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TLCD Systems on Non-Rigid Pads

*Yoyong Arfiadi[1)] and Ade Lisantono[2)]

[1), 2)] *Department of Civil Engineering, Atma Jaya Yogyakarta University, Indonesia*
[1)] *yoyong@mail.uajy.ac.id*

ABSTRACT

Reducing response of structures due to earthquake is the main concern of structural engineers. Many methods have been proposed to control the vibration of buildings; these include passive and active control systems. In practice, passive control systems are more popular than active control ones, and have been used in many buildings, due to their simplicity. Among passive control systems are tuned liquid column dampers (TLCDs). TLCDs rely on the motion of a liquid mass in tube-like containers to counteract the external force. By adjusting the sizes and properties of the liquid, the response reduction can be achieved. Most of TLCDs rest on fixed supports where the column dampers move related to the movement of floor. It is possible that TLCD systems are placed on a flexible support. This paper investigates the effectiveness of TLCD systems rest on rigid pads. When the TLCD rests on a flexible support (pad), the response reduction can also be achieved if the properties of the pad and TLCD are adjusted. The properties of the TLCDs and the properties of the pads are optimized by using real coded genetic algorithms (GAs) with the performance index is taken as H_2 norm of the transfer function from external disturbances to the regulated outputs. Numerical examples are the carried out to see the effectiveness of TLCD systems rest on flexible pads in reducing structural response subject to earthquake.

Keywords: liquid dampers, response reduction, vibration control, optimization, real coded genetic algorithms, H_2 norms

1. INTRODUCTION

The use of control systems in flexible buildings has been attempted in order to reduce the response of structures under excessive vibrations. These include passive and active control systems including their combinations. Passive control systems are interesting due to their simplicity. Several passive control systems that have been applied in real buildings are tuned mass dampers (TMDs) and tuned liquid column dampers (TLCDs). TLCDs are basically similar to TMDs where the ability to reduce the response is provided by the oscillations of liquid in a U tube. Some advantages of using TLCDs for vibration suppressions are: the liquid is easy mobilized; the TLCDs properties can be easily tuned when there are changes in the dynamic characteristics

[1)] Professor
[2)] Associate Professor

of the main systems; low manufacturing, installation, and maintenance costs; and the water in the U-tube can be used as a secondary water source in case of emergency (Hithcock et al. 1997; Kim and Adeli 2005). The first suggestion to use TLCDs for reducing the structural response is proposed by Sakai et al (1989). Sadek et al. (1998) proposed optimization of TLCDs by using linearization of velocity of the liquid utilizing Taylor series. Chen and Chao (2000) utilized Den-Hartog's method to obtain the optimal damping ratio of TLCDs systems by neglecting the damping ratio of the main systems. Wu and Chang (2006) carried out the optimization TLCDs by using frequency domain approach under a white noise disturbance. Design tables for designing TLCDs were provided for practical applications. Chang et al. (2010) utilized computational fluid dynamic model to predict the properties of TLCDs systems. To increase the capability of TLCDs in reducing vibration, Yalla et al. (2001) proposed to use semi active TLCDs. The experimental study of semi active TLCDs was conducted by Yalla and Kareem (2003).

It is to be noted that in most of the research, the TLCDs are rigidly connected to the main structures. There is a situation that the TLCDs are placed on the flexible pads on the buildings. Arfiadi (2007) conducted a preliminary study on the TLCDs rest on the flexible pads. The optimization of TLCDs properties was carried out by directly minimizing the maximum time domain response under a particular earthquake excitation. However, the computer time to obtain the optimum properties might not be accepted at the current condition.

2. EQUATIONS OF MOTION

A TLCDs system rest on flexible support is considered as shown in Fig. 1. Equations of motion can be written following Chen and Chao (2000) as follows:

$$[M_s]\{\ddot{U}_s\}+[C_s]\{\dot{U}_s\}+[K_s]\{U\ \}=\{e_s\}\ddot{u}_g \tag{1}$$

where

$$[M_s]=\begin{bmatrix} m_s & 0 & 0 \\ 0 & m_b+m_d & \alpha m_d \\ 0 & \alpha m_d & m_d \end{bmatrix},\ [C_s]=\begin{bmatrix} c_s+c_b & -c_b & 0 \\ -c_b & c_b & 0 \\ 0 & 0 & c_d \end{bmatrix},\ [K_s]=\begin{bmatrix} k_s+k_b & -k_b & 0 \\ -k_b & k_b & 0 \\ 0 & 0 & k_d \end{bmatrix},$$

