INTRODUCING A NEW TUNED MASS DAMPER SYSTEM

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ABSTRACT

Tuned mass dampers (TMD) are effective and reliable structural vibration control devices commonly attached to a vibrating primary system for suppressing undesirable vibrations induced by winds and earthquake loads. This paper introduces a newly developed semi pendulum TMD system. The proposed device is composed of a specific configuration of rolling parts which provide a long natural period for the device along with providing the appropriate force transmission or energy dissipation capacity for the system. The effectiveness of the device has been shown by a simple experimental prototype of the device. The proposed system can be utilized for various structural bodies such as buildings, bridges, etc. It can also be used for both new and existing systems to improve their seismic performance for retrofitting purposes. It can be concluded that the proposed device is a proper substitute for the conventional TMD systems in long-period as well as shorter-period structures to mitigate the seismic/wind induces vibrations in a more efficient way in terms of the overall size and/or energy dissipation capacity.

INTRODUCTION

The tuned mass damper (TMD) systems have been a major means for the vibration control of civil engineering structures(Housner, et al., 1997). They have been successfully installed in different structures from high rise buildings to long bridges such as the CN Tower (535 m) in Canada, the John Hancock Building (sixty stories) in Boston, Center-Point Tower (305 m) in Sydney, and also the largest one in the Taipei 101 Tower (101 stories, 504 m) in Taiwan, in order to reduce the vibrations due to earthquakes and wind.

The natural frequency of the TMD is tuned in resonance with the first vibration mode of the primary structure, so that a large amount of the structural vibrating energy is transferred to the TMD and dissipated viaits out-of-phase motion with the primary structure (Soong and Constantinou, 1994). Consequently, the safety of the structure is enhanced. In other words, a TMD is a kind of dynamic secondary system implemented on a primary structure whereas its natural frequency is tuned to be very close to the dominant frequency of the primary structure. In such a situation a large reduction in the dynamic responses of theprimary system can be achieved.

Single or Multiple TMDs may be designed in different kinds including Tuned Liquid Column Dampers (TLCD), LiquidColumn Vibration Absorbers (LCVA), etc(Chang, 1999). However, one common type of such devices is the pendulum type TMD such as what we have on the Taipei101.

In the Taipei 101 which is 509 meters tall, the key features of the Structural Systemare 8 steel composite steel-concretesupercolumns (8'xlO'), 8 outrigger trussesin both directions (every 8 storeys), abraced core and the largest Tuned MassedDamper (TMD) in the world-730 tons.Furthermore, setbacks in the floor plan"confuse" the wind and reduce vortexshedding.

Suppression of excessive vibrations can be dealt with limited success in three ways. Firstly,additional stiffness can be provided to reduce the vibration period of a building. Secondly,changes in mass of a building can be effective in reducing excessive wind-induced excitation.Finally, aerodynamic modifications to the building's shape, if agreeable to the building's ownerand architect, can result in a "confusion" of the vortex shading and thus in a reduction of thevibrations caused by wind.

The above traditional methods (change in stiffness, mass or aerodynamic shape) can beimplemented only up to a point beyond which the solutions may become unworkable because ofother design constraints such as cost, space, or aesthetics. Therefore, to achieve reduction indynamic response, a practical solution is to supplement the damping of the structure with amechanical damping system external to the building's structure (Jayachandran, 2003).

The development and utilization of different TMD system topologies is to overcome the inherent performance limitations of passive TMD systems. The performance limitations may be based on the robustness to changes in the structural stiffness, the spatial limitations within the structure, or the cost and lifespan of the TMD system.

TUNED MASS DAMPERS TYPES

This section focuses on different TMD system topologies. In a very general classification, Tuned Mass Damper systems may be classified into five main groups: Passive TMDs, Active TMDs, Semi-active TMDs (SATMD) and multiple TMD (MTMD) systems. Passive Tuned Mass Damper systems may then be of either Translational (TTMD) or Pendulum type (PTMD).

Passive systems are characterized by the absence of an external source of energy. As a result overall system stability is usually not a concern. A passive TMD system is any TMD topology which does not contain any active element, such as an actuator. As a result these systems are entirely mechanical.

