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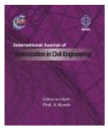

COMPARISON OF RELIABILITY BASED AND DISPLACEMENT BASED OPTIMIZATION OF TUNED MASS DAMPERS REGARDING UNCERTAINTY

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ABSTRACT

Some structural control systems have been devised to protect structures against earthquakes, which the tuned mass damper (TMD) being one of the earliest. The effect of a tuned mass damper depends on its properties, such as mass, damping coefficient, and stiffness. The parameters of tuned mass dampers need to be tuned based on the main system and applied load. In most of the papers, the parameters of TMDs have been tuned based on the nominal parameters of structures. Also, most of the studies considered the minimization of maximum displacement of structure as the objective function of optimizing the parameters of tuned mass dampers. In this study, according to the Monte Carlo method and using the Mouth Brooding Fish algorithm, TMDs have been optimized based on the reliability of structures regarding the uncertain parameters of buildings, and their efficiency in the reduction of maximum displacement and failure probability of hundreds generated buildings with uncertain parameters, are compared with the efficiency of the displacement-based optimized TMDs. The results show that the TMDs optimized regarding uncertainty have better efficiency in reducing the maximum displacement, and failure probability of buildings than the TMDs optimized regarding nominal parameters of buildings. Also, according to the results, the displacement-based optimized TMDs regarding uncertainty show better efficiency in reducing the failure probability and displacement of the buildings than reliability-based optimized TMDs.

Keywords: tuned mass damper, reliability-based optimization, monte carlo method, mouth brooding fish algorithm, uncertain parameters.

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1. INTRODUCTION

Tuned mass dampers (TMDs) are structural control systems mounted on buildings to protect them against earthquake and wind forces [1]. A TMD comprises three primary components: a mass block, a viscose damper, and a spring. [2]. The basic form of tuned mass dampers was invented by Frahm in 1909 and was used for the reduction of resonance vibrations that can occur in ships by using additional mass [3].

Various methods have been utilized to optimize the parameters of tuned mass dampers [4-9]. Arfiadi and Hadi [10] considered optimum placement and properties of TMDs using the Genetic algorithm. Zhang and Zhang [11] optimized the tuned mass damper using an improved harmony search algorithm. Jin et al. [12] used an artificial fish swarm algorithm to optimize the TMD parameters. Yucel et al.[13] have utilized the machine learning method to estimate the optimum parameters of the tuned mass damper. Kayabekir et al. [14] optimized tuned mass damper via modified harmony search. The chaotic optimization algorithm was used by Kaveh et al. [15] to optimal design of a ten-story structure and 76-story concrete tower against seismic motion and wind excitation.

Just a few of the previous studies focused on optimizing TMDs based on the reliability of the structures. The reliability-based optimization of TMD in control of a single degree of freedom structure with constrained uncertain parameters was investigated by Chakraborty and Roy. When the system parameters uncertainties are considered, the optimum parameters of TMD and the probability of failure of the controlled structures are altered, according to their findings. They concluded that raising the amount of uncertainty reduces the advantages of TMD [16]. Mrabet et al. proposed a new method of reliability-based optimization of TMD that showed good efficiency even with high-level uncertainties [17,18].

Regarding uncertain parameters of a ten-story building, Gholizad and Aghazadeh evaluated the efficiency of reliability-based optimization and displacement-based optimization. The objective function of particle swarm optimization was to minimize the lateral displacement of the structure. Monte Carlo simulation was employed to evaluate the performance of the developed TMD in their investigations. According to their results, reliability-based optimization performed better than displacement-based optimization in reducing lateral displacement of uncertain structures, and it was shown that considering uncertain parameters is important for optimizing a tuned mass damper [19].

In this paper, as the first numerical study, a TMD designed for minimizing the maximum displacement of a 10-story shear building with nominal parameters by using the Mouth Brooding Fish algorithm (MBF) that has benefits in the solution of complicated optimization problems [20], and secondly using the MBF a TMD optimized for minimizing the failure probability of the N samples with uncertain parameters and the efficiency of the TMDs are compared. In the second numerical study, firstly, a TMD was designed for another 10-story shear building to minimize the maximum displacement of the building regarding nominal parameters. Secondly, a TMD was optimized to minimize the summation of maximum displacement of N samples with uncertain parameters. Finally, a TMD was designed to minimize the summation of the failure probability of the N samples with uncertain parameters. The efficiency of the displacement-based optimization regarding nominal and uncertain parameters of the samples and the reliability-based optimization have been compared.

