STUDY ON THE OPTIMAL PLACEMENT OF VISCOELASTIC DAMPERS FOR PASSIVE RESPONSE CONTROL BY GENETIC ALGORITHMS

LI Hong-nan[1] and Qu Ji-ting[2]

[1] *Professor, Institute of Earthquake Engineering, School of Civil and Hydraulic Engineering, Dalian University of Technology, Dalian. China*

[2] *PhD, School of Civil and Hydraulic Engineering,Dalian University of Technology, Dalian. China*
Email: hnli@dlut.edu.cn, dianaqjt@yahoo.com.cn

ABSTRACT :

A new mathematical model for location optimization of viscoelastic dampers is established in this paper. Three response control indices about the storey-drift angle, storey-displacement and acceleration are considered in this model. Firstly, five combination modes of these indices are presented. On the premise that the number of dampers is fixed, this paper deals with the optimal placement of viscoelastic dampers for several building models with different number of stores and seismic ground motions at four types of sites using genetic algorithm. Secondly, two estimating indices are presented to assess the response to the optimal location under the condition of five combination modes, which can generally express the best response control and the propositional combination of the coefficients is available under different conditions. Some numerical examples are illustrated to verify the effectiveness and feasibility of the new mathematical model. At last, several significant conclusions are drawn based on numerical results.

KEYWORDS: location optimization, viscoelastic damper, genetic algorithm

1. INTRODUCTION

The technique of energy dissipation as a passive structure control means has been written into the China Seismic Code for Buildings, which can give an impulse to the use and development of this technique. Energy dissipation devices are the important part of the technique and are classified as displacement-based and velocity-based devices in the Code. Viscoelastic and viscous dampers are the two typically used velocity-based devices, and their force-deformation responses are dependent on the relative velocity and acceleration between each end of the devices. These devices are applied in seismic control of all kinds of buildings broadly because they are easily installed, safe, and cost-effective and have simple conformation performance.

Because the optimal locations of dampers will have a significant effect, many scholars have contributed themselves to the research on optimal design of viscoelastic dampers (VED) in structures and different methods have been suggested. In the past decades, with wide use of a versatile and flexible method called genetic algorithm, more and more researchers employed it into the structural control and did a lots of research work. For a certain structure, the optimal properties of dampers can be determinate. As far as optimal location of dampers is concerned, the results of optimization may be different because objective functions suggested by researchers are diverse, and the investigations all aimed at a given structure subjected to one earthquake record.

The main objective of this paper is to study the optimal position of the VED. A new mathematic model for location optimization is established. Three seismic response performance indices are considered in this model. Five combination modes of these indices are presented. On the premise that the number of dampers is fixed, this paper deals with the optimal placement of viscoelastic dampers using genetic algorithms. Several building models with different numbers of stores and ground motions at four types of sites are considered in numerical examples. Two estimating indices are brought forward to primarily estimate the reasonable combination mode of the coefficients under different conditions, which can generally express the best response control. At last, several significant conclusions are drawn.

2. ANALYTICAL MODEL OF VISCOELASTIC DAMPED SYSTEM

2.1. Force-deformation Relationship Model

A number of force-deformation relationship models of VED have been brought forward and they are applicable to different conditions. The equivalent stiffness and equivalent damping model is adopted in this paper for its wide usage and simple ness. For this model, the general relation for the resistance force F_v takes the following form:

$$F_v = c_v(\omega)\dot{u} + k_v(\omega)u \tag{2.1}$$

where $c_v(\omega)$ and $k_v(\omega)$ represent, respectively, the frequency dependent damping and stiffness coefficients of the dampers, and they can be determined as:

$$c_v(\omega) = \frac{\eta(\omega)G'(\omega)A}{\omega\delta} \; ; \quad k_v(\omega) = \frac{G'(\omega)A}{\delta} \tag{2.2}$$

