

CURRENT DEVELOPMENT OF FUNCTIONALLY UPGRADED PASSIVE DEVICES FOR SEISMIC RESPONSE REDUCTION

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ABSTRACT :

In this paper, the concept of functionally upgraded passive devices is introduced to streamline some of the state-of-the-art researches and guide the development of new passive devices that can mimic the function of their corresponding semi-active control devices for various applications. The general characteristics of this special group of passive devices are discussed and representative examples are summarized. Their superior performances are illustrated with cyclic tests of mass-variable tuned liquid damper.

KEYWORDS: passive device, tuned liquid damper, friction pendulum bearing, particle motion

1. INTRODUCTION

With a single actuator, an active control system can generate a significant control force for the improvement of the global behavior of a building or bridge system (Soong, 1990). However, the external power required to change an active system is often unavailable during a strong earthquake event. In addition to cost, the reliability and maintenance issues of a control system are two hurdles to overcome in its practical applications.

In comparison with active control, passive devices can change the behavior of a controlled structure in relatively local areas; their application in the structure often appears in multiple units in order to effectively mitigate structural vibration (Chen and Wu, 2001; 2003). Since they require no external power and little maintenance after installation, passive devices have gained increasing acceptance in practice. However, although passive devices can be optimized to achieve a performance objective under a specific loading and environmental condition, they are not adaptive to external disturbances in a conventional sense. Therefore, passive devices are in many cases less effective than active control.

The trade-off between the required external power and performance of a control strategy has led to the development and extensive research of semi-active devices and systems (Chen and Chen, 2004a, 2004b). In this case, while the performance of a properly-designed semi-active device could be similar to that of an active control system, the power required to change the parameters of the device during an earthquake event is considerably lower, making it practical to use such a device in application. On the other hand, however lower the required external power is, semi-active systems need some maintenance over the years of their service.

In this paper, a suite of passive devices that can closely mimic the behavior of their corresponding semi-active devices are introduced. They have clearly-defined counterparts, conventional passive devices, but with superior performance in certain functions. As such, these systems are herein referred to as functionally upgraded passive devices. They require virtually no maintenance in applications and expect to gain wide acceptance in engineering practices. The new concept of these systems is illustrated with a mass-variable tuned liquid damper.

2. FUNCTIONALLY UPGRADED PASSIVE DEVICES

Functionally upgraded passive devices include, but are not limited to, mass-variable tuned liquid dampers,

friction pendulum bearings with variable sliding surface curvatures, friction-variable dampers with self-centering features, and nonlinear energy sink dampers. Their general characteristics are summarized below.

2.1. General Characteristics

Functionally upgraded passive devices introduced in this paper must be discussed with respect to conventional passive systems. They add one or more functions to their corresponding passive systems. In many cases, just like semi-active devices, they are adaptable to external disturbances as the main parameters of their corresponding conventional passive device change with the level of external excitations. A functionally-upgraded passive device has three general characteristics:

- It requires no external power to operate,
- It has a clearly-defined conventional passive device and adds at least one function to the passive device, such as adaptability to external disturbances and self-centering of friction dampers, and
- Its parameters can be automatically adjusted with the use of earthquake-induced energy and power.

2.2. Mass-variable Tuned Liquid Damper

A tuned liquid damper (TLD) has three undesirable characteristics. Like all tuned dampers, a TLD is generally ineffective in suppressing the first peak response of a building to impulsive loading. It is low in energy dissipation capability for the building structure being controlled. It has low damping so that, once in motion, the sloshing motion of a TLD continues after the earthquake excitation is over (Sun, 1991). To overcome these undesirable features, a mass-variable tuned liquid damper (MVTLD) is introduced in this study.

An MVTLD can simply be constructed with a rectangular tank of sloped bottom (Xin, 2006). As illustrated in Figure 1, the tank is filled with water and fine sand particles. The sand particles are added to the water in the rectangular tank to increase the density of a mixture of sands and water after the sands are in a suspended state. The sloped bottom of the MVTLD is used to mimic the wave energy dissipating effect of a sloped beach. More importantly, the sloped bottom of the tank can set sand particles in the tank in motion more rapidly when the tank is subjected to an increasing base excitation. As a result, the MVTLD has a larger liquid-tank contact area and a larger mass than a conventional tuned liquid damper (TLD) given the same space occupied by them.

