parameters.

Metaheuristic methods like genetic algorithm (GA), particle swarm, simulated annealing, big bang big crunch were applied to solve different optimization problems. A wide application of genetic algorithm for tuning of TMD parameters was made in studies of Hadi and Arfiadi (1998), Singh et al. (2002), Desu et al. (2006), Pourzeynali et al. (2007). Leung et al. (2008 and 2009) used particle swarm optimization technique of tuned mass dampers. A global optimization algorithm EVOP developed by Ghani (1989) was used by Ahsan et al. (2011) to optimize the design of simply supported, post-tensioned, prestressed concrete I-girder bridge and succeeded in locating the global minimum. This optimization tool is capable of locating global minimum directly with high probability and without any requirement of information related to gradient or sub-gradient of objective function.

In the present study the focus is to explore this global optimization tool EVOP in order to obtain the optimum mass, stiffness and damping value of single TMD attached to top of a MDOF structure system and compare its effectiveness with other optimization approaches. The objective function selected for present case is minimization of the top deflection of primary structure.

2. EQUATION OF MOTION

Although present paper is focused on an MDOF structural system associated with single TMD on top, an approach has been developed to find the optimum parameters of TMDs installed in different story level of a multi-storied building for minimum top deflection caused by lateral excitation. The entire optimization problem has been formulated by developing a program using C++ language. A general equation of motion for any building with n number of story associated with m number of TMDs in different story level is used in developing the program for structural response minimization using EVOP. The equation of motion of the primary system is stated as follows.

$$\mathrm{M_i}\ddot{\mathrm{X}}_\mathrm{i} + \mathrm{K_i}(\mathrm{X_i} - \mathrm{X_{i+1}}) + \mathrm{K_{i-1}}(\mathrm{X_i} - \mathrm{X_{i-1}}) + \mathrm{C_i}(\dot{\mathrm{X}}_\mathrm{i} - \dot{\mathrm{X}}_\mathrm{i+1}) + \mathrm{C_{i-1}}(\dot{\mathrm{X}}_\mathrm{i} - \dot{\mathrm{X}}_\mathrm{i-1}) + \mathrm{K_j}(X_i - X_j) + C_j(\dot{X}_i - \dot{X}_j) = -M_i\ddot{u}_g \tag{2.1}$$

The equation of motion of TMD is given below.

$$\mathrm{M_j}\ddot{\mathrm{X}}_\mathrm{j} + \mathrm{K_j}(\mathrm{X_j} - \mathrm{X_i}) + C_j(\dot{X}_j - \dot{X}_i) = -M_j\ddot{u}_g \tag{2.2}$$

Where, i=1, 2,.....n and j=1, 2,.....m. In the above equation of motions M, K, C denotes mass, stiffness and damping respectively of n^{th} story in case of structure and of m^{th} TMD for dampers. X represents the absolute lateral displacement with respect to ground. $\dot{X}$ is single derivative of displacement which is velocity and $\ddot{X}$ is double derivative whic is acceleration. $\ddot{u}_g$ is the ground acceleration due to lateral excitation.

3. EVOLUTIONARY OPERATION (EVOP) ALGORITHM

In order to optimize the TMD parameters for achieving minimum response of an MDOF system, extensive evaluation of dynamic response is required which also have to satisfy the limit of variables and other constraints. For the present problem the variables used are of continuous type. This highly complex problem of dynamics with multiple local minima needs a global optimization tool for searching the global minimum. The current problem has been constructed to solve the optimization problem using EVOP. This global optimization tool has been assessed for optimization of numerous test problems and has succeeded in locating global minimum directly. It is capable of minimizing an objective function without asking information on gradient or sub-gradient. It is facilitated with automatic restarts to check whether the previously obtained minimum is the global minimum.

The algorithm of EVOP has been developed to minimize a defined objective function. The numbers of independent variables involved in the objective function are subjected to explicit constraints with specific upper and lower limit of each constraint. If any explicit constraint causes the vector-space non-convex it is then set into the group of implicit constraints with fixed upper and lower limit of each of them. These limits are either constant values or function of independent variables.

The algorithm works and progresses through six fundamental process which are explained clearly in details by Ghani (1989). The processes are generation of a 'complex', selection of a 'complex' vertex for penalization, testing for collapse of a 'complex', dealing with a collapsed 'complex', movement of a 'complex' and convergence tests. The algorithm of EVOP is presented in Figure 3.1.