where G' and G'' are defined as the shear storage modulus and the shear loss modulus of the VE material, respectively; A represents the area of VE material; δ means the thickness of the VE material; $\eta(\omega)$ is the loss factor that provides a measure of the energy dissipation capability of the VE material, and ω corresponds to the frequency at which these properties are determined. The loss factor can be expressed as:

$$\eta(\omega) = \frac{G''(\omega)}{G'(\omega)} \tag{2.3}$$

2.2. System Equations of Controlled Structural Building

The equations of motion for an N degree freedom building structure with viscoelastic dampers subjected to earthquake motion can be written in the following form:

$$[M][\ddot{u}(t)] + ([C_s] + [C_v])[\dot{u}(t)] + ([K_s] + [K_v])[u(t)] = -[M][I][\ddot{u}_g(t)] \tag{2.4}$$

where $[M]$, $[C_s]$ and $[K_s]$ represent the N×N mass, inherent structural damping and stiffness matrices of the structure; $[\ddot{u}(t)]$, $[\dot{u}(t)]$ and $[u(t)]$ are the relative acceleration, velocity and displacement vectors of N-dimension, respectively; $[\ddot{u}_g(t)]$ is the seismic excitation at the base of the structure; $[C_v]$ and $[K_v]$ denote the added damping and stiffness matrices of the VE devices, respectively.

3. OPTIMIZATION BASED ON GENETIC ALGORITHMS

3.1. Establishment of Objective Function

To design a structure with energy dissipation devices, the optimal location of dampers can make the performance indices be restricted within desired objectives as the number of dampers is fixed. Several optimization formulations have been proposed with different indices as follows: (1) The largest relative displacement of inter-storey; (2) Storey-displacement and relative displacement of inter-storey; (3) Relative displacement of inter-storey and the displacement of the peak storey, et al. These indices all focus on the deformation of the structure. If the variability about storey-drift is considered as the only performance index, the optimal location can give a better limit for the storey-drift of the system, which may magnify indices of acceleration or storey displacement. It is a crucial problem to put forward an optimization formulation considering different indices of seismic response and confirm the combination of coefficients for all the indices.

The aim of seismic control of structures is to make structures safe and comfortable in accord with the Codes. Three indices about the storey-drift angle, acceleration and storey displacement can reflect the two aspects of structural performance. Thus, a new optimization formulation is presented in this paper, expressed as a linear combination of three non-dimensional items and considered both security and coziness. In order to avoid the optimal solution applied only to the special earthquake excitation, three seismic records are used for every kind of site in the step-by-step time history analysis. The optimization formulation can be written in the following form:

$$\min Z = \alpha \frac{\theta_{\max}}{\theta_{0,\max}} + \beta \frac{a_{\max}}{a_{0,\max}} + \gamma \frac{u_{\max}}{u_{0,\max}} \tag{3.1}$$

where $\theta_{\max}$ and $\theta_{0,\max}$ mean the largest storey-drift angle of structures with and without additional energy dissipative devices; $u_{\max}$ and $u_{0,\max}$ are the largest absolute displacement of structures with and without devices; $a_{\max}$ and $a_{0,\max}$ represent the largest absolute acceleration of structures with and without devices; α, β and γ denote weight coefficients which have different values according to the application demand of the project. The combinations of the three coefficients are given in details in section 4.3.

In the context of the problem of optimal location of dampers using genetic algorithms, optimal variables need to be confirmed. It is expressed as the matrix of position consisting of 0 and 1, which indicate to locate a damper if the number is one. System analysis and location optimization procedures are programmed adopting the MATLAB programming language.

