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THE EFFECT OF THE ASSUMED INHERENT DUMPING IN THE TUNING OF TUNED MASS DAMPERS

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Abstract

As known, the damping ratio of structures is assumed as a constant value. This constant value is also used in the analysis of structures and these analysis results are used in the optimum design of active and passive control systems. In the present study, the assumed value of inherent damping of the structure is tested on tuned mass dampers that are used in the structures to reduce responses resulting from earthquakes. For this purpose, three methods are investigated by considering the increase or decrease of the damping coefficient of the superstructure. The first method is the usage of equations of Den Hartog which does not consider the inherent dumping of the structure. Secondly, the basic equations of Sadek et al. that include the inherent dumping for the optimum parameters are examined. Finally, a metaheuristic-based optimization approach using the Jaya algorithm (JA) was used in the investigation.

Keywords: Optimization, Dumping, Tuned Mass Dampers, Jaya Algorithm.

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1 INTRODUCTION

Mass dampers are devices that Hermann Frahm [1] invented in 1909 to prevent machine vibration on board, in which Ormondroyd and Den Hartog [2] put forward the first theoretical studies for this type of damper. The fact that TMDs became a part of the design took its place in architecture with research by Mcnamara [3]. Considering the mass of the structure on which TMDs are placed, SDOF has a mass of approximately 5% of the structure for a structure [4-5]. Similar to other passive damping systems, these systems, which convert mechanical energy to damping energy as a working principle, have become a preferred system for building vibration control in terms of not needing external energy, easy cost and maintenance and applicability to old buildings. Looking at the areas of use, we can see that the bridge, tower, etc. exposed to wind forces. It is seen that it is placed in structures, earthquake-effect structures and in the types of structures that are negativized by other vibrations. An example is folded pendulum with a movement ampliated capacity of ±48 cm, with a mass ratio of 4.5%, to 450 tons for the 40-storey Socar Tower (Figure 1 and 2), which was built in 2010, in Baku, capital of Azerbaijan. Another example used in TMD, Alphabetic Tower (Figure 3) in Batumi, Georgia, used standard TMD with a 3.5% mass ratio of 62.85 tons with a movement amplitude of ±24cm [6].

Figure 1. Socar Tower [7]

Figure 2. Socar Tower Folded Pendilum TMD [8]

Figure 2. Alphabetic Tower [9]

TMDs are connected to the structure with the help of spring and damper. The most appropriate account of the spring and damping parameters found in these devices is important for the efficiency of the device. A mode must be defined to the TMD to control the vibration of the structure. This defined value must be selected in accordance with the critical frequency of the structure. As a result of the theoretical studies carried out by Den Hartog, considering the mass ratio of TMD and structure (μ) in accordance with the SDOF structure, the optimum frequency (f_{opt}) is given in Equation (1) and the optimum damping ratio ($\xi_{d,opt}$) is given in Equation (2). In the equations, the frequency of the structure is ω_s and the frequency of TMD is $\omega_{d,}$ opt. The mass and damping coefficient of TMD is m_d and c_d, respectively. In Equation (3), the stiffness coefficient of TMD is accounted for k_d.

$$f_{opt} = \frac{w_{d,opt}}{w_s} = \frac{1}{1+\mu} \tag{1}$$

$$\xi_{d,opt} = \frac{c_d}{2m_d\omega_{d,opt}} = \sqrt{\frac{3\mu}{8(1+\mu)}} \tag{2}$$

$$k_d = \omega_{d,opt}{}^2 m_d \tag{3}$$

Den Hartog developed formulations for optimum damping parameters in his book called mechanical vibrations [10]. In the following years, different formulations were produced other than these assumptions [11-15]. Besides, Sadek at al. added the natural damping of the structure to the formulation. Equations 4 and 5 show these formulas [16].

$$f_{opt} = \frac{1}{1+\mu}\left[1 - \xi\sqrt{\frac{\mu}{1+\mu}}\right] \tag{4}$$

$$\xi_{d,opt} = \frac{\xi}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}} \tag{5}$$

