Mitigation of Motions of Tall Buildings with Specific Examples of Recent Applications

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ABSTRACT

Flexible structures may fall victim to excessive levels of vibration under the action of wind, adversely affecting serviceability and occupant comfort. To ensure the functional performance of flexible structures, various design modifications are possible, ranging from alternative structural systems to the utilization of passive and active control devices. This paper presents an overview of state-of-the-art measures to reduce structural response of buildings, including a summary of recent work in aerodynamic tailoring and a discussion of auxiliary damping devices for mitigating the wind-induced motion of structures. In addition, some discussion of the application of such devices to improve structural resistance to seismic events is also presented, concluding with detailed examples of the application of auxiliary damping devices in Australia, Canada, China, Japan, and the United States.

1.0 Introduction

The race toward new heights has not been without its challenges. With the advent of E.G. Otis' elevator and the introduction of structural steel, towers and skyscrapers have continued to soar skyward, where they are buffeted in the wind's complex environment. Unfortunately, these advances in height are often accompanied by increased flexibility and a lack of sufficient inherent damping, increasing their susceptibility to the actions of wind. While major innovations in structural systems have permitted the increased lateral loads to be efficiently carried, the dynamic nature of wind is still a factor, causing discomfort to building occupants and posing serious serviceability issues. The next generation of tall buildings research has been devoted in part to the mitigation of such wind-induced motions via global design modifications to the structural system or building aerodynamics and the incorporation of auxiliary damping systems, as summarized by Table 1. The following study encompasses the entire spectrum of techniques geared specifically toward reducing the toll of winds on structures, particularly those which affect occupant comfort. The strategies which will be considered include aerodynamic tailoring and a discussion of auxiliary damping systems.

In addition to their applications in Australia, Canada, China, Japan, and the United States for the mitigation of wind-induced motions, auxiliary damping devices have also gained much recognition for their performance in seismic regions. Thus, while treatment will be given primarily to wind-sensitive structures which utilize these technologies, seismic applications are also pre-

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sented.

Table 1. Means to suppress wind-induced responses of buildings

Means	Type	Method & Aim	Remarks
Aerodynamic Design	Passive	Improving aerodynamic properties to reduce wind force coefficient	chamfered corners, openings
Structural Design	Passive	Increasing building mass to reduce air/building mass ratio	Increased Material Costs
		Increasing stiffness or natural frequency to reduce non-dimensional windspeed	Bracing Walls, Thick Members
Auxiliary Damping Device	Passive	Addition of materials with energy dissipative properties, increasing building damping ratio	SD, SJD, LD, FD, VED, VD, OD
		Adding auxiliary mass system to increase level of damping	TMD, TLD
	Active	Generating control force using inertia effects to minimize response	AMD, HMD, AGS
		Generating aerodynamic control force to reduce wind force coefficient or minimize response	Rotor, Jet, Aerodynamic Appendages
		Changing stiffness to avoid resonance	AVS

SD: *Steel Damper;* SJD: *Steel Joint Damper;* LD: *Lead Damper;* FD: *Friction Damper;* VED: *Visco-Elastic Damper;* VD: *Viscous Damper;* OD: *Oil Damper;* TMD: *Tuned Mass Damper;* TLD: *Tuned Liquid Damper;* AMD: *Active Mass Damper;* HMD: *Hybrid Mass Damper;* AGS: *Active Gyro Stablilizer;* AVS: *Active Variable Stiffness*

2.0 Perception Criteria

The design of typical structures requires the engineering of system that efficiently and effectively carries the anticipated lifetime loads. In this sense, a structure may be designed to meet some functional purpose without any regard for the human element; however, this element becomes a critical component in high-rise construction. With increasing height, often accompanied by increased flexibility and low damping, structures become even more susceptible to the action of wind, which governs the design of the lateral system. While a given design may satisfactorily carry all loads, the structure may still suffer from levels of motion causing significant discomfort to its occupants. Thus many design modifications are explicitly incorporated, be they aerodynamic or structural, to improve the performance of structures to meet serviceability or perception criteria. Before discussing the techniques to mitigate these wind-induced motions, a review of the criteria for acceptable wind-induced motions of tall buildings is provided.

Wind-induced motions (Melbourne & Palmer 1992) fall into a variety of categories including the sway motion of the first 2 bending modes, termed along and acrosswind motions, a higher mode torsional motion about the vertical axis, or for buildings with stiffness and mass asymmetries, complex bending and torsion in the lower modes. Understandably, any of these motions can be quite unnerving to the structure's occupants and may trigger responses analogous to those associated with motion sickness. While the response of each person varies, symptoms may range from concern, anxiety, fear, and vertigo to extreme responses of dizziness, headaches, and nausea. As a result, numerous studies have been devoted to determining the thresholds marking the onset of these sensations, which vary with each individual.

Perception limits have been traditionally determined based on the response of individuals to tests using motion simulators (Chen & Robertson 1973, Irwin 1981, Goto 1983, Shioya et al. 1992). In most cases, such experiments rely on sinusoidal excitations; however, there appear to be some discrepancies between these testing environments and those of actual structures (Isyumov 1993). Since the motion of the structure is a narrowband random excitation inducing bi-axial and torsional responses, the use of uni-axial sinusoidal motions is questionable. In addition, the absence of visual and audio cues in the test environment neglects critical stimuli, particularly for torsional motions which are infamous for triggering visual stimulus.

From such studies of the population's thresholds for perception, criteria are defined as limits which may be exceeded in a particular return period. Typically, in North America, a ten year interval is used; however, in regions with frequent typhoons and hurricanes, a shorter return period, e.g. one year, may be necessary. Figure 1 illustrates some of the perception criteria which are currently in use. Note that typical North American practice is to use 10-15 milli-g peak horizontal accelerations at top floor for residential buildings and 20-25 milli-g for office buildings, based upon a 10 year return period (Isyumov 1993). Kareem (1988a) proposed an rms acceleration threshold of 8 to 10 millig's for a 10 year recurrence interval. The lines labeled H1-H4 are taken from the Japanese AIJ standards (AIJ 1991) and represent various levels of peak acceleration perception, with H-2 typically used for residential applications and H-3 for office dwellings. The light blue lines represent an equation for peak acceleration proposed by Melbourne (1988) based in part upon the previous findings of several parties. The expression is derived from the maximum response observed during a ten minute interval for various return periods. Also shown is Reed's (1971) constant perception limit of 5 milli-g's for a six year return period and Irwin's E2 curve (1986) for rms accelerations, also given in ISO6897 (ISO 1984), illustrating the difference between the use of rms versus peak accelerations.

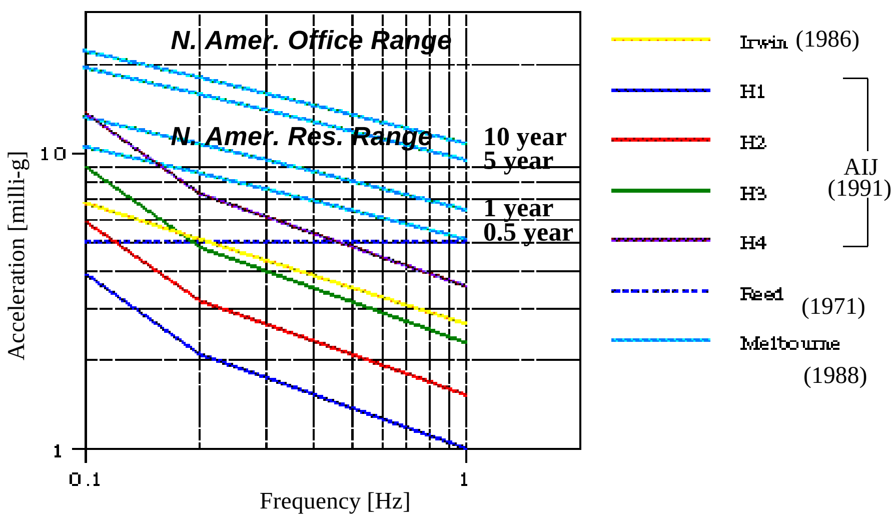


Figure 1. Various perception criteria for occupant comfort.

Criteria based on rms accelerations, as opposed to peak accelerations, offer a more accurate means of combining response in different directions based on their respective correlations (Kareem 1992). In the peak acceleration criterion, the first peaks, in each direction, are determined and subsequently combined by an empirical combination rule; however, since different response components may have a different probability structure, requiring different peak factors, care must be exercised. Further discussions have revealed that the jerkiness of the structural response may primarily be responsible for perception of motion. Quite simply, while humans are capable of adjusting to accelerations, any change in the acceleration will require additional adjustments for equilibrium. As a result, basing perception criteria on a measure of rms jerk, or the rate of change of acceleration, would better capture the stimulus which defines our perception thresholds under random motion.

In addition, frequency-dependent motion perception threshold criteria and probabilistic criteria which take into account the probabilistic distribution of human perception limits are also being considered. In particular, the frequency dependence of perception thresholds becomes critical, since there is evidence that, with decreasing frequency of oscillation, there is an increase in perception levels.

3.0 Structural Systems

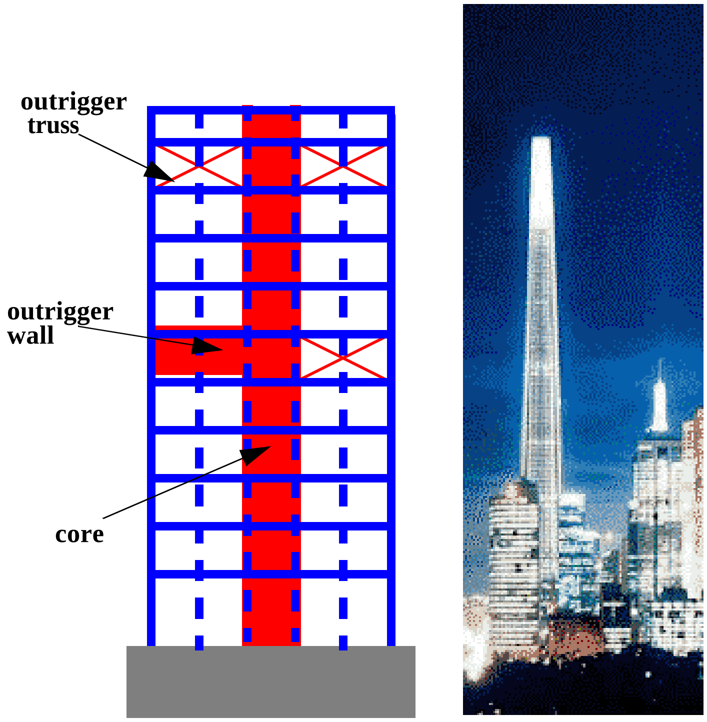
In light of human perception and serviceability concerns, a host of techniques have been developed to mitigate the unnerving motions induced by wind. Above and beyond the rudimentary design of structural systems to efficiently carry lateral loads in the structure, certain features can be engineered into the structure to improve its performance under the action of wind. If seismic effects are not a concern, by increasing the building's mass, the air/building mass ratio and the natural frequency will be reduced; however, this modification increases the non-dimensional windspeed. Therefore, this trade-off relation can occasionally increase the input wind force energy and increase the displacement, while the acceleration decreases almost in proportion to the square root of the mass. However, it is very difficult and unrealistic to increase the building's mass, considering the resulting amplification of the seismic inertia force.

On the other hand, fundamental dynamics proves that increases in stiffness will provide reductions in the amplitude of motion, but will not affect accelerations which comprise the stimulus for motion perception. Furthermore, by stiffening the structure, the jerk component, another contributing factor to motion stimulus, may increase. Therefore, the selection of an efficient structural system must include the evaluation of its ability to resist lateral wind loads with minimum jerk and acceleration levels for the upper floors.

Despite all the considerations, the appropriate selection of an efficient structural system can provide the most effective means of controlling structural response to wind in the lateral and torsional directions. This may be accomplished through any number of systems including space frames, mega frame systems, and the addition of vierendeel frames, belt trusses, super columns, vierendeel-type bandages and outrigger trusses. A structural system can also benefit from concrete or composite steel/concrete construction with higher internal damping. For example, the **Petronas Towers** in Kuala Lumpur utilized a concrete structural system which aided in improving the performance of the buildings from a serviceability standpoint. The application of a few of these strategies are highlighted in the following sections.

3.1 Outrigger Systems

The use of outrigger systems, as illustrated Figure 2a, has become a popular approach to improve the efficiency of the core system by simply engaging the exterior columns to aid in resisting part of the overturning moment resulting from lateral loads. While buildings of 35-40 stories can typically rely solely on shear wall and steel-braced core systems, which are very effective in resisting the forces and deformations due to shear racking, the resistance of these systems to the overturning component of drift decreases approximately with the cube of height (CTBUH 1995). As a result, core systems become highly inefficient for taller skyscrapers. The incorporation of outrigger walls or trusses, often 2-3 stories deep, can overcome the restrictions facing core systems by transferring some of the loads to the exterior frame.



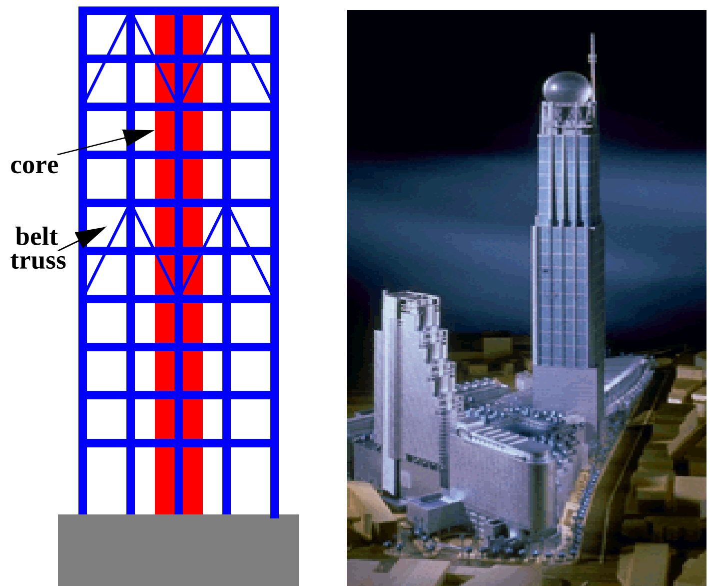
(a) (b)

Figure 2. (a) Schematic representation of outrigger system. (b) Composite sketch of Melbourne Tower. (taken from Denton, Corker, Marshall)

The incorporation of such systems has proven successful for a host of the world’s tallest buildings, including the proposed 560 m **Melbourne Tower**, to be completed in 2005. The project, shown in Figure 2b, features 2 story deep outrigger trusses every 20 stories to aid in carrying lateral loads (*Civil Engineering* 1999).

3.2 Belt/Bandage Systems

The outrigger concept has been modified via the use of belt walls/trusses as "virtual outriggers," as shown schematically in Figure 3a, accomplishing the same transfer of loads without requiring the complicated direct connection between the outrigger system and core (Nair 1998). The concept relies upon stiff floor diaphragms to transfer the moment in the form of a horizontal couple from the core to the belt wall/truss which connects the exterior columns of the structure. The wall/truss then converts the horizontal couple into a vertical couple in the exterior columns. This "virtual outrigger" system, utilizing belt walls, has been applied to the world's tallest reinforced concrete building: the 77 story **Plaza Rakyat** (Fig. 3b) office tower in Kuala Lumpur, Malaysia (Baker et al. 1998). The structure relies on a concrete shear core and 2 story exterior concrete belt walls connected to the concrete perimeter frame at two levels to carry the lateral loads without the restriction of mechanical space through the presence of conventional outrigger systems.



(a) (b)

Figure 3. (a) Illustration of "virtual outrigger" system using belt trusses; (b) Model of Plaza Rakyat *(taken from Skidmore, Owings, and Merrill, LLP).*

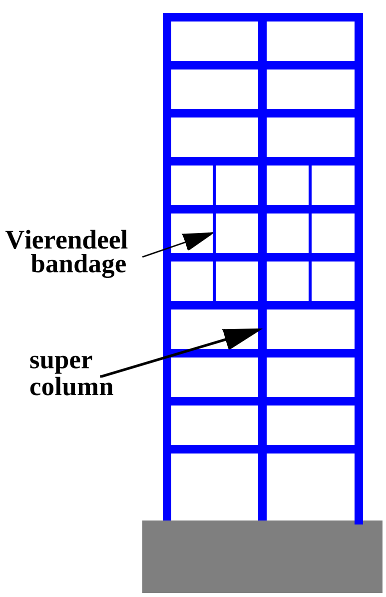


Figure 4. Schematic of Vierendeel bandage.

A similar concept, the Vierendeel bandage, shown in Figure 4, has been implemented in the 775 ft tall First Bank Place in Minneapolis (Dorris 1991). The tower, supported by a cruciform spine with steel columns and four massive composite supercolumns, lacked sufficient torsional stiffness, requiring diagonal bracing. However, to permit unobstructed views, a series of 3 story tall, 36 inch deep Vierendeel bandages were implemented. The addition of the bandages triples the tower's torsional stiffness while improving the lateral stiffness by 36%. In addition, the bandages carry the load from the upper floors and transfer it to the four major columns at the corner.