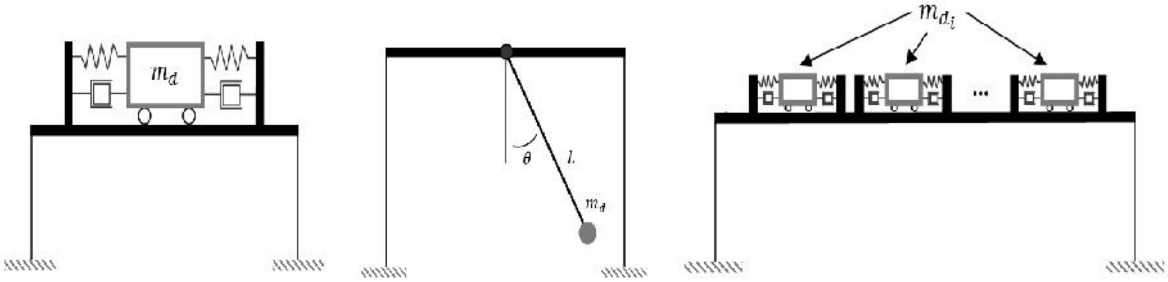
A limitation shared by all passive TMD systems is its lack of robustness to detuning conditions (Setareh et al. 2006). Outside of the narrow tuned frequency band of the TMD, the effectiveness of the TMD at reducing structural vibration is diminished. Even small deviations from the optimal tuning frequency can deteriorate the performance significantly. As a result the effectiveness of a passive TMD system is reliant on the accuracy of its initial tuning, and whether there is any structural detuning subsequently (Roffel et al., 2011).

Translational TMDs can be either unidirectional or bidirectional systems (Conner 2003). In unidirectional systems the motion of the TMD mass is restricted to a single direction, often by placing the mass on a set of rails or roller bearings, as depicted in Fig. 1(a). In bidirectional systems, the mass can move along both coordinate axes. In either topology a set of springs and dampers are placed between the TMD mass and the supporting structure which is fixed to the structure.

PTMDs replace the translational spring and damper system with a pendulum, which consists of a mass supported by a cable which pivots about a point, as illustrated in Fig. 1(b). They are commonly modelled as a simple pendulum. For small angular oscillations they will behave similarly to a translational TMD and can be modelled identically with an equivalent stiffness and equivalent damping ratio. Hence, the design methodology for both the translational TMD system and PTMD systems are identical (Conner 2003).

A major motivating factor for using a PTMD system over an equivalent translational TMD system is the absence of any bearings to support the TMD mass (Conner, 2003). The bearing support structure used in the translational TMD assembly is expensive and susceptible to wear over the lifespan of the TMD system. As a result PTMD designs can be less expensive tomanufacture and last longer. Nearly 50% of structures in Japan that use TMD systems utilize PTMD systems (Kareem et al., 2007). Examples include Crystal Tower in Osaka, Higashimyama Sky Tower in Nagoya, and Taipei 101 in Taipei (Conner 2003).

Active Tuned Mass Damper (ATMD) systems contain an external energy source, often in the form of an actuator.ATMD systems provide improved vibration suppression performance at the cost of added complexity, maintenance, and energy requirements (Conner 2003). As a result, active systems are usually employed in structures that are exposed to significant dynamic loading. Passive TMDsystems are fairly simple systems which provide excellent vibration suppression when accurately tuned and when the structure is excited by narrowband dynamic loading (Setareh 2006). Their lack of robustness to multiple-frequency narrowband excitations and structural detuning limit their performance.



(a) TTMD (b) PTMD (c) MTMD

Figure 1. Schematic of a (a) Translational, (b) Pendulumand (c) Multiple Tuned Mass Damper Systems

SATMD systems combine the advantages of both passive and active systems. These systems provide active control of either the stiffness or dampening components of the TMD system,instead of driving the system itself.