This paper is organized as follows: Section 2 presents the formulations used in the numerical studies. A methodology is presented for the reliability-based optimization of TMD in Section 3. Numerical studies on displacement-based and reliability-based optimization are provided in section 4; finally, conclusions are given in Section 5.

2. FORMULATIONS

The equation of motion of a building equipped with a TMD is equal to:

$$[M]\ddot{x}(t) + [C]\dot{x}(t) + [K]x(t) = -[M]e\ddot{x}_g(t) \tag{1}$$

where [M], [C], and [K] are the mass, damping, and stiffness matrices of the system, respectively. x, $\dot{x}$, and $\ddot{x}$ are displacement, velocity, and acceleration vectors relative to ground motion, respectively [21].

In this study, besides optimizing TMD regarding building with nominal parameters, uncertain parameters such as mass, damping coefficient, and stiffness have been considered in optimizing the tuned mass dampers. In other words, the tuned mass dampers have been tuned regarding uncertain parameters. The uncertain parameters were generated according to the following equations:

$$0 \le u(i) \le 1 \tag{2}$$

$$z(i) = \Phi^{-1}u(i) \tag{3}$$

$$parameter(i) = \frac{1}{I}\sum_{1}^{I}\mu_{parameter}(i) + z(i) \times \sigma_{parameter}(i) \tag{4}$$

where I is the number of generated values, and μ and σ are nominal properties and corresponding standard derivation of parameters [22].

In addition to the displacement-based optimization, the optimization of the tuned mass damper has been done based on the reliability of the structure. In this paper, the separation distance has been considered as the reliability condition of the structure that is calculated according to the following equation:

$$Separation\ Distance = 3 + (h - 3)/3 \tag{5}$$

where h is the height of the building in meter [23].

3. A METHODOLOGY FOR RELIABILITY-BASED OPTIMIZATION OF TMD

The Monte Carlo method is used for the Reliability-Based Optimization (RBO) of tuned mass dampers. According to the method, firstly, numbers of buildings with uncertain parameters were generated and using the MBF algorithm, the parameters of TMDs were optimized so that the minimum failure occurs in the samples under the earthquakes. The method is depicted in Fig. 1 as a flowchart.

