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Displacement Control Design Concept for Long-period Structures: Design Strategies for High-rise and Seismically Isolated Buildings Subjected to Strong Ground Motions

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ABSTRACT
Recently in Japan, an issue of excessive displacements induced by long-period/long-duration ground motions are attracting public attention. Indeed, many high-rise buildings in Tokyo far away from the epicenter suffered large displacements and long-duration shaking induced by long-period components of the ground motions in the 2011 Great East Japan Earthquake. To address this issue, the authors have been developing control strategies and devices that can suppress excessive displacements in long-period structures without increasing response shear forces and floor response accelerations. This paper provides brief review of the newly developed design concept *Displacement Control Design* and innovative devices that implement the concept.

KEYWORDS: *Displacement control design, long-period structure, high-rise building, seismic isolation, smart passive damper*

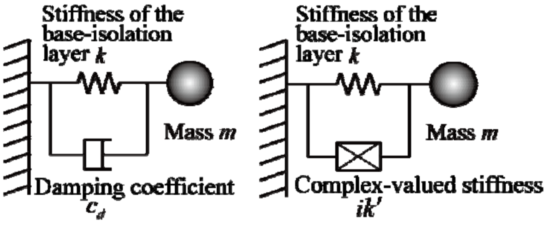
1. INTRODUCTION

The earthquake-resistant design code provision in its early stages in Japan required that structures resist seismic force produced by response acceleration. The design concept subsequently, in accordance with the increase of heights of structures to be constructed, evolved to take response displacement as well as response acceleration into account to utilize ductility of structures in reduction of required strength on the basis of the concept of energy balance. However, construction of many long-period structures such as seismic isolation buildings in recent years resulted in an issue of excessively large displacements caused by long-period components of ground motions due to extremely severe earthquakes. Although the excessive displacement does not necessarily cause structural damages, the excessive displacement itself is harmful. It is considered to be effective to incorporate certain damping devices that control vibrations in direct response to the response displacement. The authors define this concept as “displacement control design” and have developed some control strategies and devices to implement it. This paper outlines the basic concept of displacement control design and the mechanisms and application of the newly developed dampers.

2. THE CONCEPT OF DISPLACEMENT CONTORL DESIGN

Viscous damping commonly used as a damping element produces a resistance force proportional to response velocity. A rate-independent linear damping element dependent only on displacements, on the contrary, is represented by complex-valued stiffness[1]. Here, these damping characteristics are represented by velocity-dependent damping model and rate-independent linear damping model as shown in Fig. 2.1 (a) and (b), respectively. Fig. 2.2 represents the relationships between damping forces and displacements of the two models.

We compared the response time history and hysteretic response by conducting frequency domain analysis using transfer functions in order to examine the differences of response characteristics. As an analytical example, a seismic isolated building having a period of 4 seconds is employed. The superstructure is regarded as a rigid body and the analytical model reduces to single-degree-of-freedom (SDOF) system whose primary mass is 4276.8 t. As for the input ground motion, the JMA Kobe record of the 1995 Kobe Earthquake is used. The viscous damping ratio and complex damping ratio for the velocity dependent damper and rate-independent damper, respectively, are 0.2.