3.3 Tube Systems

Figure 5. Sears Tower *(taken from Skidmore, Owings, and Merrill, LLP).*

One trademark of high rise construction in the late 20th century has been the use of tube systems. From the innovative designs of Fazlur Khan, developing both the bundled and braced tube concepts, tube systems have served as a successful lateral load resisting system comprised of a series of closely spaced exterior columns and deep spandrel beams held rigidly together (CTBUH 1995). The use of such systems became quite popular following their introduction in landmark structures such as the S**ears Tower** (shown in Figure 5)**, World Trade Center Towers,** and **John Hancock Center**.

The concept is being continually extended in the construction of modern skyscrapers such as the **Shanghai World Financial Center**, (shown later in Figure 9) scheduled for completion in 2001. The design features the tube-in-tube or double tube system featuring an exterior composite tube of structural steel frame with reinforced concrete and interior tube provided by a reinforced concrete core. Under wind loads, the primary design consideration as Shanghai is often subject to typhoon events, 15 to 20% of the shear force is resisted by the interior tube, justifying the use of the double tube system in reducing wind loading (Hori & Nakashima 1998). Further discussion of this structure's incorporation of aerodynamic modifications and auxiliary damping devices is provided in subsequent sections.

3.4 Increasing Modal Mass

Other options to improve building performance in high winds may include shifting the major frequency axes from the main axes of the building shape and altering mode shapes to benefit increased modal mass in the structure's upper floors (Banavalkar 1990). The latter technique can markedly improve occupant comfort since wind-induced accelerations are inversely proportional to the effective mass. For example, this approach was applied to the **Washington National Airport Control Tower**. By eliminating transfer girders at the base and mounting the tower on a 10 foot deep pyramidal truss, base rotation of the tower was eliminated and the effective mass of the tower was increased, thereby reducing the dynamic response of the tower (Banavalkar & Isyumov 1998).

4.0 Aerodynamic Modifications

The specific concern for wind-induced effects has prompted much investigation into the relationship between the aerodynamic characteristics of a structure and the resulting wind-induced excitation level. Often aerodynamic modifications of a building's cross-sectional shape, the variation of its cross-section with height, or even its size, can reduce building motion (Kwok & Isyumov 1998). Such aerodynamic modifications include slotted and chamfered corners, fins, setbacks, buttresses, horizontal and vertical through-building openings, sculptured building tops, tapering, and drop-off corners (Kareem & Tamura 1996), as discussed below.

4.1 Modifications to Corner Geometry and Building Shape

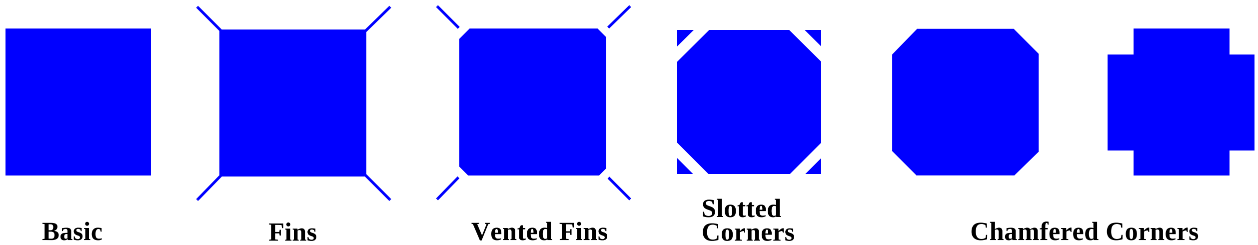
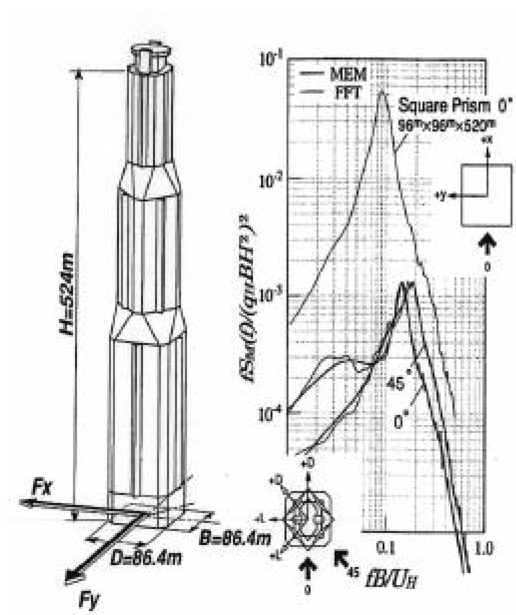


Figure 6: Aerodynamic Modifications to Square Building Shape.

Initiatives to explore the effects of building shape on aerodynamic forces have confirmed the benefits of adjustments in building configurations and corners, as illustrated in Figure 6 (Hayashida & Iwasa 1990, Hayashida et al. 1992, Miyashita et al. 1993, Shimada et al. 1989). Investigations have established that corner modifications such as chamfered corners, horizontal slots, and slotted corners can significantly reduce the alongwind and acrosswind responses when compared to a basic building shape (Kwok 1995). Significant rounding of the structure's corners, approaching a roughly circular shape, have been shown to significantly improve the response of the structure.

Such modifications were applied to the 150 m **Mitsubishi Heavy Industries Yokohama Building** (Figure 7a) which was erected in a water front area in the wake of peripheral tall buildings. To reduce the response, each of the four corners were chamfered, which consequently reduced the wind forces (Miyashita et al. 1995).

(a)



(b)

Figure 7: (a) MHI Yokohama Building *(taken from Mitsubishi Heavy Industries, Ltd.);*(b) Efficiency of changing sectional shape along vertical axis. *(taken from Shimada & Hibi 1995)*

Still, there is no definitive consensus on the benefits of corner geometry modifications, since studies have also shown that modifications to building corners, in some cases, were ineffective and even had adverse effects (Miyashita et al. 1993, Kwok & Isyumov 1998).

Improved crosswind responses have also been observed in tall buildings which vary their cross-sectional shape with height or reduce their upper level plan areas, e.g. tapering effects, cutting corners, or dropping off corners progressively as height increases. As illustrated by Figure 7b, changing the cross sectional shape along the vertical axis, coupled with effective tapering, can be especially effective in reducing the crosswind forces (Shimada & Hibi 1995). These results have been confirmed in other works and imply that the more sculptured a building's top is, the better it can minimize the alongwind and crosswind responses. Figure 8 illustrates the use of such geometries in two recent projects: The **Jin Mao Building** (Figure 8a) in China and the **Petronas Towers** (Figure 8b) in Malaysia. The Jin Mao Building exploits the use of setbacks and tapering up its 421 m facade and is crowned by ornate tiers shifted from the major axis of the structure creating an effect reminiscent of the ancient pagoda. Similarly, the benefits of tapering also were integrated into the design of the 450 m twin towers.

(a) **(b)**

Figure 8: (a) Sketch of Jin Mao Building. (*taken from Skidmore, Owings, and Merrill, LLP*); (b) Photo of upper plan of Petronas Towers (*taken from kiat.net)*

4.2 Addition of Openings

The addition of openings (Miyashita et al. 1993, Irwin et al. 1998) to a building provides yet another means of improving the aerodynamic response of that structure, though this approach, as true of any aerodynamic modification, must be used with care to avoid adverse effects. Openings completely through the building, particularly near the top, have been observed to significantly reduce vortex shedding-induced forces, and hence the crosswind dynamic response, shifting the critical reduced wind velocity to a slightly higher value (Dutton & Isyumov 1990, Kareem 1988b). However, the effectiveness of this modification diminishes if the openings are provided at lower levels of the building. The inclusion of openings and other such modifications may adversely affect habitability if they reduce the resonant vortex frequency (Tamura 1997).

Through-building openings have been used in Japan for several buildings and are being applied to the proposed new world's tallest building, the **Shanghai World Financial Center,** featuring a 54 m square shaft and diagonal face that is shaved back with the aperture cut off to relieve pressure at this location. The opening, shown atop the tower in Figure 9, measures 51 meters in diameter. The design exploits not only the benefits of through-building openings but also those provided by shifting and decreasing the cross section with increasing height, essentially tapering the 460 m tower.

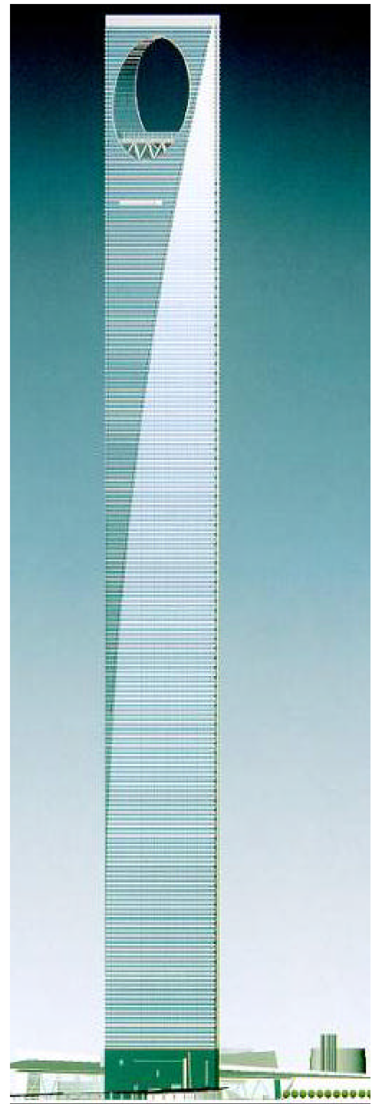


Figure 9: Shanghai World Financial Center. *(taken from Mori Building Co., Ltd.)*

However, care must always be taken in order to engineer modifications that will produce the desired effect, constantly consulting wind tunnel tests to verify the effects of altering the plan shape or employing other forms of aerodynamic modifications. Armed with modifications which avoid increasing the projected area or effective breadth of a building, engineers may achieve significant response reductions (Kwok 1995).

5.0 Damping Sources

An increase in the effective damping of a structure, accomplished by any of the four major sources of damping: structural, aerodynamic, soil, and auxiliary, will also lead to decreased structural motion. Structural damping is limited to the damping already available inherently in the materials: steel, concrete, or their composite. At times, aerodynamic damping may also contribute in the alongwind direction, depending on the wind velocity, structural shape, and building dynamic characteristics. However, the contribution in the acrosswind direction is negligible and may even become adverse at higher wind speeds, though the presence of adjacent structures may introduce different effects. Although not marked for high rise buildings, damping contributions may also be obtained from the soil-foundation interaction, i.e. soil damping. Unfortunately, these three forms of damping make only limited contributions. In addition, the damping in the structure cannot be engineered like the mass and stiffness properties of the structure, nor can it be accurately estimated until the structure is completed, resulting a certain level of uncertainty (Kareem & Gurley 1996). In cases where the inherent damping is not sufficient, auxiliary damping devices may be introduced, offering a somewhat more predictable, adaptable, and reliable method of imparting additional damping to a system.

6.0 Auxiliary Damping Sources

Unlike the mass and stiffness characteristics of the structural system, damping does not relate to a unique physical phenomenon and is often difficult to engineer without the addition of external damping systems. Furthermore, the amount of inherent damping cannot be estimated with certainty; however, a known level of damping may be introduced through an auxiliary source (Housner et al. 1997). Such sources come in the form of both active and passive systems, illustrated schematically in Figure 10, which may be further subcategorized based on their mechanism of energy dissipation and system requirements.

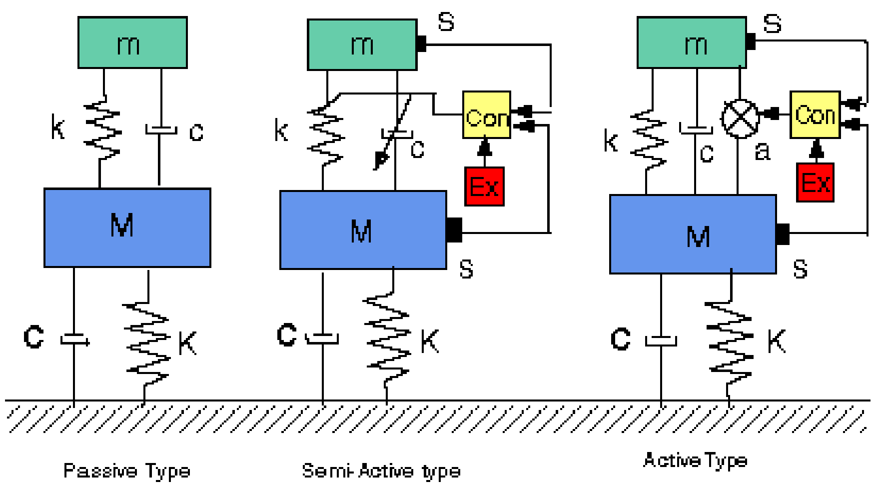


Figure 10: Schematic of various auxiliary damping devices utilizing inertial effects.
(Con: controller, a: actuator, Ex: excitation, S: sensor)

As Table 2 illustrates, such systems have become increasingly popular, especially in Japan, for the mitigation of motions as a result of wind, and in some cases, for wind and seismic considerations, as demonstrated by Table 3. Accordingly, each of these auxiliary damping systems will be discussed herein, with specific attention to notable applications of these devices to actual structures in Australia, China, Canada, Japan, and the United States to control wind induced vibrations.While the discussion of applications can be by no means exhaustive, Appendix Table 2 contains information on other applications utilizing intertial systems.

Table 2. Auxiliary damping devices and number of installations in Japan, including buildings planned to be constructed after 1997

Building Height	Passive									Active				**Total**
	SD	SJD	LD	FD	VED	VD	OD	TLD	TMD	HMD	AMD	AVS	AGS	
$H < 45m$	4	2	1	0	1	2	2	5	1	3	2	0	0	**23**
$H \geq 45m$	20	1	2	3	2	5	4	7	10	15	3	1	1	**74**
Total	**24**	**3**	**3**	**3**	**3**	**7**	**6**	**12**	**11**	**18**	**5**	**1**	**1**	**97**

See abbreviations in Appendix Table 1.

Table 3. Target excitations for response control in Japan (47 Buildings)

Target Excitation		Wind Force Only	Wind & Seismic Forces	Target Excitation		Wind Force Only	Wind & Seismic Forces
Passive	TLD	9	1	Active	HMD	13	6
	TMD	7	5		AMD	2	4
	Total	16	6		Total	15	10

6.1 Passive Dampers (With Indirect Energy Dissipation)

Commonly, auxiliary damping may be supplied through the incorporation of some secondary system capable of passive energy dissipation, for example, the addition of a secondary mass attached to the structure by a spring and damping element in order to counteract the building motion. Such passive systems (Soong & Dargush 1997) were embraced for their simplicity and ability to reduce the structural response. Among the passive devices that impart indirect damping through modification of the system characteristic, the most popular concept is the damped secondary inertial system, which will be discussed below. These systems impart indirect damping to the structure by modifying its frequency response (Kareem 1983).

6.1.1 Tuned Mass Dampers (TMDs)

Typically a TMD consists of an inertial mass attached to the building location with maximum motion, generally near the top, through a spring and damping mechanism, typically viscous and viscoelastic dampers, shown previously in Figure 10. TMDs transmit inertial force to the building's frame to reduce its motion, with their effectiveness determined by their dynamic characteristics, stroke and the amount of added mass they employ. Additional damping introduced by the system is also dependent on the ratio of the damper mass to the effective mass of the building in the mode of interest, typically resulting in TMDs which weigh 0.25%-1.0% of the building's weight in the fundamental mode (typically around one third). Often, spacing restrictions will not permit traditional TMD configurations, requiring the installation of alternative configurations including multi-stage pendulums, inverted pendulums, and systems with mechanically-guided slide tables, hydrostatic bearings, and laminated rubber bearings. Coil springs or variable stiffness pneumatic springs typically provide the stiffness for the tuning of TMDs. Although TMDs are often effective, even better responses have been noted through the use of multiple-damper configurations (MDCs) which consist of several dampers placed in parallel with distributed natural frequencies around the control tuning frequency (Kareem & Kline 1995). For the same total mass, a multiple mass damper can significantly increase the equivalent damping introduced to the system. Presently, there are several types of TMDs in use in Japan, typically employing oil dampers, though a few viscous and viscoelastic dampers being used, (Tamura 1997) as shown by Table 4. In addition, several other structures in the United States, Australia, and Canada employ TMDs.

Table 4. Mass support mechanisms and dampers for TMDs in Japan (11 buildings) (Kitamura et al. 1995)

Mass Supporting Mechanism			Damper Attached to TMD		
Pendulum Including Multiple Type	5	46%	Oil Dampers	8	73%

Table 4. Mass support mechanisms and dampers for TMDs in Japan (11 buildings) (Kitamura et al. 1995)

Mass Supporting Mechanism			**Damper Attached to TMD**		
Laminated Rubber Bearings	4	36%	Visco-Elastic Dampers	2	18%
Roller Bearings & Coil Springs	2	18%	Viscous Dampers	1	9%

6.1.2 Applications of Tuned Mass Dampers

Tuned Mass Dampers, and their variations, comprise the greatest percentage of secondary damping systems currently in use, as Appendix Table 2 reflects. Not only have they been applied to buildings, but also to chimneys, bridges and other industrial facilities in Saudi Arabia, Pakistan, Japan, Australia, the United Kingdom, Germany, Belgium, and Canada. Recent applications include TMDs in the 67.5 m **Washington National Airport Control Tower** (Banavalkar & Isyumov 1998), shown in Figure 11a, adding an estimated 3% in damping to the 0.5% inherently present, and the legs of the **Petronas Towers** 54.8 m Skybridge (Breukelman et al. 1998). The lightweight cylindrical legs of the Skybridge were highly sensitive to vortex excitations. The application of additional damping through tuned mass dampers, resulting in a total damping of 0.5%, was sufficient to prevent vortex shedding and the ensuing fatigue damage.