Multiple TMD systems, as depicted in in Fig. 1(c), use multiple TMDs to reduce structural vibrations. Instead of using a single large mass tuned to the structures natural frequency, a multiple TMD uses several smaller TMD systems (Chen et al. 2001). Multiple TMD systems are innately passive systems; however their design allows them to be more robust to detuning conditions than traditional passive TMD designs.

DISCUSSIONS ON CONVENTIONAL TUNED MASS DAMPERS PERFORMANCE

Tuned Mass Damper systems are a practical strategy in the area of structural control for flexible structures such as tall buildings. Normally, TMD systems consist of added mass with properly functioned spring and damping elements that provides a frequency-dependent damping in the primary structure. The mechanism of suppressing structural vibrations by attaching a TMD to the structure is to transfer the vibration energy of the structure to the TMD and to dissipate the energy in the damper of theTMD. The mass itself weighs only a small fraction -0.25 to 0.70%- of the building's total weight, which corresponds to about 1 to 2% of the first modal mass. In addition to the initial tuning when it is first installed, the TMD may be fine-tuned as the building period changes with time. The period may increase as the building occupancy changes, as nonstructural patricians are added, or as elements contributing nonstructural stiffness "loosen up" after initial wind storms (Jayachandran, 2003).However, the overall performance is limited by the size of the additional mass (normally about 1% of building weight) and the sensitivity related to the narrow band control and the fluctuation in tuning the TMD frequency to the controlled frequency of a structure. The mistuning or off-optimum damping can significantly reduce the effectiveness of the TMD; therefore, the TMD system may be neither reliable nor robust. In addition, a TMD system may be more effective when the forcing function (from wind or earthquake excitation) has significant spectral content at the frequency of the TMD fundamental mode. Further away from this frequency a TMD may have much less effect. Therefore, it is difficult to draw general conclusions on the effectiveness of a TMD system, especially when the structure includes inelastic behavior for seismic excitation.

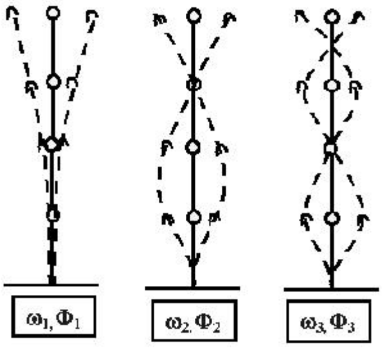


Figure 2. Typical first three mode shapes in a sample lumped mass model

Conventional TMD systems have the limitation that they are only capable of working against vibrations of the primary system with its fundamental period. To consider higher modes of the primary system, there is no individual frequency to which the TMD can be tuned and efficient for the primary system higher modes. In other words, since the fundamental period of the TMD should be a constant value which is equal to or less than the fundamental period of the primary system, considering any of the primary system higher modes will be equivalent to neglecting other modes. It means if we tune the TMD to the frequency of any individual vibration mode of the primary system it will be out of tune with all other modes. So, considering more than one mode of the primary system is practically impossible in the conventional single systems.In the proposed system, however, one may change the boundary route in order to achieve various natural frequencies for the TMD. This may help the aforementioned short come in conventional TMD systems. Fig. 2 shows the typical first three mode shapes of a lumped mass scheme.

DEVELOPMENT OF THE IDEA

The natural period of a pendulum depends only on its oscillating radius. For example, a pendulum with a natural period of 5 seconds requires a cable length of almost 6 meters. This simply means that the application of pendulum type tuned mass dampers needs occupying a large space inside the primary structure. This can be seen in the Taipei101 as an example, where the tuned mass damper system has occupied almost 5 stories in the top portion of the building.

