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Teaching-learning based optimization for parameter estimation of double tuned mass dampers

Sinan Melih Niğdeli *, Gebrail Bekdaş

Department of Civil Engineering, İstanbul University, 34320 İstanbul, Turkey

ABSTRACT

The classical methods for parameter estimation of tuned mass dampers are well known simple formulations, but these formulations are only suitable for multiple degree of freedom structures by considering a single mode. If special range limitation of tuned mass dampers and inherent damping of the main structure are considered, the best way to estimate the parameters is to use a numerical method. The numerical method must have a good convergence and computation time. In that case, metaheuristic methods are effective on the problem. Generally, metaheuristic method is inspired from a process of life and it is formulated for several steps in order to reach an optimal goal. Differently from the single tuned mass dampers, double tuned mass dampers can be also used for the reduction of vibrations. In civil structures, earthquake excitation is a major source of vibrations. In this study, optimum double tuned mass dampers are investigated for seismic structures by using a wide range of earthquake records for global optimum. As an optimization algorithm, teaching learning based optimization is employed. In this algorithm, the teaching and learning phases of a class are modified for optimization problems. The optimization of double tuned mass damper is more challenging than the single ones since the number of design variable is doubled and the design constraint about the stroke of the both masses must be considered. The proposed method is compared with the existing approaches and the methodology is feasible for parameter estimation of double tuned mass dampers.

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1. Introduction

In order to reduce mechanical vibrations, masses combined with stiffness and damping elements can be used. The name of this device is tuned mass damper (TMD) and initial form without inherent damping is invented by Frahm (1911). For random vibrations, Ormondroyd and Hartog (1928) implemented inherent damping to initial form. For that reason, TMDs are effective in the reduction of vibrations resulting from excitations with random frequency. Thus, TMDs are used in civil structures in order to reduce vibrations resulting from wind and earthquakes. In the optimum tuning of TMDs, closed form expressions are proposed but these formulas are for single degree of freedom systems (Hartog, 1947; Warburton, 1982; Sadek et al., 1997). By idealization of multiple degree of freedom systems, only a vibration mode can be used in finding TMD parameters. In the passive structural control of structures by using tuned mass dampers (TMDs), optimum parameters are depended to several factors such as excitations, soil characteristics, support conditions and TMD stroke capacity. Thus, numerical algorithms can be used and metaheuristic methods inspired by natural happenings are very effective for tuning problem.

In search of optimum parameters of TMDs for structures, metaheuristic algorithms have been employed. Metaheuristic algorithms are inspired from natural happenings such as natural evolution for Genetic Algorithm (GA) (Holland, 1975; Goldberg, 1989), swarm intelligence

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* *Corresponding author.* Tel.: +90-212-4737070 ; Fax: +90-212-4737180 ; E-mail address: melihnig@istanbul.edu.tr (S. M. Niğdeli)

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for Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 1995), behavior of ants for Ant Colony (ACO) Algorithm (Dorigo et al., 1996), musical performances for Harmony Search (HS) (Geem et al., 2001) and education in teaching learning based optimization (TLBO) (Rao et al., 2011). Hadi and Arfiadi (1998) employed GA for optimum design of TMDs positioned on multiple degree of freedom (MDOF) seismic structures. By employing GA, Marano et al. (2010) optimized TMD parameters including the mass ratio instead of using a preselected mass for TMD. Additionally, GA has been employed in several TMD optimization methods (Singh et al., 2002; Desu et al., 2006; Pourzeynali et al., 2007). PSO was also employed for the TMD problem and several closed form expressions were obtained (Leung and Zhang, 2009; Leung et al., 2008). Steinbuch (2011) employed bionic optimization for estimating the best design of TMDs for earthquake resistance of structures. HS algorithm has been widely used in optimum design of TMDs (Bekdaş and Nigdeli, 2011; Bekdaş and Nigdeli, 2013) including prevention of brittle fracture (Nigdeli and Bekdaş, 2013). Farshidianfar and Soheili investigated optimum TMD design of structures including soil-structure interaction (SSI) by using several metaheuristic algorithms like ant colony optimization (Farshidianfar and Soheili, 2013a), artificial bee colony optimization (Farshidianfar and Soheili, 2013b) and shuffled complex evolution (Farshidianfar and Soheili, 2013c). TLBO is also used in parameter estimation of TMDs for seismic structures (Nigdeli and Bekdas, 2015a).