(a)Velocity dependent model (b) Rate-independent model

Figure 2.1 Single-degree-of-freedom models

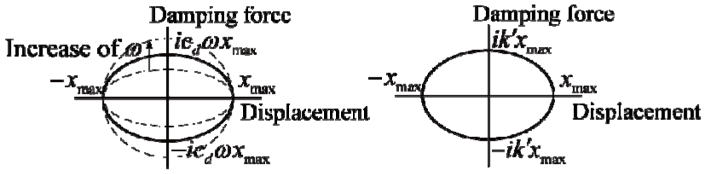


Figure 2.2 Relationships between damping forces and displacements

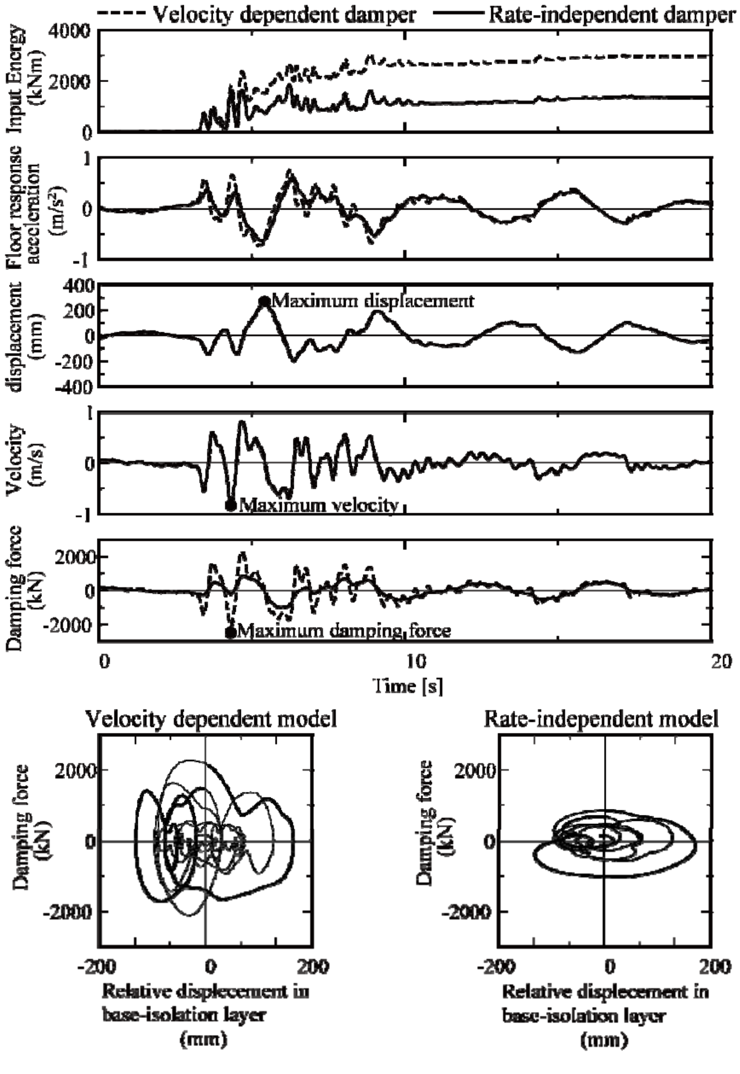


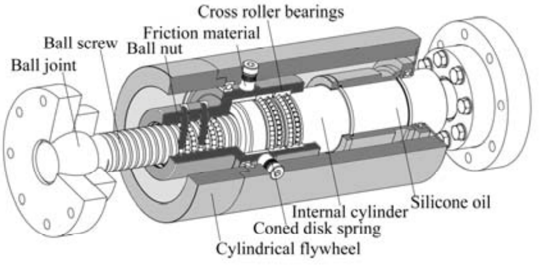
Figure 2.3 Comparison of Velocity Dependent Model and Rate-Independent Model
(JMA KOBE 1995 NS record)

Fig. 2.3 depicts the time histories the two models yielded. The thick lines in the hysteresis loops represent the one cycle hysteresis, from the time when zero velocity is marked to the next, in which the maximum displacements are included. The rate-independent linear damping model obtained the largest damping force in a loop shown in the thick line in which the maximum displacement is marked because it generates damping force in response to the displacement. On the contrary, the velocity dependent damper obtained the maximum damping force irrelevant to the maximum response displacement because it generates damping force in response not to displacement but to velocity. Thus, the maximum damping force generated by the velocity dependent damper is irrelevant to control of maximum displacement. Ground motions containing short period components as dominant frequencies such as JMA Kobe 1995 NS record particularly tend to observe phenomena mentioned above. Indeed, JMA Kobe 1995 NS record observed that the rate-independent model reduced the maximum response damping force and input energy to about halves of those obtained by the velocity dependent model.

