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Effectiveness of dynamic vibration absorbers implemented in tall buildings

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ABSTRACT

In recent decades, dynamic vibration absorbers (DVAs), such as tuned sloshing dampers (TSDs) and tuned mass dampers (TMDs) have been increasingly used to enhance the serviceability performance of tall buildings subjected to wind excitation. While the fundamental theory of ideal structure-DVA systems is well developed, there is a lack of available literature documenting the performance of DVA systems that have been installed in tall buildings. Moreover, it is challenging to directly quantify the effectiveness of DVAs installed in buildings due to the uncertainties associated with the applied wind loading. In particular, traditional methods are generally unable to directly calculate the effective damping that a DVA adds to the building.

This study presents the results of full-scale structural monitoring conducted on two tall buildings that have been equipped with DVAs to reduce wind-induced motion. The responses of the building and the DVA were monitored during significant wind events. The performance of the DVAs is directly determined by using the building and DVA responses, and the structure-DVA mass ratio, to calculate the added effective damping. The theoretical added effective damping of an ideal structure-DVA system is compared to the measured value, revealing that nonlinear effects that are typically neglected, such as friction, can significantly alter the theoretical added effective damping from its measured value at low response amplitudes. The DVAs studied have significantly decreased the wind-induced motions of the tall buildings monitored.

1. Introduction

The proliferation of tall and super-tall buildings in recent years has resulted in considerable challenges related to the performance of these structures when they are subjected to wind loading. While the lateral load resisting system of the building can be designed to resist the shear forces and overturning moments to which it is subjected during the ultimate design wind event, serviceability performance objectives during common wind events are often more challenging to achieve [1]. Without mitigation, sensitive occupants on the upper floors of the building may experience discomfort on windy days, as they are able to perceive the building motion. Moreover, the building motion may impact the performance of building partitions and decrease the longevity of facade components, thus increasing costs associated with building maintenance.

The low inherent structural damping associated with most tall buildings is one of the main contributors to their susceptibility to wind-induced motions. To reduce building motion during common wind events, supplementary damping systems, such as dynamic vibration absorbers (DVAs) have become increasingly popular [2]. Two common types of DVAs are the tuned mass damper (TMD) and the tuned sloshing damper (TSD), also known as the tuned liquid damper (TLD). These devices are often modeled as auxiliary spring-mass-dashpot systems that are coupled to the primary structure. As the building experiences a resonant response, a properly designed DVA will interact with the structure, altering its mechanical admittance function, and leading to a decreased response. McNamara [3] derived the frequency-response function and the effective damping of a structure-DVA system subjected to white noise excitation, which is now commonly used to model wind loading.

The performance of a DVA is typically quantified using the concept of effective damping [4]. The effective damping may be understood as the amount of damping that the bare structure (without a DVA) must possess to experience the same response variance as the structure equipped with the DVA. Mathematically, the effective damping for the structural mode being controlled may be expressed as:

$$\zeta_{eff} = \zeta_{str}\frac{\sigma_{str}^2}{\sigma_{str-damped}^2} \quad (1)$$

where ζ_{str} is the inherent structural damping, σ_{str} is the root-mean-square (RMS) response of the structure without a DVA, and $\sigma_{str-damped}$ is the RMS response of the structure equipped with a DVA. Alternatively,

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if the mechanical admittance function of the structure equipped with a DVA, $H_{str-damped}(\omega)$ is known, the effective damping may be calculated as [4]:

$$\zeta_{eff} = \frac{\pi}{4}\omega_{str}\left[\int_0^{\infty} |H_{str-damped}(\omega)|^2 d\omega\right]^{-1} \quad (2)$$

where ω_{str} is the natural angular frequency of the structure. The amount of effective damping that a DVA appears to add to a structure (the "added effective damping") is quantified as:

$$\zeta_{added} = \zeta_{eff} - \zeta_{str} \quad (3)$$

When a DVA is installed in an actual tall building, it has traditionally been challenging to verify its performance by calculating its effective damping or added effective damping. Equation (1) requires knowledge of both the building response with and without a DVA ($\sigma_{str-damped}$ and σ_{str}), which cannot be measured simultaneously. Tamura et al. [5] inferred the structural responses and performance with and without a DVA by conducting long term structural monitoring, but in many cases this is undesirable due to the associated costs and desire to avoid subjecting occupants to the undamped building response. Alternatively, Eq. (2) requires knowledge of the mechanical admittance function of the building equipped with a DVA. Since the external excitation is generally not known, it is difficult to calculate the mechanical admittance function from a measured response. It is possible to reconstruct the theoretical mechanical admittance function if the dynamic properties (mass, stiffness, and damping) of the building and DVA are known; however, it is often challenging to identify the properties of coupled systems from ambient vibration measurements [6,7]. Moreover, this type of system identification methodology is quite complicated, and it would be beneficial if a more practical method to predict the added effective damping produced by a DVA were available.

