Modern tall buildings have become relatively light and flexible with the plentiful application of high-strength materials in civil engineering making the structures collapse early or exceed the comfort limitation at the action of dynamic loads, such as seismic and wind. The structural vibration control in tall buildings can be a successful method of mitigating the effects of these dynamic responses. A number of control devices have been developed and some of them have been applied to the real structures in recent years.

Need of Damping Devices

All vibration control systems should improve the building’s function after an earthquake as well as to enhance the seismic performance or performance in day to day vibrations of structural members. This change translated into three engineering considerations:

- Concentration or reduction of damage in structural members to facilitate restoration after the earthquake.
- Reduction of damage (including prevention of toppling) to furniture inside the building to reduce human injury and to maintain the building’s function.
- Reduction of damage in nonstructural elements to facilitate the recovery of building function.

These aspects led to the adoption of seismic isolation and response control technologies in structural engineering. The employment of these technologies is categorized into three types:

1. Concentration of structural deformation into structural elements, including seismic isolators, that absorb energy effectively. This method ensures good seismic performance but requires special expertise in the engineering of devices.
2. Distribution of energy absorbing devices over the structural system. This method is less efficient than the method described in (1) but requires less special expertise to implement since this technology is only a slight extension of the conventional seismic design. Due to its readiness in application, use of this method has been widespread.

3. Response control technologies are also available to suppress wind induced horizontal responses, among which Hitchcock et al. [3] even investigated a general type of TLCDs that have non uniform cross-sections in the horizontal and vertical columns, termed as liquid column vibration absorber (LCVA). Recently, the application of TLCDs was further extended to the suppression of pitching motion for bridge decks (e.g., Xue et al. [7] and Wu et al. [8]). For the application to the control of horizontal motion toward implementation, some researchers have spent efforts on determining optimal TLCD designs, such as Chang et al. [9] and Chang [10] on undamped structures, Wu et al. [11,12] on damped structures, and Yalla et al. [13] on both damped and undamped structures. Their results of optimal parameters is provided for the case that loading on buildings is white-noise type, such as wide-banded along wind loads. There are also some applications of TLCD technologies, including period adjustment mechanisms. By providing a Tuned Liquid Column Damper with Period Adjustment Equipment (TLCD-PA), the behavior of the liquid motion in the liquid column damper may be regulated [14].

Various Damping Devices and Available Literature Reports

The three types of damping devices that are commonly used is as mentioned below-

Simple Passive Dampers

Simple passive dampers, including viscous, friction, and visco-elastic systems, rely on a damper mounted between a vibrating structure and a stationary object to dissipate vibration energy as heat. As the two systems move relative to each other, the simple passive damper is stretched and compressed, reducing the vibrations of the structure by increasing its effecting damping.

Passive Control Devices

Work by fastening a mass block to a structural component (such as a floor) via a spring (Figure 1). This system is set up so that, when the floor vibrates at a resonant frequency (which could be caused by dancing, for example), it induces analogous movement of the mass. Examples of Passive control device are Tuned Mass Dampers (TMDs) and Tuned Liquid Dampers (TLDs) etc.

Active Mass Damper

Active mass dampers, which are computer controlled and can also be configured to work without relying on the relative motion between the floor and a stationary object, were also considered. These systems, currently the subject of much research for controlling wind and earthquake induced vibrations, are a generally attractive solution to vibration problems because they are so effective.

Among passive control devices, tuned mass dampers (TMDs) and tuned liquid dampers (TLDs) have been widely employed for decreasing the wind and earthquake induced vibration of tall building structures. The original idea of tuned liquid column damper (TLC) was developed by Sakai et al. [1] for suppression of horizontal motion of structures. After that, quite a few research papers, namely Xu et al. [2], Hitchcock et al. [3], Balendra et al. [4], Min et al. [5] and Felix et al. [6], have verified its effectiveness for suppressing wind induced horizontal responses, among
differing dynamic response characteristics together in order to reduce their lateral vibrations due to wind or earthquake loading. It has many attractive properties such as requiring little or no floor space within either building or providing better access between higher storeys of buildings. However, its use is limited to fairly specific situations and as such has not yet been widely implemented.

