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A novel bat algorithm based optimum tuning of mass dampers for improving the seismic safety of structures

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ABSTRACT

Metaheuristic algorithms are effective for optimization with diverse applications in engineering. The optimum tuning of tuned mass dampers is very important for seismic structures excited by random vibrations, and optimization techniques have been used to obtain the best performance for optimally tuned mass dampers. In this study, a novel optimization approach employing the bat algorithm with several modifications for the tuned mass damper optimization problem is presented. In the proposed method, the design variables such as the mass, period and damping ratio of tuned mass damper are optimized and different earthquake records are considered during the optimization process. The method is then applied to a ten-story civil structure and the results are then compared with the analytical methods and other methods such as genetic algorithms, particle swarm optimization, and harmony search. The comparison shows that the proposed method is more effective than other compared methods. Additionally, the robustness of the optimum results was evaluated. The proposed approach for optimizating tuned mass dampers via the bat algorithm is a feasible and efficient approach.

1. Introduction

The vibration absorber device invented by Frahm [1] was modified with damping elements in order to damp random vibrations, and the tuned mass dampers (TMDs) were generated [2]. Thus, all mechanical systems subject to undesired random vibrations can be protected. Since civil structures are big mechanical systems that are also exposed to undesired excitations such as strong winds, earthquakes and moving traffic, tuned mass dampers have been installed in many important buildings. In addition to prevent structural failure, there are many reasons to use TMDs in structures, including the protection of sensible equipment and even preventing motion sickness of residents. Examples include the Taipei 101 building in Taipei, the Television Tower in Berlin, John Hancock Tower in Boston, Lax Theme Building in Los Angeles, Burj Al-Arab in Dubai and the Millennium Bridge in London. For the best performance, TMDs must be optimally tuned and the optimization formulation must consider the characteristics of structures and excitations.

For the tuning of TMDs, several approaches have been proposed in the literature. For example, Den Hartog [3] developed some optimum tuning formulas for frequency and damping ratios of TMDs by the change of the ratio of the masses of TMDs to the structure under consideration. These equations were derived for a single degree of freedom system, without inherent damping and excited by harmonic excitations. The representation of simple systems like beams and plates as a single of degree of freedom systems may be a good assumption and the optimum parameters of TMDs were presented by Warburton and Ayorinde [4] for light damping in the simple systems. Also, Warburton [5] proposed the expressions for the same parameters for harmonic and white noise excitations. An analytical formula is not possible for main structures with inherent damping. For that reason, the optimum TMDs can be designed by using numerical iterations [6,7]. Sadek et al. obtained the optimum tuning expressions by using curve fitting to numerically searched values and modifying the expression for systems with multiple degrees of freedom (MDOF) [8]. Chang [9] proposed several expressions for different types of TMDs. Rüdinger [10] investigated a TMD with a nonlinear power law viscous damper excited by white noise. Marano et al. [11] optimized TMDs for seismic effects by using a constrained reliability-based optimization minimizing the maximum of the dimensionless peak of displacement of the protected system with respect to the unprotected one under different input characteristics.

Recently, several studies about mass dampers have been developed. Mensah and Dueñas-Osorio proposed tuned liquid column dampers (TLCDs) in order to improve the reliability of wind turbines [12]. The optimum tuning formulation for TLCDs were developed by Di Matteo et al. [13] for random vibrations. Salvi and Rizzi proposed a numerical

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Minimax optimization for optimum tuning of mass dampers in order to provide a good performance for frames under earthquake excitations [14]. Lu et al. proposed a new eddy-current tuned mass damper in order to improve the performance of tall structures [15]. Lavan developed a multi-objective optimum design procedure in order to reduce structural responses, TMD mass and stroke [16]. Pendulum type TMDs were also proposed for seismic performance of power plants [17]. Lu et al. conducted experimental studies for particle TMDs for wind-induced vibrations [18].

The nature inspired metaheuristic algorithms have a wide application area [19–22] and these algorithms have also been attempted for the optimization of TMDs. The employed metaheuristic methods in the literature are genetic algorithm (GA) [23–27], bionic algorithm [28], particle swarm optimization (PSO) [29,30] and harmony search (HS) [31–34]. Although the optimization of TMDs have been discussed in several studies for seismic control of structures, it is still an important area that needs to be investigated since these methods use several criteria and procedures. As it is well known that earthquake excitations are random vibrations which contain different pulses like motions with different frequencies, an optimally tuned TMD should always show the best performance for different earthquake excitations. For that reason, designers must find the best TMD design which is still robust when a different excitation is applied to structure. Because of the unique characteristics of the bat algorithm defined in step 4 of Section 2, it is a suitable metaheuristic algorithm for analysing and optimizing TMD parameters in an iterative manner. One of the main advantages of the bat algorithm is its ability of finding the global optimality with quick convergence [35,36].