An important factor is the stroke capacity of TMDs. The optimum design variables may be different for a TMD system if stroke capacity is taken as a design constraint. In the study of Tributsch and Adam (2012), it is indicated that a TMD with a damping coefficient larger than the optimum one reduces maximum deflection of the TMD spring. For that reason, the stroke capacity is an effective factor for the optimum TMD properties and optimization is important in order to find a balance between performance and stroke capacity of TMD. Additionally, an energy-based theoretical model (Miranda, 2005), a damping maximized TMD (Miranda, 2012), close-form design formulas for random loads (Tigli, 2012) and Minimax optimization (Salvi and Rizzi, 2014) for TMDs have been proposed.

Another concept in passive vibration control is to use double tuned mass dampers (DTMDs) for seismic structures (Li and Zhu, 2006). Harmony search algorithm is employed in the optimization of DTMDs (Bekdaş and Nigdeli, 2014). Then, a multi-objective optimization is proposed for DTMDs employing HS and considering maximum stroke capacity of dampers (Nigdeli and Bekdaş, 2015b).

In this paper, TLBO optimization is employed for multi-objective optimization of DTMD parameters. The two objectives are the reduction of maximum top story displacement to a user defined value and the consideration of the stroke capacity by using a scaled displacement value of DTMD.

2. Methodology

A shear building with a DTMD is represented in Fig. 1. A single degree is defined for all stories and the number of the stories is defined by N. The equation of motion of the shear building subjected to ground acceleration is written as

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = -M\{1\}\ddot{x}_g(t)\,. \tag{1}$$

The M, C and K matrices are shown as Eqs. (2)-(4) and these matrices are diagonal lumped mass, damping and stiffness matrices, respectively. and these matrices are given in Eqs. (2)-(4). In the equations, $x(t)$, and $\{1\}$ are a vector containing structural displacements of all stories and DTMD (as shown as Eq. (5)), ground acceleration and a vector of ones with a dimension of (N+2, 1), respectively.

$$\mathrm{M} = diag[m_1 m_2 \ldots m_N m_{d1} m_{d2}]\,, \tag{2}$$

$$\mathrm{C} = \begin{bmatrix} (C_1 + C_2) & -C_2 & & & & & \\ -C_2 & (C_2 + C_3) & -C_3 & & & & \\ & \vdots & \vdots & \ddots & & & \\ & & & -C_N & (C_N + C_{d1}) & -C_{d1} & \\ & & & & -C_{d1} & (C_{d1} + C_{d2}) & -C_{d2} \\ & & & & & -C_{d2} & -C_{d2} \end{bmatrix}, \tag{3}$$

$$\mathrm{K} = \begin{bmatrix} (k_1 + k_2) & -k_2 & & & & & \\ -k_2 & (k_2 + k_3) & -k_3 & & & & \\ & \vdots & \vdots & \ddots & & & \\ & & & -k_N & (k_N + k_{d1}) & -k_{d1} & \\ & & & & -k_{d1} & (k_{d1} + k_{d2}) & -k_{d2} \\ & & & & & -k_{d2} & -k_{d2} \end{bmatrix}. \tag{4}$$

The symbols; m_i, c_i, k_i and x_i represents mass, damping coefficient, stiffness coefficient and displacement of i_{th} storey of structure. The parameters related with DTMD are masses (m_{d1}, m_{d2}), damping coefficients (c_{d1}, c_{d2}) and stiffness coefficients (k_{d1}, k_{d2}). The displacements of the DTMD are represented with x_{d1} and x_{d2}.