(a)

(b)

Figure 11.(a) Washington National Airport Control Tower *(taken from Civil Engineering 1996)*; (b) Boston's Hancock Tower *(taken from Boston Society of Architects).*

One of the earliest applications of this type was installed in June 1977 in the 244 m **Hancock Tower** (*ENR* 1977) in Boston, shown in Figure 11b. Two TMDs were installed at opposite ends of the 58th floor in order to counteract the torsional motion. Each unit measured about 5.2x5.2x1 m and was essentially a steel box filled with lead, weighing 300 tons, attached to the frame of the building by shock absorbers. The system is activated at 3 milli-g's of motion at which time the steel plates, upon which the devices rest, are lubricated with oil so that the weights were free to slide (Campbell 1995) The system can reduce the building's response 50% (Wiesner 1979).

Table 5. Other Configurations of TMDs Currently in Use

Host Structure	Location	Description	Installation Date	Results
CN Tower	Toronto	20 ton doughnut-shaped lead pendulums	1975	
Sydney Tower (Fig. 12a) (Kwok & Samali 1995)	Sydney	doughnut-shaped water tanks & energy dissipating shock absorbers	1981	Response Reduced 40-50%
Chiba Port Tower (Kitamura et al. 1995)	Chiba	slide-platform type	1986	Response Reduced 40%- 50%
Fukuoka Tower (Kihara 1989)	Fukuoka	slide-platform type	1989	
Higashimyama Sky Tower (Konno & Yoshida 1989)	Nagoya	inverted pendulum type w/ coil springs	1989	Response Reduced 30-50%
Huis Ten Bosch Domtoren (Kawamura et al. 1993)	Nagasaki	TMD w/ VE material made of asphalt between steel plates of laminated rubber bearings*	1992	Response Reduced 1/2-1/3
Chifley Tower (Kwok & Samali 1995)	Sydney	single pendulum w/ hydraulic cylinders	1994	ζ = +2-4%
Washington National Airport Tower (Banavalkar & Isyumov 1998)	Washington, D.C.	TMD	1997	ζ = +3%
Sendai AERU	Sendai	TMD w/ Laminated Rubber Bearings + Coil Spring	1998	Response Reduced 1/2

Another pioneering application of TMDs has been in use New York's 278m **Citicorp Building** (Petersen 1980), shown in Figure 12b, since 1978. The system, measuring 9.14 x 9.14 x 3.05 m, consists of a 410 ton concrete block with two spring damping mechanisms, one for the north-south motion and one for the east-west motion, was installed in the 63rd floor. The system was included in the overall design due to the building aspect ratio and dynamic features. The system is activated at the critical acceleration threshold of 3 milli-g's by hydraulically raising the concrete mass, allowing full motion of the block as it is regulated by two computer-controlled hydraulic actuators which push and pull the block in the east-west and north-south directions simultaneously to insure that the system behaves as an "ideal" passive bi-axial TMD (Wiesner 1979). The block, resting on a series of 12 hydraulic pressure-balanced bearings, has its motion inhibited by 2 pneumatic springs tuned to the natural period of the building. The system reduces the wind-induced response of the Citicorp Building 40% in both the north-south and east-west directions, simultaneously (Wiesner 1979).

(a) **(b)**

Figure 12: (a) Sydney Tower *(taken from Bartel Ltd.);*. (b) Citicorp Center *(taken from Flour City Architectural Metals Ltd.).*

Often, tuned mass dampers can be engineered without introducing additional mass to the structure. Three structures in Japan utilize such an approach: **Rokko-Island P&G Building** in Kobe, the **Crystal Tower** (Nagase & Hisatoku 1992) in Osaka, and the **Sea Hawk Hotel & Resort** in Fukuoka (Nagase 1998). All three structures have successfully implemented ice thermal or water tanks for the suppression of wind-induced vibrations. A few other notable applications of TMDs worldwide are provided in Table 5 with a more complete catalogue given in Appendix Table 2.

6.1.3 Tuned Liquid Dampers (TLDs)

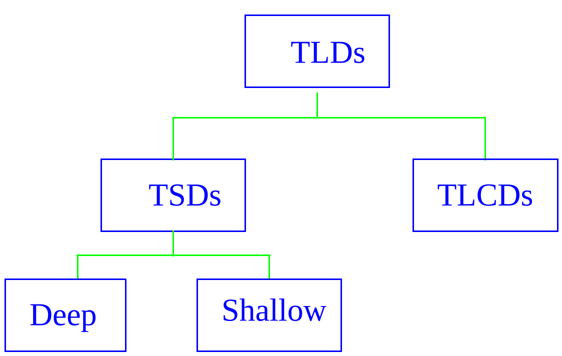


Figure 13: Schematic of the TLD Family.

Tuned Liquid Dampers, encompassing both Tuned Sloshing Dampers (TSDs) and Tuned Liquid Column Dampers (TLCDs) delineated in Figure 13, have become a popular form of inertial damping device (Fujino et al. 1992, Kareem 1990, Kareem 1993, Kareem & Tognarelli 1994, Sakai et al. 1989) since their first applications to ground structures in the 1980's (Modi & Welt 1987, Tamura et al. 1988). In particular, the TSDs are extremely practical, currently being proposed for existing water tanks on the building by configuring internal partitions into multiple dampers without adversely affecting the functional use of the water supply tanks. Considering only a small additional mass, if any, is added to the building, these systems and their counterpart TMDs can reduce acceleration responses to 1/2 to 1/3 of the original response, depending on the amount of liquid mass (Tamura et al. 1995). This, coupled with their low maintenance requirements, has been responsible for their wide use.

Currently, both deep and shallow water configurations of TSDs, which exploit the amplitude of fluid motion and wave-breaking patterns to provide additional damping, are in application worldwide. The shallow water configurations dissipate energy through the viscous action and wave breaking, though recently, Yalla and Kareem (1999) have noted and modeled the high amplitude liquid impacts or slamming phenomena. The addition of PVC floater beads may also add to the dissipation of sloshing energy. Deep water TSDs, on the other hand, require baffles or screens to increase the energy dissipation of the sloshing fluid. However, the entire water mass often does not participate in providing the secondary mass in these configurations (Kareem & Sun 1987).

While the natural frequency of a TLD may be simply adjusted by the depth of water, h_w, and the dimension of the container D_D, there are practical limitations on the water depth and thus the frequency which may be obtained by a given container design. One possible solution is the device shown in Figure 16, which adjusts the sloshing frequency of the damper using a spring mechanism so that the same device can be effective should the building experience a change in the dynamic characteristics (Shimizu & Teramura 1994). With this device, the TLD can be made into one large tank instead of using multiple containers. The extension of the TLCD concept to active control strategies is currently being investigated using a nine story steel building (Honda et al. 1992). At the structure’s top floor, a pressurized u-shaped oscillator is installed with a natural frequency which may be adjusted through the modulation of the pressure in the air chamber. In addition, other configurations such as LCVA (Hitchcock & Kwok 1993), adaptive TLCDs (Kareem 1994) and inertia pump dampers, amplitude-dependent orifice and multiple orifice systems have been explored as effective sources of secondary damping for structures.

6.1.4 Applications of Tuned Liquid Dampers

While the use of TLDs has not been particularly popular in the United States, they have been incorporated in structures elsewhere. In Australia, the 105 m **Hobart Tower** in Tasmainia was equipped with 80 TSD units after the tower was cloaked in a protective cylindrical shell. The shell, while shielding the transmission antenna from the harsh conditions, unfortunately increased the wind-induced response, necessitating the installation of the TSD units. In addition, Japanese installations of TLDs include 6 shallow TSDs, 1 deep TSD, and 5 TLCDs as of 1997. The TSDs primarily utilize circular containers for shallow configurations and rectangular ones for deep water TSDs, while the TLCDs rely on the traditional U-shaped vessel. Such applications work best for buildings with small vibrations and have been observed to reduce the structural response to 1/2 to 1/3 the original response in strong winds (Maebayashi et al. 1993).

One Japanese TSD application in the top floor of the 158 m **Gold Tower** in Kagawa features 16 units. The installation of 10 tons of TSDs was found to reduce the response to 1/2 to 1/3 of the original response. The tank, in the form of a cube, is filled with water and equipped with steel wire nets to dissipate the motion of the liquid. By adjusting these damping nets, the length of the tank, and the depth of water, the device may be appropriately tuned. There are many advantages to applications such as these: (1) there is no mechanical friction in the system so it is effective for even the slightest vibrations, (2) failure of the system is virtually impossible, (3) it is effective against the strong motion of earthquakes and winds, (4) the period is easy to adjust, and (5) the system is inexpensive and easy to maintain (Noji et al. 1991). However, there are drawbacks as well: all the water mass does not participate in counteracting the structural motion. This results in extra premium in terms of added weight to the structure without the benefit of commensurate response control.

Figure 14: Shin Yokohama Prince Hotel and TSD units installed. *(taken from Shimizu Corp.)*

An alternative TSD configuration of multi-layer stacks of 9 circular (2 m dia.) fiber reinforced plastic containers, each 22 cm high, was installed in 1991 in the 149 m **Shin Yokohama Prince Hotel (SYP)** in Yokohama, Japan (Figure 14). Each layer of the TSD was equipped with 12 protrusions installed in a symmetric radial pattern to preclude the swirling motion of the liquid and to get adequate additional damping. From observations of the performance of this installation, the hotel has been shown to successfully meet minimum perception levels prescribed in ISO 6897 Standards (max rms acceleration of 0.6 cm/s^2) with a maximum rms acceleration of 0.5 cm/s^2 (Wakahara et al. 1994), with rms response reductions of 30-50% in 20 m/s winds.

Similarly, another multi-layer configuration of 25 units was installed in the 42 m **Nagasaki Airport Tower** in 1987. Twelve cylindrical, multi-layered vessels of vinyl chloride measuring 50 cm high and 38 cm in diameter were installed on the air-traffic control room floor and the remaining thirteen distributed on each stair landing. Each vessel is divided into 7, 7 cm high layers each containing 4.8 cm of water and weighing 38 kg. Thus a total of 950 kg of TSD units was installed in the tower. Run down tests conducted to calculate the frequency and damping ratio of the tower revealed that there was more displacement due to the acrosswind component than the alongwind component and uncovered the presence of beat phenomena which was eliminated through the use of floating particles that helped to dampen the liquid motion in the containers. An examination of the tower response has shown, once again, the performance of the TSD appears to improve at even higher velocities with the response in wind reduced 35% in winds of 20 m/s (Tamura et al. 1995).

Another airport tower has also been equipped with a TSD system. Consisting of approximately 1400 vessels containing water, floating particles, and preservatives, the device was installed in the

77.6 m **Tokyo International Airport Tower at Haneda** in 1993, as shown in Figure 15. The 1400 shallow circular cylindrical vessels with 60 cm diameter and 12.5 cm height had injection taps and handles to serve as projections and 4 conical dents on the upside and base. These projections and dents provide additional stiffness for stacking the polyethylene vessels. During an actual storm, data revealed that the 22.7 kg TSD application raised the damping ratio to 1%, peaking at 7.6% as the rms acceleration grew (Tamura et al. 1996).

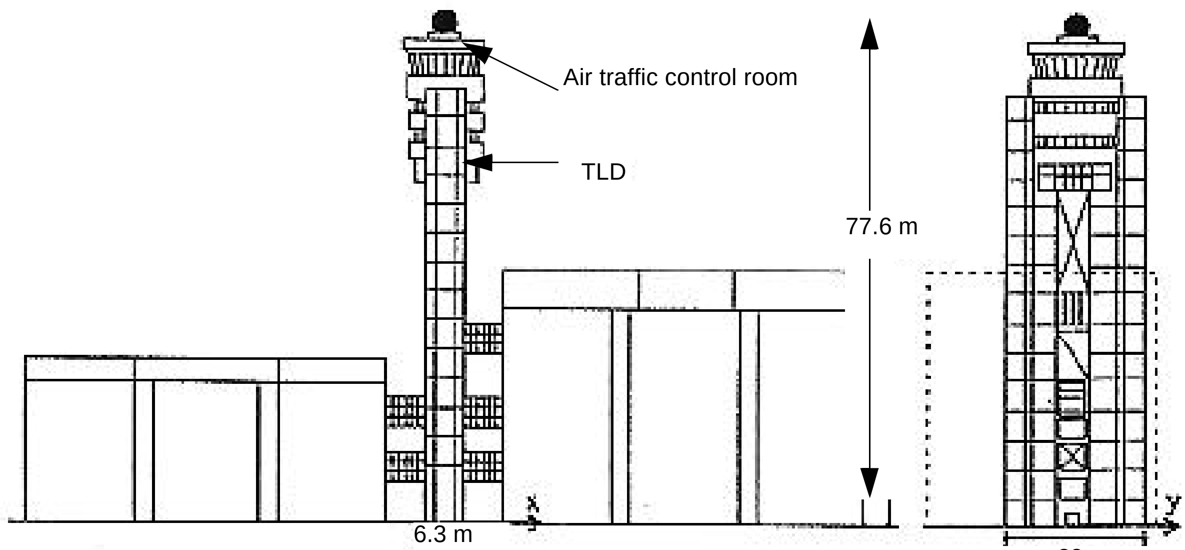
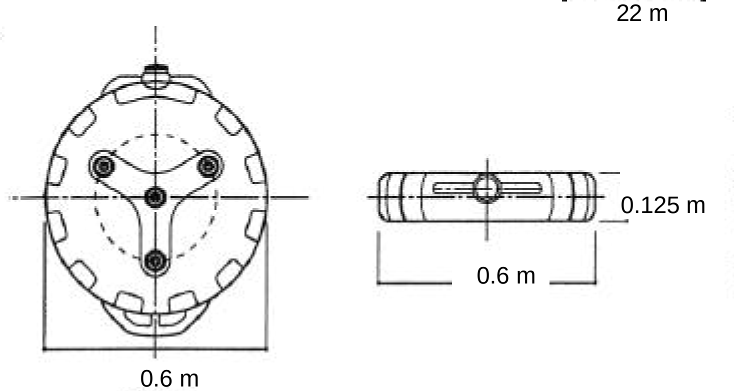


Figure 15**:** Tokyo International Airport Tower (TIAT) at Haneda and views of TLD units installed *(taken from Tamura et al. 1996).*



In addition to the various installations of TSDs, there are also some applications of TLCD technologies, including those with period adjustment mechanisms. By equipping a Tuned Liquid Column Damper with Period Adjustment Equipment (LCD-PA), the behavior of the liquid motion in the liquid column damper may be regulated. Such a system has been installed in the top floor of the 26 story **Hotel Cosima,** now called **Hotel Sofitel** (Figure 16) in Tokyo.

The LCD-PA consists of a rectangular, U-shaped tank, a pair of air rooms, and period adjustable equipment, as shown in Figure 16. When the tank is moved in the horizontal direction, fluid travels in both the vertical and horizontal directions. Thus, in one side, the air is compressed, while in the other chamber, the air pressure is reduced. The sinusoidal pressure fluctuations induce fluid movement in the subsidiary U-shaped tank, resulting in the movement of the valve and shaft and movements in the springs. The device inserted in the hotel is a rectangular based bidirectional LCD with four PA's and a total weight of 58 tons and effective liquid weight of 36 tons. The tank has a portion where liquid is free to move in any horizontal direction, four vertical reservoirs (VR) at each corner above the horizontal partition, and four air chambers separated by partitions. The PA is arranged between the two vertical reservoirs (Shimizu & Teramura 1994). The system has been observed to reduce the maximum acceleration to 50-70% of its original values and the rms acceleration to 50%, as well (Shimizu & Teramura 1994).

