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Seismic design of passive tuned mass damper parameters using active control algorithm

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ABSTRACT

Tuned mass dampers are a widely-accepted control method to effectively reduce the vibrations of tall buildings. A tuned mass damper employs a damped harmonic oscillator with specific dynamic characteristics, thus the response of structures can be regulated by the additive dynamics. The additive dynamics are, however, similar to the feedback control system in active control. Therefore, the objective of this study is to develop a new tuned mass damper design procedure based on the active control algorithm, i.e., the H_2/LQG control. This design facilitates the similarity of feedback control in the active control algorithm to determine the spring and damper in a tuned mass damper. Given a mass ratio between the damper and structure, the stiffness and damping coefficient of the tuned mass damper are derived by minimizing the response objective function of the primary structure, where the structural properties are known. Varying a single weighting in this objective function yields the optimal TMD design when the minimum peak in the displacement transfer function of the structure with the TMD is met. This study examines various objective functions as well as derives the associated equations to compute the stiffness and damping coefficient. The relationship between the primary structure and optimal tuned mass damper is parametrically studied. Performance is evaluated by exploring the h_2-and h_∞-norms of displacements and accelerations of the primary structure. In time-domain analysis, the damping effectiveness of the tune mass damper controlled structures is investigated under impulse excitation. Structures with the optimal tuned mass dampers are also assessed under seismic excitation. As a result, the proposed design procedure produces an effective tuned mass damper to be employed in a structure against earthquakes.

1. Introduction

Structural control provides an effective means to enhance performance of buildings against external disturbance or ground excitation. Most structural control applications install control devices in buildings to dissipate or resist the energy coming from winds or earthquakes. The responses of buildings are then reduced. These control devices modify the dynamics of structures to be capable of tolerating the external loadings acting on structures. In practice, passive control is a widely-accepted method for structural control applications. These passive control devices include viscous dampers, viscoelastic dampers, tuned mass dampers (TMD), friction dampers, and etc. For tall buildings, the most cost-effective passive control method is to install tuned mass dampers at higher levels.

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TMDs can significantly reduce the vibrational responses of tall buildings under seismic and wind excitations. A TMD is one type of passive control devices consisting of a mass, damper, and spring. TMDs can alter the dynamic characteristics of primary structures and transfer the energy of primary structures to themselves. Indeed, many TMDs have been successfully implemented in existing tall buildings, such as the Taipei 101 in Taipei, Taiwan, Citicorp Center in New York, USA, John Hancock Center in Boston, USA, CN Tower in Toronto, Canada, and Sydney Tower in Sydney, Australia [1]. Furthermore, a number of observation towers in Japan are also installed with TMDs [1]. In the practical perspective, most TMD applications only adopt a single TMD in buildings to attenuate structural responses.

Active mass dampers (AMD) have also been studied and applied in existing buildings. For example, Chang and Soong (1980) studied the feasibility of enhancing structural performance by means of TMD with added active control capability [2]. Hrovat et al. (1983) utilized the LQR control algorithm to determine an optimal AMD system [3]. Nishimura et al. (1992) designed an AMD system by investigating the frequency-domain responses of the controlled building [4]. Samali and Al-Dawod (2003) numerically employed fuzzy logical controller to derive AMD for a five-story benchmark building [5]. Additionally, some studies converted AMD into semi-active TMD without further input energy to structures. Abe (1996) investigated two semi-active control strategies for TMD for seismically excited buildings [6]. Viet et al. (2014) exploited groundhook controllers to implement semi-active tuned mass dampers [7]. In engineering practice, the Kyobashi Seiwa Building in Tokyo, Japan is the first building installed AMD in the world [1]. The Sendagaya INTES Building in Tokyo, Applause Tower in Osaka, and Riverside Sumida Central Tower in Tokyo are also installed with the AMD [1]. Due to smaller control authority, these AMD applications mostly improve the comfort of residents in buildings.