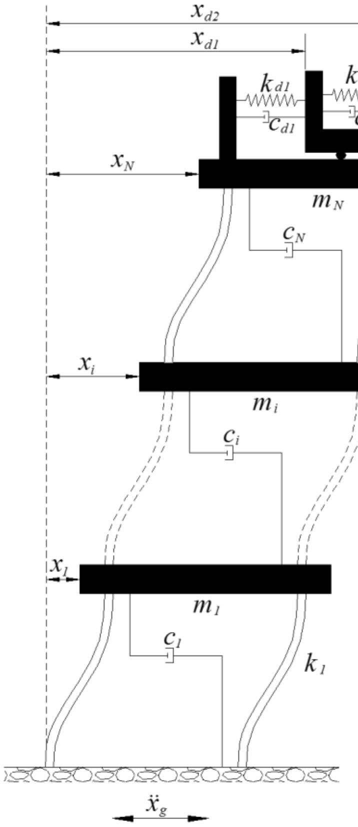

Fig. 1. Model of N-story shear building with a DTMD.

3. Teaching-Learning Based Optimization and Multi-Objective Optimization Methodology

TLBO algorithm uses two phases of the education process. These phases are called teacher and learner phases. TLBO consequently uses these phases without using a parameter in choose of the optimization type. This is a major advantage and difference of the algorithm.

As all methodologies using metaheuristic algorithms, structural properties, external excitations and ranges of design variables are defined. Then, the structure without DTMD is analyzed and the structural responses are obtained for all earthquake excitations. The objective functions are defined as Eqs. (5) and (6) and the stroke capacity objective defined by Eq. (6) contains responses of the structure without TMD. In these objectives, user defined values; x_{max} and *st_max* are the desired values for maximum displacement and stroke. If the user defined value of x_{max} is not applicable, the value is iteratively increased. Thus, x_{max} can be defined as zero for the minimization of the maximum displacement.

Before the iterative optimization process, an initial solution matrix must be generated. The vectors of the initial matrix are assigned with randomly generated design variables. The number of these vectors is equal to the population of the class. Then, teacher phase is started and existing design variables are updated by using the existing best solution as a teacher. In this phase, randomly defined teacher factor (1 or 2) is used in order to control the range of the new generation around the mean of the existing results. After the teacher phase, the student phase starts in order to improve the all existing solutions in solution matrix. In this generation, new solutions are obtained according to two existing solutions which are randomly chosen. These phases are formulized in Rao et al. (2011).

The modification of existing solutions with the new ones is done as follows. First, the objective function given as Eq. (6) is considered and if it is lower than *st_max*, the objective function is taken into consideration. The process of teacher and learner phases continue until the criteria are provided.

$$|x_N| \leq x_{max}\,, \tag{5}$$

$$max\left[\frac{max\,[\![x_{N+2}-x_{N+1}]\!]_{with\,DTMD}}{max\,[\![x_N]\!]_{without\,DTMD}},\frac{max\,[\![x_{N+1}-x_N]\!]_{with\,DTMD}}{max\,[\![x_N]\!]_{without\,DTMD}}\right] \leq st\_max\,, \tag{6}$$

In the learner phase of TLBO algorithm, if the duplicate solutions exist, the algorithm may be trap to a local optimum. In order to avoid trapping, an elitist teaching learning based optimization (ETLBO) is developed by Rao and Patel (2012). In ETLBO, the duplicate solutions are modified by generated randomly selected solutions as done in the generation of initial solutions. In this paper, TLBO and ETLBO results are presented.

4. Numerical Examples

An optimum DTMD design is investigated for a ten story structure. The mass, stiffness coefficient and damping coefficient of a story are 360 t, 6.2 MNs/m and 650 MN/m, respectively (Singh et al., 2002). FEMA P-695 (2009) far-fault ground motion set (shown in Table 1) was used in the optimization process.

Two cases for the *st_max* limitation is investigated and *st_max* was taken as 0.8 and 1 for Case 1 and 2, respectively. The possible maximum reduction of the structural displacements is targeted. The same optimization is also done by using HS (Nigdeli and Bekdaş, 2015b).