The concept of connecting adjacent buildings with a damper in order to reduce the vibrations in each of them is a relatively recent one and its actual application is even more so. It was first proposed independently by two researchers, Kunieda (1976) and slightly earlier by Klein et al. (1972). The first application was not until 1989, with the Kajima Intelligent Building complex in Tokyo, Japan. Subsequently, other low-rise applications such as a four building coupling application at Konoike Headquarters in Osaka and the more recent, completion of Harumi Triton Square buildings in Japan. The control bridges function based on the different responses of the differing structures’ differing dynamic responses to the same excitation. That is, with different motion of two adjacent structures connected by a damper, a velocity is developed across this damper, results in a damping force that dissipates the energy of the motion. This approach to damping can achieve sufficient control under the relative low-frequency of earthquake loading (Seto and Watanabe, 2000), whilst causing little reduction in usable floor space and allowing traffic between structures at high levels. The allowance for traffic can cause not only an increase in safety through alternative evacuation, but also efficiency of movement. Luco and De Barros (1998) proposed the linking of two buildings with passive dampers distributed up the height of the shorter structure and found the optimum damping values. Seto and Watanabe (2000) outlined the problems with spill over of response into higher modes that were known to occur with active damping of tall buildings. Finally in Christenson et al. (2006), the control force applied for both active and passive control systems were compared, for the varying building and connector configuration. Control force is significant in this type of damper, as it is applied as a horizontal point load to the structure and as such the elements to which the coupling is connected must be able to withstand this load. Whilst with fully active control as seen here, the large extra reduction in vibration was accompanied by an increase in control force, promising indicators for semi-active dampers were seen. These results were that with active control only providing equivalent damping as the passive system, as little as half the passive forces were seen for the limited active damper.

Some Case Studies

1. Park Tower, a 67 storey condominium / hotel building in Chicago

After initial investigations indicated that the peak acceleration of the upper floors of the Park Tower would have exceeded the maximum target value, a solution was proposed that included incorporating a Tuned Mass Damper (TMD) near the top of the building. This TMD would essentially consist of a mass of 300 tons suspended by pendulum cables and would include the use of hermetically sealed, frictionless hydraulic dampers. Rowan Williams Davies and Irwin Inc. (RWDI) are a Canadian firm who designed the TMD (Figure 1).

![Figure 1: The Tuned Mass Damper System](image1)

The main support cables are paired at each corner of the rectangular mass block. The structural steel above the mass block (blue and red in the color image), near the top of the image, is the tuning frame that can be lifted or lowered as required to tune the TMD to the frequency of the building. The red “frames” depicted in the foreground of the image are a mechanism called an “anti-yaw” mechanism. This device prevents the TMD mass from rotating (or yawing) as it swings from side to side. Two viscous dampers are also connected to the anti-yaw mechanism that will be used as a brake if it becomes necessary to stop the motion of the TMD. The angled cylindrical devices that slope from the mass to the floor are the viscous dampers specified by RWDI and supplied by Taylor Devices.

Critical components of the TMD are the dampers themselves. Several types of dampers have been considered for use in TMDs but finally a low friction hydraulic damper (As Shown in Figure 2) is being adopted.

![Figure 2: Maintenance Free Low Friction Hydraulic Damper (Patent Pending)](image2)
In order to quantify the overall improvement realized through the addition of the TMD, Figure 3 can be referred. It clearly shows peak acceleration with TMD is much less than that without TMD.

Target High-rise Building, Chuo-ku, Tokyo

The total height is 119 m, consist of 40 floors, as is shown in Figure 4(a). However the building was modeled by leaving the basement and two minor upper floors, so that it is supposed as 37-story building, as is shown in Figure 5, with a total height of 108.9 m. On the other hand, this structure is symmetric in plan as is shown in Figure 4(b).

Steel dampers and Oil dampers (Figure 6(a) and (b)) are used to see the effect on vibration control and Nagoya earthquake is selected for input of vibration because of being the strongest long-period ground motion.