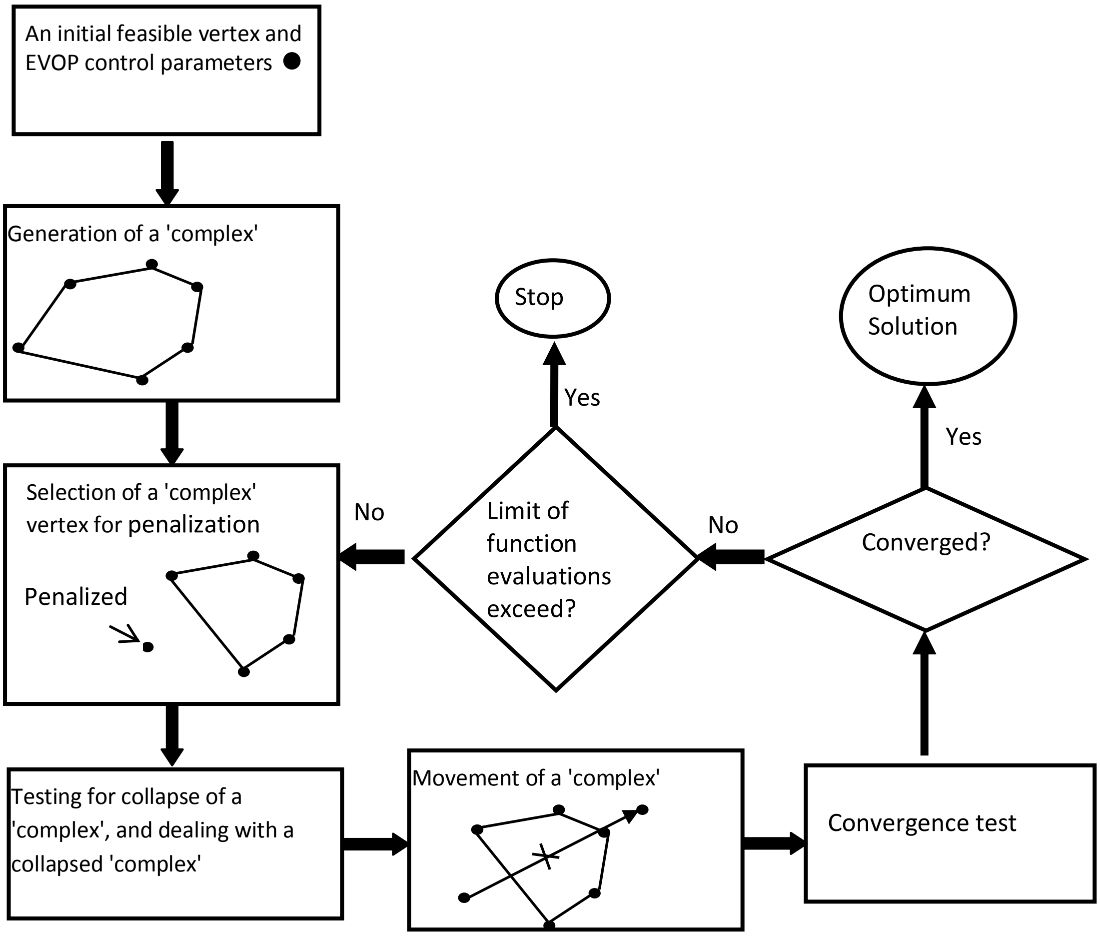

Figure 3.1 Algorithm of EVOP (after Rana, 2010)

For the present case, the entire problem has been constructed by identifying the independent variables, setting objective function to be minimized along with selecting the explicit and implicit constraints to be satisfied. After simulating the related expressions for dynamic analysis of current structural system chosen for optimization, a feasible starting point and control parameters required for EVOP has been selected and then linked the formulated problem with EVOP algorithm to perform the ultimate optimization operation. The systematic flow of the formulation steps of selected optimization problem and linking it with EVOP is illustrated in Figure 3.2.

