CHAPTER 1

INTRODUCTION

If they give you ruled paper, write the other way
- Juan Ramon Jimenez

This chapter begins with a brief literature review in the area of liquid dampers. Relevant literature is also referenced at appropriate places in later chapters of the dissertation. Some of the applications of these dampers, especially in civil engineering structures and offshore structures, are described. The motivation of the present research is presented in the next section. Finally, the organization of the dissertation is laid out in detail.

1.1 Introduction

The current trend toward buildings of ever increasing heights and the use of lightweight, high strength materials, and advanced construction techniques have led to increasingly flexible and lightly damped structures. Understandably, these structures are very sensitive to environmental excitations such as wind, ocean waves and earthquakes. This causes unwanted vibrations inducing possible structural failure, occupant discomfort, and malfunction of equipment. Hence it has become important to search for practical and effective devices for suppresion of these vibrations. This has opened up a new area of research in the last decade, aptly titled structural control (Yao, 1972).

The devices used for mitigating structural vibrations are divided into separate categories based on their system requirements (Housner *et al.* 1997). Passive control devices are systems which do not require an external power source. These devices impart forces that are developed in response to the motion of the structure, for e.g., base isolation, viscoelastic dampers, tuned mass dampers, etc. More details of such systems can be found in Soong and Dargush (1997). Active control systems are driven by an externally applied force which tends to oppose the unwanted vibrations. The control force is generated depending on the feedback of the structural response. Examples of such systems include active mass dampers (AMDs), active tendon systems, etc (Soong, 1990). Owing to the uncertainty of the power supply during extreme conditions and the large power source needed to introduce control force, passive systems are generally favored over active ones. Semi-active systems are viewed as controllable devices, with energy requirements orders of magnitude less than typical active control systems. These systems do not impart energy into the system and thus maintain stability at all times, for e.g., variable orifice dampers, electro-rheological dampers, etc. A recent paper by Symans and Constantinou (1999) provides a state-of-the-art review on semi-active devices for seismic protection of structures. Another paper by Kareem *et al.* (1999) describes the control systems for mitigation of motion of buildings under wind loading. Alternative systems are being proposed which derive the useful characteristics of both systems. One of them is hybrid control which implies the combined use of active and passive systems or passive and semi-active systems.

The most commonly used passive device is the Tuned Mass Damper (TMD), which is based on the inertial secondary system principle, and consists of a mass attached to the building through a spring and a dashpot. In order to be effective, its parameters need to be optimally tuned to the building dynamic characteristics, thus imparting indirect damping through modification of the combined structural system. Such systems have been implemented, for example, in the John Hancock tower in Boston and the Citicorp Building in New York City (McNamara, 1977).

A Tuned liquid damper (TLD)/tuned sloshing damper (TSD) (used interchangeably throughout this thesis) consists of a tank partially filled with liquid. Like a TMD, it imparts indirect damping to the structure, thereby reducing response. The energy dissipation occurs through various mechanisms: viscous action of the fluid, wave breaking, contamination of the free surface with beads, and container geometry and roughness. Unlike a TMD, however, a TSD has an amplitude dependent transfer function which is complicated by nonlinear liquid sloshing and wave breaking.