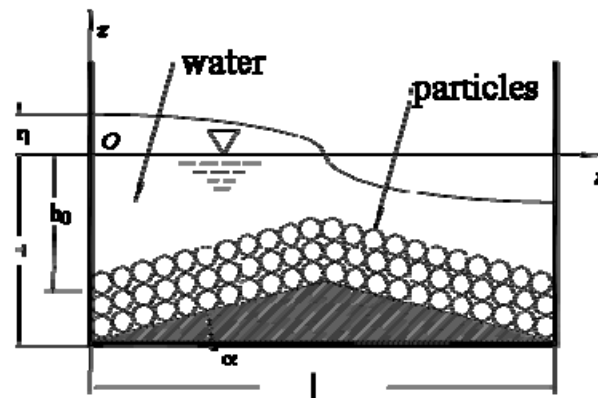


Figure 1. Schematic view of a mass-variable tuned liquid damper

Under a weak base excitation, the sand particles in the tank remain at the bottom of the tank and the water above is sloshing on the free surface. As the excitation increases, the sand particles appear in a liquefied state due to increase in pore pressure between the particles; the water and particles are sloshing together. Since the mass involved in sloshing increases with the base excitation, the proposed device is referred to as a mass-variable damper that requires no external energy. In terms of the requirements for mechanical and power services, it is a maintenance-free device.

2.3. Friction Pendulum Bearing with a Variable Sliding Surface Curvature

Friction pendulum system (FPS), as a sliding isolator, has been implemented in many existing structures (Mokha *et al.*, 1991). The sliding surface of a FPS isolator is in spherical shape so that the gravity load applied on the slider will provide a restoring stiffness and re-centering force for the isolated structure. Corresponding to the restoring stiffness, the isolated structure has a fixed natural period in second, depending upon the radius of the spherical sliding surface. As a result, FPS is sensitive to the long-period components in earthquake ground motions, such as near-field earthquake records. Indeed, the isolator displacement could be considerably amplified due to the long-period pulses present in most near-field ground motions (Lu *et al.*, 2006). In order to prevent the potential resonance that an FPS may experience, a 6th order polynomial friction pendulum isolator (PFPI) with a variable characteristic period was introduced.

As illustrated in Figure 2(a), the sliding surface of a PFPI is axially symmetric about the centerline with variable curvatures. In addition, for the convenience of comparison, the elevation profiles of two FPS bearings, denoted by FPS-2.5s and FPS-1.25s, are also plotted in Figure 2(a). The FPS-2.5s represents a FPS bearing with an isolation period of 2.5s, which is a commonly adopted period for FPS systems. On the other hand, the FPS-1.25s denotes a FPS with an isolation period of 1.25s, which represents a short-period isolator. The reason of showing FPS-1.25s is that its elevation is approximate to that of the PFPI at the same isolator displacement. The radii of the sliding surfaces for FPS-2.5s and FPS-1.25s are 1.55m and 0.39m, respectively. As shown in Figure 2(a), the elevation profile of the PFPI is defined by a 6th order polynomial function. As a result, the slope $y'(x)$ in radial direction becomes a 5th order polynomial function of the displacement as shown in Figure 2(b). The slope $y'(x)$ is also equal to the restoring force of the isolator normalized with respect to the isolator vertical load (Lu *et al.*, 2006). As illustrated in Figure 2(b), the restoring force of the PFPI starts with a softening portion and is followed by a hardening portion. The softening portion functions as a base isolation component for peak acceleration reduction in buildings while the hardening portion is to reduce the deformation of the isolator.