Shanghai World Financial Center, shown earlier in Figure 9, is also to be equipped with eight TSD units at its 91st floor upon its completion sometime in 2001 (Wakahara et al. 1998). Each tank will be 7.5 m in diameter, separated into 6 layers. The installation of the 800 ton TSD system (1% mass ratio) is anticipated to successfully reduce story drift and peak and rms accelerations to acceptable limits, when compared to ISO stan-

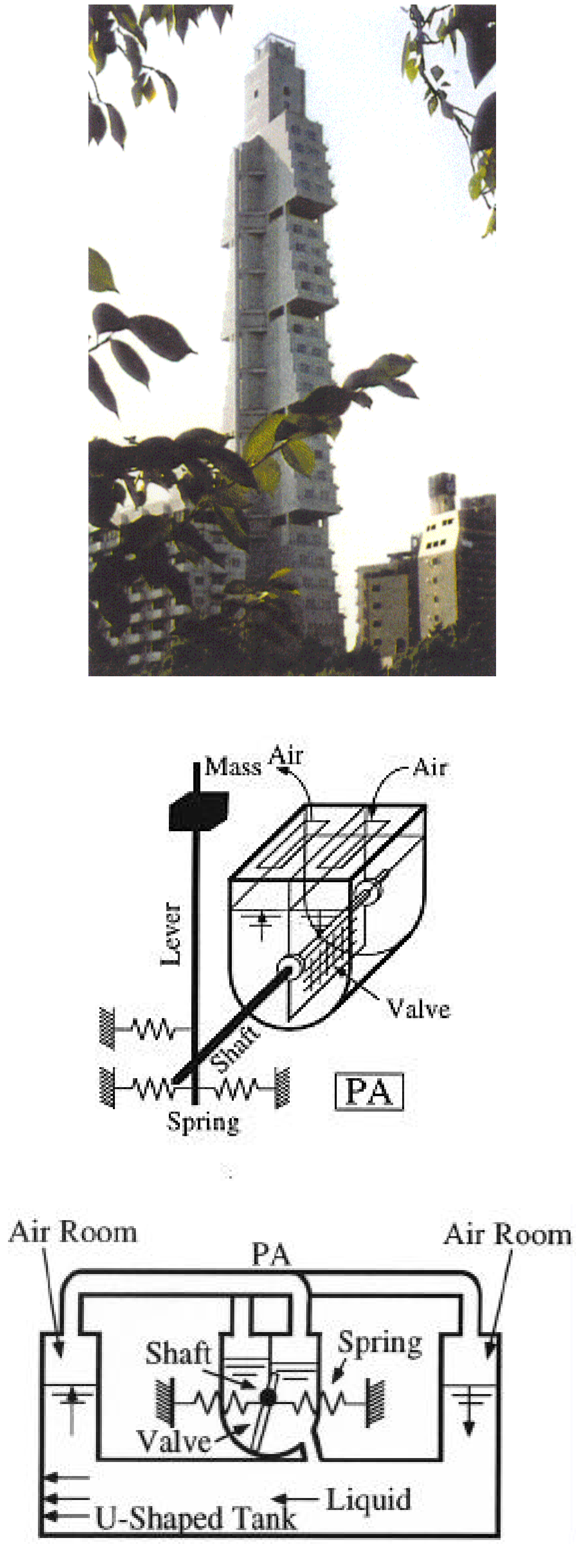


Figure 16: Cosima Hotel and sectional view of the LCD-PA concept with detail of period adjusting mechanism *(taken from Shimizu & Teramura*

dards (Hori & Nakashima 1998). Other notable installations of TSDs and TLCDs in Japan are listed in Table 6.

Table 6. Other Japanese Liquid Damper Applications

TSD applications	***Atsugi TYG Building, Narita Airport Tower**, **Yokohama Marine Tower** (Wakahara et al. 1994)*
TLCD applications	***Hotel Cosima, Hyatt Hotel in Osaka, Ichida Building** in Osaka (Shimizu & Teramura 1994)*
See Appendix Table 2 for more details and applications.	

6.1.5 Impact Dampers

Impact Dampers (Masri & Caughey 1966, Reed 1967) serve as a practical and unique form of inertial system. The devices are typically in the form of small rigid masses suspended from the top of a container mounted at its side to the structure, as shown schematically in Figure 17. The container is designed to a specified dimension so that an optimal spacing is left between the suspended mass and the container, allowing collisions to occur between the two as the structure vibrates. While gap distance serves as a major parameter in the design of such systems, the suspension length and mass size are also of extreme importance, dictating the frequency of the system. This type of damper is particularly effective for masts and tower-like structures with oscillations in one plane and is being used widely, particularly for rooftop masts (Koss & Melbourne 1995).

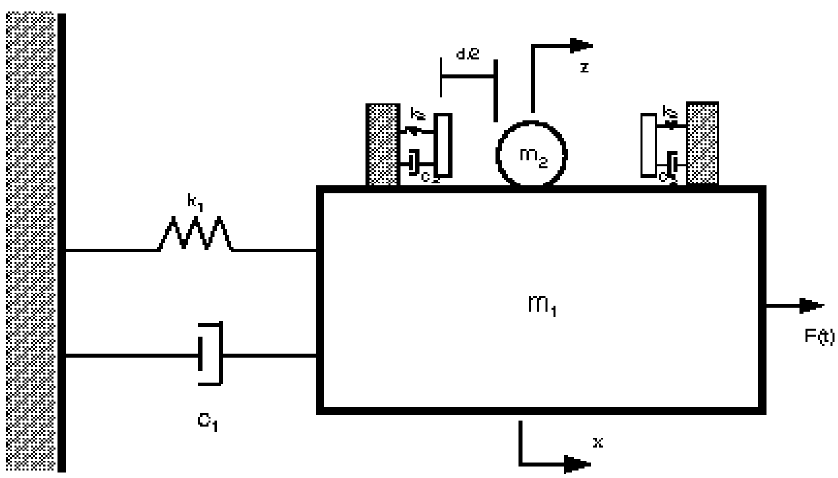


Figure 17: Schematic of an impact damper.

6.1.6 Applications of Impact Dampers

While impact dampers have been used extensively to control the vibrations of turbine blades, printed circuit boards, and machine tools, their application for the vibration of large structures is still relatively limited (Ying & Semercigil 1991). Early applications of impact dampers in the form of chains encased in plastic were utilized by the Navy in their communications antennas.

These pioneering applications proved that displacements could be significantly reduced via the impact of the coated chains (Reed 1967). This form of impact damper, termed Hanging Chain Damper (HCD), with rubber coated chains housed in cylinders combines the benefits of the inelastic impacts with the added internal friction of the chain links rubbing against each other. These technologies have been repeatedly used in towers, masts, and light poles in Australia and Japan to control vibrations due to wind, as summarized by Table 7.

Table 7. Applications of Impact Dampers in Australia and Japan

Structure	Height [m]	Device
Australian Applications		
Tower	30	3 HCDs
Mast	24.7	4 HCDs to control 1st mode, 1 HCD for 2nd mode
Mast	25	1 HCD with 6 m chain
Mast	17	4 HCDs for 1st mode, mast itself used as cylinder for HCD for 2nd mode
Japanese Applications		
Light Poles of Oonaruto Bridge (1986) and in Yokohama (1988); Bridge Pylons in Fuchuo-ku (1992)		

6.2 Passive Dampers (with Direct Energy Dissipation)

Passive systems may also raise the level of damping in a structure through a direct energy dissipation mechanism, such as the flow of a highly viscous fluid through an orifice or by the shearing action of a polymeric/rubber-like (viscoelastic) material. Other classes of passive systems with direct energy dissipation include Viscous Damping Devices (VDDs), Friction Systems, and Metallic Dissipators. The application of such mechanisms to structures, particularly for seismic events, has grown in popularity both in the United States and in Japan, as they require very little space and can be easily retrofitted into existing frames. Their efficiency under large amplitude events such as earthquakes has made them a popular choice in seismic areas, as discussed in the proceeding sections.

6.2.1 Viscoelastic Dampers (VEDs)

Viscoelastic dampers have served as one of the earliest types of passive dampers to be successfully applied to structures (Mahmoodi et al. 1987). VEDs commonly use polymeric or rubberlike materials which are deformed in shear to provide both energy dissipation and a restoring force and are particularly effective in the high frequency range and at low vibration levels against strong winds and moderate earthquakes (Maebayashi et al. 1993). This form of damper, usually consisting of steel plates which sandwich the viscoelastic (VE) material, is readily installed as part of a diagonal brace, where it can dissipate vibrational energy by the shearing action of the VE material. The force generated by this system is dependent on the velocity and is out of phase with the displacement, further making these devices particularly efficient in a building's diagonal bracing system, such as rod and piston dampers (Chang et al. 1992).

Ongoing work is being done to explore the performance of such VED systems under various excitation records. Preliminary studies indicate that these devices not only add damping to the system, but also stiffness, raising the natural frequency of the test structure, and perform satisfactorily for both steel and concrete structures (3M 1995). However, since the VE damper's properties (storage and loss moduli analogous to spring and dashpot constants, respectively) are dependent on vibrational frequency and environmental temperature, the system may manifest varied performance based on the particular situation. Research indicates, though, that the damper properties remain somewhat constant with strains below 20% for a given temperature and frequency (Chang et al. 1992, Oh et al. 1992).

6.2.2 Applications of Viscoelastic Dampers

To date, VEDs have been installed in four buildings in the United States for the minimization of wind-induced vibrations, with the earliest installation being the World Trade Center Towers in New York. These applications are summarized in Table 8 (3M 1995):

Table 8. US Applications of VEDs to Reduce Excitation Due to Wind

Building (Location)	Location & Installation Date	Number of Units	Location in Structure	Performance
World Trade Center Towers (Mahmoodi et al. 1987)	New York 1969	10,000/tower	installed in lower chord of trusses that support the floors	ξ=2.5-3% in Hurricane Gloria
Columbia SeaFirst Building (Mahmoodi & Keel 1986)	Seattle 1982	260	parallel to main diagonal braces of building	ξ=3.2% at design wind and upto 6.4% in storms
Two Union Square Building	Seattle 1988	16	parallel to four columns on one floor of bldg	
Torishima Riverside Hill Symbol Tower	Japan 1999	224	8 VED/floor on first 19 floors 4 VED/floor on 20-38 floors	Wind acceleration response: 80%

In Japan, VEDS have been used to reduce the wind-induced response of several buildings: **Seavans South Tower** in Tokyo (1991), the **Old Wooden Temple, Konohanaku Symbol Tower** (1999), **ENIX Headquarter Building,** the **Sogo Gymnasium** in Chiba (1993), the **Goushoku Hyogo Port Distribution Center** (1998) with viscoelastic joint dampers which reduce the seismic response by one half, and the **Torishima Riverside Hill Symbol Tower,** whose 1999 installation features 8 VEDs per story for the 1st to 19th floors and reduces to 4 VEDs per story for the 20th to 38th stories. In addition, the **Chientan Railroad Station** in Taipei, Taiwan has also been equipped with 8 viscoelastic units to control the wind-induced vibrations of its unique suspended dragon boat roof (Cermak et al. 1998).

Although the use of VEDs to control excitations due to wind has been commonplace for over 20 years, their use in seismic applications has just begun to flourish (Samali & Kwok 1995). Their installation in the form of rubber-asphalt attached to the walls in one direction of every floor of a 24 story building was found to improve the structural responses under earthquake conditions by 30% (Maebayashi et al. 1993). There have been numerous other seismic applications, particularly in the area of retrofitting, in the United States, including the **Santa Clara Civic Center Office**

Building.

6.2.3 Friction Systems

The application of direct damping through friction systems permits plastic behavior by providing non-linearity while allowing the structure itself to remain elastic. The systems, carefully controlled by a sliding surface, feature a very large initial stiffness and the possibility of nearly perfect rectangular angular hysteretic behavior (Aiken & Clark 1994). There are two main types of friction dampers in use in steel-framed buildings: rigid frame friction dampers, providing real plastic hinges which may be replaced easily following an earthquake, and braced frame friction dampers, which utilize diagonal bracing which slips at a predetermined stress value.

Since the aforementioned systems have a predictable slip load and uniform hysteretic behavior, they are excellent for damping seismic vibrations and may also be applied to reduce wind-induced vibrations (Taylor & Constantinou 1996). Presently such systems are in use in several buildings in Canada which feature friction braces and some in Japan which use piston-type friction dampers (Aiken & Clark 1994).

6.2.4 Applications of Friction Systems

There have been several applications of friction systems, as exemplified by Table 9.

Table 9. Some Applications of Friction Systems

Building	**Structure/ Use**	**Year**	**Height (m)**	**Fundamental Natural Frequency (Hz)**	**Equipment/Mechanism**
Sonic City Office Tower, Ohmiya	Steel/Office	1988	140	w/o Dampers: 0.32 (x), 0.33 (y) w/ Damper: 0.35 (x), 0.36 (y)	x-dir: 4 dampers/floor y-dir: 4 dampers/floor friction force/damper: 10 t
Asahi Beer Tower, Tokyo	Steel/Office	1989	94.9	w/o Dampers: 0.32 (x&y) w/ Damper: 0.35 (x&y)	x-dir: 2/floor (1st-20th floors) y-dir: 2/floor (1st-20th floors)

6.2.5 Viscous Damping Devices (VDDs)

Viscous Damping Devices (Oil Dampers: Viscous Fluid Dampers or Oil Pressure Dampers) have become quite common in the construction of new structures and retrofits in seismic zones, prior to their development and subsequent application in military operations. This form of damper dissipates energy by applying a resisting force over a finite displacement through the action of a piston forced through a fluid-filled chamber for a completely viscous, linear behavior, or in damping walls which use a full-story steel plate traveling in a wall filled with viscous material to provide added damping. Through careful design, the devices are capable of providing viscous damping to the fundamental mode and additional damping and stiffness to higher modes, and may, in effect, completely suppress their contributions, raising the structural damping to 20-50% of critical. By incorporating fluid viscous dampers to control wind induced vibrations, structures may be built with reduced lateral stiffness, as the fluid dampers alone reduce the wind deflection by a factor of 2 to 3, greatly improving occupant comfort without creating localized stiff sections (Taylor & Constantinou 1996).

Though operating on the same premise as many of the other forms of energy dampers, the fluid damper holds several advantages. Foremost, the performance of the VDD is essentially out of phase with primary bending and shearing stresses in the structure. Thus, the devices may be effectively employed to reduce both the internal shear forces and deflections. Furthermore, by requiring no external power source and little maintenance, they have become very attractive options for civilian applications, having proven their durability and effectiveness in over 100 years of large scale military use (Taylor & Constantinou 1996).

6.2.6 Applications of Viscous Damping Devices

Other passive systems also exist and are gaining rapid popularity, especially in the design of seismically vulnerable structures. In this area, the application of Viscous Damping Devices (fluid inertial dampers) has been notable. The first use of VDDs for seismic zones was in 1993 in the earthquake-resistant design of the **San Bernadino County Medical Center** in California. The addition of VDDs to the system helped to keep displacements under 22 inches and lengthened the effective period to 3.0 seconds (Asher et al. 1994).

Since that installation, there have been numerous other seismic applications, including the **Pacific Bell Emergency Communications Building** (Sacramento, CA), **Woodland Hotel** (Woodland, CA), the **CSUS Science II Building** (Sacramento, CA) and recently for the seismic retrofit of bridges. In fact, they were even been installed (1984) in the **North American Air Defense Command** in Wyoming for the possible loads caused by a nuclear attack and have been proposed for use in residential structures (Taylor & Constantinou 1996).

While such devices have witnessed widespread application in seismic zones, they have also been installed in several structures for the explicit purpose of controlling wind-induced vibrations, as Table 10 reflects (Taylor & Constantinou 1996).

Table 10. Applications of Viscous Damping Device to Reduce Wind-Induced Excitation

Structure	Location	Installation Date	Type & Number of Dampers	Additional Information
Rich Stadium	Buffalo, NY	1993	12 Fluid Dampers 50 kN, ± 460 mm stroke	Dampers connect light poles to stadium wall to eliminate base plate anchor bolt fatigue
28 State Street	Boston, MA	1996	40 Fluid Dampers 670 kN, ± 25 mm stroke	used in diagonal bracing for serviceability issues
Petronas Twin Towers	Kuala Lumpur City	1995	12 Fluid Dampers 10 kN, ± 50 mm stroke	part of mass damping system in skybridge legs
Building A		1995	80 Oil Dampers, ± 60 mm stroke	Increased Damping by 2.1% of critical

In addition to these applications, viscous dampers were also installed in **Sato Building** in Tokyo (1992), the **Shimura Dormitory** in Tokyo (1993) and the **Structural Planning Headquarters** (1999) in addition to a viscous damping wall installed in the **TV Shisuoka Media City Building**, an office building in Shizuoka, Japan, in 1993. For this latter application, a total of 170 walls were implemented with the device in the x and y directions on each of the building’s 14 floors. Other viscous damping wall installations in Japan include **Daikanyama Apartment House, Postal Service Administration (Kanto Area) Government Office** (Kihara et al. 1998) and the **Academic Information Center.**

6.2.7 Metallic Dissipators

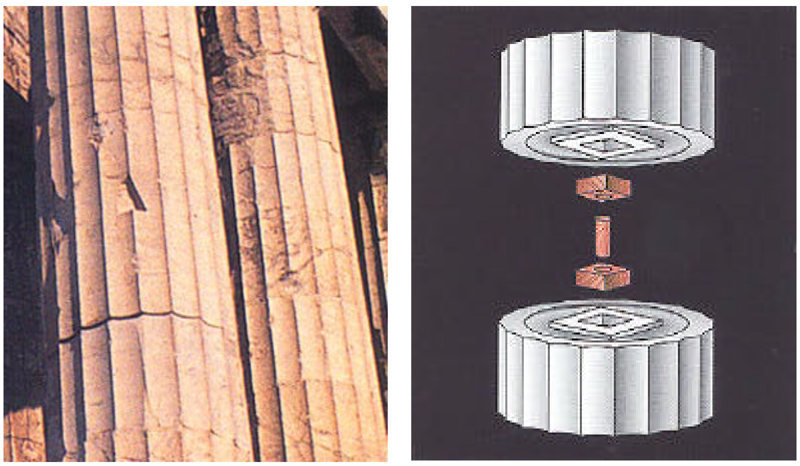


Figure 18: (a) Photograph of columns in Greek Parthenon; (b) Schematic of lead dowel action in columns *(taken from National Geographic 1992).*

Another passive device, metallic dissipators, uses the plastic deformation of mild steel, lead, or special alloys to achieve predictable hysteretic behavior, as was achieved by the ancient architects of the Parthenon for improved resistance to earthquakes. The Greek builders, around 400 BC, recognized the importance for lateral resistance in their famous temples, incorporating socketed dowels which linked the drum-like layers comprising their columns (National Geographic Society 1992). Greek temples, such as the Parthenon, whose columns are shown in Figure 18a, relied on iron dowels embedded in lead to accomplish this aim. The marble disks of the columns could then slide horizontally in an earthquake while maintaining the gravity loads on the structure. During this action, shearing of this lead core, shown in Figure 18b, and the frictional resistance generated between the two disks of marble, provided an additional mechanism for energy dissipation. Over 2300 years later, in 1993, Japanese engineers followed in the great builders footsteps when they installed 12 steel dampers in the **Chiba Ski-Dome**, a modern indoor ski stadium.