$$\{e_s\}=-\begin{Bmatrix} m_s \\ m_b+m_d \\ \alpha m_d \end{Bmatrix},\ \{U_s\}=\begin{Bmatrix} u_s \\ u_b \\ u_d \end{Bmatrix} \tag{2}$$

and m_s = mass of the structure, m_b = mass of the TLCD's support, $m_d = \rho A_y L$ = mass of the liquid, where ρ = liquid density, A_y = cross sectional area of the tube, L = 2 H + B, H = vertical length of the liquid, B = horizontal length of the liquid, c_s = damping factor of structure, c_b = damping factor of the TLCD's support,

$$c_d = 0.5\rho A_y C_d |\dot{u}_d| \tag{3}$$

C_d = head loss coefficient, k_s = stiffness of the structure, k_b = stiffness of the TLCD support,

$$k_d = 2\rho\, A_y\, g \tag{4}$$

is the stiffness of the TLCD, g = gravitational constant,

$$\alpha = B / L \tag{5}$$

is the length ratio, u_s = displacement of the structure, u_b = displacement of the TLCD's support, u_d = displacement of the liquid and u_g = ground displacement. The dot represents derivative with respect to time.

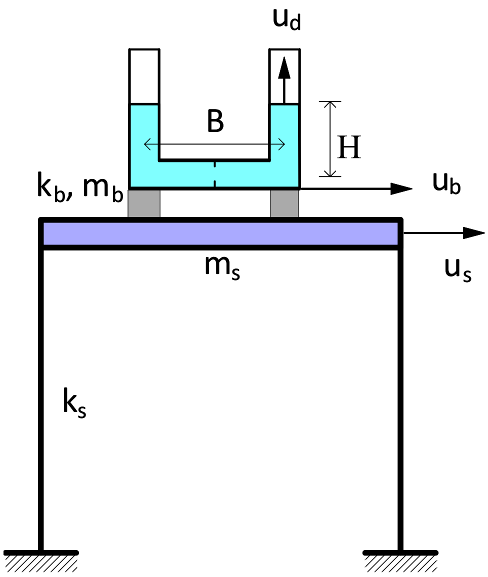

Fig. 1. TLCDs on flexible support

Eq. (1) can be converted into state space equations:

$$\{\dot{\mathbf{Z}}\} = [\mathbf{A}]\{\mathbf{Z}\} + \{\mathbf{E}\}\mathrm{w} \tag{6}$$

where

$$\{\mathbf{Z}\} = \begin{Bmatrix} \{U_s\} \\ \{\dot{U}_s\} \end{Bmatrix},\ [\mathbf{A}] = \begin{bmatrix} [\mathbf{0}] & [\mathbf{I}] \\ -[\mathbf{M}_s]^{-1}[\mathbf{K}_s] & -[\mathbf{M}_s]^{-1}[\mathbf{C}_s] \end{bmatrix},\ \{\mathbf{E}\} = \begin{Bmatrix} \{\mathbf{0}\} \\ [\mathbf{M}_s]^{-1}\{\mathbf{e}_s\} \end{Bmatrix}, \text{ and } \mathbf{w} = \ddot{u}_g \tag{7a-d}$$

3. OBJECTIVE FUNCTION

As the objective function is taken as H_2 norm of the transfer function from external disturbance to the regulated output:

$$[\mathbf{T_{zw}}] = [\mathbf{C_z}](s[\mathbf{I}] - [\mathbf{A}])^{-1}\{\mathbf{E}\} \tag{8}$$

where $[\mathbf{T}_{zw}]$ = transfer function from disturbance w to the regulated output {z}, s = Laplace variable, and $[\mathbf{C_z}]$ = matrix to relate the regulated output and state vector of the form

$$\{\mathbf{z}\} = [\mathbf{C_z}]\{\mathbf{Z}\} \tag{9}$$

By choosing the appropriate value in matrix $[\mathbf{C_z}]$ the designer has the flexibility to define the response to be minimized whether displacement or velocity. In the current problem, the displacement of the structure is taken as the regulated output.