Dynamic Response of the Target High-rise Building with Damper Devices

The experimental investigation showed that adding of dampers reduces considerably the dynamic response under Nagoya earthquake (the strongest long-period ground motion) in both cases, adding steel and oil dampers. This can be seen from Figure 7(a) and (b) that maximum response for drift and shear force are less incase of dampers than no dampers.

Crystal Tower, Osaka, Japan

Applications of TMD systems to high-rise buildings began with an office building named “Crystal Tower” in Osaka, which was completed in 1990. The exact number of existing buildings equipped with TMDs is not reported, but the firm
with which the writers work has designed and constructed seven high-rise buildings with TMDs, including “Crystal Tower.”

A new type of tuned mass damper was developed and applied in an office building in Osaka (Building C). As shown by the vertical section of the building in Figure 8, this building is seismically isolated below the third floor level. The isolating system of this building uses newly developed mechanical bearings called a linear slider, each of which supports 30,000kN of the building weight. Basic properties of the building are summarized in Figure 9.

Such seismic isolation is very effective for earthquakes, but not necessarily beneficial for winds. Especially for high-rise buildings, the application of a seismic isolation system sometimes causes adverse effects under wind loading. This building is designed so that the friction of the linear sliders prevents the isolation floor from moving and disturbing residential comfort during winds. Furthermore, when wind load is large enough to move the isolation floor, a locking system consisting of multifunction oil dampers installed in the isolation floor would automatically lock the isolation floor. Hence, this building is essentially identical to conventional (non-isolated) high-rise buildings during strong winds. The layout and set up of TMD used is shown in Figure 10.

Sport City Tower Doha

The Aspire Tower is a 318 meter (1,050 feet) structure located in the Sports City complex in Doha, Qatar. Designed by architect HadiSimaan, and AREP and engineer Ove Arup and Partners, Aspire Tower served as the focal point for the 15th Asian Games hosted by Qatar in December 2006. An assesment of the buildings dynamic performance indicated, that additional damping would be needed to reduce lateral accelerations at the top under wind loading to improve comfort levels. A feasibility study of various options for a total of 3% critical damping showed, that a TMD directly below the highest viewing levels was the most practical solution for the range of predicted frequencies. Therefore a TMD with an effective mass of 140 t, designed as a folded pendulum system was installed within the tower core (see Figure11) which reduced the height of the required envelope by about a half, but needed a rigid frame to transfer the tension between the first and second stage . Shaping the TMD mass in this way facilitated fitting the TMD within the circular plan shape of the core (Figure11). Energy dissipation of the TMD is achieved by dashpot dampers, which also incorporate bumper stops to prevent excess movements of the mass in extreme situations.

Isolators and Dampers designed by Akira Nishimura- see Figure 12
Conclusion

Benefits of Vibration Dampers for High-Rise Design

- Performance Benefits: When VDs are introduced at key locations instead of a number of coupling beams they add distributed viscous damping, which reduces wind and earthquake vibrations including accelerations, velocities and displacements (drifts) as well as the overall design forces. VDs lead to more efficient designs and increased safety and resilience against large hurricanes and earthquakes.

- Overall Design Benefits: Incorporating VDs can reduce structural materials over the height of the structure or an increase in the number of stories for a given structural configuration. As opposed to commonly used vibration absorbers, VDs do not take up valuable leasable space at the top of the structure and do not require monitoring, maintenance or tuning over the life of the structure to ensure adequate performance. Vibration Dampers can also be used to reduce both wind and earthquake induced vibrations.

Beside the challenge to design dynamic devices such as a Vibration Damper (VDs) and ensure all of its specifications by preliminary tests, the challenge to document the effectiveness of a VDs application on a high-rise building can be achieved using practical identification methods. The determined results show that the application of a large scale VD is an efficient solution to reduce occurring wind/seismic induced horizontal and lateral vibrations with a comparatively small effort and a comparatively small additional mass. The reduction leads to an increase of comfort and to possibilities for ever lighter and slender structures.

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