Engineering Structures 160 (2018) 314–327

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Performance-based optimal design of tuned impact damper for seismically excited nonlinear building

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ARTICLE INFO

Keywords:
Passive control
Tuned impact damper
Particle damper
Reduced-order model
Differential evolution algorithm
Performance-based optimal design

ABSTRACT

This paper proposes a performance-based optimal design method for a tuned impact damper system, which is composed of a solid mass in a container and is located at the top of a 20-story complex nonlinear benchmark building of the third generation. This benchmark building is a steel frame, accounting for nonlinear response via material non-linearity (bi-linear hysteresis) concentrated at the ends of moment-resisting beam-column joints, and is designed for the SAC PhaseIIISteel Project. In order to illustrate the real-world implementable optimal design approach for designing an optimal tuned impact damper system attached to practical complex structures, a reduced-order data-driven physical model is developed by using the response data specifically from finite element model and the optimization-based parameter identification algorithm. The reduced-order model has been iteratively constructed to be consistent favorably with the finite element model on the aspects of both modal frequencies and mode shapes. Based on the reduced-order model, the optimal parameters of the tuned impact damper system are subsequently designed by adopting proposed performance indices and the differential evolution algorithm conveniently. The optimal vibration control effects are evaluated by using the original finite element model structure with the optimal tuned impact damper. Such optimal performance is also compared with that of the original finite element model with a conventionally designed tuned impact damper system. The results show that the optimal designed tuned impact damper system not only can significantly mitigate the peak and root mean square values of dynamic displacements, but also can reduce effectively the number of plastic hinges of the nonlinear benchmark structure compared with that with the conventional design. Furthermore, the performance-based optimal design can lead to a better robust performance of the tuned impact damper system in the cases of the main structure subjected to unknown earthquake excitations.

1. Introduction

In recent years, structural vibration control has been recognized widely as an efficient approach to mitigate the dynamic response of civil infrastructure systems under arbitrary external excitations such as earthquakes, wind, etc. Since Yao introduced the concept of vibration control to civil engineering in 1972 [1], various control strategies and systems have been widely studied in theory innovation and design methodology for practical engineering application, including passive control, active control, semi-active control and hybrid control [2]. Tuned mass damper (TMD) is a traditional passive control device shown to be effective and reliable with widely real-world applications, such as in Shanghai Center Tower [3], Taipei 101 [4], Milad Tower [5] and Chiba Port Tower. However, TMDs have some inherent limitations such as narrow tuned frequencies, poor durability and deterioration over time. Consequently, several researchers have introduced the particle damping technology [6–13] into TMDs and developed a new passive control device named as particle tuned mass damper (PTMD) [14–18] to overcome the shortcomings of conventional TMDs. PTMDs combine characteristics from conventional TMDs and particle dampers by capturing on the strengths of different damping approaches. In the area of PTMD applied to civil engineering structures, Yan et al. [19] carried out a series of shaking table test for a 1/10 scale model bridge with/without tuned particle dampers to evaluate the system's performance and proposed a finite element method for numerical simulation based on the energy principle. Lu et al. [20] conducted an aero-elastic wind tunnel experiment by attaching a PTMD onto a 1/200 scale benchmark model and a shaking table test for a five-steel frame to evaluate the vibration control effects of PTMDs subjected to earthquake excitations. In addition, Lu et.al [21–24] proposed a simplified simulation method based on the hypothesis of an equivalent single-particle damper to analyze vibration control effect of PTMDs. For the main structure, the structural

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https://doi.org/10.1016/j.engstruct.2018.01.042
Received 7 September 2017; Received in revised form 22 December 2017; Accepted 13 January 2018

damping is also essential to the dynamic analysis, Hirwani et.al [25–31] have carried out many research with/without considering the damping coefficient.

However, the previous studies on PTMD are mostly based on simple linear-elastic structures in the engineering laboratory, not involving with the practical engineering application to complex structures, such as Shanghai Center Tower, Carton Tower, etc. In recent years, some researchers have made remarkable efforts to the engineering application of various damping devices. For example, Lu et al. [3] proposed a high-rise benchmark building based on Shanghai Center Tower to evaluate the effectiveness of different vibration control devices applied to complex engineering structures. Therefore, the determination of PTMD parameters, which is valuable for a complex structure, becomes a difficult problem. The practical engineering structures mostly respond into the nonlinear range under the action of large seismic excitations, and the added damping caused by PTMD system can limit the extend of such nonlinearity in the main structure. Consequently, it needs to evaluate the vibration control effect of PTMD system according to the nonlinear performance indexes, such as number of plastic hinges and damage of main structure. Furthermore, the parameters of the PTMD system in the previous studies are determined by experimental data analysis and conventional engineering experiences based on a fundamental assumption that the collision between the particles and the container is rigid [9,10], which apparently is not its optimal solution in realistic conditions. Therefore, in order to reduce the dynamic response of the complex structure in practical engineering applications, it is necessary to propose an effective and simple method to determine the optimal solution of the PTMD system. Due to the highly nonlinear and complex problems existing in the collisions between particles in a PTMD system, being a special case, the tuned impact damper (TID) system which has only one particle in the damper system is studied in this paper, comprising a first step to apply a nonlinear damper system to a nonlinear primary structure.