3. IMPRIMENTATION IN SEISMIC CONTROL

By supporting a rotational mass damper consisting of a viscous damping element and apparent mass produced by ball screw mechanism in parallel configuration obtains a tuned mass damper-like energy dissipation device to construct an effective seismic control system [2-10]. The authors denoted this system as the tuned viscous mass damper (TVMD) system. The rotational mass damper is equipped with a rotational friction mechanism to restrict damping forces to avoid excessively large reaction forces, which is referred to as the force restricted viscous mass damper (FRVMD; Fig. 3.1) [11,12].

As shown in Fig. 3.2, the secondary mass multiplied by the absolute response acceleration generates the control force in a conventional TMD, which is known to be effective against wind-induced vibrations[13]. The secondary mass of the TMD, however, is usually insufficient for the control of earthquake-induced vibrations[14]. On the other hand, the TVMD can provide a secondary mass several thousand times as large as the physical mass that is activated by inter-story relative accelerations. Thus, a sufficient apparent mass can be obtained for the control of vibrations induced by severe earthquakes.



*Colored portions represent rotating parts

Figure 3.1 Schematic Representation of Force Restricted Viscous Mass Damper

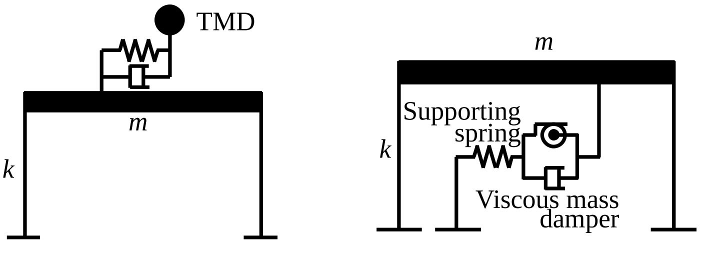


Figure 3.2 TVMD and Conventional TMD

Fig. 3.3 represents the energy dissipated per cycle by the viscous damper, viscous mass damper, and tuned viscous mass damper having the same damping element. As depicted in Fig. 3.3, the secondary vibration system tuned to the primary system enlarges the deformation of the damping element resulting in more efficient energy dissipation in the damping element having the same damping coefficient.

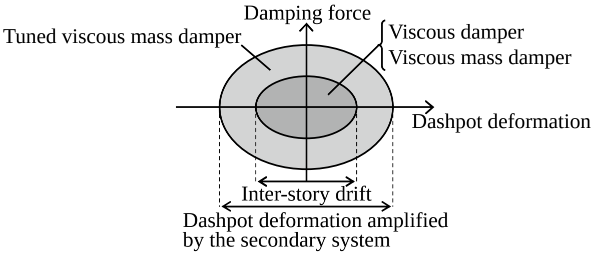
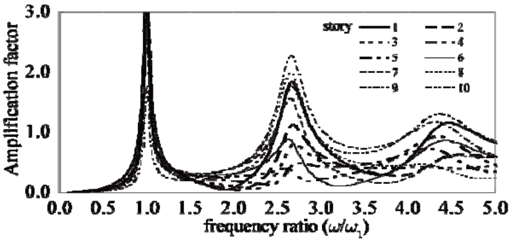
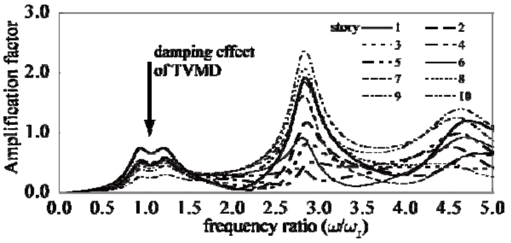


Figure 3.3 Energy Dissipated in Damping Elements

Fig. 3.4 shows the displacement amplification factor of a ten story building containing TVMDs subjected to harmonic excitations. The TVMD system is tuned to the primary first mode and has apparent mass distribution proportional to that of primary stiffness. It can be observed that only the amplification factors in the vicinity of the first mode (the tuned mode) is suppressed without changing the amplification factors of the other modes. Thus, TVMD is a seismic control device that performs selective damping to the tuned mode and almost never affects the other modal responses. It is worth noting that the TVMDs incorporated into a long-period structure and tuned to the first mode to control response displacements induced by long-period/long-duration ground motions can be categorized as rate-independent damping devices that comply with the concept of the displacement control design because they can avoid excessively large damping forces produced by the higher modes having shorter periods.