The optimization process has several advantages in terms of its ability to compare multiple results at the same time in achieving the design variables. Metaheuristic algorithms using numerical reputations for optimum design variables are a variant of an appropriate optimization for the detection of TMD efficiency. There are varieties of metaheuristic algorithms such as genetic algorithm (GA) [17-26], Bionic Algorithm [27], Ant colony optimization (ACO) [28], Particle swarm optimization (PSO) [29-30], Harmony search algorithm (HS) [31-36], Artificial bee colony optimization (ABC) [37], Teaching-Learning-Based optimization (TLBO) [34, 35, 38], Flower pollination algorithm (FPA) [34, 35, 39, 40], Bat Algorithm (BA) [41], Jaya Algorithm (JA) [42, 43].

In this study, Jaya algorithm optimization and equations of Sadek et al. [16] and Den Hartog [10] are used for a single degree of freedom system (SDOF). Then, the optimum values obtained as a result of these 3 methods were compared in case of the change of the damping ratio of the structure that is different from the assumed value in the optimization.

2 DYNAMIC ANALYSIS OF STRUCTURE

Simulink model was created on MATLAB [44] for optimization. The optimum parameters of TMD was calculated and results under earthquake data within the defined time interval (0.001) are obtained for far-field ground motion records given in FEMA P-695: Quantification of Building Seismic Performance Factors [45]. SDOF model used in the study is shown schematically in Figure 4. The mass, rigidity and damping coefficient of the SDOF structure are expressed as m, k and c, respectively. The mass, rigidity and damping coefficient of TMD added to the structure is m_d, k_d, c_d, respectively and the displacement in structure is shown as x and TMD displacement is shown as x_d.

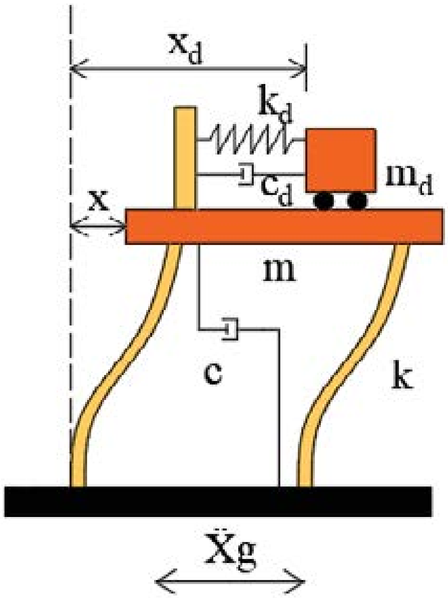

Figure 4. The physical model

Ground acceleration is shown by $\ddot{x}_g$. The motion equation for the SDOF structure used in the study is given in Equation 6. By including TMD, the equations of the motion of the 2 degrees of freedom system are shown as Equations 7 and 8.

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_g \tag{6}$$

$$m\ddot{x} + (c + c_d)\dot{x} - c_d\dot{x}_d + (k + k_d)x + k_d x_d = -m\ddot{x}_g \tag{7}$$

$$m_d\ddot{x}_d - c_d\dot{x} + c_d\dot{x}_d - k_d x + k_d x_d = -m\ddot{x}_g \tag{8}$$

3 THE OPTIMIZATION METHODOLOGY

Using motion equations and TMD parameter calculations from the work of Den Hartog [10] and Sadek et al. [16], the main structure and damping parameters were calculated. For the earthquake records, which were then excited to the SDOF system, the maximum critical acceleration and displacement that will occur in the main structure were determined. The JA [45] developed by Rao, a metaheuristic algorithm inspired by victory, was selected for system optimization. With the codes prepared on the Matlab, JA was applied to optimize the system and maximum acceleration and displacements were obtained for the same earthquake records. The damping value of the SDOF structure was increased by 100 between 500-1500 Ns/m and the critical displacement and total acceleration values for all earthquake records were determined by the oprimum values of Den Hartog, Sadek et al. and JA. It has been computed and tabulated without the TMD structure and TMD structure.

