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Design and experimental study of a hybrid vibration absorber for global vibration control

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ABSTRACT

A simple and practical hybrid vibration absorber (HVA) is proposed for global vibration control of flexible structures under random stationary excitations. The HVA, regulated by a pole placement controller, uses a linear translational feedback signal to synthesize active moment via a moment actuator. It is shown, analytically and experimentally, capable of damping vibration in the entire primary structure. While the passive tuned mass damper (TMD) can suppress tonal vibration in the primary structure at the vicinity of the coupling point, it enhances vibration at other locations and other frequencies. The presented HVA, in contrast, can provide more than 48% extra broadband attenuation on vibrations at multiple points when compared with the passive TMD in experimental verification on a beam structure. Up to 85% extra broadband attenuation can be observed at the coupling point. The proposed HVA is a simple and economic alternative for engineers to retrofit the conventional TMD to a higher performance HVA for damping vibrations at multiple locations of the primary structure.

1. Introduction

The viscous damper is a well-known, effective and economic device for attenuating vibrations in structures like frames [1,2] and bridges [3–6]. Practically, a viscous damper may be mounted between two vibrating structures in order to damp relative motion [1–6]. It is also possible to mount a viscous damper between a vibrating structure and a relatively "fixed" base such as ceiling or ground to be a "hooked damper" [7,8]. No matter which mounting method is used, a viscous damper needs a backed-up point at one end. This restriction may limit the applicability of viscous dampers in some mechanical structures with free-end boundaries, or some applications where it is impossible to find nearby rigid supports.

The tuned mass dampers (TMD), on the other hand, are widely used for structural vibration control [9–13]. Fig. 1 shows a TMD for vibration control in many skyscrapers, such as the "Taipei 101". It only requires a point of attachment instead of a point of rigid support [14]. The vibration of the primary structure will cause the suspended mass to swing. As a result, tensions in the suspension cables are different, creating coupling moment and force to counteract the structural vibration [15]. A TMD is extremely effective attenuating vibration in a narrow frequency range in the vicinity of the mounting position. It could, however, develop some negative effect at points far away from the coupling location [16] or enhance vibration in other frequencies. If one increases damping ratio of a TMD to avoid enhancing vibration in other frequencies, the attenuation dip will be deteriorated since a TMD requires weak damping to suppress narrow-frequency vibration of the primary structure. Some researchers propose to find optimal damping ratio for the TMD based on accurate knowledge of eigen-functions, resonant frequencies and modal damping ratios of the primary structure. After choosing the optimal damping ratio for a TMD, how to implement it accurately is another practical problem.

The above problems of the TMD may be solved by integrating an active element into a conventional TMD. One may retrofit a TMD to a hybrid vibration absorber (HVA) with better performance for broadband vibration control [17,18]. Recent advances in the designs of HVA can be found in the literature [17,20–22]. Most available active controllers focus on suppressing vibration at a single point. A simple HVA is proposed by the authors for broadband vibration control over multiple points in a primary structure [23].

In the literature, most researchers assume accurate knowledge of eigen-functions and eigen-state feedback of the primary structures for controller design, implementation and stability analysis. In real applications, eigen-functions and eigen-states of primary structures are usually not available with sufficient accuracy. Active controller design may be based on identified models like discrete-time transfer functions. The design and stability analysis of controllers will be different due to different models and mathematical tools. This problem is addressed here. A simple active controller is designed and implemented based on a TMD similar to the one shown in Fig. 1. The new system only uses a linear accelerometer and a moment actuator to form a practical and economic HVA

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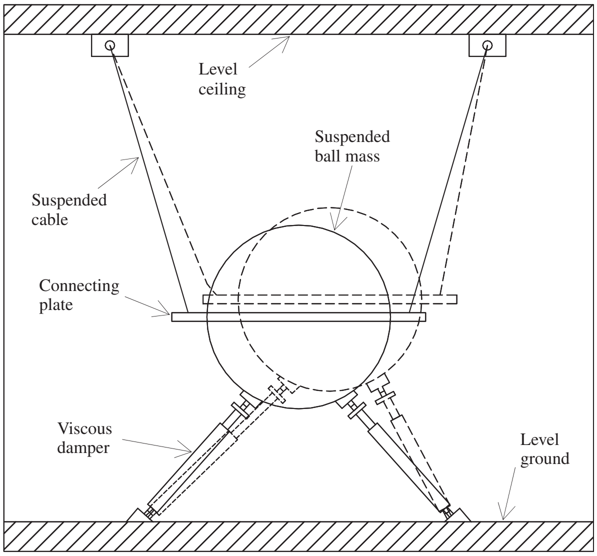

Fig. 1. 2D schematic of a tuned mass damper used in many skyscrapers like the "Taipei 101".

for structural vibration control. The proposed HVA is able to damp global broadband vibration in primary structures. Experimental data are presented to demonstrate the excellent global control performance.