The H_2 norm is calculated by (Doyle et al. 1989):

$$\left\|[\mathrm{T}_{\mathbf{zw}}]\right\|_2 = \left[\frac{1}{2\pi}\int_{-\infty}^{\infty} \mathrm{tr}\left\{[\mathbf{T_{zw}}^*(j\omega)][\mathbf{T_{zw}}(j\omega)]\right\}d\omega\right]^{1/2} \tag{10}$$

where $\|[\mathbf{T}_{zw}]\|_2$ = H_2 norm of transfer function from w to $\{\mathbf{z}\}$, ω = excitation frequency, j = imaginary number, $(\cdot)^*$ = complex conjugate transpose of $(\cdot)$ and tr is *trace* of $(\cdot)$. In the state space form, the H_2 norm is computed using (Doyle et al. 1989):

$$\left\|[\mathrm{T}_{zw}]\right\|_2 = \left[\mathrm{tr}\left([\mathbf{C_z}][\mathbf{L}_c][\mathbf{C}_z]^T\right)\right]^{1/2} \tag{11a}$$

$$\left\|[\mathrm{T}_{zw}]\right\|_2 = \left[\mathrm{tr}\left(\{\mathbf{E}\}^T[\mathbf{L_o}]\{\mathbf{E}\}\right)\right]^{1/2} \tag{11b}$$

Where $[\mathbf{L_c}]$ dan $[\mathbf{L_o}]$ can be obtained from Lyapunov equation:

$$[\mathbf{A}][\mathbf{L}_c] + [\mathbf{L}_c][\mathbf{A}]^T + \{\mathbf{E}\}\{\mathbf{E}\}^T = \{\mathbf{0}\} \tag{12a}$$

$$[\mathbf{A}]^T[\mathbf{L}_o] + [\mathbf{L}_o][\mathbf{A}] + [\mathbf{C_z}]^T[\mathbf{C_z}] = \{\mathbf{0}\} \tag{12b}$$

4. OPTIMIZATION

To optimize the TLCDs properties and the flexible pad, genetic algorithms (GA) proposed by Holland (1992) were used. In GAs, the solution is considered as a population of candidates. These candidates (individuals) experience evolutionary process through selection, crossover and mutation. The individuals in the population are selected by using a roulette wheel selection procedure. Each individual in the population has its own fitness according to the defined objective function. The candidates experience crossover and mutation to produce offspring. The selection, crossover and mutation are done generation per generation such that at the final generation, the most fit individual is taken as the optimum value of design variables.

In this paper real coded genetic algorithms (RC-GAs) was used. In RC-GAs, design variables were represented by using real numbers (Michalewics 1996, Herrera et al. 1998, Arfiadi and Hadi 2001). In the process, a simple mutation and balanced crossover (Herrera et al. 1998) were used in the algorithms. In addition an elitist strategy (Grefenstette 1986), such that the most fit individual is always passed on to the next generation, was used in the analysis. To increase the variability in the population, new individuals are always inserted in the new generation replacing a portion of old individuals. The flowchart of RC-GA used in this paper can be seen in Fig. 2.

5. NUMERICAL SIMULATION

Consider a single degree of freedom system with the following properties: m_s = 20 t, c_s = 12.57 kN-s/m k_s = 789.57 kN/m^2, and α = 0.4. Variable designs to be obtained are: A_y, k_d, m_b, k_b and c_b where the liquid density = 1 t/m^3. RC-GAs are used to obtain the design variables, where the maximum generation = 500; probability of crossover = 0.8; probability of mutation = 0.2; the new inserted individuals to replace old individuals = 10% of the population. As the H_2 norm is used, C_d is taken equals to zero in the analysis. This can be considered as the lower bound of damping inclusion of TLCDs. Three cases are investigated, i.e., when the mass ratios $\mu = m_d/m_s$ are taken equal to 1%, 5 % and 10%. The results are shown in Table 1.

Table 1. Design variables for different mass ratio

Design variables	Mass ratio		
	μ = 1%	μ = 5%	μ = 10 %
A_y (m)	0.073	0.351	0.696
k_d (kN/m)	1.423	6.886	13.657
m_b (t)	9.345	9.034	8.343
k_b (kN/m)	105.08	102.59	102.15
c_b (kN-s/m)	19.536	20.36	20.665
L (m)	2.758	2.85	2.873
B (m)	1.103	1.14	1.149

Note that for each mass ratio, at the initial generation, the design variables produce negative fitness, which shows that the optimum vales are difficult to obtain. However after several generations the simulation is stabilized. The best fitness for μ = 10 % is depicted in Fig. 3.