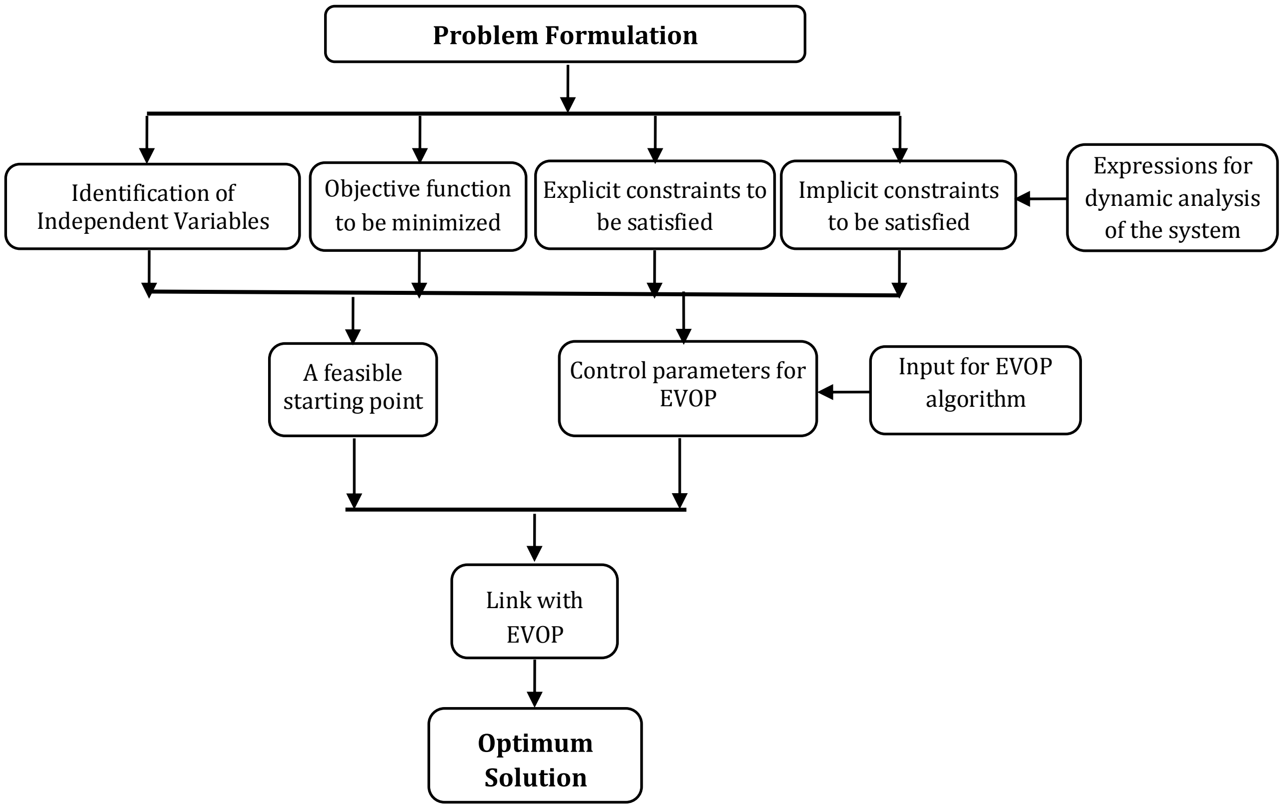

Figure 3.2 Problem formulation flowchart

EVOP control parameters and input parameters used for the present study are shown in the Table 3.1.

Table 3.1. EVOP control parameters and input parameters

EVOP Control Parameters	Default values	Range	Input Parameters with values
Reflection coefficient, α	1.6	1.0 to 2.0	Number of complex vertices, K = 6
Contraction coefficient, β	0.5	0 to 1.0	Maximum number of times the three functions can be collectively called, LIMIT = 100000
Expansion coefficient, γ	2.0	>1.0	
Convergence parameter, Φ	10-13	10-16 to 10-8	Dimension of the design variable space, N = 3

4. APPLICATION OF EVOP IN TMD OPTIMIZATION

To explore EVOP for the optimization of TMD parameters, a ten story shear building was chosen from the example of Hadi and Arfiadi (1998). The building has uniform mass of 360 t, stiffness of 650 MN/m, and damping coefficient of 6.2 MNs/m at each story. For the purpose of calculating inter-story drift, height of each story was assumed as 10.0m. To analyze the problem using EVOP the objective function is selected as top deflection of structure. The structural response has been simulated under lateral excitation and solved using central difference method. The independent variables identified are mass, stiffness and damping values of TMD. In the expressions written for constraints, the explicit constraints are defined as mass, stiffness and damping value of TMD and implicit constraint is set to maximum interstory drift. The selected values for initial feasible vertex and limit of constraints are presented in the following Table 4.1.

Table 4.1. Initial feasible values of independent variable and limits of constraints

	Initial feasible value	Upper limit	Lower limit
Mass (t) (Explicit Constraint)	105	108 (3% of total story mass of primary structure)	0
Stiffness (kN/m) (Explicit Constraint)	3750	5000	0
Damping (kNs/m) (Explicit Constraint)	151.5	200	0
Intersotry Drift (m) (Implicit Constraint)	-	0.1	0

After setting the initial values and constraint limits for the problem, the maximum story displacement with respect to ground were calculated by the developed program due to El Centro (1940) NS earthquake and the obtained maximum top displacement was defined as the objective function for minimization. Finally optimum TMD parameters were obtained for minimum top displacement.