2. Theory

The HVA presented here is simpler than its previous version [23] in the feedback sensor. A single-axis translational accelerometer, which is easily available and easy to install, is used instead of an angular displacement sensor. While it is possible to measure angular displacement with a piezoelectric sensor, the signal is proportional to the averaged bending over sensor length instead of angular displacement at a point. If the sensor length is not significantly smaller than the dimension of the primary structure, then spatial average effects of a piezoelectric sensor cannot be approximated accurately by a spatial Dirac delta function as assumed by many researchers in the literature. This is a problem in our experiments with a scaled primary structure, or other applications with small size primary structures. The translational accelerometer, on the other hand, is economic and smaller than the scaled primary structure in our experiments or other similar applications. The seemingly trivial sensor replacement causes some non-trivial changes of model properties, which could affect the controller design. The "unusual" combination of a translational feedback sensor with a moment actuator can be an alternative to some applications where the "usual" combination of translational sensors with force actuators or angular sensors with moment actuators could not be adopted due to some possible unforeseeable difficulties. It is explored in this study in details to show that the proposed HVA is independent of combinations of feedback sensors with actuators. The proposed HVA also differs from available counterparts since its parameters do not depend on accurate knowledge of eigen-functions of the primary structure and the controller does not require eigen-state feedback. This is a significant feature since eigen-functions and eigen-states of the primary structure are not available with sufficient accuracy in most practical applications. Even if eigen-functions of the primary structure are available accurately, eigen-state feedback requires multichannel feedback signals measured at multiple points of the primary structure. For ease of practical implementation, the proposed HVA parameters depend on the identified transfer function and a single feedback signal. Structural vibration response is monitored in experimental study in terms of mean square velocity and power spectral density (PSD) to evaluate the performance of the active controller on global vibration control. Some theoretical issues relating to the difference in mathematical model, the design and analysis tool are clarified here and in Section 3.2 respectively.

A cantilever beam, shown in Fig. 2, is used as the primary structure for theoretical study and experimental verification. The angular, linear displacements and velocity of the beam are denoted as $\theta(x,\ t)$, $w(x,\ t)$ and $\upsilon(x,\ t)$ respectively. The HVA is coupled with the beam at $x = x_a$ in Fig. 2. The angular displacement of the suspended mass is denoted as $\phi(t)$. A coupling moment generated by the HVA is denoted as $\tau(t)$. Its effect on the beam is described by $\tau(t)\delta(x - x_a)$, where $\delta(x - x_a)$ is a spatial Dirac delta function. The external disturbance is modeled by a moment function excited at $x = x_d$ and denoted as $r(t)\delta(x - x_d)$, where $r(t)$ is a stationary and random time function. Damping and displacement of the beam satisfy the Kelvin-Voigt [24] and Euler-Bernoulli hypothesis respectively. The dynamic equations of the coupled system can be written as

$$\rho\ddot{w}(x,t) + CI\dot{w}''''(x,t) + EIw''''(x,t) = \frac{\partial[r(t)\delta(x-x_d)]}{\partial x} + \frac{\partial[\tau(t)\,\delta(x-x_a)]}{\partial x},\quad 0<x<L \tag{1}$$

$$\tau(t) = k[\phi(t) - \theta_a(t)] + m_{\mathrm{act}}(t) \tag{2}$$

$$\tau(t) = -J\ddot{\phi}(t) \tag{3}$$

In Eq. (1), ρ, C, E and I represent, respectively, mass per unit length, damping coefficient, Young's modulus and second moment of cross-sectional area of the beam. Eq. (2) models the temporal effects of the coupling moment $\tau(t)$, with the active component $m_{act}(t)$ generated by a moment actuator. Effect of the rotational

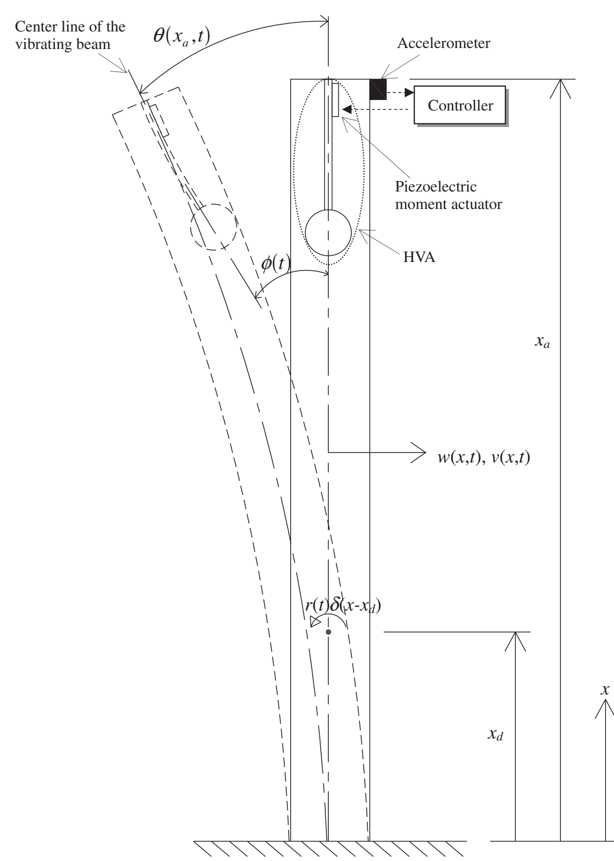

Fig. 2. Cantilever beam coupled with the proposed hybrid vibration absorber (HVA) at point $x = x_a$ under an external moment excitation $r(t)\delta(x - x_d)$ at point $x = x_d$.