The ranges for the design variables such as masses, periods and damping ratios of DTMD are between 0.1% and 5% of total mass of the structure, between 0.5 and 1.5 times of the critical period of the structure and between 1% and 30%, respectively. The optimum DTMD parameters (for HS, TLBO and ETLBO approaches) are given in Table 2. The performance of DTMD on reduction of structural displacements is discussed in the conclusions.

5. Conclusions

The optimum results are found according to the critical excitation of 44 far-field excitations and the BOL090 component of Düzce record of Düzce earthquake is the critical one. For the structure without DTMD, the maximum displacement of the structure is 0.4101 m. By using the stroke capacity of Case 1, this value is reduced to

0.2771 m, 0.2882 m and 0.2760 m for HS, TLBO and ETLBO, respectively. TLBO algorithm trap to a local region for Case 1. Thus, ETLBO is effective in obtaining the best results. The maximum displacements are 0.2626 m (HS), 0.2509 m (TLBO) and 0.2508 m (ETLBO) for Case 2. The effectiveness of TLBO and ETLBO is similar for the second case since the restriction of the stroke is low. In Fig. 2, the first and top storey displacement plots are shown for the first case of DTMD for ETLBO approach results.

According to the results, the methodology employing TLBO can trap to local optimum results. For that reason, ETLBO is an effective modification of the method. The proposed method for the optimization of DTMDs is suitable and global optimum results can be effectively found if the elitist version of TLBO is used.

Table 1. FEMA P-695 far-field ground motion records.

Earthquake Number	Date	Name	Component 1	Component 2
1	1994	Northridge	NORTHR/MUL009	NORTHR/MUL279
2	1994	Northridge	NORTHR/LOS000	NORTHR/LOS270
3	1999	Duzce, Turkey	DUZCE/BOL000	DUZCE/BOL090
4	1999	Hector Mine	HECTOR/HEC000	HECTOR/HEC090
5	1979	Imperial Valley	IMPVALL/H-DLT262	IMPVALL/H-DLT352
6	1979	Imperial Valley	IMPVALL/H-E11140	IMPVALL/H-E11230
7	1995	Kobe, Japan	KOBE/NIS000	KOBE/NIS090
8	1995	Kobe, Japan	KOBE/SHI000	KOBE/SHI090
9	1999	Kocaeli, Turkey	KOCAELI/DZC180	KOCAELI/DZC270
10	1999	Kocaeli, Turkey	KOCAELI/ARC000	KOCAELI/ARC090
11	1992	Landers	LANDERS/YER270	LANDERS/YER360
12	1992	Landers	LANDERS/CLW-LN	LANDERS/CLW-TR
13	1989	Loma Prieta	LOMAP/CAP000	LOMAP/CAP090
14	1989	Loma Prieta	LOMAP/G03000	LOMAP/G03090
15	1990	Manjil, Iran	MANJIL/ABBAR--L	MANJIL/ABBAR—T
16	1987	Superstition Hills	SUPERST/B-ICC000	SUPERST/B-ICC090
17	1987	Superstition Hills	SUPERST/B-POE270	SUPERST/B-POE360
18	1992	Cape Mendocino	CAPEMEND/RIO270	CAPEMEND/RIO360
19	1999	Chi-Chi, Taiwan	CHICHI/CHY101-E	CHICHI/CHY101-N
20	1999	Chi-Chi, Taiwan	CHICHI/TCU045-E	CHICHI/TCU045-N
21	1971	San Fernando	SFERN/PEL090	SFERN/PEL180
22	1976	Friuli, Italy	FRIULI/A-TMZ000	FRIULI/A-TMZ270

Table 2. The ranges of design variables and optimum values (DTMD).