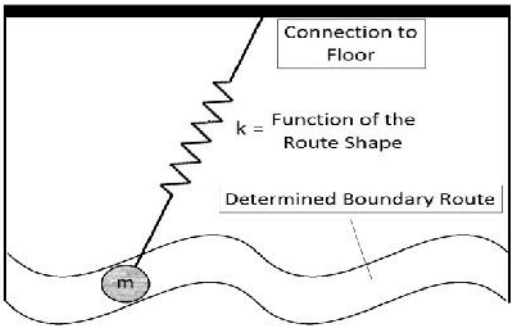


Figure 3. A simple schematic shape of the device

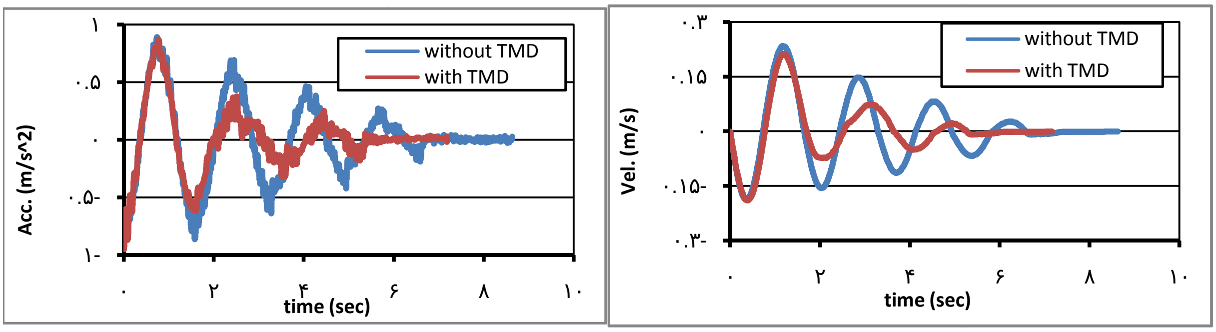
Tuning the conventional TMD systems to the fundamental period of the primary system is a major problem in the conventional TMD systems: a) Due to the changes in the weight of structures, conventional TMD systems can never guarantee that the natural frequency of the primary system, to which the TMD is tuned, remains constant. Consequently the conventional TMDs can never guarantee the designed performance of the TMD; b) Even if we can exactly tune the TMD to the first mode of the primary system, we know that the actual behaviour of the structure to a vibration is not only in the form of its first modal shape, but a combination of all modal shapes. Thus, tuning the TMD to the first mode includes some practical error.

In the conventional systems it is not possible to obtain very long natural periods for the TMD because:a) It will occupy very large volume in the whole system. For example, if we want to achieve a fundamental period of 10 seconds for the TDM in the form of a pendulum, it will need a cable with meters of length and b) If we use a soft (in terms of stiffness) route to achieve the long period for the TMD, we will have to reduce the amount of the horizontal component of the force which is going to act oppositely to the motion of the primary structure.

Considering the aforementioned issues, this paper introduces a newly developed semi pendulum TMD system. The proposed device is composed of a specific configuration of rolling parts which provide a long natural period for the device along with providing the appropriate force transmission or energy dissipation capacityfor the system. Since the natural period of this device is longer than that of a pendulum with the same cable length, the total size of the proposed device can be considerably smaller than the similar pendulum type ones. Fig.3 shows a simple shape of the device.

EXPERIMENTAL TESTING

The effectiveness of the device has been shown by a simple experimental prototype of the device. A device as in Fig. 3 has been experimentally made and its effect has been checked by imposing different routes in which the TMD travels. Fig.4 shows the velocity and acceleration time history responses of a single degree of freedom oscillator during a free vibration.



(a) Acceleration Response (b) Velocity Response

Figure 4. Experimental results showing the effectiveness of the new TMD in terms of (a) acceleration and (b) velocity SDOF responses

For this, the SDOF oscillator is freely released from a specific initial displacement while it is once equipped with the proposed TMD and the other time oscillates without the application of the new TMD. It can be seen that the responses with TMD have lower amplitudes as than those without the TMD. The graphs also show that when the new TMD is applied, the overall duration of vibration if the system under control has decreased which indicates the proper damping of the responses.

CONCLUSIONS

The proposed system can be utilized for various structural bodies such as buildings, bridges, etc. It can also be used for both new and existing systems to improve their seismic performance for retrofitting purposes.Based on the results, it can be concluded that the proposed device is a proper substitute for the conventional TMD systems in long-period as well as shorter-period structures to mitigate the induced vibrations in an efficient way in terms of the overall size and/or energy dissipation capacity.

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