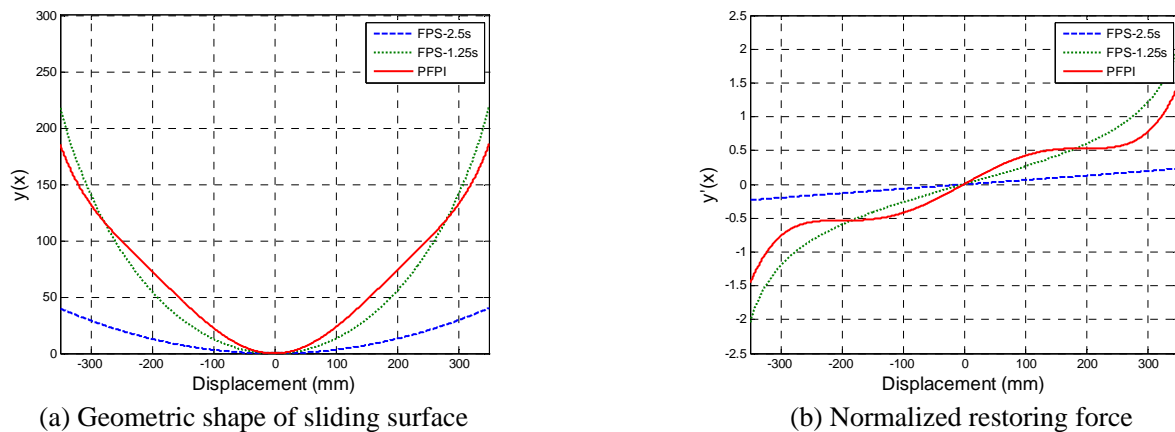


Figure 2. Comparison between an FPS and a PFPI

2.4. Friction-variable Dampers

Friction is an effective way of energy dissipation that has been used in practice since ancient times. The amount of energy dissipation depends upon the clamped force and the sliding distance experienced between two rigid parts that can move against each other. To maximize the energy dissipation, the clamped force is typically set to high for strong earthquakes. Such a friction system, however, may dissipate zero energy since the two parts of the system may be stick to each other and experience no slippage under small or moderate earthquakes. This potential stick phase of a friction system usually results in sudden motions or jerks, which is harmful in building applications. Therefore, friction variable dampers are desirable for the mitigation of multiple earthquake hazard levels.

A friction-variable damper can be constructed with two steel plates clamped together by two parallel links whose ends are free to rotate but restrained for translational motions in all directions. The interface of the two plates is designed in a curved shape as shown in Figure 3. As the top plate is moving against the bottom plate in either direction, the clamped force on the friction surface between the plates increased from two sources: elongation of the two clamping links and change in thickness of the two plates at the location of each link. When the links are elongated, the tension force in each link increases so that the clamped force applied on the friction surface increases. Similarly, the minimum thickness of the two plates is arrived at the initial position of the links. As the two plates move against each other, due to the curved friction surface, the plates at the location of links become thicker, resulting in further increase of the clamped force. Depending on the design of the curved shape of the friction surface, various clamped forces as a function of the slip between the two plates can be generated. Although no external power required, the behavior of the friction damper is similar to a semi-active friction device such as piezoelectric friction dampers (Chen and Chen, 2004a; 2004b).

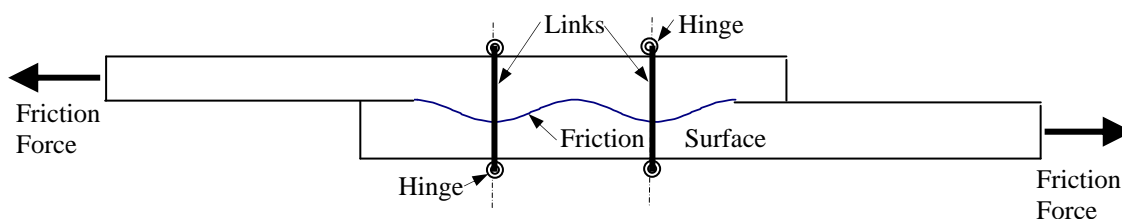


Figure 3. Schematic view of a friction-variable damper

Recently, self-centering features were introduced into friction damping devices (Zhang and Zhu, 2006). They were realized by incorporating superelastic nitinol wire strands between two parts of a friction device. By changing the ratio between the yield strength of the nitinol wire strands and the friction between two parts, nearly self-centering performance of the friction device can be achieved. A similar concept can be introduced to the friction-variable damper schematically shown in Figure 3 to add the self centering feature. The hysteresis loop of the friction damper illustrated in Figure 3 depends on the shape of the friction surface. When the shape of the interface surface is defined by $y(x) = e|x(t)| + g|\dot{x}(t)|$ where e and g are two constants, the hysteresis loop is similar to those described in Chen and Chen (2004a; 2004b).

2.5. Nonlinear Energy Sink Dampers

Tuned mass damper (TMD) has been applied to high rise buildings and bridges for the suppression of wind-induced vibration and other narrow frequency band vibration induced by machine operation and human walking. Earthquake loads, however, have a much wider band of frequency components. In this case, multiple TMDs have been considered to suppress several dominant modes of vibration (Chen and Wu, 2001; 2003). In addition, after the earthquake excitation is over, part of the energy stored in the TMD during the earthquake may not be dissipated and instead imparted back to the building being controlled. This will cause unwanted vibration even after the earthquake.