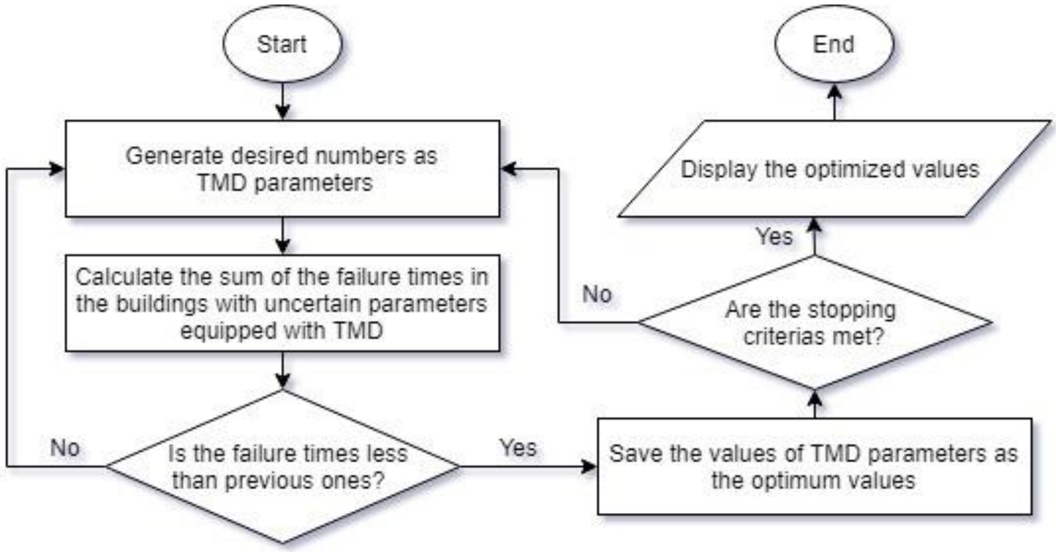

Figure 1. Flowchart of the method

As shown in Fig.1, firstly, the MBF algorithm generates the desired values as the parameters of the tuned mass damper. Then the failure probability of the *N* samples with uncertain parameters is calculated, and the optimum values of the tuned mass damper leading to minimum failure probability are displayed. The parameters of the MBF algorithm used herein, including the size of the fish population (nFish=50), were set according to what is suggested in [24].

4. NUMERICAL STUDIES

4.1 Example 1

As the first example, a comparison between the efficiency of displacement-based optimized TMD regarding Nominal parameters (DBO-N) and reliability-based optimized TMD regarding uncertain parameters (RBO) in reducing maximum displacement and failure probability of the buildings has been done. In the example, a ten-story shear building [25] with a TMD located on the top floor was investigated. The mass, stiffness, and damping coefficient of each structure story were 360 tons, 650000 kN/m, and 6200 kNs/m, respectively. Design variables, including the mass of TMD (m_d), damping coefficient of TMD (c_d), and stiffness of TMD (k_d), were searched up to 108 tons, 275 kN.s/m, and 4428 kN/m, respectively.

The reliability-based optimization has been done regarding thousand generated buildings with uncertain parameters using the MBF algorithm for minimizing the failure probability of samples. To generate samples with uncertain parameters, the standard deviation is considered equal to 10% of each parameter. The failure condition was determined based on the separation distance of the ten-story building equal to 0.12 m. The objective function of the reliability-based optimization was to minimize the summation of failures that occurred in the thousand generated samples under the El-Centro earthquake. The results are presented in Table 1.

Table 1: Comparison of the methods

	DBO-N				RBO
	Lee et al. [26]	CSS [27]	MOCS [28]	MBF [29]	MBF
m_d (tons)	108	108	108	108	108
c_d (kNs/m)	271	88	160	57	101
k_d (kN/m)	4126	4207	4428	3269	4097
Red. of max disp. (%)	32.9	34.8	35.1	36.4	36.0
Red. of failure prob. (%)	0.6	5.8	14.7	38.1	47.2

As presented in Table 1, the optimum TMD using MBF reduces the maximum displacement of the ten-story building with nominal parameters more than other optimization methods. Moreover, the displacement-based optimization and reliability-based optimization of TMDs, have approximately equal effects on reducing the maximum displacement of the building, while reliability-based optimization of TMDs has a significant effect on reducing the failure probability. In other words, the reliability-based optimized TMD has shown a better effectivity in both reductions of the maximum displacement and the failure probability of the generated buildings with uncertain parameters. The maximum displacement of the buildings equipped with displacement-based optimized TMD regarding nominal parameters and the maximum displacement of the buildings equipped with reliability-based optimized TMD regarding uncertain parameters can be seen in Fig. 2.

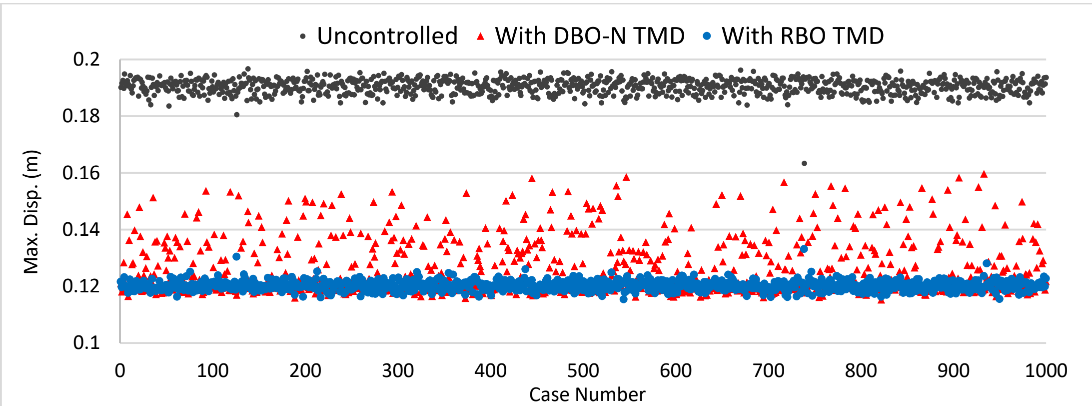

Figure 2. The maximum displacement of thousand generated samples with and without TMD