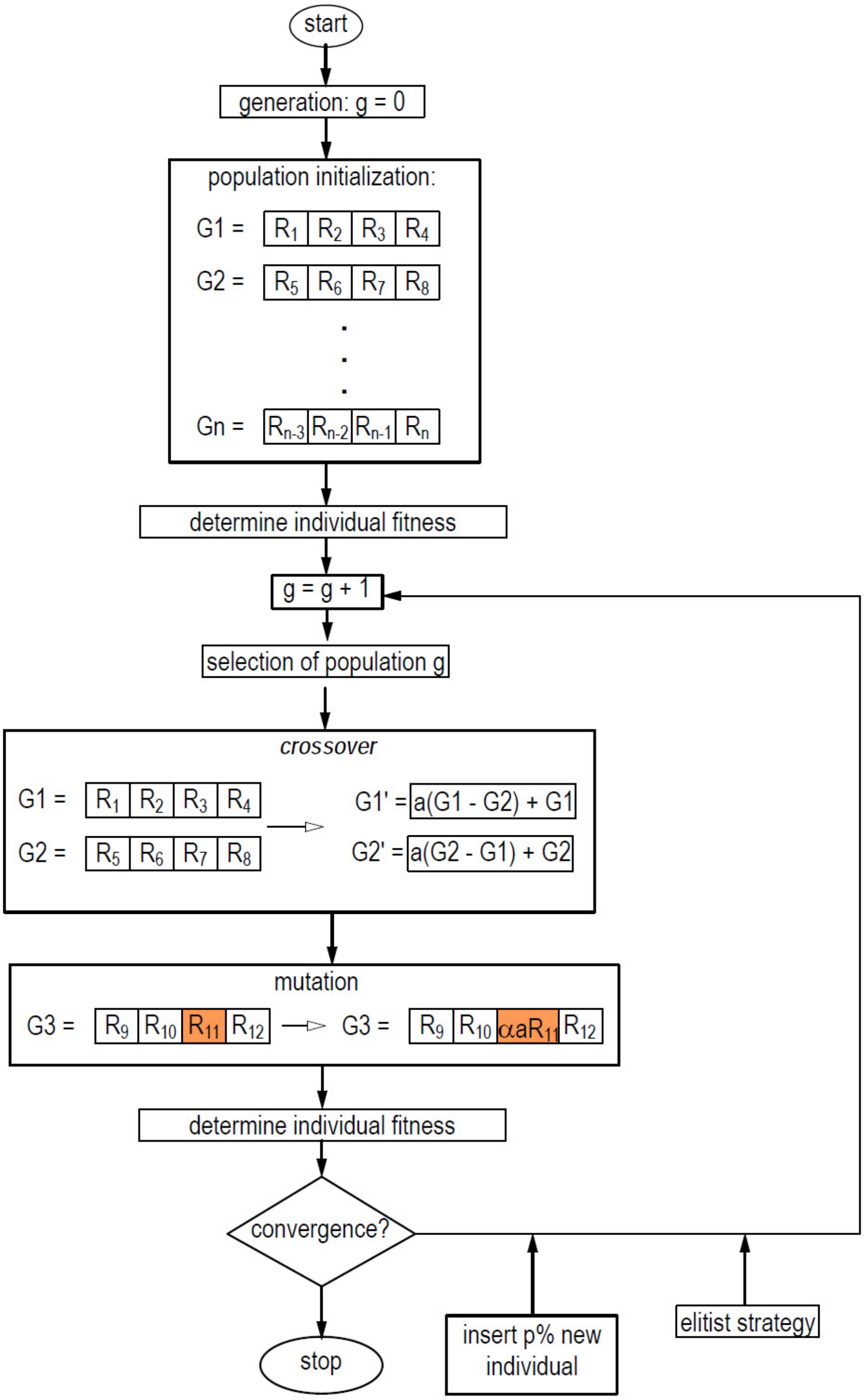

Fig. 2 Flowchart RC-GA used in this paper

To see the effectiveness of TTCDs on flexible pads in reducing structural reponse, the structures is simulated under El Centro 1940 NS, Kobe 1995 NS, Hachinohe 1968 NS and Northridge 1994 NS excitations scaled to 0.1g. The results of the simulation are shown in Table 2.