Alternatively, a nonlinear TMD can be designed to widen the effective frequency band for earthquake applications. For this purpose, an “energy sink” device was proposed by Vakakis *et al.* (2003). Functioning as a vibration absorber, the device is composed of a mass, a dashpot, and a nonlinear hardening or softening spring. Once installed on a primary structure (e.g., on top of a building), the device can rapidly and irreversibly absorb energy from the primary structure. The energy is actually dissipated without spreading back to the primary structure. Its performance is superior to the conventional TMDs.

3. PROOF-OF-CONCEPT TESTS OF AN MVTLD

As an example of the proposed functionally upgraded passive devices, the characteristics and validation of an

MVTLD are discussed in greater details in this section. An emphasis is placed on the understanding of the motion of particles in a water tank and the shake table tests of mass-variable dampers for their seismic effectiveness in reduction of peak acceleration and story drift. The adaptability of the dampers to external excitations is of particular interests.

3.1. Experimental Observations on Particle Motion in a Water Tank

To understand the behavior of particles in water, a 165-mm long rectangular tank made of plexiglass plates was built and tested on a small shaker under a horizontal harmonic excitation of 1.7 Hz. The plastic particles used in the tests had a specific weight of 1.2. Both a V-shaped and a W-shaped bottom of the tank were considered. The images corresponding to the peak displacement responses under various levels of excitation, represented by the shaker displacement amplitude, d_{\max} , are presented in Figure 4(a) for the V-shaped bottom and Figure 4(b) for the W-shaped bottom to illustrate the mobilization process of the particles. These results clearly indicated that the mass of a mixed water and particles changes with the level of excitations. As the base excitation increases, more particles are mixed with the sloshing water. In this way, the concept of an MVTLD can be realized in applications. In comparison with the flat-bottom tank (not shown), the particles in the sloped-bottom tank are much easier to be lifted, particularly in the tank with the W-shaped bottom. This can be clearly observed in the case of $d_{\max}=20$ mm where particles for the W-shaped bottom surpassed over the apex of the triangle bottom.