As shown in Fig. 2, reliability-based optimized TMD has a better efficiency in reducing the maximum displacement of the thousand generated buildings. It can be concluded that optimization regarding uncertainty is a better method for optimizing the tuned mass dampers than optimization regarding nominal parameters.

4.2 Example 2

As the second example, another ten-story shear building was used. The structural properties are taken from [30]. In this example, firstly, the TMD was optimized based on reducing the displacement of nominal buildings. Secondly, the TMD was optimized to reduce the displacement of all thousand generated buildings with uncertain parameters. Finally, the TMD was optimized based on the reliability of all the thousand buildings regarding uncertain parameters. The mass, damping coefficient, and stiffness of TMDs were explored for the ranges given in Table 2 [31].

The optimum parameters of the Displacement-Based Optimized TMD regarding Nominal parameters (DBO-N), Displacement-Based Optimized TMD regarding Uncertain parameters (DBO-U), and Reliability-Based Optimized TMD regarding uncertain parameters (RBO) are presented in Table 3. The failure condition was determined based on the separation distance of the ten-story building equal to 0.12 m. The TMDs have been optimized according to the more critical earthquake (EQ1) among the earthquakes presented in Table 4, using the MBF algorithm.

Table 2: Ranges of design variables

	Minimum	Maximum
m_d (tons)	5.5	55.4
c_d (kN.s/m)	4.9	48.9
k_d (kN/m)	43.7	437.4

Table 3: Optimum parameters of TMDs

	DBO-N TMD	DBO-U TMD	RBO TMD
m_d (tons)	51.1	55.2	52.2
c_d (kN.s/m)	48.9	48.9	43.7
k_d (kN/m)	437.4	437.4	432.2

Table 4: Earthquake records were used in the example

ID	Name	Station	Year	Mag	R (km)
EQ1	Hector Mine	Hector	1999	7.1	10.3
EQ2	Duzce_ Turkey	Bolu	1999	7.1	12.0
EQ3	Manjil_ Iran	Abbar	1990	7.4	12.5
EQ4	Superstition Hills-02	Poe Road	1987	6.5	11.2

The efficiency of the TMDs on the reduction of maximum displacement and failure probability of the thousand samples under the earthquakes presented in Table 4 are compared and presented in Table 5. The peak ground accelerations of all the earthquakes are scaled to 0.25g in this example. The records of earthquakes were obtained from the Pacific Earthquake Engineering Research Center [32].

Table 5: Average reduction of maximum displacement and failure probability of all samples equipped with optimized TMDs under the earthquakes

	Max Displacement Reduction (%)			Failure Probability Reduction (%)		
	DBO-N	DBO-U	RBO	DBO-N	DBO-U	RBO
EQ1	36.6	37.9	37.5	95.0	99.5	99.0
EQ2	21.0	21.9	21.7	39.0	49.0	48.0
EQ3	20.0	25.4	22.9	53.5	77.0	64.0
EQ4	16.1	18.5	17.8	7.5	26.5	18.5
Average	**19.5**	**25.9**	**21.4**	**48.7**	**63.0**	**57.4**

As presented in Table 5, both DBO-U TMD and RBO TMD had a better efficiency in reducing the maximum displacement of thousand samples and their failure probability than DBO-N TMD. It means optimizing the tuned mass damper is better to be done regarding uncertain parameters of buildings than based on nominal parameters. Moreover, according to the results, the DBO-U TMD had better efficiency in reducing failure probability and maximum displacement of the buildings than DBO-N and RBO TMDs. The percentage reduction of the displacement and failure probability of the building equipped with TMDs are illustrated clearly in Figs. 3 and 4, respectively.