From Table 2, it is shown that the effectiveness of TLCDs in reducing vibration is different for different excitations. The most effective reduction is achieved under El Centro excitation, which can be as large as 45%. The response reduction under Northridge earthquake is not too effective; the reduction is only approximately 10%. From the table it is shown also that for the range of mass ratio under consideration, the effect of mass ratio is not significant. The time history response subject to Hachinohe 1968 NS for μ = 5% is depicted in Fig. 4.

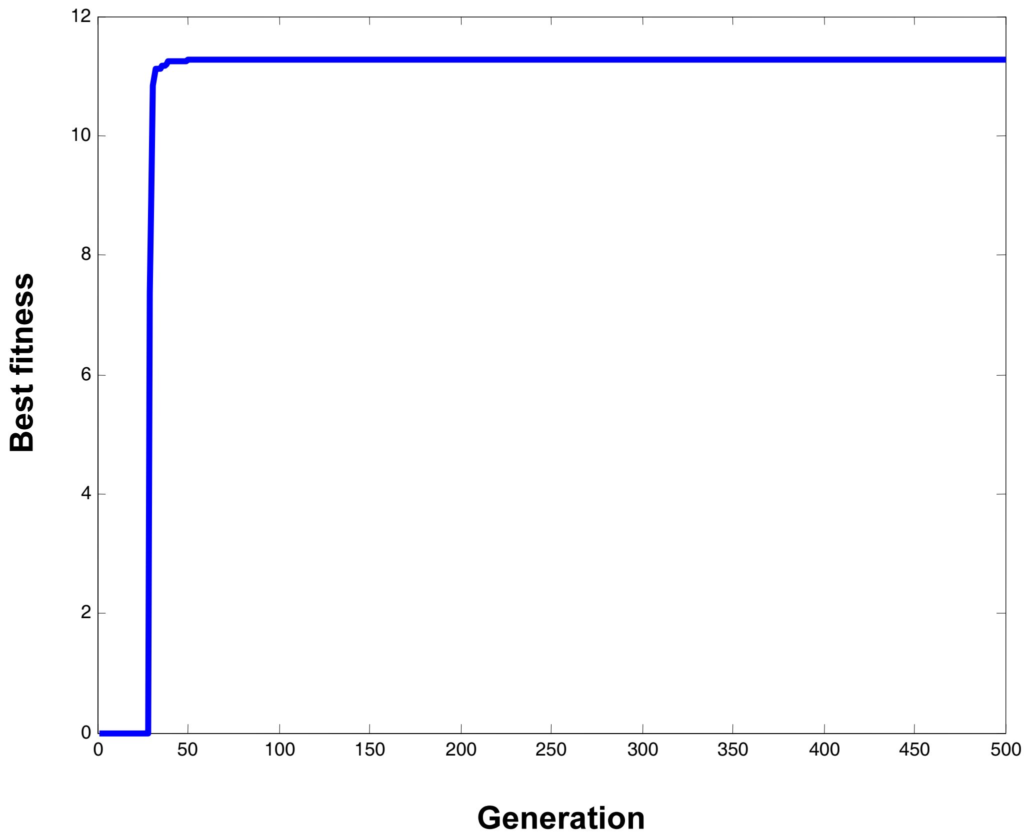

Fig. 3. Best fitness for μ = 10 %

Table 2. Results of simulations for various earthquake

Displacement of structure		Response reduction (%)
El Centro	μ = 1 %	45
	μ = 5 %	44.8
	μ = 10 %	44.9
Kobe	μ = 1 %	34.9
	μ = 5 %	34.8
	μ = 10 %	34.8
Hachinohe	μ = 1 %	17.4
	μ = 5 %	17.4
	μ = 10 %	17.6
Northridge	μ = 1 %	9.9
	μ = 5 %	10.3
	μ = 10 %	10.7

