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Vibration control performance of tuned mass dampers with resettable variable stiffness

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ABSTRACT

Vibration control of civil engineering structures using tuned mass dampers (TMDs) is a widely acknowledged control strategy based on numerous analytical and experimental verifications. Although the design and application of traditional linear TMD systems are well established, nonlinear TMD systems that may have better control performance remain in the developmental stage. The TMD systems have two main problems, i.e. detuning effect and excessive TMD's stroke. To improve the overall performance of TMD systems, a novel semi-active TMD named resettable variable stiffness TMD (RVS-TMD), is proposed. The RVS-TMD consists of an undamped TMD and a resettable variable stiffness device (RVSD). This RVSD is composed of a resettable element and a controllable stiffness element. By varying the stiffness of controllable stiffness element in the RVSD, force produced by the RVSD can be controlled smoothly through a semi-active control law. By operating the resettable element, the hysteretic loops of the RVSD can cover all four quadrants in the force–deformation diagram and, thus, increases energy dissipation. In other words, both stiffness and damping of the RVS-TMD are adjustable via only the RVSD device. The harmonic and seismic responses of a building equipped with the RVS-TMD were investigated. Numerical results show that the proposed RVS-TMD system can avoid detuning effect automatically and assure the optimal control performance as desired when the frequency of primary structure is changed.

1. Introduction

Vibration control of civil engineering structures using tuned mass dampers (TMDs), which has been through numerous analytical and experimental verifications, is a widely accepted control strategy [1–8]. Notably, TMDs can be incorporated into any structure with less interference than other energy-dissipation devices. The TMDs have been used in high-rise buildings, observatory towers, building floors, railway bridges, and pedestrian bridges against natural and man-made loadings since 1970 [9–12]. A TMD system consists of an added mass with properly functioning spring and damping elements that provide frequency-dependent damping for a primary structure. By attaching a TMD, vibration energy in a structure can be transferred to the TMD and dissipated via damping. Although traditional linear TMD systems are well developed, the existing TMD systems have two main deficiencies: (1) the detuning effect; and (2) an exceedingly large TMD's stroke. The detuning effect occurs when TMD's frequency is not tuned to the desired value. The exceedingly large TMD's stroke occurs when the damping mechanism of the TMD becomes inefficient.

To improve the performance of TMD systems, a considerable degree at success in using semi-active TMD systems, combining a passive TMD system with a semi-active control device has been realized [13–16]. The semi-active devices can be in one of several forms, including a magneto-rheological damper [17–20], a variable friction damper [21–26], a variable stiffness device [27–29], or a resettable stiffness damper [30,31]. A semi-active control device generally has the following advantages over an active control device [32]: (1) force generated by a semi-active device, which is exerted by the relative motion between the device and structure, is a passive (resistance) force. That is, the force applied by the device is always related to the motion of structural components to which it is attached. (2) A semi-active device generates a passive force, such that it does not pump energy into controlled structures. The problem of control instability is thus eliminated. (3) Controlling the internal parameters of a semi-active device generally requires much less control energy than employing an active device. Among the many semi-active devices, the variable stiffness device (VSD) is relatively new. The VSDs are either an on–off-type VSD [33–35] or continuous-type VSD [36–39]. Prototypes of both VSDs have been verified analytically and experimentally.

The on–off-type VSD originated from a structural control system called active variable stiffness (AVS) system proposed by

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Kobori et al. [40], in which variable stiffness was achieved by adding additional stiffness using an on/off switch. The AVS concept was progressed further into a class of control devices commonly referred to as the resettable semi-active stiffness dampers (RSASDs). Generally, an on–off-type VSD is modeled by constant stiffness connected in series with a resetting device functioning as an on–off switch. The spring and resetting device are modeled using pressurized gas (or oil) and some gas-based (or hydraulic) valves and parts. The general resetting control law for the on–off-type VSD is based on Lyapunov theory, which resets VSD stiffness periodically when the relative velocity across the damper equals zero. Each resetting releases the accumulated vibration energy captured and stored in the stiffness part of the VSD, dissipates the vibration energy of the VSD; therefore, the on–off-type VSD is very effective in suppressing displacement response [33–35].

Some previous researches focused on the continuous-type VSD. Nagarajaiah et al. [36,37] designed a semi-active continuously and independently variable-stiffness (SAIVS) device, which consists of four springs arranged in a rhombus configuration. By altering the angle of the rhombus-shaped springs, the SAIVS device can vary stiffness continuously and smoothly. Lu et al. [39] developed a leverage-type stiffness controllable isolation system (LSCIS). Taking the advantage of a simple leverage mechanism, isolation stiffness of the LSCIS can be controlled by adjusting the pivot point position of the leverage arm. However, because these devices lack resetting ability, the resistant force of a VSD is limited to the same direction as device deformation. That is, the hysteretic loop produced by the continuous-type VSD can only exist in the first and third quadrants of the hysteretic diagram (force–displacement diagram). Therefore, the continuous-type VSD dissipates less energy than the on–off VSD, which has a hysteretic loop covering all four quadrants. Sun and Nagarajaiah [41] proposed a semi-active tuned mass damper (STMD) with variable damping and stiffness devices in parallel to enhance the control performance of the continuous-type TMD. Both the damping and stiffness of the TMD can be altered smoothly.