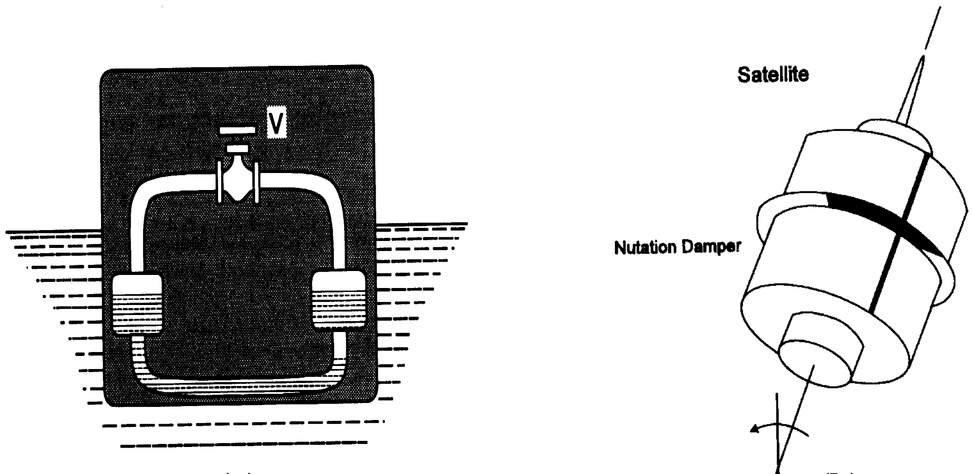
The TLDs can be broadly classified into two categories: shallow-water and deep-water dampers. This classification is based on the ratio of the water depth to the length of the tank in the direction of the motion. A ratio of less than 0.15 is representative of the shallow water case. In the shallow water case, the TLD damping originates primarily from energy dissipation through the action of the internal fluid's viscous forces and from wave breaking. For the deep-water damper, baffles or screens are needed to enhance damping. The damping mechanism is therefore dependent on the amplitude of the fluid motion, wave breaking patterns, and screen configuration. The deep-water damper has one drawback in the fact that a large portion of water does not participate in sloshing and adds to the dead weight. At an intermediate level of fill depth, the container can be utilized for building water supply. If the existing water tanks are not utilized, the large space occupied by water containers may, in some cases, require a part of the building roof. However, most practical installations of TLDs use many smaller tanks so as to maximize the effective mass of liquid engaged in sloshing.

Tuned liquid column dampers (TLCDs) are a special type of TLDs relying on the motion of the column of liquid in a U-tube-like container to counteract the forces acting on the structure, with damping introduced through an valve/orifice in the liquid passage (Sakai *et al.* 1989). The damping is amplitude dependent since the valve/orifice constricts the dynamics of the liquid in a non-linear way.

1.2 Literature Review

TLDs were proposed in the late 1800s where the frequency of motion in two interconnected tanks tuned to the fundamental rolling frequency of a ship was successfully utilized to reduce this component of motion, as shown in Fig. 1.1 (Den Hartog, 1956). Initial applications of TLDs for structural applications were proposed by Kareem and Sun (1987); Modi *et al.* (1987) and Fujino *et al.* (1988). In the area of satellite applications, these dampers were referred to as *nutation dampers* (Fig. 1.1(b)).

Sakai *et al.* (1991) proposed a new type of liquid damper which was termed as a tuned liquid column damper (TLCD) and described an application for cable-stayed bridge towers. TLCDs were studied for wind excited structures by Honda *et al.* (1991); Xu *et al.* (1992) and Balendra *et al.* (1995). Studies were also made for determining certain optimal characteristics of these passive devices by Gao *et al.* (1997); Chang and Hsu (1999); and Gao *et al.* (1999). The performance of TLCDs for seismic applications has been studied by Won *et al.* (1996) and Sadek *et al.* (1998).



(a) (b)

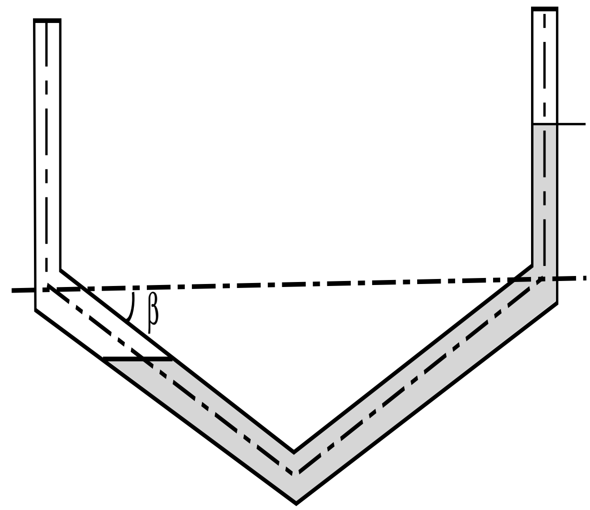
Figure 1.1 (a) Frahm Anti-rolling tanks (b) Nutation dampers in satellite applications

Most of the earlier studies concerned passive versions of TLCDs. This means that the design involves no control of the damping characteristics. The damper was designed to be optimal at design amplitudes of excitation but was non-optimal at other amplitudes of excitation. In order to solve this difficulty, semi-active and active systems were proposed by Kareem (1994); Haroun *et al.* (1994); and Abe *et al.* (1996). A similar active system was proposed for TLDs by Lou *et al.* (1994), in which a baffle was placed inside the liquid damper. The orientation of the baffle changed the effective length of the damper thereby making it useful as a variable-stiffness damper.

