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An equivalent method for optimization of particle tuned mass damper based on experimental parametric study

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ABSTRACT

A particle tuned mass damper (PTMD) is a creative combination of a widely used tuned mass damper (TMD) and an efficient particle damper (PD) in the vibration control area. The performance of a one-storey steel frame attached with a PTMD is investigated through free vibration and shaking table tests. The influence of some key parameters (filling ratio of particles, auxiliary mass ratio, and particle density) on the vibration control effects is investigated, and it is shown that the attenuation level significantly depends on the filling ratio of particles. According to the experimental parametric study, some guidelines for optimization of the PTMD that mainly consider the filling ratio are proposed. Furthermore, an approximate analytical solution based on the concept of an equivalent single-particle damper is proposed, and it shows satisfied agreement between the simulation and experimental results. This simplified method is then used for the preliminary optimal design of a PTMD system, and a case study of a PTMD system attached to a five-storey steel structure following this optimization process is presented.

1. Introduction

How to increase the structural safety and reliability under dynamic loads, such as earthquakes, winds, impacts, etc., which may cause excessive responses of the structure and discomfort feelings of the occupants, has always been an important issue in civil engineering area. The disaster reduction theory [1] has advanced from increase of structural resistance by strengthening the elements and material, to dissipation or insulation of the input energy by technological innovations. The theory of energy absorption that was initially proposed by Kelly and Skinner [2] has many practical applications in modern society, which was mainly achieved by attaching auxiliary devices, such as energy dissipation braces, damping outrigger systems [3], dampers [4–7], or exerting external energy inputs, etc., to adjust the dynamic characteristics of the structure and thus control the responses.

According to the state of external energy supply, the vibration control can be categorized as passive control, active control, hybrid control and semi-active control, among which the passive control has wide applications due to its simple concept and mechanism. The tuned mass damper (TMD) [8], a typical passive control device with the advantages of simple characteristics, convenient installation, low cost and favorable control effects under specific tuning frequency, has been widely researched and applied in tall and slender structures to reduce the responses, such as high-rise buildings [9], wind

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turbine towers [10], and pedestrian bridges [11]. Tanaka and Mark [12] conducted a parametric study of the TMD based on the aero-elastic wind tunnel test of a 1/1000 scale model of the CAARC Standard Tall Building to investigate its efficiency in suppressing the wind-induced vibrations. However, the narrow bands of the suppression frequency, ineffective reduction for non-stationary vibrations and sensitivity problems owing to mistuning limit the vibration control effects of the TMDs. According to Clinton [13], the TMDs were sensitive to surrounding environment, such as wind velocity, temperature, relative humidity and the type of earthquakes.

The particle damper (PD), a new type of passive control device that makes an improvement based on the traditional impact damper, utilizes both momentum transfer and energy dissipation achieved by collisions among particles, collisions between particles and the container wall, friction and sound radiation to attenuate the vibration [14]. The particle damper, which has wide reduction frequency bands, ruggedness, reliability, insensitivity to extreme temperatures and causes slight changes to the primary structure, has attracted many scholars to study on its damping performance [15–17]. However, compared to the relatively mature design processes of the TMDs, inherent puzzlements regarding to the working mechanism of the particle dampers are still remained.

Considering the advantages and limitations of both TMDs and PDs, a combinative damper - particle tuned mass damper (PTMD), is generated by suspending a multiple particle damper on the top of a structure, which can broaden the suppression frequency bands through collisions and thus improve the reduction efficiency and durability. Yan et al. [18] experimentally investigated the vibration reduction effects of a tuned particle damper attaching to a viaduct system under seismic loads and founded that the suppression frequency band was wider than that of the TMDs; Lu et al. [19,20] performed an aero-elastic wind tunnel test on a reduced-scale Benchmark model attached with a PTMD and analyzed the influence of some parameters, such as auxiliary mass ratio, particle density, mass ratio of container to particles and wind velocity, on the vibration control effects for wind-excited responses of high-rise buildings.

Actually, the PTMD introduces the nonlinear damping into the linear TMD within the concept of nonlinear energy sink (NES) in order to transfer the energy from the primary structure to the nonlinear damping devices and dissipate it. The NES usually has nonlinear stiffness or nonlinear damping to widen the band of resonant frequencies. In addition, the NES has the function of target energy transfer and dissipation to alternate the energy distribution in space and frequency. For example, Roberson [21] proposed a nonlinear dynamic vibration absorber by attaching a secondary system by means of a spring whose load-deflection characteristics was sum of a linear and cubic term, which proved to be capable of dissipating energy in a wider range of frequencies than the traditional linear TMDs under earthquakes. Spencer [22,23] founded that the responses of a nine-storey structure attached with a NES could be significantly and quickly reduced under seismic and explode inputs through shaking table tests and field tests, and the NES was efficacious in a wide range of frequencies.

Up till now, the research on the PTMD is in the early stage, especially for the theoretical and numerical study. The core issue to evaluate the damping performance of the PTMD is still the numerical simulation of the highly nonlinear behavior of particles. Papalou and Masri [24] proposed an approximate analytical solution by equating the multi-unit particle damper to a single-unit impact damper based on certain equivalent principles and shown that this method can provide an adequate estimate of the structural responses when the damper was operating in the vicinity of the optimum range of parameters; Xia et al. [25] proposed a coupling simulation algorithm for the particle damper based on the discrete element method and finite element method, and the analytical and experimental results were compared; Lu et al. [26] numerically investigated the performance of both vertical and horizontal particle dampers under different dynamic loads by using discrete element method and used the concept of *Effective Momentum Exchange* to characterize the underlying physics of operating particle dampers; Lu et al. [27] further established a high-fidelity simulation process to account for all significant interactions among the particles and with the host structure system based on the modified discrete element method; Wang and Wu [28] developed a novel simulation method based on multiphase flow theory of gas particle to study the vibration characteristics of a cantilever rectangular plate with particle dampers, and the numerical predictions agreed well with the experimental results. Moreover, Sanchez and Carlevaro [29] conducted a nonlinear dynamic analysis of a single-degree-of-freedom (SDOF) mechanical model with a particle damper, and the optimum gap size for the best performance of granular damping was obtained.

However, further study to understand the underlying physical mechanics of the PTMD is necessary and there are scarcely guidelines for optimization design of the particle dampers for now. In this paper, free vibration tests and shaking table tests are carried out to investigate the damping performance of the PTMD. The influencing principles of some key parameters are discussed, through which the guidelines for the optimization of the PTMD can be concluded. A simplified analytical solution by equating the PTMD to a single-particle damper is presented and proves to have the reasonability and accuracy in estimating the vibration control effects of the PTMD. Furthermore, a convenient procedure on the preliminary design of a PTMD by using the proposed equivalent method is put forward and shows the optimal vibration reduction effects through a case study of applying the PTMD to a five-storey steel structure.

2. Experimental investigation

2.1. Experimental setup

The main structure in the experiment is a one-storey steel frame structure, as shown in Fig. 1(a). Its dimensions are 320 mm × 110 mm × 500 mm, and the mass is 1.6 kg. The lateral stiffness in the longitudinal direction is 500 N/m. An additional

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