3.2. Estimating Indices for Combination Modes of Coefficients

For different form of buildings with different number of stores and ground motions at four types of sites, the optimal results about five kinds of combination modes of coefficients may be different. In order to compare these modes with one another to decide which one can generate better control of the structures with optimal location of dampers, two estimating dimensionless indices are proposed. These indices can be expressed as root-mean-square values of corresponding variables as following form:

$$J_1 = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\theta_{i,\max}}{\theta_{0,i,\max}}\right)^2, \quad J_2 = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{a_{i,\max}}{a_{0,i,\max}}\right)^2 \tag{3.2}$$

where $\theta_{i,\max}$ and $\theta_{0,i,\max}$ imply the mean values of largest storey-drift angle of structures with and without additional energy dissipative devices for the i th floor; $a_{i,\max}$ and $a_{0,i,\max}$ represent the mean value of largest absolute acceleration of structures with and without the devices, respectively. J_1 and J_2 all take responses of every floor into consideration, which can reflect the response control in general. For five combination modes of coefficients, the two indices should be calculated respectively for different building with optimal located dampers. The smaller the values of the indices are, the better the combination mode is.

4. NUMERICAL ANALYSIS

Three building models with short, intermediate and long periods have been used in this paper, respectively.

Numerical analyses have been done in order to realize the different optimal locations to diverse structures at different type of sites. The parameters of genetic algorithms are taken as: the terminate generation of genetic operation is 400 and the probability of crossover and mutation are 0.8 and 0.2.

4.1. Building Structural Models

Building 1: For a 5-storey shear building with uniform properties, the parameters are taken as: the mass is 2.0×10^5 kg, the story stiffness is 4.2×10^8 N/m, and the height of story is 3.3m. The damping ratio is 5%, and period of the structure is 0.4817s.

Building 2: A 10-storey shear building is considered. The mechanical properties of this building are depicted in Table 4.1. The damping ratio is 5%, and period of the structure is 1.4583s.

Building 3: The third structure is a 16-storey shear building. Its mechanical properties of this building are provided in Table 4.2. The damping ratio is 5%, and period of the structure is 2.3848s.

For building 1 and 2, three and six viscoelastic dampers are chosen to be located, respectively，and it is assumed that there is one damper in each storey. The numbers of dampers installed in the third building is eight on each floor and 72 in totally. The typical viscoelastic damper with two viscoelastic layers is designed with such parameters: $G' = 1.5 \times 10^7 N/m^2$, $G'' = 2.01 \times 10^7 N/m^2$, $A = 3 \times 10^{-2} m^2$ and $\delta = 1.3 \times 10^{-2} m$.

4.2. Earthquake Records

Different earthquake records, even though similar intensities, lead to widely varying responses and results based on a single record may not be conclusive. In this paper 12 earthquake records are chosen, three for each type of site, shown in Table 4.3. The values of peak ground accelerations are scaled to 400gal.

Table 4.1 Mechanical properties of 10-storey building

Floor	Mass (kg)	Highness (m)	Stiffness (N×m-1)
1	1.520×10^6	3.0	2×10^9
2	1.520×10^6	3.0	1×10^9
3	1.349×10^6	3.0	1.43×10^9
4	1.349×10^6	3.0	1.11×10^9
5	1.349×10^6	3.0	1×10^9
6-9	1.349×10^6	3.0	0.769×10^9
10	1.187×10^6	3.0	0.417×10^9

Table 4.2 Mechanical properties of 16-storey building

Floor	Mass (kg)	Highness (m)	Stiffness (N×m-1)
1	4.84×10^6	3.6	5.1×10^9
2	4.67×10^6	3.0	3.6×10^9
3	4.35×10^6	3.0	3.8×10^9
4	4.31×10^6	3.0	3.21×10^9
5-9	4.07×10^6	3.0	2.54×10^9
10-13	3.81×10^6	3.0	2.13×10^9
14-16	3.57×10^6	3.0	1.92×10^9