Most structures under the influence of environmental loads experience both lateral and torsional motions; therefore, one option is to have separate TLCDs each oriented in particular directions, or to simply have a bi-directional U-tube (Fig. 1.2(a)). This new configuration consists of a box container with vertical tubes like a candelabrum concept, or a partitioned container, consisting of stacked U-tube sets ranging in both directions with a common liquid base. The design eliminates the increased weight incurred by stacking two independent orthogonal U-tubes. One can also have orifices between the partitions (Kareem, 1993).

Multiple Mass Dampers (MMDs) with natural frequencies distributed around the natural frequency of the primary system requiring control have been studied extensively by Yamaguchi and Harnpornchai (1993); Kareem and Kline, (1994); and Yalla and Kareem (2000). Such systems lead to smaller sizes of TLCDs which would improve their construction, installation and maintenance, and also offer a range of possible spatial distributions in the structure. The tuned multiple spatially distributed dampers, offer a significant advantage over a single damper since multiple dampers, when strategically located, are more effective in mitigating the motions of buildings and other structures undergoing complex motions (Bergman *et al.* 1990).

Shimizu and Teramura (1994) have proposed and reported implementation in buildings, a new bi-directional tuned liquid damper with period adjustment equipment. Other adjustments in shape have been proposed by researchers. To help the damper liquid maintain its column shape, a V-shaped TLCD can be adopted as shown in Fig. 1.2(b) (Gao *et al.* 1997). Another variation of TLCD is proposed, which is termed as LCVA, which allows the column cross-section to be non-uniform. The performance of LCVA is compared to that of TLCD and is found to be as or even more effective. Other advantages include versatility and architectural adaptability, since its natural frequency is determined not only by the length of the liquid column but also the area ratio of the horizontal and vertical portion of the tube (Hitchcock *et al.* 1997; Chang and Hsu, 1998).



(b)

Figure 1.2 (a) Bi-directional TLCD (b) V-shaped TLCD

1.3 Applications

1.3.1 Ship/Offshore applications

The operation of a ship is affected by the motions and forces induced by rolling, which can cause cargo damage, discomfort to passengers and reduce crew efficiency. The use of devices for stabilizing motion in ships dates back to 1862 when W. Froude introduced them followed by a practical application by P. Watts in 1880. In 1911, H. Frahm proposed the use of a U-shaped tank as a roll stabilizer. Since early installations of such passive anti roll tanks in the 1950s, this concept has been applied widely on commercial vessels. The latest ship stabilizers are capable of both heel and roll control using water tanks. The stabilizer is equipped with a roll indicator which is a microprocessor-based computer that constantly calculates the root mean square roll, the heel and the average apparent roll period (Honkanen, 1990) There are three basic types of passive/ controlled passive tanks, which are used for roll stabilization in ships, as shown in Fig. 1.3, namely:

free surface, U-tube tanks and free flooding tanks. *Free surface tanks* are open tanks and can have baffles/nozzle plates to provide internal damping. Different rolling frequencies can be matched by changing the liquid level in the tank. *U-tube tanks* consist of two tanks partially filled with liquid, with the air spaces connected by a duct and a crossover duct at the tank bottom. Damping is provided by restricting the flow of air between the tanks. *Free flooding tanks* are not as popular as other tank systems. It is similar to a U-tube tank except that the tanks are not connected to one another; however, there is an airduct connecting the top of the tanks. The tank natural period is set by the size of the inlet ducts relative to the tank's internal free surface. It is to be noted that all these stabilizers affect only the roll amplitude and not the roll period (Sellars and Martin, 1992).