The following is the equation for JA shown as Equation 9. The process of optimization based on a random assignment using the best and worst solution for the objective function obtained from Rao's work [45].

$$X_{new,i} = X_{old,i} + r_1\left(X_{best} - \left|X_{old,i}\right|\right) - r_2\left(X_{worst} - \left|X_{old,i}\right|\right) \tag{9}$$

X_{best} and X_{worst} used to obtain new solutions are the best solution and worst solution, respectively. The expression that randomly assigns between 0 and 1 is written as r_1 and r_2. The newly founded result for the ith solution ($X_{new,i}$) is obtained via the existing one shown as $X_{old,i}$. The process of generating optimized new solutions and deriving existing solutions is continued for the number of iterations.

4 THE OPTIMUM RESULTS

For the investigation, the parameters of the SDOF structure are taken as 1000 kg, 120000 N/m and 1000 Ns/m for m, k, and c, respectively. By using these parameters, the optimum results for a 5% mass of TMD are given in Table 1 for different approaches.

Table 1: The optimum results.

Method	Den Hartog [10]	Sadek et al. [16]	JA
m_d (kg)	50	50	50
c_d (Ns/m)	139.4143	270.2948	79.4850
k_d (N/m)	5442.1769	5334.3060	7467.6313

5 DISCUSSION AND CONCLUSIONS

The investigation was done by taking 5% less and more of the assumed damping valur with 100 Ns/m intervals. The displacement and acceleration maximum values are reported in Table 2 for the critical excitation with the most effect on the structure. This record is the MUL279 record of the 1994 Northridge earthquake.

As seen from Table 2, the displacement values are reduced by 30.3%, 37.4% and 42.5% for the methods of Sadek et al., Den Hartog and JA, respectively. The reduction percentages for the acceleration are 32%, 37.7% and 48.6% for Sadek et al., Den Hartog and JA, respectively. It is seen that the best method is the use of optimization algorithms like JA.

Table 2: The responses for different damping coefficient values.

c (Ns/m)	Without TMD		With TMD					
			Sadek et. al. [16]		Den Hartog [10]		JA	
	x (m)	$\ddot{x}$ (m/s^2)	x (m)	$\ddot{x}$ (m/s^2)	x (m)	$\ddot{x}$ (m/s^2)	x (m)	$\ddot{x}$ (m/s^2)
500	0.2305	27.6931	0.1486	17.3602	0.1288	15.5914	0.1281	13.4663
600	0.2177	26.1615	0.1425	16.6482	0.1240	15.0228	0.1211	12.8844
700	0.2058	24.7464	0.1370	16.0236	0.1199	14.4949	0.1150	12.3404
800	0.1948	23.4298	0.1321	15.4692	0.1166	13.9941	0.1102	11.8342
900	0.1846	22.2273	0.1275	14.9393	0.1135	13.5810	0.1056	11.3630
1000	0.1765	21.2588	0.1231	14.4474	0.1105	13.2404	0.1014	10.9210
1100	0.1688	20.3615	0.1190	13.9781	0.1076	12.9108	0.0990	10.6213
1200	0.1616	19.5112	0.1151	13.5300	0.1049	12.5975	0.0968	10.3847
1300	0.1549	18.7241	0.1114	13.1140	0.1023	12.3001	0.0946	10.1603
1400	0.1487	17.9807	0.1079	12.7154	0.0998	12.0122	0.0926	9.9429
1500	0.1427	17.2813	0.1045	12.3343	0.0973	11.7334	0.0906	9.7322

For the damping values less than the assumed value, the performance of the TMD increases. For example, a 51.4% reduction occurs for the acceleration, when c value is the minimum by using JA. The opposite can be said for the increasing damping values. By this conclusion, it is seen that TMDs are more effective for the system with low inherent damping. Also, TMDs are effective when the damping coefficient value is different from the assumed one.

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