(a) Uncontrolled system



(b) TVMD controlled system

Figure 3.4 Displacement amplification factors under harmonic excitations

Fig. 3.5 compares the performance of FRVMDs and oil dampers incorporated into a fifty-story high-rise building subjected to TAFT 1952 EW record that is scaled such that its PGV is 0.5 m/s. Five FRVMDs or oil dampers are located on each floor for each cases.

Each oil damper has a maximum load capacity of 1,000 kN and a relief load of 800 kN. Thus, five dampers on each story result in an equivalent damping ratio of 0.6 % first modal critical damping. Combining the equivalent damping and the inherent damping ratio of 2 % obtains a damping ratio of 2.6%.

Incorporating multiple types of FRVMDs tuned to specified modes into a building enables a TVMD seismic control system to perform multi-modal control[5,11]. Thus, FRVMDs tuned to the first mode are incorporated into the first to 35th floor and those tuned to the second mode are incorporated into 36th to 50th floor in the TVMD controlled case, where the secondary mass amplification factor in a FRVMD is 6,940.

Comparison between the oil damper controlled and TVMD controlled cases observes that inter-story drifts yielded by the both cases are almost identical, whereas the maximum damper forces yielded by the FRVMDs are approximately halves of those yielded by the oil dampers except stories around the top as shown in Fig. 3.5.

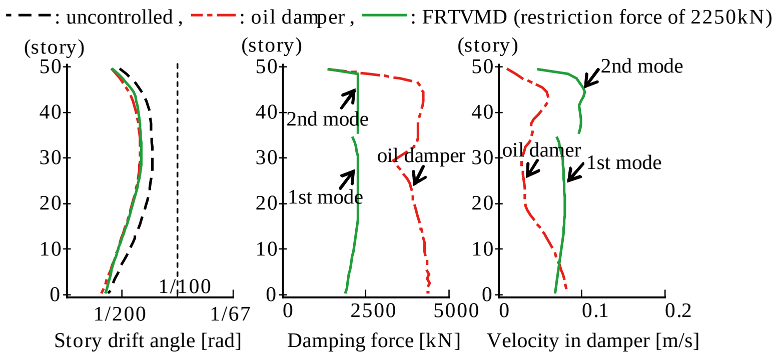


Figure 3.5 Maximum responses yielded by TAFT 1952 EW record (PGV = 0.5 m/s)

4. IMPLIMENTATION IN SEISMIC ISOLATION

As mentioned in Section 2, the rate-independent linear damping model incorporated into a long-period structure is a promising option to implement the concept of displacement control design. Since no physical elements exist to implement ideal rate-independent linear damping owing to its non-causality[15], it is a viable option to employ an active or a semi-active control device with a control algorithm that mimics the behaviour of the damping model[16-20]. A magneto-rheological (MR) fluid damper is one of the suitable semi-active devices to implement the displacement control design concept because arbitrary and relatively large resistance forces can be obtained by controlling the electric current applied to the magnet coil in the damper.

Let $X(i\omega)$, ω_0, h, and m be the Fourier transform of the isolator displacement, the fundamental circular frequency, the damping ratio, and the total mass of the superstructure, where ω is the excitation frequency. Obviously, the damping force in the frequency domain $\mathcal{F}[c\dot{x}(t)] = ic\omega X(i\omega) = 2ih\omega_0\omega m X(i\omega)$ is proportional to the excitation frequency. The role of the digital filter we propose here is to eliminate the frequency dependency from the damping forces. Thus, the transfer characteristics of the target filter can be expressed by the function $G(i\omega) = \omega_0 / \omega$. To obtain the transfer characteristics, a first order Butterworth low-pass filter (Eq. (4.1), Fig. 4.1(b)) is applied to the response velocity to eliminate the frequency dependency of the response velocity in high frequencies. The time delay caused by the Butterworth filter is compensated by a delay compensating filter, which derives velocity of the free vibration at the time that is t_a second after the present time t (Eq. (4.2)).