Table 4.3 The severest real ground motions

Site	Group	Records	Comp.	Interval (s)	Time (s)	Peak value (cm/s^2)
Ⅰ	F1	1985, La Union, Michoacan Mexico	N00E	0.01	62.71	162.79
	F2	1994, Los Angeles Griffith Observation, Northridge	360	0.005	28.75	163.80
	N1	1988, Zhutang, A, Langcang	S00E	0.01	25.32	541.60
Ⅱ	F3	1971, Castaic Old bridge Route, San Fernando	N69W	0.02	61.87	265.40
	F4	1979, El Centro, Array#10, Imperial valley	N69W	0.01	37.07	168.21
	N2	1988, Gengma Gengma1	S00E	0.02	12.36	140.75
Ⅲ	F6	1984, Coyote Lake Dam, Morgan Hill	285	0.02	59.98	1137.80
	F7	1940, El Centro-Imp Vall Irr Dist, El Centro	270	0.02	53.47	210.10
	N3	1988, Gengma Gengma 2	S00E	0.02	16.56	90.02
Ⅳ	F8	1949, Olympia Hwy Test Lab, Western Wash.	356	0.02	89.16	161.63
	F9	1981, Westmor and, Westmoreland	90	0.02	88.43	353.97
	N4	1976, Tianjin Hospital, Tangshan	WE	0.01	19.19	104.18

4.3. Combination modes of coefficients in optimal function

In order to primarily confirm the combination of weight coefficients α, β and γ, pilot calculations are done about the values of the coefficients. Taking α as the main factor, five intervals are considered from which the value of α is set as follows: 1-0.8, 0.8-0.6, 0.6-0.4, 0.4-0.2 and 0.2-0. Five kinds of combination modes are proposed, shown in Table 4.4.

Table 4.4 Combination modes of optimal coefficients

Mode	α	β	γ	Objective of optimization
1	1	0	0	Considering storey-drift angle only, namely security;
2	0.7	0.1	0.2	Taking storey-drift angle as the main factor, maximal acceleration and storey displacement as additive factors;
3	0.5	0.3	0.2	The weight of storey-drift angle is half the importance;
4	0.1	0.7	0.2	Acceleration are the main factor;
5	0	1	0	Considering acceleration only, namely amenity.

4.4. Optimal Results

Based on the above combination modes of coefficients in the objective function, the location optimizations of dampers for three structures at four types of site are done.

(1) 5-storey building
The optimal locations are uniform for different types of site when coefficients are assumed as combination mode 1 to 5. The dampers are positioned at the bottom of the structure with one on each storey from the first to the third floor. For the low building chosen in this paper, it has no influence on the optimal solution for whether the acceleration factor is taken into account or not as the security factor is considered.

(2) 10-storey building
The results indicate that optimal solutions are the same for the combination mode 1 and 2, as well as the mode 4

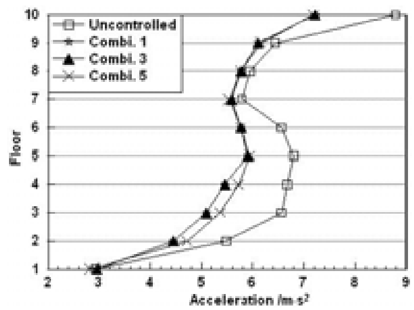
and 5. In other words, the controlled effect of structural response is the same for mode 1 and 2, or for mode 4 and 5. Concisely, combination mode 1, 3 and 5 are taken for analysis and illumination. The optimal locations of dampers are shown in Table 4.5. For the site Ⅰ, the optimal locations are uniform for the mode 1 and 3. The dampers are mainly located on the upper parts of the building. If the mode 5 is adopted, the dampers will be placed averagely on the upper six floors. For the site Ⅱ, dampers are positioned at the middle and top part. For the site Ⅲ, the optimal locations are uniform for the mode 1 and 3 also. It indicates that the appropriate increase in acceleration weight has less effect on the optimal results.