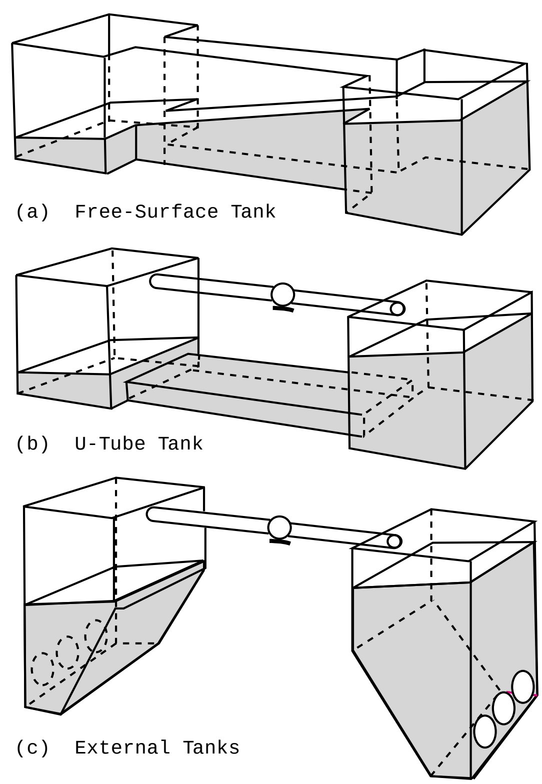


Figure 1.3 Types of passive/ controllable-passive tanks for ships

The excitations acting on most offshore structures are mostly due to wind, waves and ocean currents. The sloshing motion of the liquids in storage tanks on fixed offshore structures affects its dynamic response. By prudent selection of the tank geometry, platform response may be reduced by using the tanks as dynamic vibration absorbers. Therefore, no new equipment is required, but only optimum configuration of tankage that is already required for storage of water, fuel, mud or crude oil (Vandiver and Mitome, 1978). Passive, active and semi-active motion reduction systems such as fin and tank stabilizers, variable mooring systems, controlled and uncontrolled air cushions, perforated pontoons and columns with gas-spring-like tide tanks have been researched and applied to floating platforms and other offshore structures like semi-submersibles (Ehlers, 1987). For floating offshore structures like TLPs (tension leg platforms), the system with controllable mooring tension and variable attaching position are considered. The horizontal low frequency motions of TLPs can be reduced by active control using dynamic positioning system thrusters. Other mechanisms include active pulse generators, open bottom tanks and pressurized passive air cushions. Control of offshore platforms using active mass dampers, active tendons and thrusters can be found in Suhardjo and Kareem (1997).

Patel *et al.* (1985) considered a passive open bottom tank system in TLPs relying upon the oscillations of the water columns in the tanks. A platform which lies on 4-6 columns containing gas-spring-like tank systems is another consideration, (Delrieu, 1994). Huse (1987) has studied free surface damping tanks to reduce resonant heave, roll and pitch motions of semi-submersibles and other offshore structures. The damping tanks will be situated at the water line and will be open to the sea through suitable restrictions (Fig.1.4(a)). As shown in the figure, the tank is open to the sea and the atmosphere through two openings. As the structure undergoes vertical motion, the sea water will flow in and out of the tanks. By choosing a suitable opening size relative to the free surface area of the tank, the water level in the tank will fluctuate with a certain phase lag relative to the vertical motion of the structure. This will produce a damping force which would reduce the resonant heaving motion of the structure. Ehlers (1987) considers a semi-active control method for a structure equipped with open bottom tanks, but the valves in the upper part can be opened or closed (Fig.1.4 (b)). The relative vertical motion between the water columns in the tanks and the structure is influenced by the position of the valves because of the air which is trapped in the tank when the valve is closed. These systems however, can be used only for reduction of vertical motions and not horizontal motions. For some applications, this is very important since damping in the vertical mode is extremely small.