Love and Tait [8] recently proposed a simple method to estimate the added effective damping of nonlinear structure-DVA systems when the structure is subjected to white noise random excitation. The method provides a direct calculation of the added effective damping based on the DVA-structure mass ratio and the responses of the structure and DVA(s). It was found to provide satisfactory results when evaluated using nonlinear simulations, as well as scale-model testing on a structure-TSD system. The benefit of this method is that it enables the performance of the DVA to be evaluated without using long-term monitoring with and without the DVA installed as was done in Ref. [5], nor does it require the dynamic properties of the system to be estimated using sophisticated system identification algorithms (such as Ref. [9]) to reconstruct the theoretical mechanical admittance function of the structure.

The purpose of the current study is two-fold. Firstly, it seeks to evaluate the model proposed by Love and Tait [8] using data collected from full-scale structural monitoring of two tall buildings equipped with DVAs. Its predictions are compared to the theoretical level of added effective damping using the estimated properties of the building and DVA. Secondly, the study seeks to evaluate the performance of the full-scale DVAs considered, to confirm that the devices are providing significant acceleration reductions. The first building is 10 Barclay Street in New York City, which is equipped with a unidirectional TSD. The second building studied is an anonymous super-tall slender tower that is equipped with two bi-directional TMDs.

2. Background

2.1. Structure-DVA system

If the directions of motion of the two structural sway modes are perpendicular, and the DVA direction of motion is aligned with the structural mode it is controlling, the structure-DVA system may be represented as shown in Fig. 1. A total of n DVAs with nonlinear damping may be tuned to a single structural mode. In Fig. 1, M_{str}, ω_{str}, and ζ_{str} are

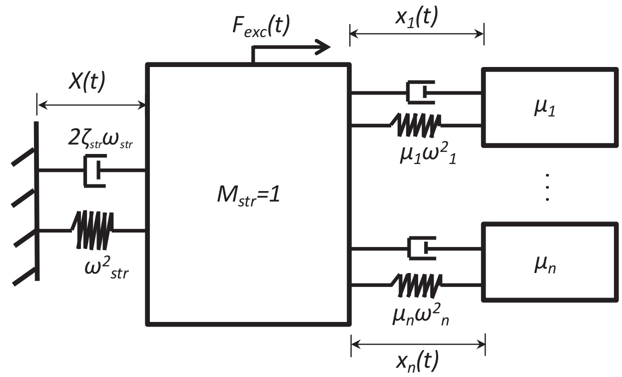

Fig. 1. Model of structure equipped with multiple DVAs.

the generalized mass, natural angular frequency, and damping ratio of the structure, respectively, while ω_i and ζ_i are the natural frequency and damping ratio of the ith DVA, respectively. When the damping force of the DVA is nonlinear, statistical linearization techniques are employed to represent the damping ratio as amplitude-dependent equivalent viscous damping [10]. The external force applied to the structure is $F_{exc}(t)$, displacement response of the structure is $X(t)$, and the relative displacement between the structure and the ith DVA is $x_i(t)$. The equations of motion for the structure and the ith DVA mass are:

$$\left(1+\sum_{i=1}^{n}\mu_i\right)\ddot{X}(t)+\sum_{i=1}^{n}\mu_i\ddot{x}_i(t)+2\omega_{str}\zeta_{str}\dot{X}(t)+\omega_{str}^2X(t)=F_{exc}(t) \quad (4)$$

$$\ddot{x}_i(t)+2\omega_i\zeta_i\dot{x}_i(t)+\omega_i^2x_i(t)=-\ddot{X}(t) \quad (5)$$

where each dot above a variable denotes a time derivative. If the structure-DVA system is bi-directional, another independent set of equations, and a corresponding set of dynamic properties exist for the perpendicular direction. In this study, the properties in the X- and Y-directions will be distinguished (when necessary) using the subscripts X and Y, respectively. The natural cyclic frequency, f (in units of Hz) is related to the angular frequency by $\omega = 2\pi f$. The solution to the equations of motion is straightforward, but tedious, and can be found elsewhere [3,11].

In this study, TSDs are represented as equivalent mechanical systems using well-known formulae for sloshing in a rectangular tank [12]. The tank has a length, L, width, b, and quiescent water depth, h, and is equipped with screens to increase the liquid damping. When screens are present in deepwater TSDs, they can be represented as an equivalent mechanical system, and have been shown to be effective in reducing building motion [12].

2.2. Added effective damping estimation

For structures subjected to white noise excitation, the mean rate of energy input into the system (that is, the mean power) depends only upon the excitation amplitude and the mass of the structure [13]. Therefore, for a stationary system, the mean power input and output for the system does not change when a DVA is coupled to the structure. By making use of this property, it has been shown that the added effective damping produced by a DVA can be calculated as [8]:

$$\zeta_{added} = \frac{\omega_{str}\sum_{i=1}^{n}\mu_i E[\ddot{X}(t)\dot{x}_i(t)]}{2\sigma^2_{\ddot{X}-damped}} \quad (6)$$

where $\sigma^2_{\ddot{X}-damped}$ is the variance of the structural acceleration, and $E[\ddot{X}(t)\dot{x}_i(t)]$ represents the covariance between the structural acceleration and the DVA relative velocity. Since the response of the structure and DVA are measured, only the DVA-structure mass ratio and natural angular frequency of the structure need to be estimated. In most cases, the mass ratio is known with reasonable accuracy, and if the as-