Table 4.5 Location optimization of dampers for 10-storey structure

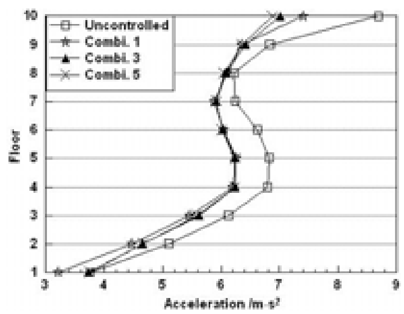
Site	Combi.1	Combi.3	Combi.5
Ⅰ	2 6 7 8 9 10	2 6 7 8 9 10	5 6 7 8 9 10
Ⅱ	1 2 5 6 7 8	2 5 6 7 8 10	2 6 7 8 9 10
Ⅲ	2 4 5 6 7 10	2 4 5 6 7 10	2 6 7 8 9 10
Ⅳ	2 3 4 5 6 7	2 4 5 6 7 8	2 5 6 7 8 10

(3) 16-storey building
The optimal locations of dampers indicate that the results are the same for the combination mode 1 and 2, while different for the mode3, 4 and 5. For the site Ⅰ, the dampers are mainly located at the middle part of the structure. Considering the site Ⅱ and Ⅲ, the dampers are placed at the bottom and middle part. Dampers are positioned at the middle and top part of the building for the site Ⅳ. It means that the acceleration weight has an impact upon the optimal locations for high buildings. Considering the space of the paper, the locations are not given in detail.

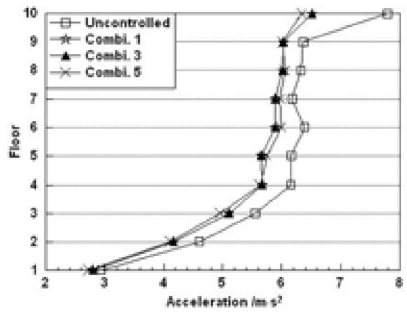
The step-by step time history analysis is utilized to obtain the responses of structures at four types of sites when the dampers are located in structures according to the optimal results with five modes of coefficients combination. As the space of the paper is limited, some of the envelope diagrams of the 10-story building for different sites are displayed shown in Figures 1.



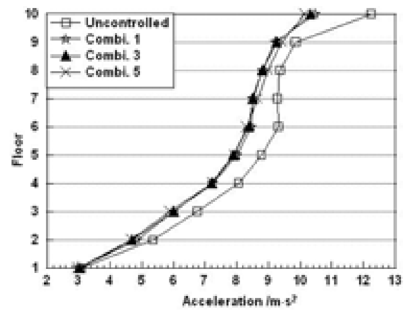
(a) Site Ⅰ



(b) Site Ⅱ



(c) Site Ⅲ



(d) Site Ⅳ

Fig. 1 Envelope diagrams of maximal acceleration for 10-storey structure

4.5. Comparisons between Different Combination Modes

(1) 10-storey building
As far as acceleration is concerned, it is not obvious that which mode can give a better control for the structures with dampers located optimally from Fig. 1 directly. For example, the mode 1 has better control for the bottom part, while the mode 5 controls best for the top part at the site Ⅱ. Thus, indices J_1 and J_2 are calculated to estimate which mode is the best in response control. The results shown in Table 4.6 indicate that the mode 3 is the best one for drift-angle control at all four sites. When the acceleration is taken into consideration, the mode 5 is the best for the site Ⅲ and Ⅳ, while the mode 1 is better than the mode 5 for the site Ⅰ and Ⅱ. Considering security and coziness at the same time, the mode 3 is the most ideal one for the structural control.

Table 4.6 Estimate indices of objective function for 10-stroey structure

Site	J1			J2		
	Combi.1	Combi.3	Combi.5	Combi.1	Combi.3	Combi.5
Ⅰ	0.7164	0.7164	0.7392	0.7927	0.7927	0.8048
Ⅱ	0.7696	0.7694	0.7724	0.8242	0.8550	0.8506
Ⅲ	0.7246	0.7246	0.7313	0.8519	0.8519	0.8439
Ⅳ	0.7886	0.7774	0.7748	0.8334	0.8269	0.8262

(2) 16-storey building
Indices J_1 and J_2 are calculated for the 16-storey building shown in Table 4.7. The results indicate that the mode 3 is the best one for the drift-angle control at all four sites and for the acceleration control at the site Ⅱ. The mode 5 is better than the mode 3 for the acceleration control at the site Ⅰ, Ⅲ and Ⅳ.When security and coziness are all taken into consideration, the mode 3 is the most ideal one.