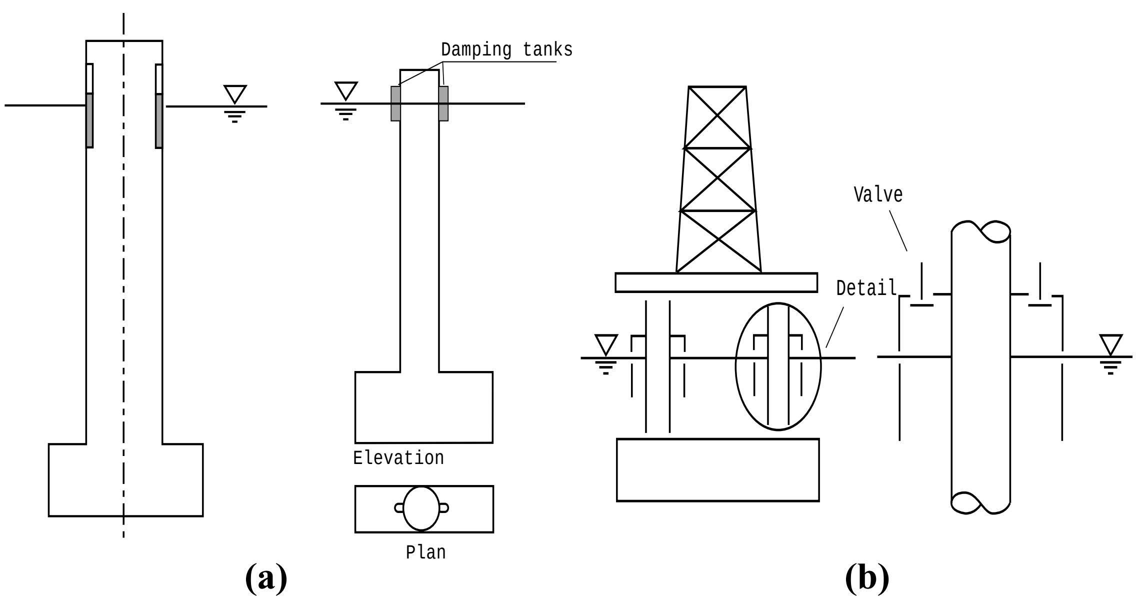


Figure 1.4 (a) Free surface damping tanks (b) Semi-active control for structure with open bottom tanks

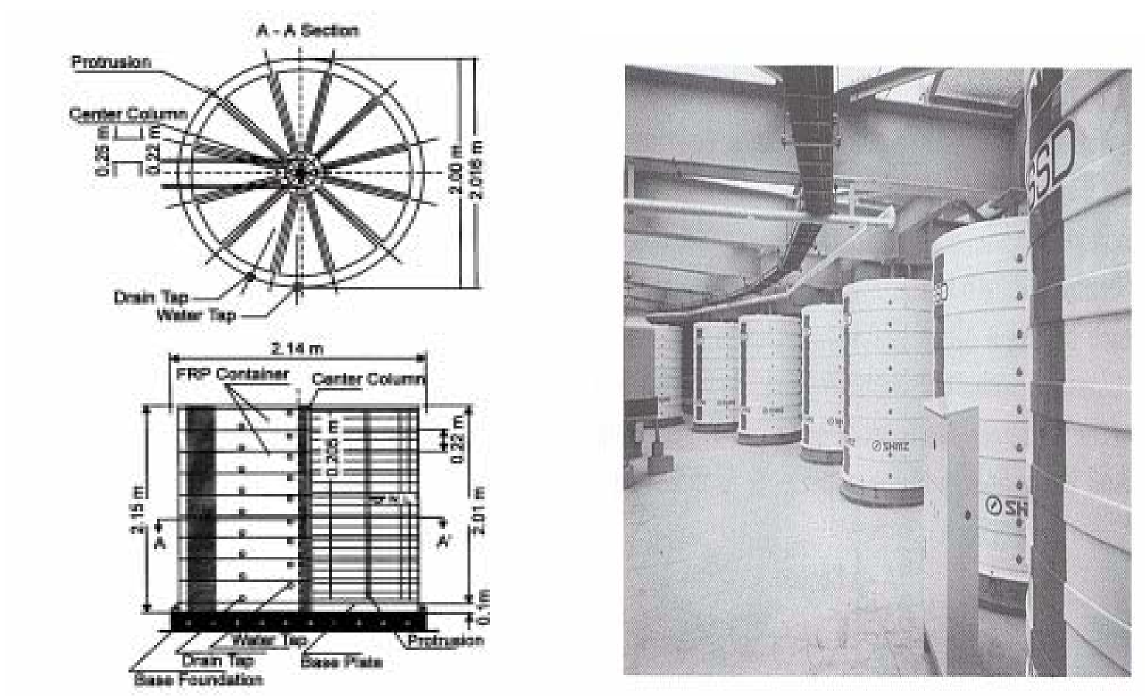
1.3.2 Structural Applications

There have been several applications of TLDs in Japan, an example of which is the MCC Aqua Damper^{TM} which was installed in the Gold Tower in Chiba, Japan (Fig. 1.5). The *Aqua Damper* is a cubic tank filled with water in which steel wire nets are installed across the water movement. The TLD frequency is adjusted by changing the length of the tank and the depth of water. The damping, on the other hand, is adjusted by manipulations of the damping nets. The top floor of the 158 m tall Gold Tower was installed with 16 units of the *Aqua Damper* totalling 10 tons of water (approximately 1% of the tower's weight) and has witnessed a improved response of 50-60% of the original structural response prior to the installation of the *Aqua Damper* (MCC Aqua Damper Pamphlet).