One type of metallic dissipator, Added Damping And Stiffness (ADAS) devices, utilize a series of steel plates which undergo distributed flexural yielding when the assemblage is sheared (Aiken & Clark 1994). Most plastic deformations during an event will then be in the ADAS devices, and therefore, damage to the primary building components is limited (Perry & Fierro 1994). Other examples of metallic dissipators include lead extrusion dampers using a piston to extrude lead through a constricted orifice within a confined cylinder to give very stable hysteretic behavior over repeated yield cycles. These systems are currently in use in Japan and New Zealand. Other recent developments include shape memory alloys such as the nickel-titanium alloy, Nitinol, which have the ability to undergo a reversible phase transformation under stress, dissipating energy similar to yielding steel but without permanent damage (Aiken & Clark 1994).

6.2.8 Applications of Metallic Dampers

In recent years, there has been a considerable increase in the number of installations of metallic damping devices in seismic areas. One example is an ADAS installed in the **Wells Fargo Bank** in San Francisco, along with bracing and additional upgrading to improve its ability to resist earthquakes. The ADAS system consists of 50 ksi steel plates cut in an hour-glass shape that bends in double-curvature flexure when subjected to lateral loading (Perry & Fierro 1994). Several other applications of metallic dampers are provided in Table 11.

Table 11. Applications of Metallic Dampers in Japan

Building	Structure/Use	Installation Date	Height	Mechanism
Fujita Corp. Main Office (Tokyo)	Steel/Office	1990	19 story	20 Lead Dampers x 2 directions
KI Building (Tokyo)	Steel/RC/Office	1989	5 story bldg & 9 story bldg	12 Steel Dampers
Hitachi Main Office (Tokyo)	Steel/Office	1984	72.6 m	Steel Damper
Ohjiseishi Building (Tokyo)	Steel/Office	1991	81.4 m	Steel Damper
Sea Fort Square	Steel and Reinforced Concrete/ Hotel, Residence		93.65 m	120 Honeycomb Steel Dampers
ART Hotels Sapporo	Steel/Hotel	1996	90.4 m	x-dir: 952 Steel Dampers y-dir:1068 Steel Dampers (slits)
Two Apartment Houses	Reinforced Concrete/Residential		5 stories	Steel Joint Damper Bell Shape
Garden City School Complex	Steel/School		75.5 m	Honeycomb Steel Damper for torsional vibration
New Central Government Office Building No. 2	Steel/Office		99.5 m	Low-Yield Steel (& Viscous Damper)
Taisho Medicine Headquarter	Steel and Reinforced Concrete/ Office		38.75 m	Honeycomb Steel Damper
Kobe Fashion Plaza (Kobe)	Steel/Store, Hotel	1997	81.6 m	Steel Dampers on 12th -18th Floors
Nissei Sannomiya Building	Steel/Office	1997	61.7 m	16 Steel Dampers (Double Column)/story
Miyagi Prefectural Office East Building	Steel & Reinforced Concrete/ Office	1998	64.5 m	Hypermild Steel Bracing (164 Total)
Keio Department Store	Steel/Department Store	1998 (retrofit)	9 stories	31 Honeycomb Steel Dampers/story

Table 11. Applications of Metallic Dampers in Japan

Building	Structure/Use	Installation Date	Height	Mechanism
Kobe Distribution Center	Steel/Warehouse	1998	4 stories	40 Lead core beams + K brace
Art Hotels Sapporo	Steel/Hotel	1998	90 m	Total 2020 Slit Steel Dampers

6.2.9 Application of Alternative Passive System

Another form of passive damper also being developed for use in seismic applications is comprised of an inverted T-shaped lever, which amplifies the damping force and is accompanied by a pair of oil dampers (Kani et al. 1992). A similar system with an oil damper and I-shaped lever (instead of the T-shaped lever) has been implemented on a full-scale level to a 12 story residential structure in May of 1993 and was found to achieve an effective damping of 10%.

6.3 Active Dampers

In the quest to control the vibration of structures, passive control had originally been favored for its simplicity and reliability - the devices remained functional without an external power source and posed no significant risk of generating an unstable situation. Still, without the use of control mechanisms, the devices were incapable of adjusting to a variation in any parameters of the system. Clearly, more efficient and swifter control could be obtained from a system with the ability to respond to changes - hence, active control emerged, producing smaller devices that were capable of controlling the vibration of structural systems. This aim is accomplished through the use of hydraulic or electro-mechanical actuator systems driven by an appropriate control algorithm, such as: closed loop or feedback, in which the control forces are determined by the feedback response of the structure, open loop or feedforward, in which the control forces are determined by measured external excitations, or closed-open loop or feedforward-feedback, in which the control forces are determined by both measured response of the structure and measured external excitation. Active systems include active mass drivers, active variable stiffness systems (AVS), active tendon control systems, active gyro stabilizers (AGS), active aerodynamic appendages, and active pulse control systems.

6.3.1 Active Mass Dampers (AMDs)

In the particular case of inertial systems, such as the more common Active Mass Damper (AMD) shown earlier in Figure 10, a control computer analyzes measured response signals and introduces a control force, based on the feedback of the velocities/accelerations of the structure. The actuator operates on the secondary mass, in either sliding or pendulum form, to counteract the building motion. Though these systems require smaller damper masses and have efficiency levels superior to those of their passive counterparts, they fall victim to higher operation and maintenance costs and reliability concerns. AMDs have been found to reduce actual structural responses in wind by 1/3 to 1/2 of their uncontrolled values. Currently in Japan, multi- and single pendulum AMDs and active systems utilizing standard, hollow, and linear rubber bearing systems are in application

(Tamura 1997, Sakamoto 1993, Sakamoto & Kobori 1996), as illustrated by Table 12, followed by a list of buildings in Japan utilizing AMDs, shown in Table 13.

Table 12. Mass supporting mechanisms and actuators for AMDs and HMDs in for 19 Buildings in Japan (Kitamura *et al.* 1995)

Mass Supporting Mechanism			**Actuator**		
Pendulums Including Multiple Type	8	42%	AC Servo-Motors and Ball Screws	13	68%
Laminated Rubber Bearings	7	37%			
Linear Bearings	3	16%	Hydraulic Actuators	6	32%
V-Shaped Rail on Rollers	1	5%			

Table 13. Japanese Applications of AMDs in Actual Buildings

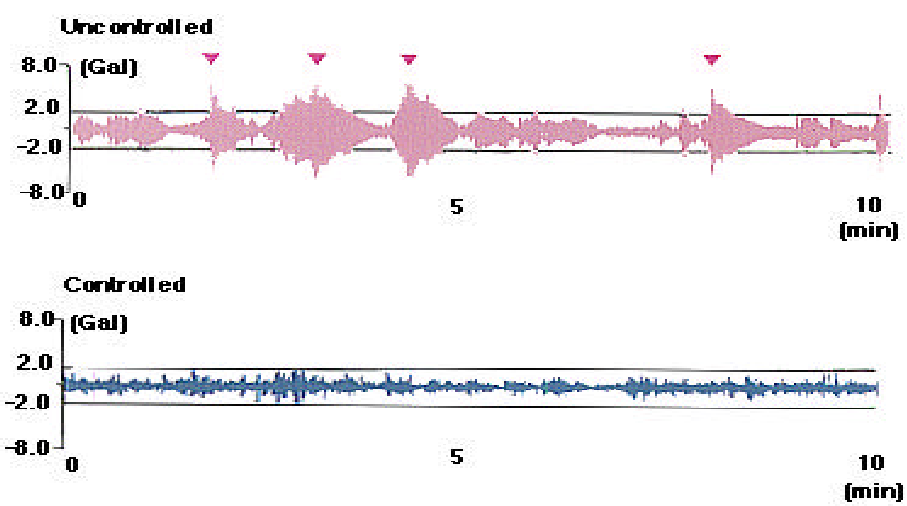
Name	Location	Date	Height (m)
Kyobashi Siewa Building	Tokyo	1989	33
Sendagaya INTES Building	Tokyo	1991	44
Hanku Chayamachi Building (Applause Tower)	Osaka	1992	161
Riverside Sumida Building	Tokyo	1994	134
Herbis Osaka	Osaka	1997	189

6.3.2 Applications of Active Mass Dampers (AMDs)

Kajima Corporation was responsible for the world’s first installation of an AMD when it equipped the 33 meter tall flexible steel **Kyobashi Siewa Building** (Fig. 19a) with such a system in August of 1989 (Koshika et al. 1992). The system, (Fig. 19b) installed to protect the building from earthquakes and strong winds, is capable of responding in 1/100 of a second to vibrations with sensors to detect motions and tremors at the ground and in the building, specifically at the basement, 6th, and 11th floors. Two AMDs were installed by positioning one large AMD unit (4 ton) in the middle to control large oscillations and tremors for the entire building and one smaller unit (1 ton) to the side to counteract torsion. The 2 damper masses are suspended by a wire rope and driven by servo hydraulic actuators. Two pumps and an accumulator act as the hydraulic pressure source for the actuator, providing rapid pressurization and low energy cost. The system, while only about 1.5% of the building's weight, can reduce the response 1/2 to 2/3. A time history of the acceleration of the building’s top floor, shown also in Figure 19c, illustrates the reduction of the response under the action of wind, limiting the accelerations below perception thresholds.

(a)

(b)



(c)

Figure 19: (a) Kyobashi Siewa Building and (b) its AMD unit: (c) performance of structure under wind. *(taken from Kajima Corporation)*.

Several other flexible buildings in Japan have employed AMDs, as shown by Table 14. Among these applications, the 58 m **Sendagaya INTES Building** in Tokyo is especially notable. The building was fitted with 2 AMD units, one to control the torsion and the other translation. The AMD units were designed to move in only one direction, since the north-south winds were the only ones of interest. The designers were able to avoid the addition of extra dead weight, in this case, by using the ice thermal storage tank of the air conditioning system of the building as the mass for the AMD (2@36 tons) under the action of a hydraulic actuator with $\pm$15 cm stroke. The masses are supported by multi-stage rubber bearings which reduce the control energy consumed in the AMD and make smooth movements. After installation, some full-scale data reflecting its performance in strong winds was recorded. Studies have shown the added damping to be approximately 2-4% of critical (Yamamoto et al. 1998). During strong winds of a maximum 30.6 m/s, the response of the primary mode frequency on a 30 second interval was reduced by 18% in translation and 28% in torsion. In addition, data on the performance of the system under several earthquakes confirms a response reduction of 57% (Higashino & Aizawa 1993).

Another instance in which the AMD mass was provided by elements already existing in the structure is the **Hanku Chayamachi Building**, also known as the **Applause Tower** (Higashino & Aizawa 1993) in Osaka, shown in Figure 20. The heliport, resting on multi-stage rubber bearings at the building's top was chosen as the AMD mass, with a weight of 480 tons, thus saving money while not adding any additional weight to the structure. A digital controller, servo mechanism and hydraulic design were implemented along with two 5 ton thrust actuators for both the x and y directions. Free vibration tests have revealed the success of this endeavor: increasing the damping ratio from 1.4% to 10.6%.

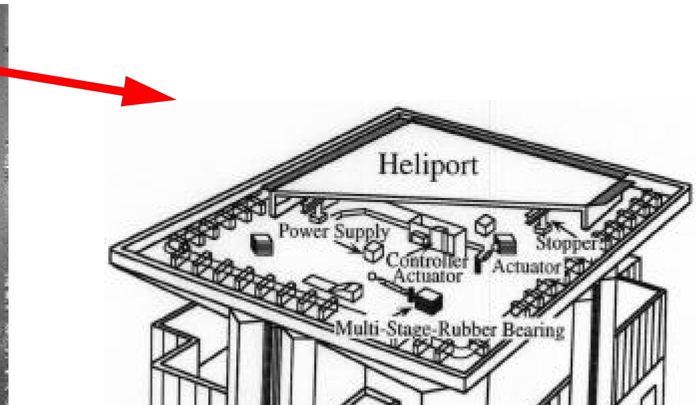


Figure 20: Hankyu Chayamachi Building (Applause Tower) and heliport used as AMD mass. *(taken from Takenaka Corporation)*

However, the application of active mass systems has not been limited exclusively to Japan. An active mass damper system was designed for incorporation in the 340 m **Nanjing TV Tower** in China (Reinhorn et al. 1998). Due to space limitations, passive systems, which were initially considered, could not be incorporated. The system consists of a 590 kN ring-shaped mass, approximately 1% of the tower mass, which slides on friction bearing. The ring mass has an outer radius of 4.75 m with inner radius of 3.9 m and is controlled by three servo-hydraulic actuators with a stroke of +1.5 m.

Table 14. Other Applications of AMDs in Japan

Building	Device	Damper Weight	Performance	Additional Information
Riverside Sumida Building (Suzuki et al. 1994, Annaba et al. 1998)	2 masses, servo motors & ball screws, uni-directional, linear bearings	2@15 t	damping ratio increased from 0.85% to 8.0% and reduced response 20-30% in earthquake	±100 cm stroke; capable of controlling multiple modes: 1st - 3rd transverse modes and 1st torsional mode
Herbis Osaka (Takenaka 1997)	2 masses, restoring force by suspended pendulum	2@160 t	observed under 1997 Typhoon	utilizes 2 ice thermal storage tanks masses; also employs rubber dampers at lower levels
See Appendix Table 2 for more applications and details.				

6.3.3 Active Variable Stiffness (AVS) System

The AVS system is a new form of active control devices that actually changes the stiffness of a structure (Sakamoto & Kobori 1996). The active variable stiffness system is an anti-resonant type of seismic control system designed to control the vibrations of a structure, even in strong earthquakes. Its installation requires placing large inverted V-shaped braces on each story at both ends of the structure as to inhibit transverse motion. Each installation is then attached to the variable stiffness device, which is activated by opening the valve within. When this valve is closed, the system is "locked" in place. By analyzing the seismic ground motions, the controller optimally alters the frequency of the structure by selecting the appropriate stiffness for the building from those available and locking or unlocking different braces to achieve it. Thus, resonant behavior can be eliminated through the successful adjustment of structural stiffness (Sakamoto 1993).

6.3.4 Application of Active Variable Stiffness System

The prototype application of the AVS system was applied in 1990 to a control building of the shaking table test facility in the complex of **Kajima Technical Research Institute**, in Tokyo, Japan, for observation of its performance. Sensors at the base of the structure analyze the seismic ground motions of the first floor with an earthquake motion analyzer. This information is forwarded to the AVS controller, which engages the system if the ground floor acceleration exceeds 10 cm/s^2 and alters the rigidity of the structure by selecting the optimum rigidity to attain the lowest level of response. The inverted V-shaped braces installed on both short sides of the 3 story (12 m) building, with the peak of the "V" attached to the beam, are adjusted by the cylinder lock device, which is the opening or closing valve within the device, dictating a state of "free" or "lock." The electricity required is only 20 W per device, and thus, in case of blackout, a small emergency generator is capable of booting up the system. The system has shown to effectively reduce the response in a real earthquake observed on November 11, 1991, with its performance still being monitored to date (Sakamoto 1993).

6.3.5 Additional Applications of Active Control

Active Gyrostabilizers, which has been observed to perform best in tower-like structures, have been developed commercially for application (Kazao et al. 1992). The system is composed of a high-speed rotating flywheel called a "rotor" and a supporting frame for the rotor called a "gimbal." The system has two servo motors: one rotating the flywheel at high speed levels, and the other controlling the angle of the gimbal to generate the gyroscopic moment actively. The moment along the y-axis stabilizes the bending response of the structure on which the gyro is placed. The sensor system measures the horizontal velocity at the top of the structure, and PD operation is executed on the velocity response by an A/D converter. The executed signals from the digital computer are D/A converted and sent to the servo driver as the speed instruction to obtain the control moment giving precession to the gimbal. The absolute angle of the gimbal is also measured and fedback to give a slight restoring force to the gimbal. A full-scale demonstration was conducted on a 60 m tower-like structure equipped with 2 gyrostabilizers with a 408 kg flywheel rotating at 1260 rpm. The system is supported by a gimbal driven by a servo motor with reduction gear. The damping coefficient, found through free vibration tests, without control was found to be 0.96% and with the addition of the device, the damping coefficient was found to increase to 8.1%. Under actual wind loads, the peak response acceleration with control was reduced to 30% to 80% of that without control, and the rms response acceleration with control was reduced to 25% to 60% of the tower alone.