Table 4.7 Estimate indices of objective function for 16-stroey structure

Site	J1				J2			
	1	3	4	5	1	3	4	5
Ⅰ	0.4645	0.4568	0.4690	0.4680	0.7435	0.6696	0.6704	0.6671
Ⅱ	0.5606	0.5480	0.6063	0.6063	0.7287	0.7228	0.8009	0.8009
Ⅲ	0.5172	0.5130	0.5267	0.5264	0.9421	0.8773	0.9071	0.8748
Ⅳ	0.6165	0.5950	0.6192	0.6306	0.7235	0.6665	0.6880	0.7050

5. CONCLUSION

(1) Generally, the optimal locations are different when the coefficients of objective function are combined in different modes. If different sites are considered, the location optimization results are different either.
(2) It has no influence on the optimal solution for low buildings whether the coziness is taken into account or not as the security factor is considered at four types of sites. The dampers are all placed at bottom part averagely. The objective function can be predigested as:

$$\min Z = \frac{\theta_{\max}}{\theta_{0,\max}}$$

(3) However, it affects the response of high-rise buildings a lot whether the acceleration factor is taken into consideration in the objective function or not. The numerical results for the 16-storey buildings at four types of site indicate that the combination mode with $\alpha = 0.5$, $\beta = 0.3$ and $\gamma = 0.2$ is the most logical one to obtain effective reduction in earthquake-induced response because the security and amenity are taken into consideration. The objective function can be taken as:

$$\min Z = 0.5\frac{\theta_{\max}}{\theta_{0,\max}} + 0.3\frac{a_{\max}}{a_{0,\max}} + 0.2\frac{u_{\max}}{u_{0,\max}}$$

(4) It can be concluded from the numerical analyses that the objective functions only considered as the security factor are not applicable for all structures. It is reasonable for low buildings, while the effect of acceleration shall be taken into consideration in the optimal objective function for intermediate and long period structures.

REFERENCES

Makris N, Constantinou MC. (1990). Viscous Damper: Testing, Modeling and Application in Vibration of Seismic Isolation. NCEER Rep. 90-0028, State Univ. of New York at Buffalo.
Li Hong-nan, Chang Zhi-guo and Zhao Bo-dong. (2002). Study on optimization of structural vibration control by GA. Earthquake Engineering and Engineering Vibration 22:5, 92-96.
Li Hong-nan and Jin Qiao. (2003). AMD active control for irregular buildings using GA-BP neural network. Earthquake Engineering and Engineering Vibration 23:2, 134-142.
Zhang RH and Soong TT. (1992). Seismic design of viscoelastic dampers for structural applications. Journal of Structural Engineering, ASCE 118:5, 1375-1392.
Singh MP and Moreschi LM. (2002). Optimal placement of dampers for passive response control. Earthquake Engineering and Structural Dynamics 31, 955-976.
Zhou Yun, Xu Zhaodong and Deng Xuesong. (1998). Optimal installation of the dampers in the viscoelastic structures. World information of earthquake engineering 14:3, 15－20.
Zhang Qin, Lou Wenjuan and Chen Yong. (2003). The objective function and realization of optimal placement for viscoelastic dampers. Industrial construction 33:6, 10-13.
Chang KC, Lai ML, Soong TT, Hao DS and Yeh YC. (1993). Seismic behavior and design guidelines for steel frame structures with added viscoelastic damper. NCEER 93-0009, National Center for Earthquake Engineering Research, Buffalo, NY.
Xu Zhao-dong, Zhou Yun and Zhao Hong-tie. (1999). Optimum design method of the viscoelastic structure. Journal of Xi'an University of Architecture and Technology(Natural Science Edition) 31:3, 246-248.
Xie Li-li and Zhai Chang-hai. (2003). Study on the severest real ground motion for seismic design and analysis. Acta Seismologica Sinica(English Edition) 25:3, 250-261.