Figure 1.5 Aqua dampers (*Courtesy: MCC Aqua damper literature*)

A battery of TLDs were installed in the Shin Yokohama Prince Hotel (SYPH) in Yokohama, Japan (Fig. 1.6). The TLD system prescribed was a multi-layer stack of 9 circular containers each 2 m in diameter and 22 cm high, yielding a total height of 2 m.

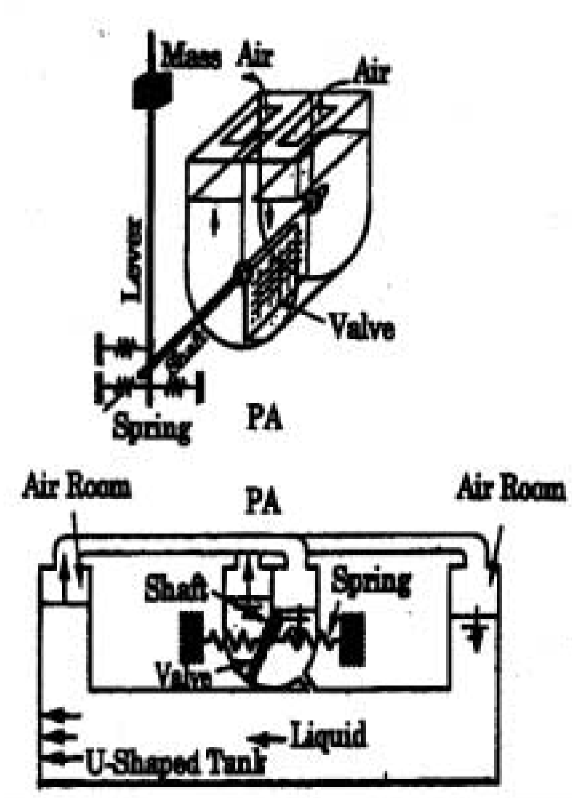
Details of the system can be found in Tamura *et al.* (1995). Before and after the installation of the TLD in March of 1992, full-scale measurements were taken to document the performance of the auxiliary damping system. It was found that the RMS accelerations in each direction were reduced 50% to 70% by the TLD at wind speeds over 20 m/s, with the decrease in response becoming even greater at higher wind speeds. The RMS acceleration without the TLD for the building was over 0.01 m/s^2, which was reduced to less than 0.006 m/s^2, defined by the ISO as the minimum perception level at 0.31 Hz. Similar installations are reported for Nagasaki airport tower, Tokyo international airport tower and Yokohama marine tower (Tamura *et al.* 1995).



(a) **(b)**

Figure 1.6 (a) Schematic of TLDs installed in SYPH (b) Actual installation in the building (taken from Tamura *et al.* 1995)

A TLCD has also been installed in the Hotel Cosima in Tokyo (Fig. 1.7). The hotel is a 26 story steel building with a height of 106.2 meters. This building has a large height to width ratio and is therefore wind sensitive. The foundation of the building is firmly connected to the ground using high strength steel pretensioned grout anchors. In addition, a super structure is adopted as the frame of the building in order to resist earthquakes and wind loads. The 58 ton TLCD with pressure adjustment, called MOVICS, was installed in the top floor and has been observed to reduce the maximum acceleration by 50-70% and the RMS acceleration by 50% (Shimizu and Teramura, 1994). Other MOVICS systems have been installed in the Hyatt Hotel in Osaka and the Ichida Building in Osaka.



(a)

(b)

Figure 1.7 (a) Liquid damper with pressure adjustment concept (b) Installed in Hotel Cosima, Tokyo

Recently, Liquid Dampers have been planned for the proposed Millennium Tower, Tokyo Bay, Japan. Due to this supertall building's exposure to typhoons, external damping sources are needed to control the wind induced vibrations. In addition to massive steel blocks at the top, there are water tanks with ducts between them. The water would provide passive resistance under normal conditions, but under high winds, the sensors trigger a pumping mechanism, changing the control mode from passive to active (Sudjic, 1993). Figure 1.8 shows the schematic of the circular TLD concept in this tower.