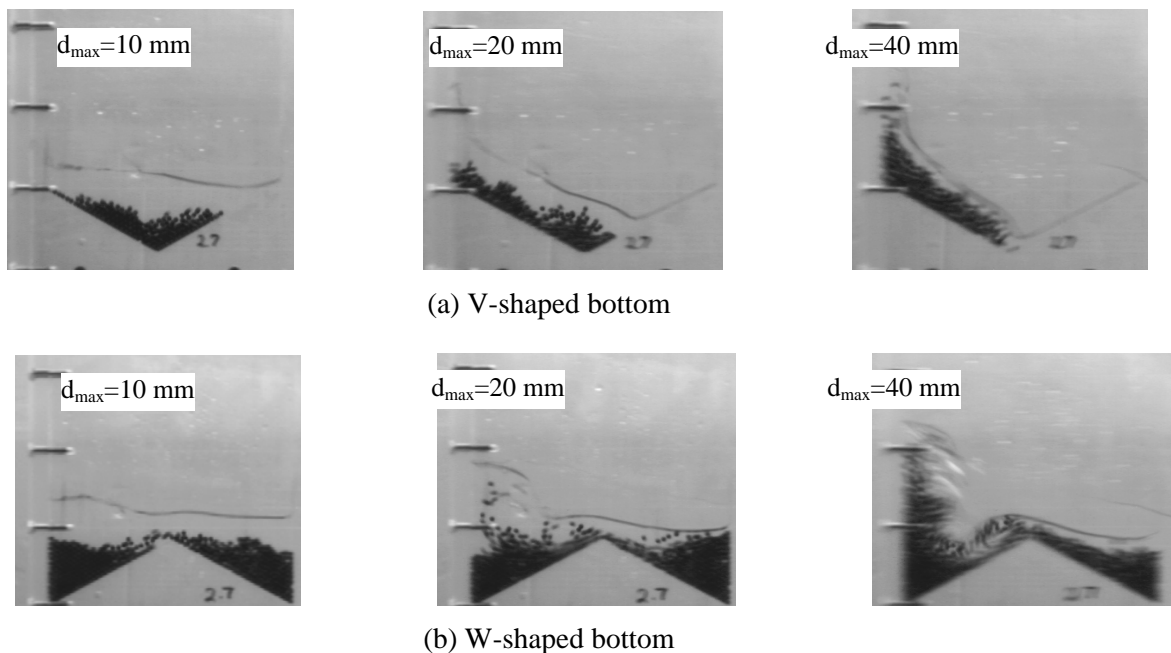


Figure 4. Particle motion in a rectangular tank of sloping bottom

3.2. Shake Table Tests of a 3-story Building Frame with/without TLDs

The structure used for this experimental study is a $\frac{1}{4}$ -scale, three-story steel frame at the Missouri University of Science and Technology. The prototype structure is 1.22m long, 0.61m wide, and 2.54m tall. The properties of the steel structure were identified with a series of shake table tests under harmonic loading (Xin, 2006). The fundamental frequency and its corresponding damping ratio of the steel structure are 2.55 Hz and 0.52%, respectively.

A 0.762m \times 0.508m \times 0.508m water tank was designed to mitigate the peak response of the 3-story steel frame. To enable the simulation both for a flat-bottom and a sloped-bottom shape, rigid bottom inserts were designed with movable configurations. The tank was installed on the third floor with three C-channels as a conventional or a mass-variable TLD device, depending on the content and the bottom shape of the tank. The tank was divided into four smaller tanks in the direction of loading, two pairs of two identical tanks (130 mm and 140

mm long), to tune the natural frequency of the water sloshing in two tanks to approximately 95% of the fundamental frequency of the steel structure, 2.55 Hz. An properly cut foam was inserted in the middle of the tanks, to keep the total weight of the water-sand mixture in the mass-variable TLD system the same as that of the water in the regular TLD so that their performance can be compared on a common basis. The mass of any TLD is 1.6% of the mass of the building structure.

The calculated natural frequencies of various TLD configurations are listed in Table 1. As expected, the natural frequency of the water sloshing in a tank of W-shaped bottom is lowest, and that of the flat-bottom tank is highest.

Table 1. Calculated natural frequencies of various TLD configurations

Tank & length Bottom shape	TLD1 & 130 mm	TLD2 & 140 mm
Flat	2.34	2.19
V-shape	2.28	2.13
W-shape	2.22	2.07

To evaluate the performance of the proposed MVTLD, a far-field and a near-field historical record were used during the experimental study. The records used are the N-S component of the 1940 El Centro earthquake and the N-S component of the 1995 Kobe earthquake. Since the shake table has a maximum stroke of only ± 25.4 mm, to generate significant structural responses for the control experiment, both earthquake records were compressed in time to make their dominant frequencies approximately equal to the fundamental frequency, 2.55 Hz, of the structure under consideration. The scale factors used were 1/2.091 for El Centro earthquake and 1/2.102 for Kobe earthquake.

Since the shake table input is a displacement signal in voltage, the two acceleration time histories were converted to displacement time histories by double integrations with zero initial conditions. Note that a Butterworth high pass filter was used for acceleration and velocity functions in frequency domain. Furthermore, to investigate the adaptability of the proposed MVTLD system, two levels of these earthquake inputs were designed as summarized in Table 2 to run the shake table. In the table, each earthquake is denoted by the first letter of its name and its intensity is represented by the numerical number following the designated letter. For example, E1 stands for the first level El Centro earthquake. Both peak acceleration and stroke are also specified in Table 2 for each earthquake.

Table 2. Multi-level earthquake inputs

Earthquake	El Centro		Kobe	
	Stroke (mm)	Designation	Stroke	Designation
1 (0.0973g)	14.0	E1	6.48	K1
2 (0.177g)	25.4	E2	11.7	K2

3.3. Effectiveness of the MVTLD

Table 3 shows the peak acceleration reductions under various excitations. It can be seen that the proposed MVTLD systems can substantially reduce the absolute floor acceleration of the frame structure. In comparison with the conventional TLD system, the MVTLD with the W-shaped bottom is equally effective under low excitations but significantly more effective under strong earthquake inputs. The MVTLD with the V-shaped bottom is also considerably more effective for strong earthquakes, but less effective for weak earthquakes since the V-shaped bottom is more difficult to get sand particles in motion. With the mass-variable strategy (W-shaped bottom), the floor acceleration of the structure was further reduced by 12.2% for the E2 excitation and 10.3% for the K2 excitation in comparison with the conventional TLD controlled responses.