6.4 Hybrid Dampers

Another genre of control systems, hybrid systems, were also devised to overcome the shortcomings of a passive system, e.g. its inability to respond to suddenly applied loads like earthquakes and weather fronts. In the case of a TMD, the building may be equipped with a passive auxiliary mass damper system and a tertiary small mass connected to the secondary mass with a spring, damper, and an actuator. The secondary system is set in motion by the active tertiary mass, and it is driven in the direction opposite to the TMD, magnifying its motion, and hence, making it more effective (Sakamoto 1993, Sakamoto & Kobori 1996).

Hybrid Mass Dampers (HMDs), behave as either a TMD, utilizing the concept of moving mass-supported mechanisms of the same natural period as the building, or an AMD according to the wind conditions and building and damper mass vibration characteristics (Tamura 1997). As a result of this unique feature, the devices are often termed tuned active dampers (TAD). The active portion of the system is only used when there is high building excitation, otherwise, it behaves passively. In such systems, the device will typically maintain active control, and in the event of a power failure or extreme excitations which exceed the actuator capabilities, will automatically switch into passive mode until the system can safely resume normal operations. This combination of passive and active systems in Japan has been found to reduce structural responses by more than 50%. While these systems are expensive to install, the reduced operation of the AMD implies low maintenance and operation costs.

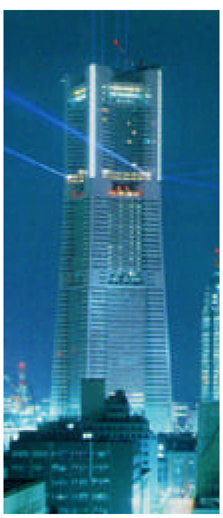
Japanese researchers have devoted numerous studies toward the application of hybrid devices in structures. In fact, most applications of active control technologies are of the hybrid type, as Table

15 reflects. The following section will discuss some of these applications in more detail.

Table 15. Japanese Applications of HMDs (18 Buildings)

Name	Location	Date	Height (m)
Osaka ORC200	Osaka	1992	200
Ando Nishikicho Building	Tokyo	1993	68
Dowa Kasai Phoenix Tower	Osaka	1994	145
Hamamatsu ACT City	Hamamatsu	1994	212
Hirobe Miyake Building	Tokyo	1994	30
Hotel Ocean 45	Miyazaki	1994	154
Kansai Airport Control Tower	Osaka	1994	86
Long Term Credit (LTC) Bank	Tokyo	1993	130
Mitsubishi Heavy Industries Building	Yokohama	1994	152
MKD8 Hikarigaoka Building	Tokyo	1993	100
NTT CRED (RIHGA Royal Hotel) Building	Hiroshima	1994	150
Osaka World Trade Center	Osaka	1994	252
Plaza Ichihara	Chiba	1995	61
Porte Kanazawa	Kanazawa	1993	131
Rinku Gate Tower Building	Osaka	1995	255
Shinjuku Park Tower	Tokyo	1993	227
Yokohama Landmark Tower	Yokohama	1993	296
Yoyogi 3-Chrome Kyodo Building	Tokyo	1998	89

6.5 Applications of Hybrid Dampers



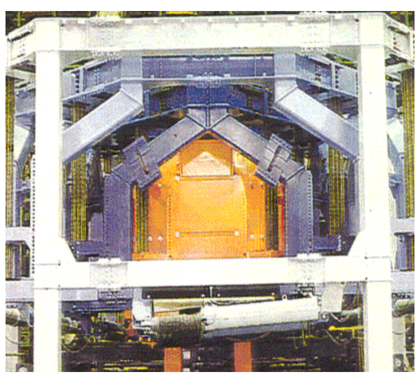
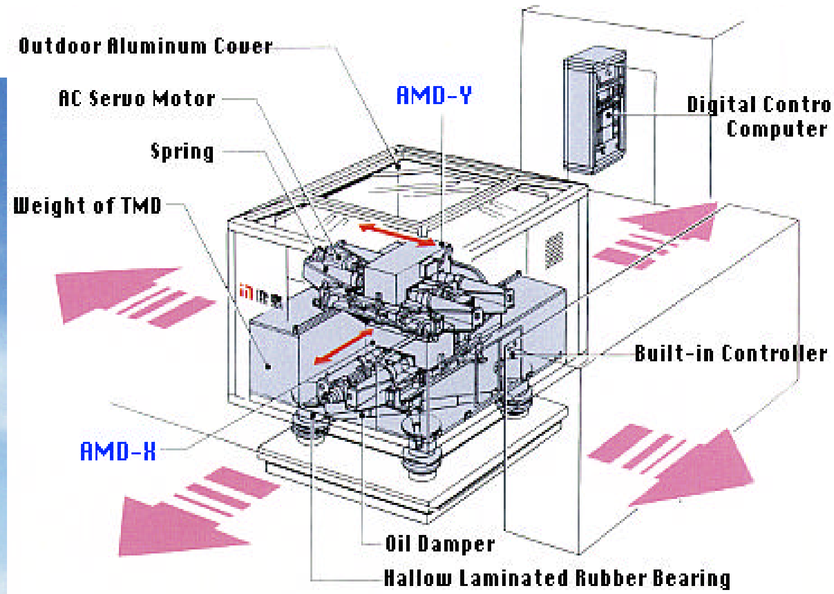


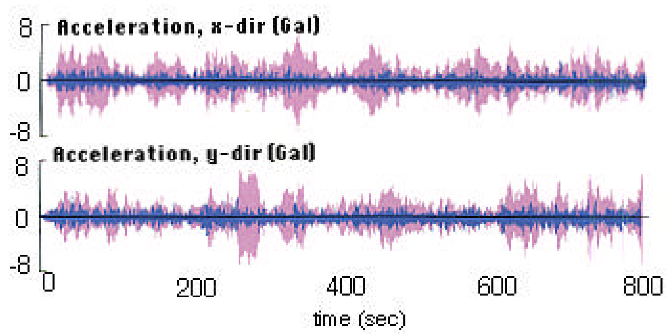
Figure 21: Landmark Tower and TAD unit installed within. *(taken from Mitsubishi Heavy Industries, Ltd.)*

One notable application of HMD technology is the **Landmark Tower** (Fig. 21) in Yokohama. The tower is a 296 m tall, 70 story, steel and reinforced concrete structure, weighing 260,000 tons. In June of 1993, a TAD system was installed on the penthouse first floor (282 m above ground), consisting of 2 units, each comprised of a three-stage pendulum active in 2 directions with tuned spring system and control system with an AC servomotor (Yamazaki et al. 1992). The multi-stepped pendulum (Fig. 21) has a period of 6.0 s and, through the use of a natural period regulator which can alter the effective length of the pendulum, may be adjusted to values as low as 4.3 seconds, in order to correspond to various fundamental periods including that of the tower. Each unit measured 9 meters square, standing 5.0 meters tall and weighing 250 tons, including the pendulum itself which weighs 170 tons. The additional mass was installed in the center of a three-nested structure with the three frames connected by triplicated ropes of element wire. Oil dampers with variable damping coefficients were installed between each frame to insure stability and safety. The damping coefficient is 3000 N-s/cm when the device stops and 300 N-s/cm while the system is functioning, which corresponds to the optimum damping coefficient for a passive TMD (Yamazaki et al. 1992).

(a)



(b)



(c)

Figure 22: (a) Ando Nishikicho Building; (b) Schematic representation of its hybrid system; (c) performance of system, controlled and uncontrolled
(taken from Kajima Corporation)

The TAD control system regulates the additional mass by a state-vector feedback system using as state variables the displacement and velocity of the mass and the floor on which the device is installed (Yamazaki et al. 1992). Free-vibration tests concluded that the wind-induced response was diminished by 50%, consistent with theoretical estimates. Using a maximum pendulum stroke of only 1.70 meters, the system insures the habitability requirement of 5.8 cm/s^2 for a 5-year wind (approximately a 43 m/s wind at the top of building) and has reduced the building sway by 50% (Yamazaki et al. 1992). A similar device with 2 TADs is installed in the **ACT Tower** (Miyashita et al. 1998) in Hamamatsu City, Japan, and the control tower of the **Kansai Airport** (Morita et al. 1998) serving the Osaka/Kyoto area. Several other buildings, shown in Table 16, employ similar pendulum systems.

Another hybrid device has been installed in the **Ando Nishikicho Building**, (Fig. 22a) which is a 14 story building highly susceptible to strong winds. The system was installed near the top, at the building's center of gravity, and consists of a 2-direction simultaneous control with oil dampers and laminated rubber bearings as vibration isolators to prevent vibration and noise. The AMD driving system is comprised of an AC servo motor and ball screws mounted one on top of the other in a criss-cross manner, as shown in Figure 22b. The TMD weighs 18 tons, approximately 0.3%-0.8% of the building weight, while the AMD units each weigh 2 tons, or 10%-15% of the TMD weight (Sakamoto & Kobori 1993). The system is capable of handling excitations from earthquakes of Japanese Intensity 5 and strong winds with a return period of 5-20 years. Beyond these levels, the passive control by TMD runs until normal excitation levels resume.

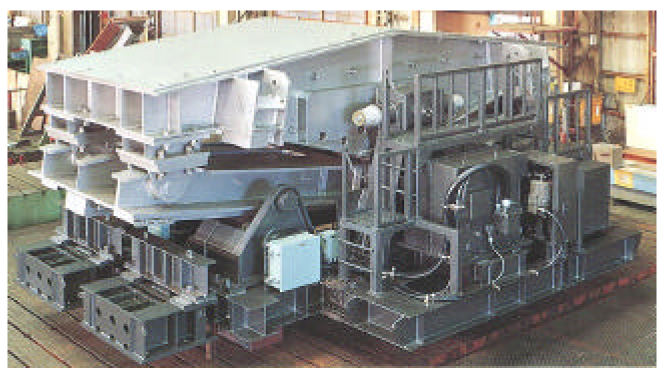
Performance tests have shown that the system was successful, increasing damping by 6.4% in the x-direction and 8.5% in the y-direction, reducing the displacements and accelerations in the x-direction 58% and 69%, respectively, while reducing displacements 30% and accelerations 52% in the y-direction, as illustrated by the time histories in Figure 22c. This system and a similar system in the **Dowa Kasai Phoenix Building** are capable of performing in large earthquakes. Other similar systems are also shown in Table 16.

Figure 23: ORC 200 Symbol Tower and HMD unit installed inside. *(taken from Yasui Architects & Engineers, Inc.)*

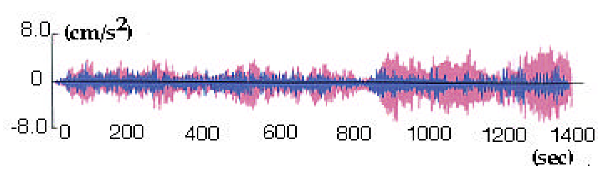
The **Osaka Resort City (ORC) 200 Symbol Tower** (Fig. 23) has also benefited from the installation of two HMD units on the top floor, following its sensitivity to torsional vibrations and lateral vibrations in the transverse direction. The units (Fig. 23) behave as HMDs in the transverse direction and TMDs in the other, each weighing approximately 100 tons with a ±100 cm stroke and a maximum control force of 7.0 tonf. For safety purposes, the system features air brakes to lock the device in the event of large amplitude structural motion. The HMD's effectiveness was confirmed under winds of 17 m/s, with the structural response suppressed about 1/2 to 1/3 (Maebayashi et al. 1993).

Another hybrid system features a weight sliding on rollers like a pendulum, resulting in a smaller system than the equivalent suspended pendulum device, measuring 7.6 m x 4.4 m x 3.5 m high. In this way, the system overcomes the space requirements that a lengthy pendulum may require. The active forcing of the system is provided by an electric motor. The use of suboptimal control technique based on the minimum normal method overcame spillover instabilities affecting the higher mode vibrations as well as the effects of modeling error (Nishimura et al. 1988). The vibration period of the weight can be precisely adjusted because the apparent length of the pendulum can be altered simply by adjusting the rail angle, the system may be tuned to a range of frequencies between 3.7 and 5.8 seconds (Tanida et al. 1994). This adjustment is accomplished by altering the thickness of the spacers between the rail and the weight. The system has been observed to be particularly effective against long-period vibrations and reduces the vibrations of the top stories of high-rise buildings. This, coupled with its effectiveness against moderate and small earthquakes and its ability to quickly suppress residual free-vibrations, made it the perfect system to be installed in Tokyo's **Shinjuku Park Tower,** (Fig. 24a) which houses the **Park Hyatt Hotel** in its upper floors (Koike et al. 1998).

(a)



(b)



(c)

Figure 24: (a) Shinjuku Park Tower, (b) hybrid system installed and (c) its performance. *(taken from Kajima Corporation)*

Wind tunnel tests and analytical studies of the 52 story structure indicated strong levels of first mode oscillation in the transverse direction (Kobori et al. 1991). For this reason, three of these units (Fig. 24b) were installed on the 38th floor of the South Tower. The auxiliary masses of the system weigh only about 0.25% of the above-ground building weight. Each unit had an auxiliary mass of 110 tons, with a maximum stroke of ±100 cm. Free vibration tests revealed that the inherent damping of 1.1% was increased to 4.9% by the HMD units. Since then, the structure has been monitored under the action of typhoons and earthquakes and was found to reduce the response by about 50% during a 1996 typhoon, as illustrated by the acceleration response time history in Figure 24c with the pink and purple lines denoting uncontrolled and controlled response, respectively (Koike et al. 1998).

Table 16. Details of Additional HMD Applications in Japan.

Building	System Type	System Dimensions	Additional Information
MHI Yokohama Bldg. (see Figs. 7a & 27) (Miyashita et al. 1995)	TAD: 2 stage pendulum, active in 2 directions	5.4 m x 5.4 m, x 4.2 m	0.8 m stroke, 80 t (60 t pendulum)
Dowa Kasai Phoenix Bldg. (Sakamoto & Kobori 1993)	2 AMDs + TMD	30 ton TMD + 2 x 6 ton AMDs (total wt=42 t)	ball bearings, laminated rubber bearings for TMD; TMD: ±50 cm; AMD: ±100 cm
Kansai Int'l Airport Control Tower (see Fig. 28) (Hirai et al. 1994; Moritaka et al. 1998)	2 TADs: pendulum, active in two directions	2.2 m x 2.2 m x 2.2 m, TAD: 5 t each	control sway and torsion in wind, AC servo motors & ball screws for driving, approximately 50% reduction of wind response
Hotel Ocean 45 (Tomoo & Keiji 1998)	HMD (x-dir) + TMD (y-dir)	100 t mass ±100 cm stroke	multistage rubber bearings, AC servomotors & ball screws, optimal state feedback, VE damping
LTC Bank of Japan (Teramoto et al. 1998)	HMD utilizing heat storage tanks	2x30 t mass ±100 cm stroke	reduced max acceleration in wind by 50% and RMS 30%
Yoyogi 3-Chrome Kyodo Building	TMD (x-dir) + HMD (y-dir)	40 ton, bi-directional x 2	analysis results: 50% response reduction
Other notable applications of HMDs in Japan: (18 total Japanese applications)			
ACT City Building (multi-stepped pendulum in one direction and passive damper in the other); **NTT CRED Motomachi Building** (also known as the **RIHGA Royal Hotel**) (2 stage pendulum, active in one direction - see Figs. 25 & 26); **Porte Kanazawa** (Aizawa et al. 1997); **Experimental Elevator Building** (Watakabe et al. 1998) *See Appendix Table 2 for more applications and details.*			

Figure 25. NTT CRED Motomashi Building *(taken from Mitsubishi Heavy Industries, Ltd.)*

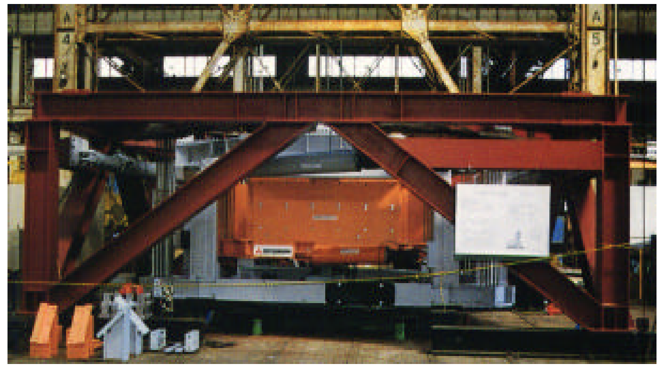


Figure 26. HMD installed in NTT CRED Motomashi Building ((*taken from Mitsubishi Heavy Industries, Ltd.)*