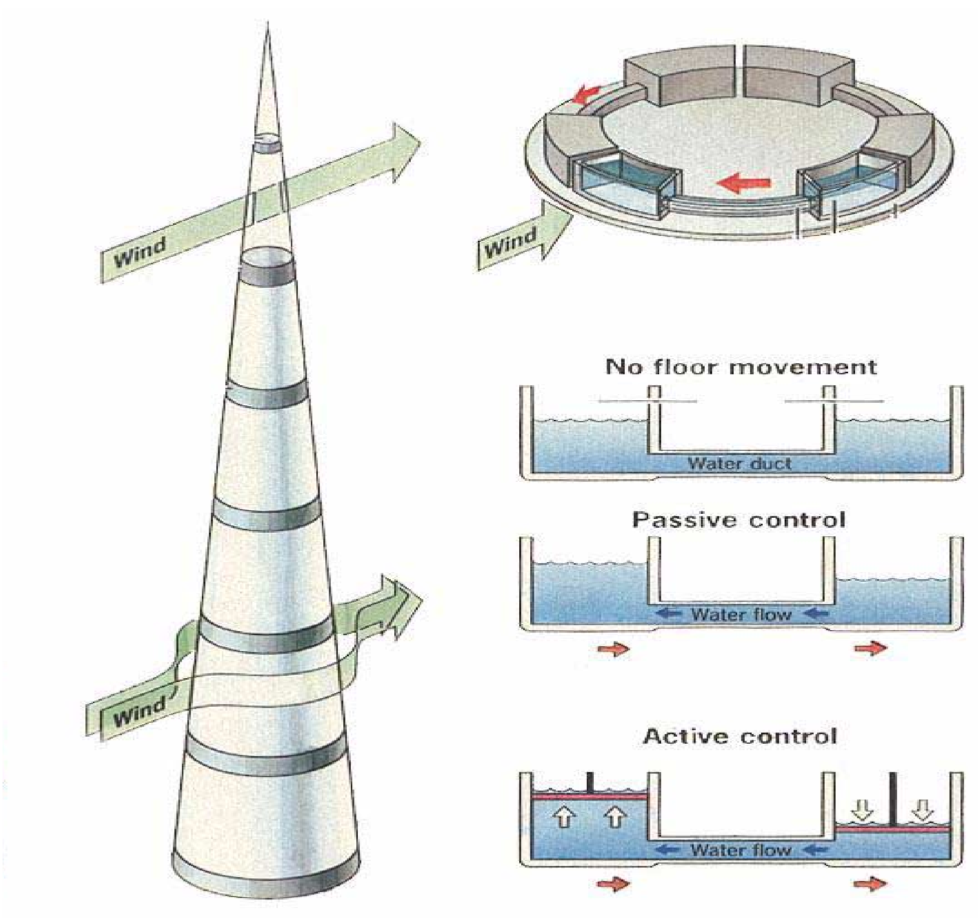


Figure 1.8 Millennium tower: passive and active TLCD concept

A TLD is also planned to limit the wind induced motion of the proposed Shangai Financial Trade Center in China. This building will have a square shaft with a diagonal face that is shaved back (Fig. 1.9(a)). An aperture is cut out of the top to relieve aerodynamic pressure (*Engineering News Record, May 1996*). Both the TLD and the aerodynamic aperture will ensure to keep building motion within acceptable limits. TLDs are also being considered for the newly proposed 2000 ft building in Chicago, namely, the 7 South Dearborn project.

(a)

(b)

Figure 1.9 (a) Shanghai Financial Trade Center (b) 7 South Dearborn Project

Liquid tanks are being used to reduce the aerodynamic forces, in particular the torque components, which cause instability during construction of long-span bridges. (Brancaleoni 1992; Ueda *et al.* 1992). Liquid vibration absorbers are also used in tall chimneys. These have been proven to be economical, can be easily adjusted to the physical and architectural requirements, and are extremely fail-safe. They are usually designed as a part of the circular gangway or as a coupling body for the connecting forces of a group of chimneys (Fig. 1.10).