To evaluate the effectiveness of present approach of optimization, results obtained using EVOP were compared to those obtained using two different approaches adopted by Hadi and Arfiadi (1998) and Lee et al. (2006). In case of optimizing dynamic parameters of TMD, Hadi and Arfiadi (1998) and Lee et al. (2006) only considered stiffness and damping of TMD. But in current methodology optimum value of TMD mass has also been searched along with stiffness and damping while performing the optimization process.

The comparison among optimum TMD parameters and maximum story displacements with respect to ground obtained using three optimization approaches are enlisted in Table 4.2 and Table 4.3 respectively.

Table 4.2. Comparison among TMD parameters for different optimization approaches

Optimum Parameters	Without TMD	With TMD (GA)	With TMD (Lee et al.)	With TMD (EVOP)
Mass (t)	-	108	108	107.995
Stiffness (kN/m)	-	3750	4126.93	3346.406
Damping (kNs/m)	-	151.5	271.79	66.024

Table 4.3. Comparison among story displacement with respect to ground for different optimization approaches

Dispalcement (m)	Without TMD	With TMD (GA)	With TMD (Lee et al.)	With TMD (EVOP)	%Reduction (GA)	%Reduction (Lee et al.)	%Reduction (EVOP)
Storey 1	0.031	.019	0.02	0.018728	38.71	35.48	39.58
Storey 2	0.06	.037	0.039	0.036557	38.33	35.00	39.07
Storey 3	.087	.058	0.057	0.052977	33.33	34.48	39.11
Storey 4	.112	.068	0.073	0.067714	39.29	34.82	39.54
Storey 5	.133	.082	0.087	0.081631	38.35	34.59	38.62
Storey 6	.151	.094	0.099	0.093736	37.75	34.44	37.92
Storey 7	.166	.104	0.108	0.103761	37.35	34.94	37.49
Storey 8	.177	.113	0.117	0.111502	36.16	33.90	37.00
Storey 9	.184	.119	0.123	0.116998	35.33	33.15	36.41
Storey 10	.188	.122	0.126	0.119682	35.11	32.98	36.34
Storey TMD	-	.358	0.282	0.413981	-	-	-

From the above comparison it can be observed that, using EVOP the structural response which is taken as story displacement has been minimized more efficiently with the accomplishment of better and more economic choice of selected TMD parameters. Optimum parameters of TMD obtained using EVOP are found to be smaller than those obtained by Hadi & Arfiadi (1998) using GA and Lee et al. (2006). The percentage of reduction of displacement is also higher compared to other two approaches selected for comparison. Maximum inter-story drift at the point of optimum value is found to be

0.006m. However allowable limit of inter-story drift can be set depending on the design consideration of structural system.

5. CONCLUSION

In current approach, an attempt has been made to adopt a global optimization algorithm EVOP for structural control under seismic excitation. In this regard a computer program has been developed to construct the optimization problem. A ten story structure associated with TMD on roof was selected for optimization process and top displacement was minimized for El Centro (1940) NS earthquake. Afterwards a comparison with the results obtained from two different approaches was made to prove the effectiveness and reliability of EVOP. A higher percentage of structural response reduction was achieved with a choice of smaller mass, stiffness and damping of TMD with the application of EVOP. From the study it has been established that the selected optimization technique EVOP has the high probability of locating global minimum. Moreover, by observing the potential of EVOP in locating the global minimum effectively and considering the feasibility aspect, it can be concluded that EVOP is effective in optimizing vibration control problems.

ACKNOWLEDGEMENT
The authors would like to greatly acknowledge the help of Mr. Ghani in the process of understanding EVOP algorithm.

REFERENCES

Ahsan, R., Rana, S. and Ghani, S. N. (2011). Cost Optimum Design of Post Tensioned I Girder Bridge Using Global Optimization Algorithm. *ASCE Journal of Structural Engineering*

Bakre, S. V., Jangid, R. S. (2007). Optimal parameters of tuned mass damper for damped main system. *Struct Control and Health Monitoring* **14:3**, 448–470.

Bishop, R. E. D., Welboum, D. B. (1952). The problem of the dynamic vibration absorber. *Engineering (London),* 174 and 769.

Den Hartog, J. P. (1947). Mechanical vibrations, McGraw-Hill, 3rd ed, New York.

Desu, N. B., Deb, S. K., Dutta, A. (2006). Coupled tuned mass dampers for control of coupled vibrations in asymmetric buildings. *Structural Control and Health Monitoring.*, **13:5**, 897–916.