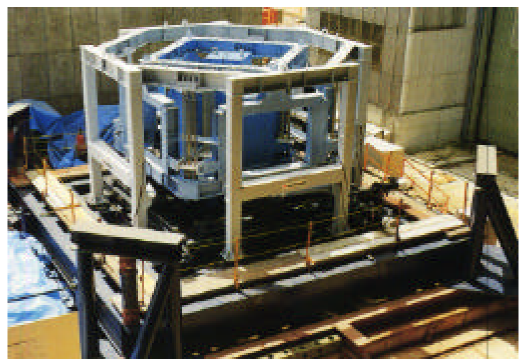


Figure 27. HMD installed in Mitsubishi Heavy Industries Building *(taken from Mitsubishi Heavy Industries, Ltd.)*

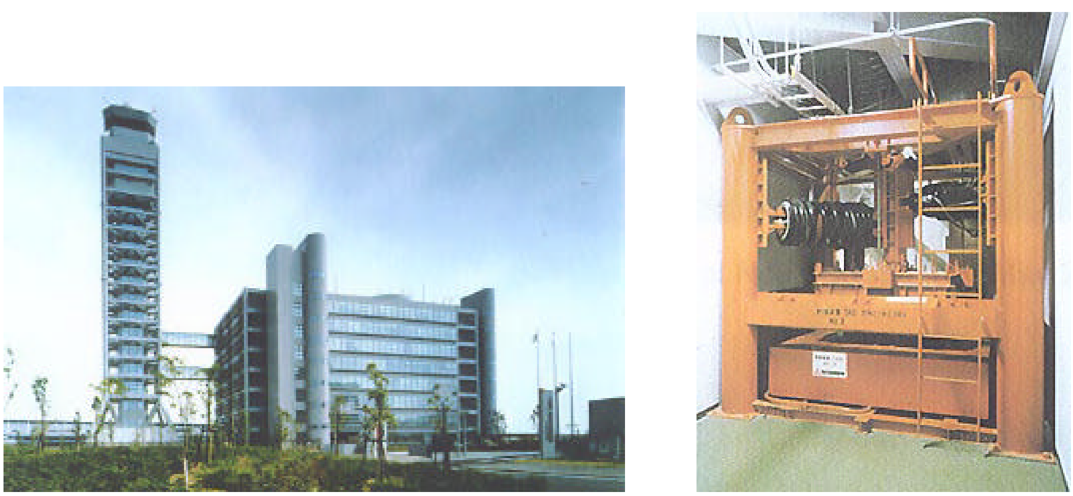


Figure 28. Kansai International Airport Tower and HMD unit installed within. *(taken from Yasui Architects & Engineers, Inc.)*

6.6 Semi-Active Dampers

Following extensive work in both active and passive control, researchers have developed a new generation of control devices, semi-active control, which combine the best features of its parent devices. Possessing the adaptability of active control without the potential for instability, semi-active systems can respond quickly to a sudden gust front or earthquake and provide damping which is excitation-level independent, unlike passive systems which operate at non-optimal values of damping most of the time. Preliminary work indicates that such devices can approach performance levels obtained by active systems without the risk of destabilization or high power requirements (Spencer & Sain 1997). This latter feature is particularly attractive. Since the devices do not introduce mechanical energy into the system, power requirements are relatively low, insuring that the system can remain operational even on battery power during extreme events such as earthquakes.

Semi-active devices range from impact configurations to variable orifice concepts for applications to conventional hydraulic fluid dampers (Symans & Constantinou 1996). Such concepts may also be extended to TLCDs. In the case of TSDs, an analogous semi-active control would adjust the screen or vane openings or control a membrane over the free surface for optimum damping (Kareem & Tognarelli 1994). While semi-active devices which employ forces generated by surface friction have also been considered, the work in controllable fluid devices has gained much notoriety for potential semi-active applications, the details of which are briefly presented in the following section. The numerous experimental studies, including full-scale work on bridges for seismic retrofit, confirms the applicability of this emerging technology.

6.6.1 Electrorheological (ER)/Magnetorheological (MR) Dampers

The motivation for the development of controllable fluids for semi-active applications was partially the result of the unsuccessful search for valves that would respond quick enough to regulate semi-active orifice devices efficiently and effectively. Since these controllable fluid concepts do not require moving parts such as valves, they have been embraced as a viable technology for application in civil engineering structures. Currently, two forms of controllable fluid semi-active dampers are currently being investigated in the United States: the ER (Stevens et al. 1984, Gavin & Hanson 1994, Morishita & Mitshi 1992, Morishita & Ura 1993, Makris et al. 1995) and MR (Spencer et al. 1996) dampers which are capable of producing control performance comparable to active systems without the requirement for large power sources, nor the potential risks involved with introducing additional energy into the system. The “smart” fluids, which provide the energy dissipative mechanism for these devices, develop resistive forces under the application of an electrical or magnetic field, as their respective names suggest. As a result, the degree of polarization of the fluid, and thus its dissipative capacity, may be modified by the regulation of the voltage source which controls the fields. Unlike variable orifice systems which are limited by the performance of their valves, the electro or magnetic fields utilized by these systems activate in mere milli-seconds.

Similar to the hybrid devices, semi-active devices provide passive control under normal operations without any power requirements, but respond quickly to provide optimal levels of damping during seismic events. In fact, such systems can be powered in their “active” mode by traditional, low-voltage power sources. In light of these attractive features, semi-active controllable fluid dampers pose a viable solution to the ongoing problem of structural vibrations.

7.0 Concluding Remarks

A discussion of the various techniques used to mitigate building motion was presented, including structural and aerodynamic solutions. This paper also addressed a number of passive and active motion control devices for improving the performance of tall buildings under wind loads for human comfort considerations, as well as several seismic applications. Detailed examples of practical applications of such devices to buildings in Australia, Canada, China, Japan, and the United States were provided.

In light of the wide spectrum of methods to mitigate wind-induced motion presented in this paper, it is perhaps best to conclude with an innovative project which integrates several of these design approaches. Sir Norman Foster's **Millennium Tower** concept, proposed for construction in Japan, soars 2500 feet skyward with a base the size of Tokyo's Olympic Stadium (Sudjic 1993). The structure exploits an aerodynamically favorable shape through its circular plan, coupled with the benefits of tapering with height, permitting it to perform efficiently in wind. The resulting cone shape, shown in Figure 29a, concentrates its mass in the lower floors to additionally improve the structure's resistance to earthquakes. The performance in wind is further supplemented by the inclusion of a "through-building" opening near the top of the structure, shown in Figure 29b. Meanwhile, the structural system relies on transfer girders, also shown in Figure 29a, to distribute gravity loads to the exterior double helix and column system. This exterior helix casing not only carries the structures load's but also helps to disrupt the wind flow around the structure, further improving the vibration performance. In addition to these aerodynamic and structural modifications, the incorporation of an auxiliary damping system is also planned. As shown in Figure 29c, the systems of water tanks would be located at two levels in the structure and serve as a hybrid liquid damper system, combining the benefits of passive control at low excitation levels,

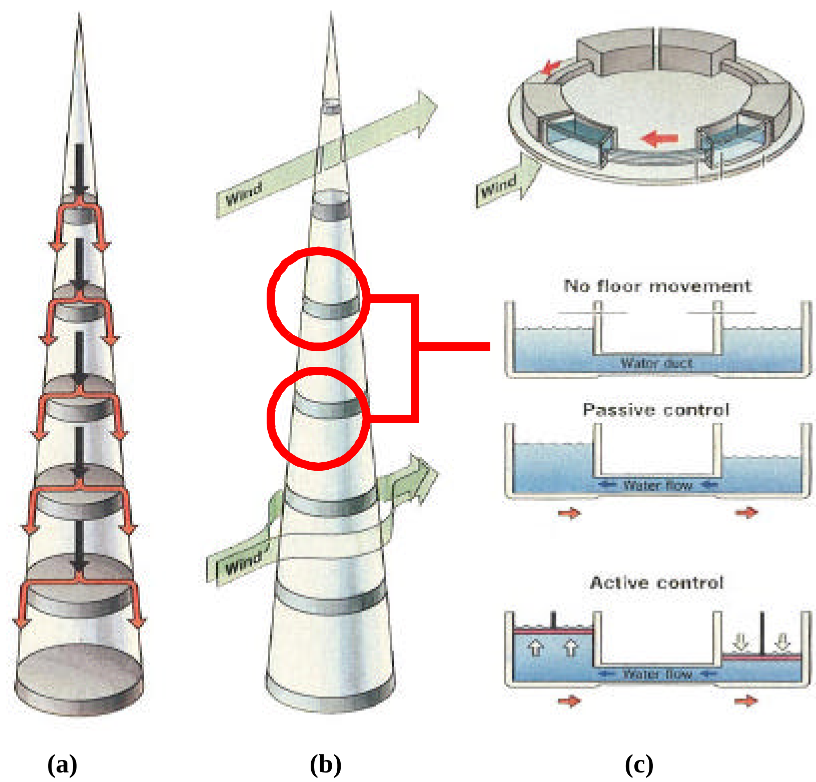


Figure 29: Design concepts for Millennium Tower: (a) load transfer; (b) aerodynamic modifications; (c) auxiliary damping scheme *(taken from Sudjic 1993).*

with the optimum control provided by the active driving of the water levels in the tanks available, an attractive feature in light of the typhoons which frequent this region.

While the incorporation of such technologies permit today's structures to reach even greater heights, it is interesting to note that these concepts are by no means new. Nearly 1200 years ago the ancient Japanese builders were building Millennium Towers of their own. In the design of their famous pagodas (Fig. 30), the Japanese utilized many of the concepts presented here since, making these structures also resistant to both the action of typhoons and earthquakes. The secret of their enduring strength and stability lies in their tapered configuration, the variation of their cross-section with height, and the fact that the energy dissipation occurs at each level, since the levels are not attached to one another and may freely slide to and fro independently. The shinbashira, the central pillar attached to the ground, serves as a snubber, constraining each level from swinging too far in any direction. As the independent levels impact this fixture, energy is introduced which is dispersed through soil damping. Thus, the concepts of secondary intertial systems, friction and impact dampers, and aerodynamic tailoring are not so revolutionary. For the same strategies exploited in modern times for urban skyscrapers, today's counterpart of the pagoda, have been ingeniously tapped by the ancient Japanese builders for centuries.

Figure 30: Schematic of Japanese Pagoda *(taken from Winds 1998.).*

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9.0 Works Cited

AIJ. (1991), *Guidelines for the Evaluation of Habitability to Building Vibration.* Architectural Institute of Japan, Tokyo.

Aizawa, S., Ohtake, K., Yamamoto, M., Azuma, T., Miyazaki, M., and S. Fujimori. (1997), The Characteristics of Wind Fluctuation and the Results of Structural Control at Porte Kanazawa, *Summaries of Technical Papers of Annual Meeting*, AIJ, B-2: 937-938 (In Japanese).

Asher, J., Young, R., and R. Ewing. (Oct. 1994), Seismically Damping the San Bernadino County Medical Center, *Structural Engineering Forum*: 39-43.

Baker, W.P., Brown, C.D., and R.C. Sinn. (July 1998), Belt Wall/Core Interacting System for 77-Story Plaza Rakyat Tower, *Proceedings of Structural Engineers World Congress*, San Francisco, CD-ROM: T114-3.

Banavalkar, P. (1990), Structural Systems to Improve Wind Induced Dynamic Performance of High Rise Buildings, *Journal of Wind Engineering and Industrial Aerodynamics,* 36: 213-224.

Banavalkar, P. V. and N. Isyumov. (July 1998), Tuned Mass Damping System to Control Wind-Induced Accelerations of Washington National Airport Air Traffic Tower Control Tower, *Proceedings of Structural Engineers World Congress*. San Francisco, CD-ROM: T179-2.

Breukelman, B., Irwin, P., Gamble, S., and G. Stone. (July 1998) The Practical Application of Vibration Absorbers in Controlling Wind Serviceability & Fatigue Problems, *Proceedings of Structural Engineers World Congress,* San Francisco, CD-ROM: T179-7.

Campbell, R. (3 March 1995), A True Tall Tale About the Hancock Tower, *Boston Globe*: 29 &34.

Cermak, J.E., Kawakita, S., Bienkiewicz, B., Peterka, J., Lai, M.-L., Nielsen, E.J., Woo, H.G.C., Boggs, D., Chan, J., Chang, K.C., and S.L. Danielson. (July 1998), Viscoelastic Damping System to Mitigate Wind-Induced Dynamic Response of Long-Span Roof, *Proceedings of Structural Engineers World Congress*, San Francisco, CD-ROM: T179-3.

Chang, K.C., Soong, T.T., Oh, S-T., and M.L. Lai. (1992), Effect of Ambient Temperature on a Viscoelastically Damped Structure, *Journal of Structural Engineering,* ASCE, 118(7): 1955-1973.

Chen, P.W. and L.E. Robertson. (1973), Human Perception Threshold of Horizontal Motion, *Journal of Structural Division*, ASCE, 98: 1681-1695.

Civil Engineering. (Aug. 1996), No More Flapping in the Wind, ASCE: 14.

Civil Engineering. (Feb. 1999), World's Tallest Building Will Grow Down Under, ASCE: 16.

CTBUH. (1995), *Structural Systems for Tall Buildings*, Mc Graw Hill, NY.

Dorris, V. K. (29 July 1991), Configuration Poses Challenges, *Engineering News-Record*: 24-25.

Dutton, R. and N. Isyumov. (1990), Reduction of Tall Building Motion by Aerodynamic Treatments, *Journal of Wind Engineering and Industrial Aerodynamics*, 36(2): 739-747.

ENR. (Aug. 1977), Tuned Mass Dampers Steady Sway of Skyscrapers in Wind:14-15.

Fujino, Y., Sun, L., Pacheco, B.M. and Chaiseri, P. (1992), Tuned Liquid Damper (TLD) for Suppressing Horizontal Motion of Structures, J. Engrg. Mech., 118(10): 2017-2030.

Gavin, H.P. and R.D. Hanson. (1994), Electrorheological Dampers for Structural Vibration Suppression, Report No. UMCEE 94-35, Dept. of Civil Engineering and Environmental Engineering, University of Michigan, Ann Arbor, MI.

Goto, T. (1983), Studies on Wind-Induced Motion of Tall Buildings Based on Occupants' Reactions, *Journal of Wind Engineering and Industrial Aerodynamics,* 13.

Hayashida, H., and Y. Iwasa. (1990), Aerodynamic Shape Effects on Tall Building for Vortex Induced Vibration, *Journal of Wind Engineering and Industrial Aerodynamics,* 33(1-2): 237-242.

Hayashida, H., Mataki, Y., and Y. Iwasa. (1992), Aerodynamic Damping Effects of Tall Building for a Vortex Induced Vibration, *Journal of Wind Engineering and Industrial Aerodynamics*, 43(3): 1973-1983.

Higashino, M., and S. Aizawa. (1993), The Application of Active Mass Damper System in Actual Buildings, *International Workshop on Structural Control,* Honolulu, Hawaii:82-93.

Hirai, J., Abiru, H. and E. Tsuji. (1994), Study on Tuned Active Damper for Control Tower of Kansai International Airport, *Promotion of Theoretical and Experimental Studies on Vibration Control for Buildings, Special Research Committee on Structural Response Control,* AIJ: 123-130.

Hitchcock, P.A. and K.C.S. Kwok. (1993), Vibration control of structures using liquid column vibration absorber, *Asia-Pacific Vibration Conference '93,* Kitakyushu: 799.

Honda, S., Kagawa, K., Fujita, K., and T. Hibi. (1992), Damping of Wind-Induced Vibration on Medium High Buildings, *Summaries of Technical Papers in Annual Meeting,* AIJ:1093-1094 (in Japanese).

Hori, T. and H. Nakashima. (July 1998), Structural Design of Shanghai World Financial Center, *Proceedings of Structural Engineers World Congress*, San Francisco, CD-ROM: T105-3.

Housner, G.W., et al. (1997), Structural Control: Past, Present and Future, Special Issue of *Journal of Engineering Mechanics*, 123(9).

ISO. (1984), *Guidelines for the Evaluation of Response of Occupants of Fixed Structures, Especially Buildings and Off-shore Structures to Low-Frequency Horizontal Motion (0.063 to 1 Hz), ISO6897-1984(E)*, International Organization for Standardization, Geneva.

Irwin, A. (1981), Perception, Comfort and Performance Criteria for Human Beings Exposed to Whole Body Pure Yaw Vibration and Vibration Containing Yaw and Translational Components, *Journal of Sound and Vibration*, 76(4).

Irwin, A. (1986), Motion in Tall Buildings, *Proceedings of Conference on Tall Buildings, Second Century of the Skyscraper*, Chicago.

Irwin, P., Breukelman, B., Williams, C., and M. Hunter. (July 1998), Shaping and Orienting Tall Buildings for Wind, *Proceedings of Structural Engineers World Congress*, San Francisco, CD-ROM: T114-1.

Isyumov, N. (17-19 May 1993), Criteria for Acceptable Wind-Induced Motions of Tall Buildings, *International Conference on Tall Buildings*, Council on Tall Buildings and Urban Habitat, Rio de Janerio.

Kani, N., Ogura, K., Tsujita, O., Hosozawa, O. and Y. Shinozaki. (1992), A Design Method and Development of Damping Amplifier System for Passive Response Controlled Structure, *Proceedings of 10th World Conference on Earthquake Engineering*: 4165-4170.