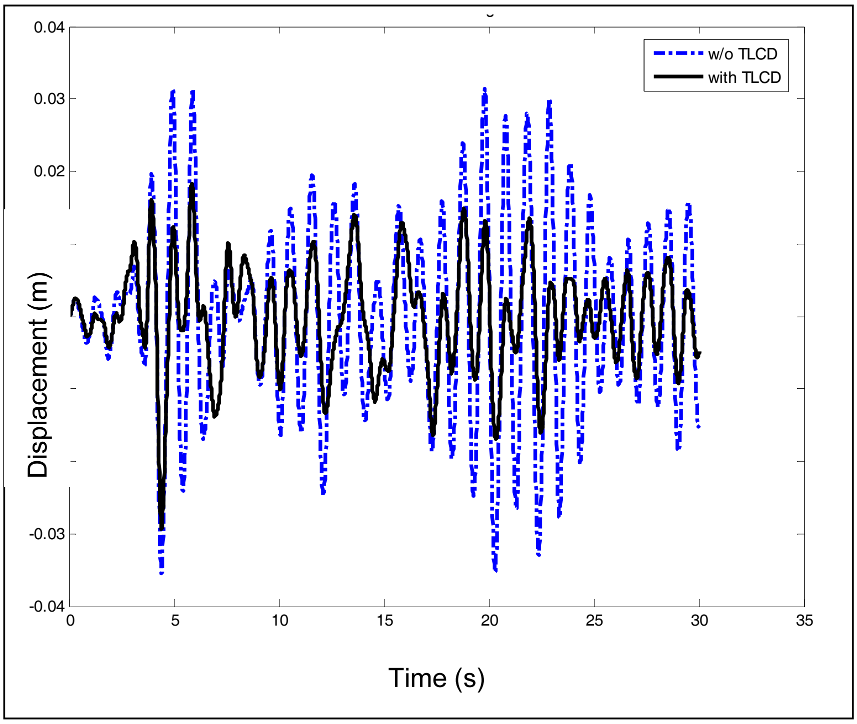

Fig. 4. Time history response due to Hachinohe 0.1 g for μ = 5 %

It is also interesting to see the ratio of width to the height of liquid in the tube. For the mass ratio μ = 5 %, the values of α are varied. RC-GAs were utilized to obtain other properties of TLCDs. The resulting TLCDs properties is shown in Table 3.

Table 3. TLCDs properties for different α

α	A_y (m2)	k_b (kN/m)	c_b (kN-s/m)	m_b (ton)	k_d (kN/m)	L (m)	B (m)	H (m)
0.1	0,377	104,34	19,867	8,703	7,399	2,05	0,27	0,89
0.2	0,368	103,94	20,131	8,860	7,221	2,72	0,54	1,09
0.3	0,372	104,13	20,32	9,060	7,3015	2,69	0,81	0,94
0.4	0,345	103,24	20,042	8,937	6,7603	2,90	1,16	0,87
0.5	0,350	102,19	20,716	9,344	6,8638	2,86	1,43	0,71
0.6	0,348	101,93	20,568	9,398	6,8335	2,87	1,72	0,57
0.7	0,345	100,52	21,617	9,994	6,7595	2,90	2,03	0,44

By using different values of α it can be shown that the same response reduction can be achieved as shown in Fig. 5.