Table 3. 3rd floor peak acceleration reduction (%)

Input	E1	K1	E2	K2
Conventional TLD	16.4	15.2	10.7	9.8
V-shaped MVTLD	12.3	10.9	23.5	18.6
W-shaped MVTLD	16.4	14.1	22.9	20.1

As the excitation level increases, the nonlinearity of the conventional TLD device becomes more obvious. Therefore, the TLD effectiveness decreases. However, the mass-variable strategy alleviated the nonlinearity of water sloshing. Furthermore, the large excitation caused more sand particles lifted and increased the effective mass of the TLD device. Therefore, for MVTLDs, the control effect under high level excitations is even better than under low level excitations. This is a distinctive characteristic of a MVTLD from the conventional TLD.

3.4. Near-field versus Far-field Ground Motion Effects

Table 3 also indicates that, in all cases, the reduction at the 3rd floor acceleration is higher under the far-field E1 Centro earthquake. These results indicate that TLD is generally more effective for far-field ground motions than for near-field motions.

Due to its passive working mechanism, particularly for deep-water TLD, a TLD device needs some time to be set in motion before it becomes effective in vibration mitigation. As a result, a TLD device may not be able to reduce the first peak response due to impulsive loading, for example, earthquake-induced ground motions. Since the mass of sloshing motion is a critical factor for the required set-in-motion time, the proposed MVTLD is expected to perform better in terms of first peak reduction in comparison with the traditional TLD devices. This section is focused on the seismic effectiveness of the MVTLD of W-shaped bottom in first peak reduction of the earthquake-induced response. For this reason, only two seconds of time history responses spanning over the peak ground acceleration are presented in Figures 5(a, b), corresponding to the high level of earthquakes. It is clearly shown that the reduction in peak acceleration is significant with the use of an MVTLD.

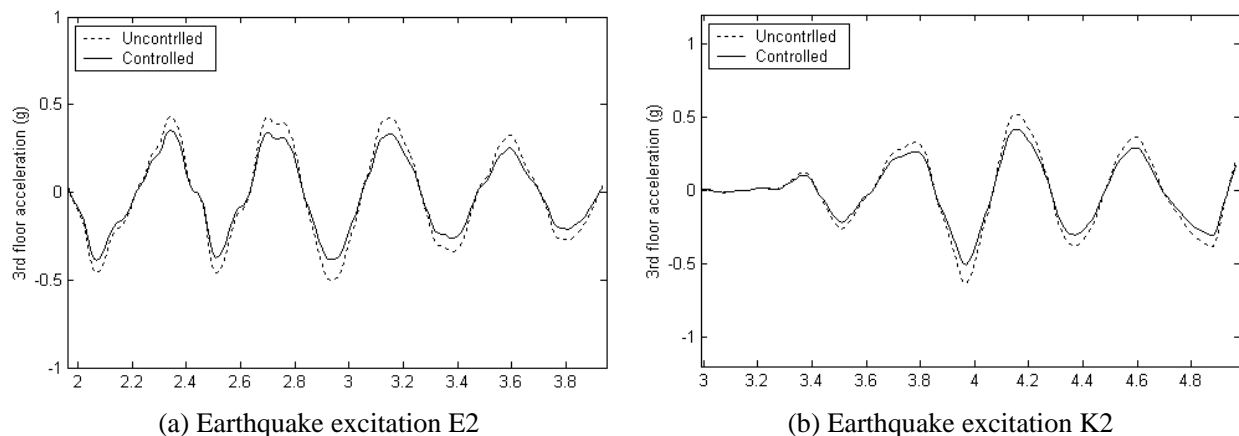


Figure 5. W-shaped bottom MVTLDs controlled versus uncontrolled floor accelerations

4. CONCLUDING REMARKS

The concept of functionally upgraded passive devices has been introduced in this paper to streamline some of the state-of-the-art developments in structural control and guide the future developments of new passive systems. The general characteristics of these devices were presented and exemplified with four types of recently-proposed passive systems, including MVTLD systems, PFPI bearings, friction-variable dampers, and nonlinear energy sink dampers. The functions added to their corresponding conventional passive devices (TLD,

FPS, friction dampers, and TMD) include the adaptability to external disturbances, self-centering feature of friction devices, first peak reduction ability, and frequency-independent suppression of both acceleration and displacement.

The performances of functionally upgraded passive devices were illustrated with the shake table tests of a building with an MVTLD. The shake table test results have shown that the MVTLD can further reduce the building acceleration by more than 10% in comparison with its corresponding TLD due to increased mass in water sloshing motion by added particles. The new damper is adaptive to external excitations as the particles in water gradually become suspended. Such a damper requires no external power to operate and thus little maintenance during their life span, but it behaves like a semi-active system.

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