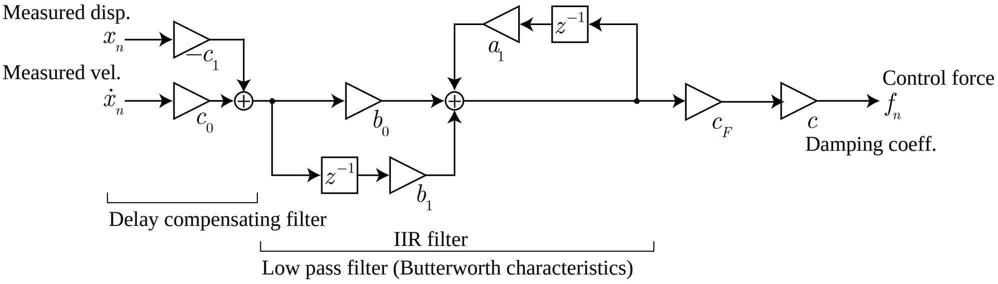


Figure 4.1 Diagram of the Digital Filter

$$H_{BW}(i\omega) = \frac{1}{1 + \dfrac{i\omega}{\omega_0}} \tag{4.1}$$

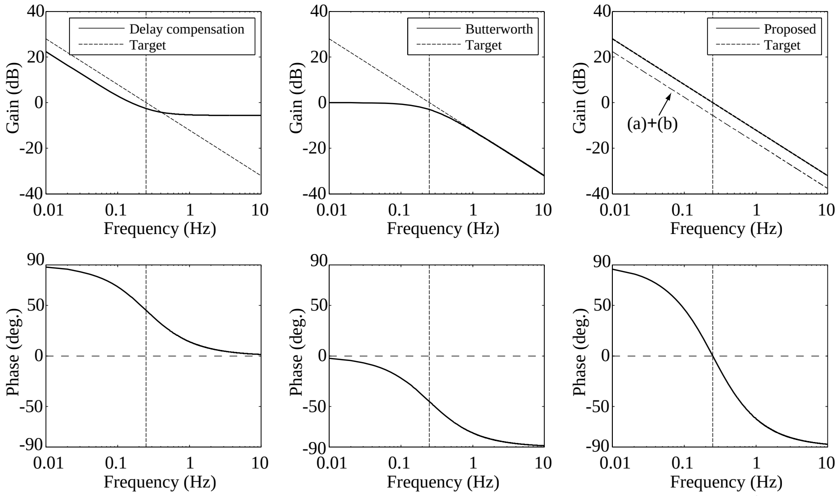
$$x(t + t_a) \simeq c_0\dot{x}(t) - c_1 x(t) \tag{4.2}$$

where,

$$c_0 = e^{-h\omega_0 t_a}\left(\cos\omega_D t_a - \frac{h}{\sqrt{1-h^2}}\sin\omega_D t_a\right) \tag{4.3}$$

$$c_1 = e^{-h\omega_0 t_a} \frac{\omega_0 \sin \omega_D t_a}{\sqrt{1-h^2}} \tag{4.4}$$