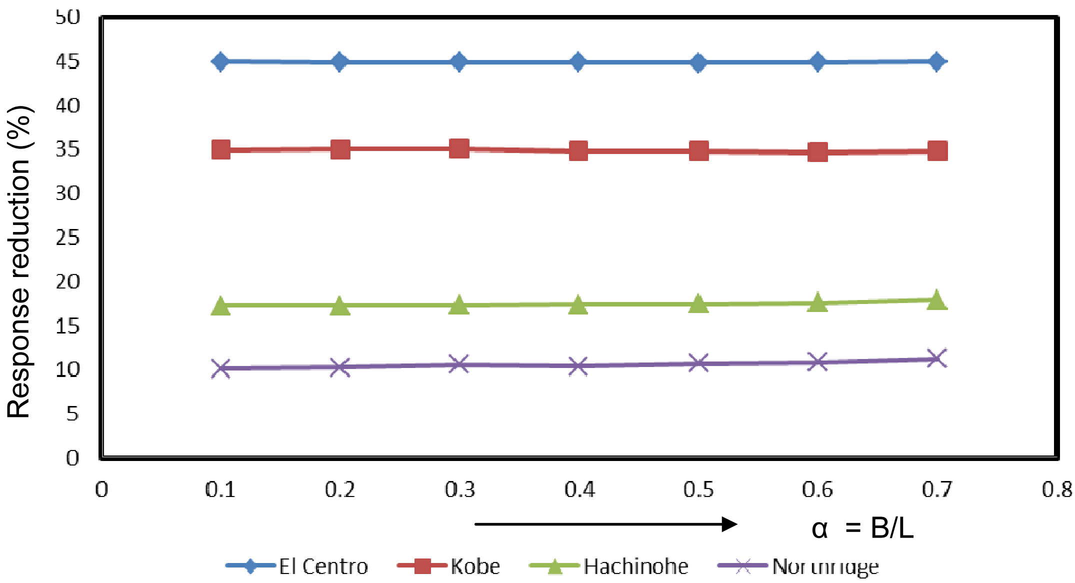

Fig. 5. Response reduction for different values of α

6. CONCLUSION

The optimization of TLCDs rest on the flexible support was carried out in this paper. RC-GAs were used to obtain the properties of TLCDs and their support. The objective function is taken as the H_2 norm of transfer function from disturbances to the regulated output. The regulated output is displacement of the structure. In the optimization, the lower bound damping inclusion from TLCDs is considered by taking value of C_d equals to zero. The structure was then simulated under El Centro 1940 NS, Kobe 1995 NS, Hachinohe 1968 NS and Northridge 1994 NS earthquakes. The effectiveness of TLCDs on flexible support in reducing the response is different for different excitations. The largest effectiveness is achieved under El Centro 1940 NS excitation, while the lowest one is due to Northridge 1994 NS earthquake. In the analysis, the influence of the mass ratio is also not significant to the response reduction. In addition, different values of ratio of width to height of liquid in the tube can be chosen with the same effectiveness of response reduction.

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REFERENCES

Arfiadi, Y (2007). "Flexible mounted tuned liquid column dampers for reducing structural response". *Proceedings of the 1st International Conference of European Asian Engineering Forum (EACEF).* Jakarta, 26-27 September.

Arfiadi, Y and Hadi, M. N. S. (2001). "Optimal direct (static) output feedback controller using genetic algorithms". *International Journal of Computer and Structures*, Vol. 79 No. 17, 1625-1634.

Chang, C.H., Wu, J.C., Cheng, C.M., Lin, Y.Y. (2010). "Computational fluid dynamic simulation for horizontal movement tuned liquid column damper". *The fifth international symposium on computational wind engineering, Chapel Hill,* North Carolina, May 23-27.

Chen, Y.H. and Chao, C.C. (2000). "Optimal damping ratio of TLCDs". *Structural Engineering Mechanics*, 9(3): 227-240.

Doyle, J. C., Glover, K., Khargonekar, P. P. and Francis, B. A. (1989). "State-space solutions to standard H_2 and H_∞ control problems". *IEEE Transaction on. Automatic Control*, Vol. 34, No.8, 831-847.

Grefenstette, J. J. (1986). "Optimization of control parameters for genetic algorithms." *IEEE Transaction on Systems, Man and Cybernetics*, Vol. 16, No. 1, 122-128.

Hadi, M. N. S. and Arfiadi, Y. (1998). "Optimum design of absorber for MDOF structures". *Journal of Structural Engineering*, ASCE, Vol. 124, No.11, 1272-1280.

Herrera, F., Lozano, M. and Verdegay, J. L. (1998). “Tackling real-coded genetic algorithms: operators and tools for behavioural analysis”. *Artificial Intelligence Review*, Vol. 12, 265-319.

Hithcock, P.A., Kwok, K.C.S. and Watkins, R.D. (1997). “Characteristics of liquid column vibration absorbers (LCVA)-I”. *Engineering Structures*, 19(2(, 126-134.

Holland, J. H. (1992). *Adaptation in natural and artificial systems*. MIT Press, Mass.

Michalkewicz (1996), *Genetic algorithms + data structures = evolution program*. Springer, Berlin.

Sadek, F., Mohraz B. and Lew , H.S. (1998). “Single and multiple tuned liquid column dampers for seismic applications”. *Earthquake Enginnering and Structural Dynamics,* 27, 439-463.

Sakai, F., Takeda, S. and Tamaki, T. (1989). “Tuned liquid column damper- new type device for suppresion of building vibration”. *Proceedings of International Conference on High rise Building*, 926-931, Nanjing, China

Wu, JC. and Chang, CH. (2006). “Design table of optimal parameters for tuned liquid column damper responding to earthquake”. *The 4th Internasional Conference on Earthquake Engineering*, Taipei, Taiwan, October 12-13, paper no. 165.

Yalla, S. K., Kareem, A. (2003). “Semi-Active Tuned Liquid Column Dampers: experimental study”. *Journal of Structural Engineering, ASCE*, Vol. 129, 960-971

Yalla, S.K., Kareem, A. and Kantor, J.C. (2001). “Semi-active tuned liquid column dampers for vibration control of structures”. Engineering Structures 23: 1469-1479.