Kareem, A., (1983), Mitigation of Wind Induced Motion of Tall Buildings, *Journal of Wind Engineering and Industrial Aerodynamics*, 11(1-3): 273-284.

Kareem, A. (1988a), Wind-Induced Response of Buildings: A Serviceability Viewpoint, *Proceedings of National Engineering Conference*, American Institute of Steel Construction, Miami Beach, FL.

Kareem, A. (1988b), Aerodynamic Loads on Buildings: A Compendium of Measured PSD on a Host of Building Shapes and Configurations, Unpublished Wind Tunnel Study, University of Houston.

Kareem, A. (1990), Reduction of Wind Induced Motion Utilizing a Tuned Sloshing Damper, *Journal of Wind Engineering and Industrial Aerodynamics*, 36: 725-37.

Kareem, A. (1992), Serviceability Issues and Motion Control of Tall Buildings, *Proc. of Structures Congress*, San Antonio.

Kareem, A. (27-30 June 1993), Tuned Liquid Dampers: Past, Present, and Future, *Proceedings of the 7th U.S. National Conference on Wind Engineering*.

Kareem, A. (1994), The Next Generation of Tuned Liquid Dampers, *Proceedings of the First World Conference on Structural Control,* Los Angeles.

Kareem, A. and K. Gurley. (1996), Damping in Structures: its Evaluation and Treatment of Uncertainty, *Journal of Wind Engineering and Industrial Aerodynamics,* 59: 131-157.

Kareem, A., and S. Kline. (1995), Performance of Multiple Mass Dampers Under Random Loading, *Journal of Structural Engineering*, 121(2), 348-361.

Kareem, A., and W.-J. Sun. (1987), Stochastic Response of Structure with Fluid-Containing Appendages, *Journal of Sound and Vibration*, 119(3): 389-408.

Kareem, A., and Y. Tamura (1996), Mitigation of Wind-Induced Motions of Tall Buildings, *Tall Building Structures: A World View, Council on Tall Buildings and Urban Habitat,* Lehigh University.

Kareem, A., and M. Tognarelli. (Oct. 1994), Passive & Hybrid Tuned Liquid Dampers, *Structural Engineering Forum*: 26-30.

Kawamura, M., Maebayashi, K., and K. Shimada. (1993), Application of a Tuned Mass Damper System Using Laminated Rubber Bearings to a Tower Structure (Design, Test, and Recorded Vibration During Typhoons), *Proc. of International Conference on Tall Buildings,* Rio de Janerio.

Kazao, Y., Tanaka, M., Yamada, M. and S. Sakamoto. (1992), Active Vibration Control of a Structure Using Gyrostabilizers, Proceedings of First International Conference on Motion and Vibration Control: 158-163.

Kihara, H. (Oct. 1989), Examples of Practicable Applications of Dampers, (1) Fukuoka Tower, *Struct*., 32 (In Japanese).

Kihara, S., Shibuya, T., Okuzono, T., Takahashi, O., and M. Miyazaki. (July 1998), High-Rise Government Office Building with Viscous Damping Walls, *Proceedings of SEWC,* San Francisco, CD-ROM: T190-2.

Kitamura, H., Tamura, Y., and T. Ohkuma. (May 1995), Wind Resistant Design & Response Control in Japan Part III: Structural Damping & Response Control, *Proceedings of 5th World Congress Council on Tall Buildings and Urban Habitat,* Amsterdam.

Kobori, T., Ban, S., Yamada, T., Muramatsu, S., Takenaka, Y., Arita, T., and T. Tsujimoto. (1991), Earthquake and Wind Resistant Design of Shinjuku Park Tower. *Proceedings of the 2nd Conference on Tall Buildings in Seismic Regions,* Los Angles.

Koike, Y., Tanida, K., Mutaguchi, M., Murata, T., Imazeki, M., Yamada, T., Kurokawa, Y., Ohrui, S., and Y. Suzuki. (July 1998), Application of V-Shaped Hybrid Mass Damper to High-Rise Buildings and Verification of Damper Performance, *Proceedings of Structural Engineers World Congress*, San Francisco, CD-ROM: T198-4.

Konno, T. and M. Yoshida. (Oct. 1989), Examples of Practical Applications of Dampers, (4) Higashima Sky Tower, *Struct*., 32 (In Japanese).

Koshika, N., Sakamoto, M., Ikeda, Y., and T. Kobori. (1992), Control Effect of Active Mass Driver System During Earthquakes and Winds, MOVIC.

Koss, L.L. and W.H. Melbourne. (1995), Chain Dampers for Control of Wind-Induced Vibration of Tower and Mast Structures, *Engineering Structures*, 17(9): 622-625.

Kwok, K.C.S. (Jan. 1995), Aerodynamics of Tall Buildings, *A State of the Art in Wind Engineering: International Association for Wind Engineering,*Ninth International Conference on Wind Engineering, New Delhi.

Kwok, K.C.S. and N. Isyumov. (July 1998), Aerodynamic Measures to Reduce the Wind-Induced Response of Buildings and Structures, *Proceedings of Structural Engineers World Congress*, San Francisco, CD-ROM: T179-6.

Kwok, K.C.S., and B. Samali. (1995), Performance of Tuned Mass Dampers Under Wind Loads, *Engineering Structures*, 17(9): 655-667.

Maebayashi, K., Tamura, K., Shiba, K., Ogawa, Y., and Y. Inada. (Dec. 1993), Performance of a Hybrid Mass Damper System Implemented in a Tall Building, P*roceedings of International Workshop on Structural Control:* 318-328.

Mahmoodi, P. and C.J. Keel. (1986), Performance of Viscoelastic Structural Dampers for the Columbia Centre Building, *Building Motion in Wind* (Eds. N. Isyumov and T. Tschanz), ASCE, New York: 83-106.

Mahmoodi, P., Robertson, L.E., Yontar, M., Moy, C., and L. Feld. (1987), Performance of Viscoelastic Structural Dampers in World Trade Center Towers, Dynamics of Structures, *Structures Congress '87*, Orlando, FL.

Makris, N., Burton, S., Hill, D. and M. Jordan. (1995), Analysis and Design of an Electrorheological Damper for Seismic Protection of Structures, *Proc. SPIE Conf on Smart Structures and Materials*, I. Chopra, ed.: 184-194.

Masri, S.F. and T.K. Caughey. (1966), On the Stability of the Impact Damper, Transactions of the ASME, September: 586-592.

Melbourne, N.H. and J.C.K. Cheung. (1988), Designing for Serviceable Accelerations in Tall Buildings, *4th International Conference on Tall Buildings*, Hong Kong and Shanghai: 148-155.

Melbourne, N.H. and T.R. Palmer. (1992), Accelerations and Comfort Criteria for Buildings Undergoing Complex Motions, *Journal of Wind Engineering and Industrial Aerodynamics*, 41-44: 105-116.

Miyashita, K., Ohkuma, T., Tamura, Y., and M. Itoh. (1993), Wind-Induced Response of High-Rise Buildings: Effects of Corner Cuts or Openings in Square Buildings, *Journal of Wind Engineering and Industrial Aerodynamics*, 50: 319-328.

Miyashita, K., Nakamura, O., Tagaya, K., and H. Abiru. (1995), Wind Tunnel Tests and Full Scale Measurements of High-Rise Building Equipped with TAD, *Proceedings of the 5th East Asia-Pacific Conference on Structural Engineering and Construction*: 1262-1266.

Miyashita, K., Itoh, M., Fujii, K., Yamashita, J., and J. Takahashi. (1998), Full-scale Measurements of Wind-Induced Responses on the Hamamatsu ACT Tower, *J. of Wind Engineering and Industrial Aerodynamics*, 74-76:943-953.

Modi, V.J. and F. Welt. (1987), Vibration Control Using Nutation Dampers, *International Conference on Flow Induced Vibrations*, London, England: 369-376.

Morishita, S. and J. Mitsui. (1992), Controllable Squeeze Film Damper (An Application of Electro-Rheological Fluid), Trans. ASME, *J. Vibration and Acoustics*, 114: 354-357.

Morishita, S. and T. Ura. (1993), ER Fluid Applications of Vibration Control Devices and an Adaptive Neural-Net Controller, *J. Intelligent Material Systems and Structures*, 4.

Morita, H., Yamaura, N., Tsukitani, T., and H. Tsuji. (July 1998), Application of Tuned Active Damper to Control Tower of Kansai International Airport, *Proceedings of Structural Engineers World Congress*, San Francisco, CD-ROM: T198-6.

Nagase, T. (1998), Tuned Pendulum Mass Damper Using Water Tank Installed in a 36-story Hotel Building, Proceedings of Second World Conference on Structural Control, Kyoto, Japan: 139-146.

Nagase, T. & T. Hisatoku. (1992), Tuned Pendulum Mass Damper Installed in Crystal Tower, *Journal of the Structural Design of Tall Buildings:* 35-56.

Nair, R.S. (1998), Belt Trusses and Basements as "Virtual" Outriggers for Tall Buildings, *Engineering Journal,* AISC, Fourth Quarter, 35(4): 140-146.

National Geographic Society. (1992), *The Builders*. National Geographic Society.

Nishimura, H., Yoshida, K., and T. Shimogo. (1988), An Optimal Active Dynamic Absorber for Multi-Degrees-of-Freedom Systems, *Trans. JSME, Series C*, 54(508): 2948-2966 (In Japanese).

Noji, T., Yoshida, H., Tatsumi, E., Kosaka, H., and H. Hagiuda. (1991), "Verification of Vibration Control Effect in Actual Structure (Part 2)," *Journal of Structural and Construction Engineering,* Transactions of the AIJ:145-152 (in Japanese).

Perry, C., and E. Fierro. (Oct. 1994), Seismically Upgrading a Wells Fargo Bank, *Structural Engineering Forum*: 32-37.

Petersen, N.R. (1980), Design of Large Scale Tuned Mass Damper, *Structural Control.* North Holland, Amsterdam, The Netherlands: 581-596.

Oh, S.T., Chang, K.C., Lai, M.L., and E.J. Nielsen. (1992), Seismic Response of Viscoelastically Damped Structure Under Strong Earthquake Ground Motions, P*roceedings of the 10th World Conference on Earthquake Engineering*, Madrid, Spain.

Reed, J.W. (1971), Wind Induced Motion and Human Comfort, Research Report 71-42, Massachusetts Institute of Technology.

Reed, W.H., III. (1967), Hanging-Chain Impact Dampers: A Simple Method for Damping Tall Flexible Structures, *International Research Seminar - Wind Effects on Buildings and Structures*, Ottawa, Canada: 284-321.

Reinhorn, A., Soong, T.T., Helgeson, R.J., Riley, M.A., and H. Cao. (1998), Analysis, Design and Implementation of an Active Mass Damper for a Communication Tower, *Proceedings of the Second World Conference on Structural Control* Kyoto, Japan: 1727-1736.

Sakai, F., *et al*. (Mar 1989), Tuned Liquid Column Damper - New Type Device for Suppression of Building Vibrations, *Proceedings of International Conference on High Rise Buildings,* Najing, China.

Sakamoto, M. (9-10 Dec. 1993), Practical Applications of Active Structural Response Control and Earthquake & Strong Wind Observation Systems, P*lanning Workshop for the Hong Kong International Full-Scale Control Test Facility*, Hong Kong University of Science & Technology.

Sakamoto, M. and Kobori, T. (Dec. 1996), Applications of Structural Response Control (Reviews from the Past and Issues Toward the Future), *Proceedings of the Second International Workshop on Structural Control*, Hong Kong.

Sakamoto, M. and T. Kobori. (1993), Practical Applications of Active and Hybrid Response Control Systems, *International Workshop on Structural Control. Honolulu*, Hawaii:52-66.

Samali, B., and K.C.S. Kwok. (1995), Use of Viscoelastic Dampers in Reducing Wind- and Earthquake-Induced Motion of Building Structures, *Engineering Structures*, 17(9): 639-654.

Shimada, K., and K. Hibi. (1995), Estimation of Wind Loads for a Super-Tall Building (SSH), *The Structural Design of Tall Buildings*, John Wiley & Sons, Ltd., 4:47-60.

Shimada, K., Tamura, Y., and K. Fujii. (1989), Effects of Geometrical Shape on Response of Tall Building, *Journal of Wind Engineering*, JAWE, 41: 77-78 (in Japanese).

Shimizu, K. and A. Teramura. (1994), Development of vibration control system using U-shaped tank, *Proceedings of the 1st International Workshop and Seminar on Behavior of Steel Structures in Seismic Areas*, Timisoara, Romania: 7.25-7.34.

Soong, T.T. and G.F. Dargush. (1997), *Passive Energy Dissipation Systems in Structural Engineering,*. Wiley & Sons, New York.

Spencer, B.F. Jr., and M.K. Sain (1997), Controlling Buildings: A New Frontier in Feedback, IEEE Control Systems, 17(6): 19-35.

Spencer, B.F. Jr., Dyke, S.J., and Sain, M.K. (1996), Magnetorheological Dampers: a New Approach to Seismic Protection of Structures, *Proc. of Conf. on Decision and Control*: 676-681.

Stevens, N.G., Sproston, J.L. and Stanway, R. (1984), Experimental Evaluation of Simple Electroviscous Damper, *J. of Electrostatics*, 20: 167-184.

Sudjic, D. (15 May 1993), Their Love Keeps Lifting Us Higher, *Telegraph Magazine*: 17-25.

Suzuki, T., Kageyama, M., and A. Nobata. (Sept 1994), Active Vibration Control System Installed in a High-Rise Building, *Obayashi Corporation Technical Report.*

Symans, M.D. and M.C. Constantiou. (1996), Experimental Study of Seismic Response of Structures with Semi-Active Damping Control Systems, *Proceedings of Structures Congress X.IV*, Chicago, April 15-18.

Takenaka Corp, AMD System in Herbis Osaka, Company brochure.

Tamura, Y. (1997), Application of Damping Devices to Suppress Wind-Induced Responses of Buildings, *Proceedings of the 2nd European and African Conference on Wind Engineering,* Palazzo Ducale, Genova, Italy, 1:45-60.

Tamura, Y., Fujii, K., Ohtsuki, T. Wakahara, T. and R. Kohsaka. (1995), Effectiveness of Tuned Liquid Dampers Under Wind Excitation, *Engineering Structures,* 17(9): 609-621.

Tamura, Y., Fuji, K., Sato, T., Wakahara, T. and M. Kosugi. (1988), Wind Induced Vibration of Tall Towers and Practical Applications of Tuned Sloshing Dampers, *Proceedings of Symposium/Workshop on Serviceability of Buildings,* Ottawa, Canada, 1: 228-241.

Tamura, Y., Kohsaka, R., Nakamura, O., Miyashita, K., and V. Modi. (1996), Wind-Induced Responses of an Airport Tower- Efficiency of Tuned Liquid Damper, *Journal of Wind Engineering and Industrial Aerodynamics*, 65: 121-131.

Tanida, K., Mutaguchi, M., Koike, Y., and T. Murata. (1994), Development of V-Shaped Hybrid Mass Damper and Its Application to High-Rise Buildings, *Promotion of Theoretical and Experimental Studies on Vibration Control for Buildings,* Special Research Committee on Structural Response Control, Architectural Institute of Japan: 39-50.

Taylor, D.P. and M.C. Constantinou. (1996), Fluid Dampers for Applications of Seismic Energy Dissipation and Seismic Isolation, Publication of Taylor Devices, Inc., 1996.

Tomoo, S. and S. Keiji. (July 1998), Dynamic Characteristics of a Triangular-Plan High-Rise Building and Its Active Vibration Control System, *Proceedings of Structural Engineers World Congress*, San Francisco, CD-ROM: T198-5.

Wakahara, T., Shimada, K., and Y. Tamura. (24-28 Apr. 1994), Practical Application of Tuned Liquid Damper for Tall Buildings, A*SCE Structures Congress & IASS International Symposium,* Atlanta.

Watakabe, M., Chiba, O., Tohdo, M., Ebisawa, H., Hora, H., Fujita, T., and T. Kamada. (1998), Response Control Performance of Active-Passive Mass Damper Applied to Slender Tall Building, *Proceedings of the Second World Conference on Structural Control,* Kyoto: 1776-1786.

Wiesner, K. (2-6 Apr. 1979), Tuned Mass Dampers to Reduced Building Wind Motion, *ASCE Convention and Exposition*, Boston.

Winds. (Aug. 1988), official magazine of JAL, 8.

Yalla, S.K. and A. Kareem. (1999), Modeling Tuned Liquid Dampers as “Sloshing-Slamming” Dampers, *Proceedings of 10ICWE*, Copenhagen, Denmark.

Yamazaki, S., Nagata, N., and H. Abiru. (1992), Tuned Active Dampers Installed in the Minato Mirai (mm) 21 Landmark Tower in Yokohama, *Journal of Wind Engineering and Industrial Aerodynamics*, 41-44: 1937-48.

Ying, Z., and S.E. Semercigil. (1991), Response of a New Tuned Vibration Absorber to an Earthquake-Like Random Excitation, *Journal of Sound & Vibration*, 150(3): 520-530.