$$\omega_D = \sqrt{1-h^2}\,\omega_0 \tag{4.5}$$



(a) Delay compensating filter (b) Butterworth filter (c) Proposed filter

Figure 4.2 Bode Plots

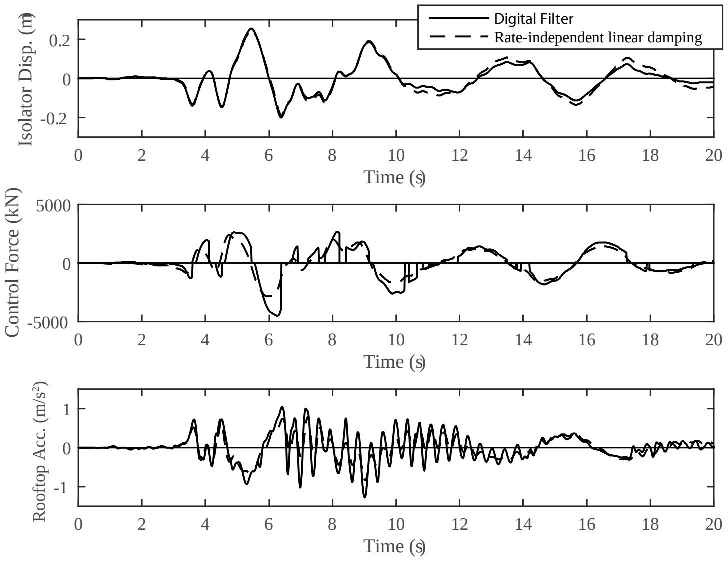


Figure 4.3 Time histories (JMA Kobe record of the 1995 Kobe Earthquake)

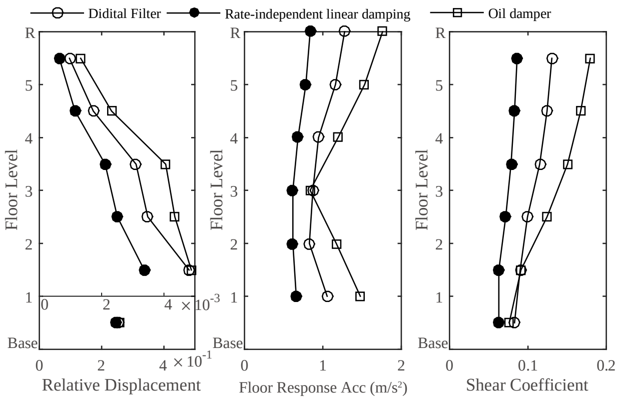


Figure 4.4 Comparisons on Maximum Responses (JMA Kobe record of the 1995 Kobe Earthquake)

As shown in Fig. 4.2, combining the delay compensation filter (Fig. 4.2(a)) and the Butterworth filter (Fig. 4.2(b)) obtains the proposed filter (Fig. 4.2(c)) whose magnitude (gain) is inverse proportional to excitation frequency. The distortion of the phase angle at the fundamental frequency vanishes when the advance time t_a is chosen according to the following equation.

$$t_a = \frac{1}{\omega_D}\tan^{-1}\sqrt{\frac{1-h}{1+h}} \tag{4.6}$$

The gain c_F in Fig. 4.1 is determined such that the magnitude of the proposed filter at the fundamental frequency vanishes.

$$c_F = \frac{2\omega_0}{\sqrt{c_0^2\omega_0^2 + c_1^2}} \tag{4.7}$$

Bi-linear z-transform of Eq. (4.1) yields the infinite impulse response (IIR) filter shown in Fig. 4.1.

Fig. 4.3 compares the time histories of a 5-story base-isolated building containing ideal rate-independent linear damping and an MR damper controlled with the proposed algorithm. Since the MR damper is semi-active device, it does not generate the control forces having opposite direction of the response relative velocity in the damper. This resulted in deteriorated responses; nevertheless the MR damper obtained better responses than an oil damper with a relief valve which achieves the same maximum isolator displacement as those of the other damping elements as shown in Fig. 4.4.

5. CONCLUDING REMARKS

In this paper, it is elucidated that the “displacement control” design strategies using rate-independent damping devices which generate damping forces in direct response to displacements are effective for long-period structures such as high-rise and/or seismic isolated buildings. Ideally, a rate-independent linear damping element can be represented by complex-valued stiffness, whose non-causality brings about difficulty to the realization in real time operation. The authors developed tuned viscous mass dampers for seismic control of high-rise buildings and a new control algorithm for a magneto-rheological damper to be incorporated into seismic isolated buildings that mimics the behaviour of rate-independent linear damping. Applications of these devices enable reduction of displacements in long-period building structures without deterioration of floor response accelerations. These devices are, so to speak, smart passive dampers and are effective against the future expected extreme seismic events.

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