El Centro (1940) NS earthquake. http://www.vibrationdata.com/elcentro.htm.

Falcon, K. C., Stone, B. J., Simcock, W. D., Andrew, C. (1967). Optimization of vibration absorbers: A graphical method for use on idealized systems with restricted damping. *Journal of Mechanical Engineering Science,* **9:5**, 374–381.

Frahm, H. (1911). *Device for damping of bodies*. US Patent No: 989,958.

Ghani, SN. (1989). A versatile algorithm for optimization of a nonlinear non differentiable constrained objective function. UKAEA Harwell Report Number R13714, ISBN 0-7058-1566-8, HMSO Publications Centre, PO Box 276, London, SW85DT.

Hadi, M. N. S., Arfiadi, Y. (1998). Optimum design of absorber for MDOF structures. *Journal of Structural Engineering (ASCE).* **124:11**, 1272–1279.

Ioi, T., Ikeda, K. (1978). On the dynamic vibration damped absorber of the vibration system. *Bulletin of the Japanese Society of Mechanical Engineers*. **21:151**, 64–71.

Lee, C. L., Chen, Y. T., Chung, L. L., Wang, Y. P. (2006). Optimal design theories and applications of tuned mass dampers. *Engineering Structures*. **28:1**, 43–53.

Leung, A. Y. T., Zhang, H., Cheng, C. C., Lee, Y. Y. (2008). Particle swarm optimization of TMD by non-stationary base excitation during earthquake. *Earthquake Engineering and Structural Dynamics*. **37:9**, 1223–1246.

Leung, A. Y. T., Zhang, H. (2009). Particle swarm optimization of tuned mass dampers. Engineering Structures. **31:3**, 715–728.

Lin, C. C., Wang, J. F., Ueng, J. M. (2001). Vibration Control identification of seismically excited mdof structure-PTMD systems. *Journal of Sound and Vibration*. **240:1**, 87–115.

Marano, G. C., Greco, R., Chiaia, B. (2010). A comparison between different optimization criteria for tuned mass dampers design. *Journal of Sound and Vibration*. **329:23**, 4880–90.

Ormondroyd, J., Den, Hartog J. P. (1928). The theory of dynamic vibration absorber. *Journal of Applied Mechanics Trans. ASME*. **50:7**, 9–22.
Pourzeynali, S., Lavasani, H. H., Modarayi, A. H. (2007). Active control of high rise building structures using fuzzy logic and genetic algorithms. *Engineering Structures*. **29:3**, 346–357.
Rana, R., Soong, T. T. (1998). Parametric study and simplified design of tuned mass dampers. *Engineering Structures*. **20:3**, 193–204.
Rans, S. (2010). Cost Optimization of Post-Tensioned Prestressed Concrete I-Girder Bridge System. Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.
Rundinger, F. (2007). Tuned mass damper with nonlinear viscous damping. *Journal of Sound and Vibration*. **300:3-5**, 932–348.
Sadek, F., Mohraz, B., Taylor, A. W., Chung, R. M. (1997). A method of estimating the parameters of tuned mass dampers for seismic applications. *Earthquake Engineering and Structural Dynamics*. **26:6**, 617–635.
Singh, M. P., Singh, S., Moreschi, L. M. (2002). Tuned mass dampers for response control of torsional buildings. *Earthquake Engineering and Structural Dynamics*. **31:4**, 749–769.
Snowdon, J. C. (1959). Steady-state behavior of the dynamic absorber. *Journal of Acoustical Society of America*. **31:8**, 1096–1103.
Thompson, A. G. (1981). Optimum damping and tuning of a dynamic vibration absorber applied to a force excited and damped primary system. *Journal of Sound and Vibration*. **77:3**, 403–415.
Warburton, G. B., Ayorinde, E. O. (1980). Optimum absorber parameters for simple systems. *Earthquake Engineering and Structural Dynamics*. **8:3**, 197–217.
Warburton, G. B. (1982). Optimum absorber parameters for various combinations of response and excitation parameters. *Earthquake Engineering and Structural Dynamics*. **10:3**, 381–401.
Villaverde, R. (1985). Reduction in seismic response with heavily-damped vibration absorbers. *Earthquake Engineering and Structural Dynamics*. **13:1**, 33–42.
Villaverde, R., Koyama, L. A. (1993). Damped resonant appendages to increase inherent damping in buildings. *Earthquake Engineering and Structural Dynamics*. **22:6**, 491–507.
Villaverde, R., Martin, S. C. (1995). Passive seismic control of cable-stayed bridges with damped resonant appendages. *Earthquake Engineering and Structural Dynamics*. **24:2**, 233–246.