When the TID system is applied to practical engineering structures, it is necessary to optimize a series of TID parameters to maximize the vibration control effect and minimize the damage of main structure after the large earthquake excitations. However, there are often a large number of degrees of freedom in the complex engineering structure; consequently, it will be a large time burden to optimize the parameters of the TID system based on the original finite element (FE) model of complex structure. Therefore, an equivalent reduced-order model tuned to be consistent well with the FE model on the aspects of both modal frequencies and mode shapes is required in the process of designing the TID system. Based on the reduced-order model, the optimal parameters of TID can be designed by some optimal algorithm. In the area of other damper devices applied to complex engineering structures, some researchers have already conducted a series of studies and achieved some economic results. Xu et al. [32] explored the vibration control effects of active mass driver control system applied to the wind-induced vibration of the Canton Tower based on the simplified 2-D finite element model. Zhang et al. [33] introduced the TMD to seismic design of the intake tower, which was simplified into a 2D multi-degree of freedom (MDOF) model to design the optimal parameters for the TMD systems. Li et al. [34] proposed a reduced-order controller with Guaranteed cost control to compensate the time-delay of active mass damper (AMD) control system and take into account the high-order modal information of the original structure. Ozbulut et al. [35] investigated the vibration reduction ratio of a 20-story nonlinear benchmark structure with a new re-centering variable friction device (RVFD). Sadek et al. proposed the optimal parameters of TMDs for MDOF structures [36]. Rana and Soong designed a TMD for a single degree of freedom (SDOF) structure and a certain vibration mode of a MDOF by numerical optimization, and investigated the controlling of multiple structural vibration modes using multi-TMDs [37]. Bakre et al. derived equations of optimum parameters for TMD applied to a SDOF main system for various excitations and objective functions, such as dynamic displacement, velocity and base shear [38]. In addition, many intelligent algorithms such as the genetic algorithm [39], bionic algorithm [40], particle swarm optimization [41] and harmony search (HS) algorithm [42] have been proposed to design the optimal parameters for the TMD damping system.

In this paper, a performance-based optimal design method of TID system is proposed. A TID with optimal parameters is attached to a 20-story nonlinear benchmark building of third generation, comprising a first step to apply TID system to realistic engineering structures, to investigate its vibration control effects based on the FE model according to some nonlinear performance indexes such as number of plastic hinges, component energy consumption compared with that of the conventional designed TID. Furthermore, the reliability of the control performance is explored through a large number of earthquake records to evaluate the robustness of the TID system based on performance optimal design. Finally, some conclusions for practical engineering application of the TID system are presented.

2. Methodology and finite element model

2.1. Design procedure

Performance-based optimal design method of tuned impact damper (TID) including three phases is proposed in this paper, as shown in Fig. 1. At Phase 1, for a complex high-rise structure, such as Shanghai Center Tower, TaiPei 101, Carton Tower et al., there are often a large number of degrees of freedom and high frequency dynamic response in the original finite element (FE) model. In order to design a series of optimal parameters of the TID system efficiently, a 3-D equivalent reduced-order model, which accounts for displacement response of two orthogonal directions and torsional response along the elevation direction, has to develop specifically from original FE model. As the first step to apply TID system to realistic engineering structures, the 20-story nonlinear benchmark building selected in this paper is condensed to a 2-D reduced-order model by differential evolution (DE) algorithm at Phase 1, which has been elaborately tuned to be consistent well with the FE model on the aspects of both modal frequencies and mode shapes for capturing the main dynamic response of the original FE model [43]. At Phase 2, a series of optimal parameters of TID system are designed based on the linear reduced-order model by DE algorithm similarly, including mass ratios of particle and container, damping ratios of particle and container, rigid coefficient and gap clearance; therefore, the computation can be simplified significantly. At Phase 3, a TID system with optimal parameters is attached to an original nonlinear complex structure to validate its vibration control effect based on the FE model according to some performance indexes, especially for some nonlinear performance indexes, such as number of plastic hinges, component energy consumption et al. Furthermore, the robustness of the TID system based on performance optimal design is evaluated and some conclusions for practical engineering application of the TID system are presented.

2.2. Optimization algorithm

The differential evolution algorithm has received much attention in solving the complicated optimization problem since it is first proposed by Storn and Price [44] with a gradient-free characteristic as a simple and efficient heuristic methodology. The differential evolution algorithm is a hybrid algorithm that combines the larger population concept of genetic algorithm, the adaptive mutation of evolutionary algorithm and adopts the greedy selection strategy, which makes the DE algorithm more robust and faster than evolutionary algorithms and genetic algorithms. The standard procedure of the DE-based Optimization algorithm can be briefly summarized for better reference as follows:

Step 1: Initialization