Noting that the continuous-type variable stiffness TMD prevents the detuning effect, while the on–off-type variable stiffness TMD reduces TMD's stroke. This paper presents a novel resettable variable stiffness TMD (RVS-TMD) which combines the advantages of both continuous-type and on–off-type variable stiffness TMDs is proposed. First, the proposed RVS-TMD system configuration, which consists of a TMD system and an RVSD, is characterized. A semi-active control strategy for the RVSD is then introduced. The hysteretic behavior and harmonic response of the RVS-TMD system are investigated and discussed. Finally, the seismic behavior of a structural system controlled by the RVS-TMD is simulated and compared with those using different (passive and active) TMD systems. These comparisons consider the performance indices of primary structural responses and TMD's stroke. The detuning effect is also investigated.

2. System modeling and equation of motion

2.1. Resettable variable stiffness TMD (RVS-TMD)

Fig. 1 shows the schematic diagram of a primary structure equipped with the RVS-TMD. The TMD is supported on a sliding platform, consisting of guide rails, sliding blocks, and springs. The springs provide stiffness, resilience, and tuning frequency. Moreover, the RVSD consists of a variable stiffness and resettable device as seen in Fig. 2(a). Symbols $u_d(t)$ and $k_d(t)$ denote the force and controllable stiffness of the RVSD, respectively; $d_e(t)$ represents the elongation of variable stiffness; and $d_s(t)$ denotes resettable device displacement. For comparison, Fig. 2(b) and (c) show mathematical models of the on–off type and continuous type VSDs, respectively. The RVSD combines the functions of both VSDs. Fig. 3 shows the overall mathematical model of a structure equipped with the RVS-TMD. The stiffness of the RVS-TMD sliding platform is modeled by a spring with stiffness k_s. The masses of the RVS-TMD and primary structure are denoted by m_s and m_p, respectively; and c_p and k_p are the damping and stiffness coefficients of the primary structure.

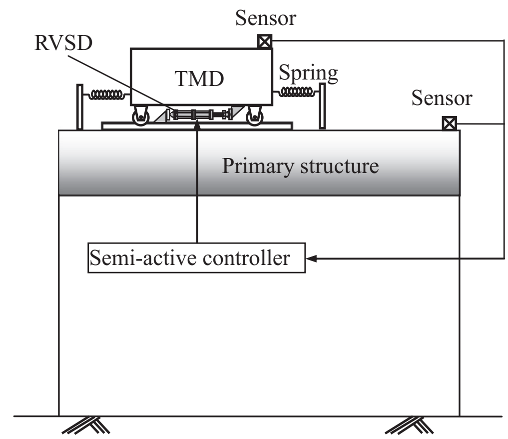

Fig. 1. Schematic diagram of a semi-active tuned mass damper.

2.2. Control philosophy of RVS-TMD

The control philosophy of RVS-TMD is illustrated in this section. The only controllable device in the RVS-TMD system is the RVSD, which is composed of a resettable element and a controllable stiffness element. To alleviate the detuning effect, the dynamic response of the RVS-TMD can be attenuated by altering the variable stiffness $k_d(t)$ in real time. The target stiffness $\hat{k}_d(t)$ at any instant is computed as

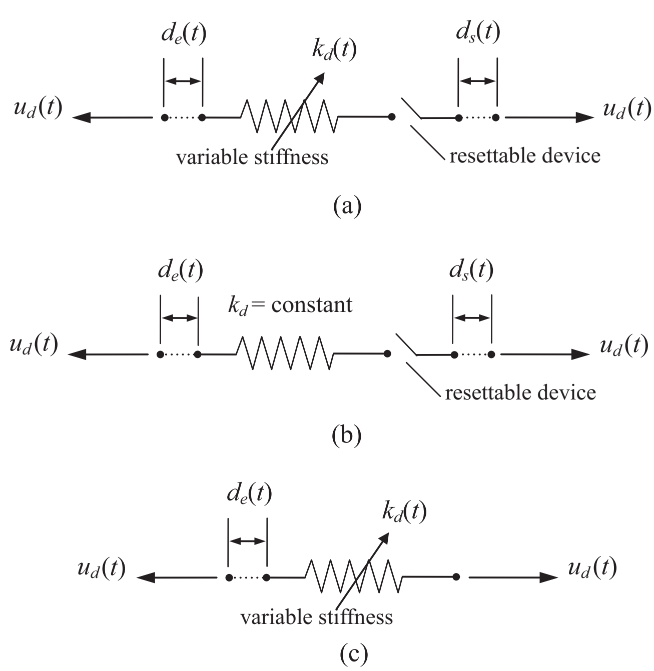

Fig. 2. Mathematical models for different types of variable stiffness devices. (a) Proposed RVSD. (b) On–off type VSD. (c) Continuous type VSD.