Figure 1.10 TLDs installed in chimneys

1.4 Motivation of Present Work

A recent paper by Hitchcock *et al.* (1999) describes the full scale installation of a bi-directional passive liquid column vibration absorber (LCVA) on a 67m steel frame communications tower. The LCVA is a passive system with no orifice to control the damping. The authors observed that "*At wind speeds less than approximately 10 m/s, the standard deviation of the tower acceleration before and after SLCVA system installation are essentially the same due to the motion of the SLCVA liquid being insufficient to dissipate significant vibrational energy. At wind speeds of approximately 20 m/s, the response of the tower is reduced by almost 50% after installation of the SLCVA system.*" This shows the inadequacy of the passive systems to perform optimally at all levels of excitation. For e.g., at low amplitudes, the liquid velocity is insufficient to generate an optimal value of damping to reduce the motion substantially. On the other hand, at high amplitudes of excitation, the damping introduced at the orifice may be more than the optimal and again the efficiency of the TLCD decreases. Similar observations were made in both experimental and full-scale studies of Tuned Sloshing Dampers (TLDs) which rely on the sloshing of the liquid in a rectangular/cylindrical container to control the vibration of the primary structure.

In the proposed research, new models for TLDs and TLCDs are developed. It has been acknowledged by researchers that the sloshing of liquid at high amplitudes is a non-linear phenomenon. This work presents a new model using sloshing-slamming analogy of TLDs based on impact characteristics. The main thrust of this research is to develop the next generation of liquid dampers. Control concepts are introduced in order to correct some of the problems inherent in the existing dampers, mainly the potential of liquid dampers not being fully realized due to their damping being dependent on motion amplitudes or the level of excitation. TLCDs are particularly attractive, in this regard, due to the following reasons:

1. A mathematical model is available for the TLCD, due to which the tuning of the damper is precise, and makes it amenable for semi-active and active control.

2. The amount of damping needed to suppress a particular vibration can be easily ascertained and controlled through the orifice. The orifice opening ratio affects the headloss coefficient which in turn affects the effective damping of the liquid damper. Proportional valves can be actuated by a small voltage signal to obtain the required damping.

3. Arbitrariness of shape, giving it versatility and adaptability for housing in available space, and flexibility in architectural and aesthetic appearance.

4. The TLCD can be tuned by changing its frequency of the TLCD by way of adjusting the liquid column in the tube. This is an attractive feature should the tuning become desirable in case of a change in the primary system frequency.

The advantages of liquid damper systems include low cost and maintenance because no activation mechanism is required. The liquid damper systems are easily mobilized at all levels of structural motion, whereas the mechanism activating a TMD must be set to a certain threshold of excitation. The most important advantage, however is that such containers can be utilized for building water supply, unlike a TMD where the dead weight of the mass has no other functional use. A more elaborate cost analysis of the two systems is presented in Chapter 8.

1.5 Organization of Dissertation

The next chapter discusses new modeling efforts for TLDs. A new sloshing-slamming (S^2) damper analogy has been developed for the sloshing dampers. This is based on two approaches: firstly, numerical simulation of the differential equations involving impact phenomenon; and secondly, explicitly including the impact characteristics in the equations of motion. The equivalent linearization techinique is utilized to derive linear models from the nonlinear ones.

In chapter 3, mathematical model of TLCD is examined in light of the equivalent linearization technique. The optimum absorber parameters for TLCDs are determined for various loading cases. The absorber parameters for multiple-TLCDs are also determined.

Chapter 4 presents a common phenomenon which occurs in coupled system, namely, the *beat phenomenon*. The focus of this chapter is to mathematically understand the beat phenomenon followed by experimental validation.

Chapter 5 discusses the development of semi-active strategies for TLCDs. The efficiency of the semi-active algorithms is illustrated through the use of appropriate examples.

Chapter 6 discusses some of the experimental studies on TLDs. Impact characteristics are derived based on experimental studies. A new type of testing method, namely the hardware-in-the-loop methodology is presented as an new method for testing dampers..

Chapter 7 describes the experiments with TLCDs. Optimum absorber parameters derived in chapter 3 are compared with experimental results. Experiments conducted to show the validity of the semi-active scheme are also discussed.

Chapter 8 deals with cost and reliability analysis for a tall building serviceability under wind loading. Design guidelines and practical considerations are also delineated. Chapter 9 discusses some of the important conclusions drawn from the present research and future work to be done in this area.