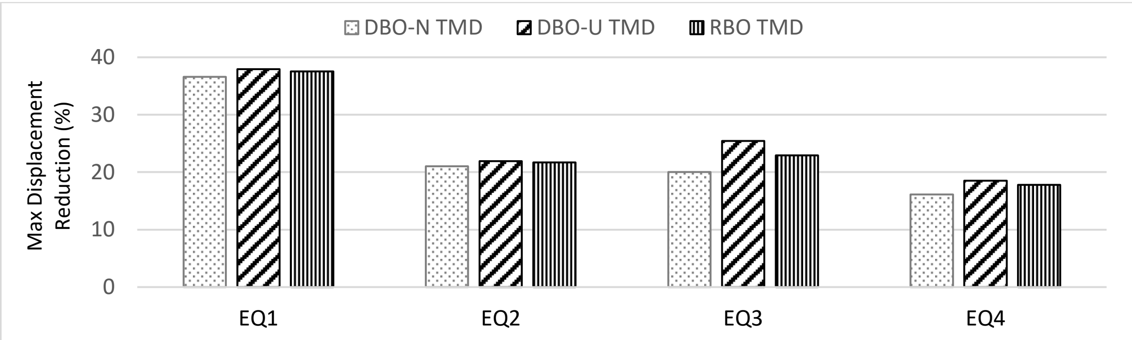

Figure 3. Average reduction of maximum displacement of all samples equipped with TMDs

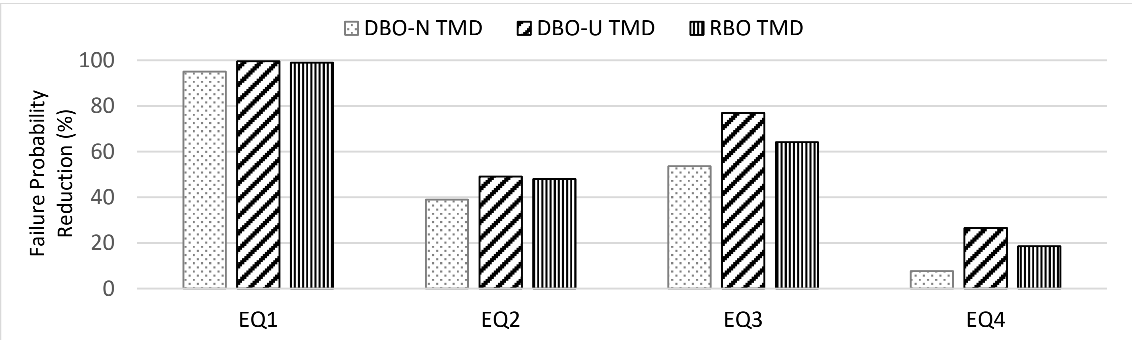

Figure 4. Average reduction of failure probability of all samples equipped with TMDs

5. CONCLUSION

A comparison of the efficiency of the displacement-based optimized TMDs regarding nominal and uncertain parameters of *N* samples and reliability based optimized TMDs that are optimized to minimize the summation failure probability of *N* sample buildings with uncertain parameters have been done, and the following results are concluded:

- Optimization of TMDs regarding uncertain building parameters is more trustable than the optimization of TMDs regarding nominal parameters of buildings. One of the drawbacks of passive control systems is that the systems should be tuned based on the properties of the structures, while in reality, certain parameters of buildings such as stiffness and mass are not clear for designers, and it may lead to the inefficiency of TMDs that are designed according to the nominal parameters of structures. Based on the paper results, it was proved that, fortunately, considering uncertain structure parameters in the tuning of TMDs can cover the defect of the passive tuned mass dampers.
- Displacement-based optimized TMDs regarding uncertainty showed better efficiency than reliability-based optimized TMDs in reducing the failure probability and maximum displacement of buildings with uncertain parameters. The objective function of the optimization of TMDs is another debate in the designing process. Reduction of maximum displacement of structure, reduction of summation drifts of stories, reduction of input energy, and reduction of failure probability of structures can be considered the objective of optimization of a TMD. The comparison of the displacement-based and reliability-based optimization of TMDs proved that minimizing the maximum displacement of structure could be considered a better objective function in optimizing TMDs.

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