Design variable	HS		TLBO		ETLBO	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Mass (t)	160.18-169.56	178.64-173.16	180-180	179.50-179.82	164.34-180	179.51-179.79
Period (s)	0.5666-0.6775	0.6399-0.7077	0.5669-0.4946	0.6519-0.6710	0.5819-0.7947	0.6521-0.6677
Damping ratio (%)	28.28-18.68	28.88-9.35	30-1	26.31-1	27.64-27.44	26.26-1

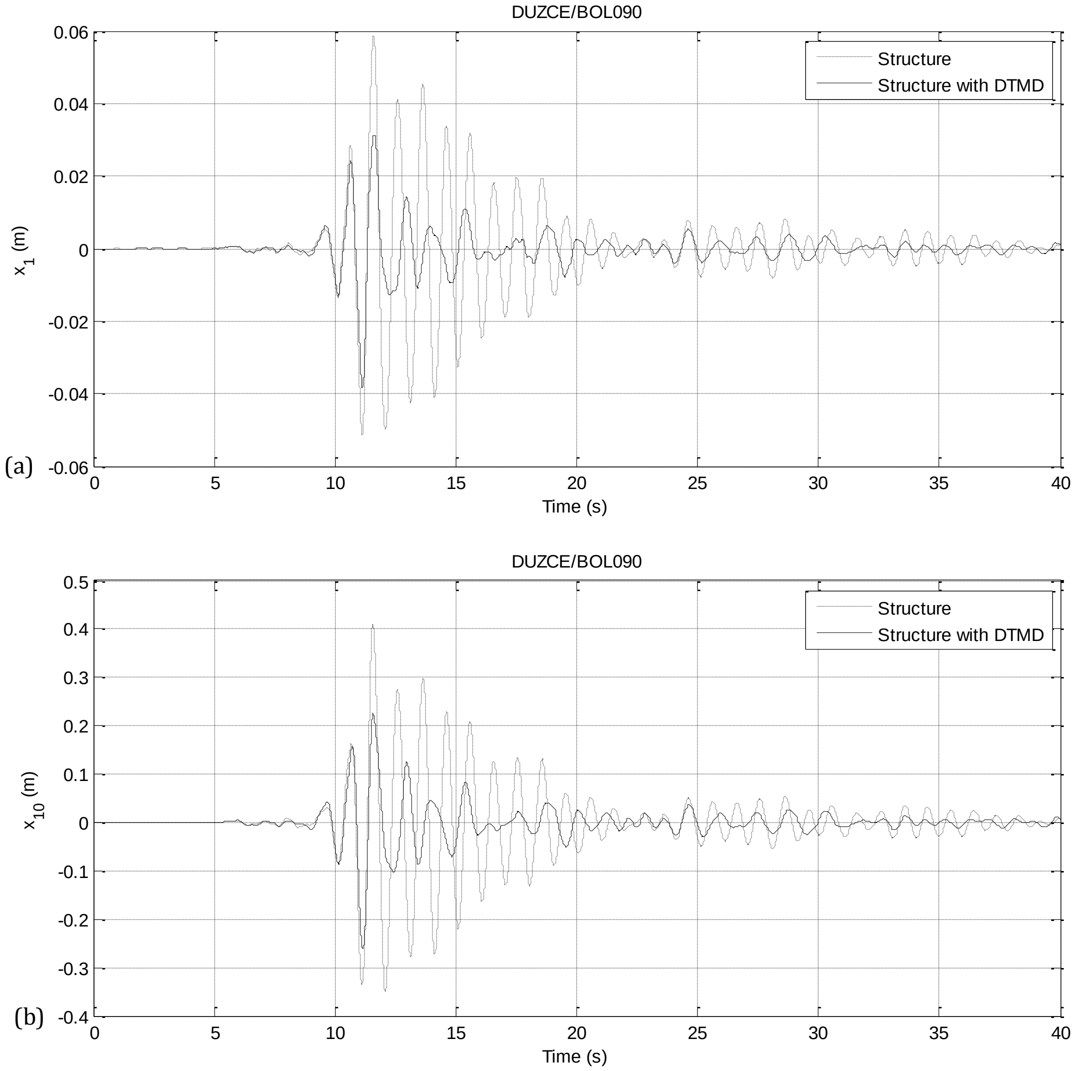

Fig. 2. The time history plots for the critical excitation: (a) CASE 1; (b) ETLBO.

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