Many researchers conducted parametric studies to better design a TMD for response reduction of tall buildings, i.e., different dynamic characteristics of primary structures or different design objectives. A comparison between different TMD optimization criteria are introduced by Marano et al. (2010) [8]. For an undamped primary structure, Den Hartog (1956) determined optimal TMD parameters when subjected to harmonic excitation [9], and Warburton (1982) explored control effectiveness of a single TMD in a structure under various types of inputs [10]. In addition, Tsai and Lin (1993) derived the solution to obtain optimal TMD parameters by minimizing steady-state responses of damped primary structures subjected to excitation at support [11]. Bakre and Jangid (2007) proposed the design of optimal TMD parameters by minimizing the root-mean-square responses of primary structures [12] and Lin et al. (2000) optimized TMD for a multiple degree-of-freedom (MDOF) primary system [13]. In these two studies, both undamped and damped structures were considered. Various design objective functions (e.g., the root-mean-square displacement or acceleration of the primary structure) were employed to derive the optimal TMD parameters when subjected to wind or seismic loading. These TMD design methods are all effective in accordance to their design objectives. When the primary structure has inherent damping, the design methods become more complicated.

Active control algorithms have been extensively studied for structures against earthquakes. Soong and Manolis (1987) carried out an active control simulation on a simple building using the linear-quadratic-regulation (LQR) control algorithm [14]. Chung et al. (1988) experimentally implemented active control using the LQR control method on a building by shaking table testing [15]. Spencer et al. (1994) developed a frequency-domain optimal control algorithm based on the H_2/LQG control method [16]. Dyke et al. (1994a and 1994b) experimentally verified acceleration feedback using the H_2/LQG control method for seismic protection of buildings [17,18]. In passive control, the additive energy dissipation devices can be treated as feedback control. Subsequently, the design of passive control devices can be realized by active control algorithms.

The interaction between the TMD and building can be viewed as feedback control and realized by static or dynamic output feedback control. One popular feedback control strategy is the linear quadratic regulator (LQR) control algorithm [19], which is categorized as a static full-state feedback control scheme in the h_2-norm sense. With a Kalman estimator, the LQR control algorithm is extended to be the linear quadratic Gaussian control algorithm [16], which is categorized as a dynamic output feedback control scheme with a full-state estimation. The LQR control algorithm can be appropriately transformed into a static output feedback control scheme by introducing one additional Lyapunov equation [20]. The static output feedback control in the h_2-norm sense can also be realized by a wide variety of approaches with some constraints [21,22]. In addition to the h_2-norm sense, the static output feedback control can be derived from the h_∞-norm sense [23,24]. Therefore, all these output feedback control algorithms can be an optimal design solution to linear TMDs for seismically excited buildings when the structure-control system is presented in an appropriate mathematical form.

Because active control algorithms seek a high-performance feedback controller to be obtained, this study proposes a new design procedure of optimal tuned mass dampers based on the active control algorithm. In this design procedure, the mass, damping coefficient, and stiffness of a single degree-of-freedom (SDOF) primary structure are known, while the mass ratio between the single TMD and structure is predetermined. The stiffness and damping coefficient of a TMD are derived from the LQR control objective functions in terms of a single weighting scalar. These control objective functions are formed with respect to an output of the primary structure. Subsequently, the optimal TMD is determined by minimizing the maximum peak in the displacement transfer function. Three types of optimal TMDs are designed from the displacement-, velocity-, and acceleration-based objective functions. These optimal TMDs are compared to the one proposed by Den Hartog [9] in terms of TMD stiffness and damping coefficient as well as resulting dynamic characteristics of the TMD-controlled structure. Performance of a primary structure with the optimal TMDs is evaluated in the h_2 and h_∞ norms of floor displacements and accelerations. The proposed design procedure is also examined by impulse and seismic excitation in order to explore the damping effectiveness of the optimal TMDs and to verify the designed TMDs with respect to the control objectives. As shown in the results, the proposed design procedure yields effective stiffness and damping coefficient to be obtained for TMDs.