In order to provide sufficient damping of seismic vibrations, the characteristics of a TMD must be tuned so as to achieve the required, special properties of passively controlled system. The tuning of TMDs is a process in which the optimum parameters are found, often in an iterative manner. The parameters of a TMD are related with its frequency, mass and damping coefficient. In Fig. 1, a multi-story structure with TMDs is shown by employing a degree of freedom in the transactional direction for each story and TMD.

In several existing studies, simple expressions were proposed for the optimum frequency ratio (f_{opt}) and damping ratio ($\xi_{d,opt}$). These expressions depended on a constant mass ratio (μ) and only a single (critical) vibration mode was considered. Several formulas of the optimum TMD frequency and damping ratio are given in Table 1.

In the close form expressions, the damping ratio (ξ) of the main structure is considered in the approach by Sadek et al. [8] and Leung and Zhang [30]. By finding f_{opt} and $\xi_{d,opt}$, the optimum frequency of the TMD ($w_{d,opt}$) and the optimum damping coefficient of TMD ($c_{d,opt}$) are found for a structure with the frequency described as w_s. Since the close form expressions were derived for a single degree of freedom (SDOF) system, a multiple degrees of freedom (MDOF) system must be idealized and be related to a SDOF system. In the idealization of the structure, the modal mass for the first critical frequency is taken as the mass of the structure in calculating the mass ratio. Also, according to the proposal of Sadek et al. [8], the frequency ratio for MDOF systems is nearly equal to the ratio for SDOF systems with a modified mass ratio as $\mu\Phi$. Also, the optimum damping ratio for SDOF systems is multiplied by Φ for the modification of MDOF systems. Here, Φ is the amplitude of the first mode shape at a location where the TMD is located. This amplitude is calculated for the unit modal participation factor (Γ_i).

The use of close form expressions for MDOF systems is essentially based on some assumptions and idealizations that may not be exactly valid in practice. In contrast, by using proper metaheuristic algorithms such as the bat algorithm, it is possible to find the optimum parameters for multi-story structures subject to random excitations such as earthquake-induced ground motions. Therefore, a methodology employing the Bat Algorithm is proposed for solving the present TMD optimization problem.

In this paper, the recent bat algorithm (BA) is modified to solve the TMD optimization problem. A novel methodology is developed in order to find the optimal values of the design variables such as the mass of TMD (m_d), period of TMD (T_d) and damping ratio of TMD (ξ_d) for multi story seismic structures. Different from the other optimization algorithms using equations for the objective function, BA is combined with the numerical analyses process of seismic structures and time domain histories of the structures are considered as optimization objective results. Since the optimization problem does not have explicit, analytical solutions, the nonlinearity of this problem necessitates a novel approach by modifying the use of the bat algorithm so as to be suitable for a dynamic analyses problem and the tuning of TMD parameters for structures subject to excitations with wide variety of frequencies. In addition, we will compare the results obtained by our proposed approach with those obtained by other methods. Therefore, this paper is organized as follows. Section 2 provides the detailed formulation of the TMD problem, and discusses the optimization methods. Then, Section 3 provides some numerical examples, followed by discussions and conclusions in Section 4.

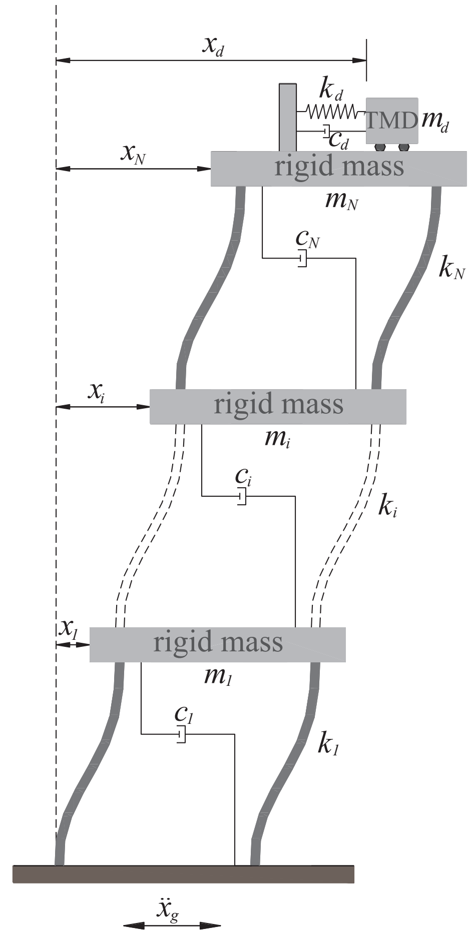

Fig. 1. Physical model of a structure with TMDs.

2. Design and optimization methodology

The formulation of the TMD problem will be described along with the description of the optimization procedure. Three design variables to be optimized are the mass of TMD (m_d), period of TMD (T_d) and damping ratio of TMD (ξ_d). The optimization algorithm to be used is mainly the bat algorithm, and the comparison will be made with other algorithms and close form expressions.

In the methodology, the bat algorithm is combined with the dynamic analysis process of seismic structures to generate an effective novel optimization approach for tuning of TMDs. The proposed