CHAPTER 8
DESIGN, IMPLEMENTATION AND RELIABILITY ISSUES

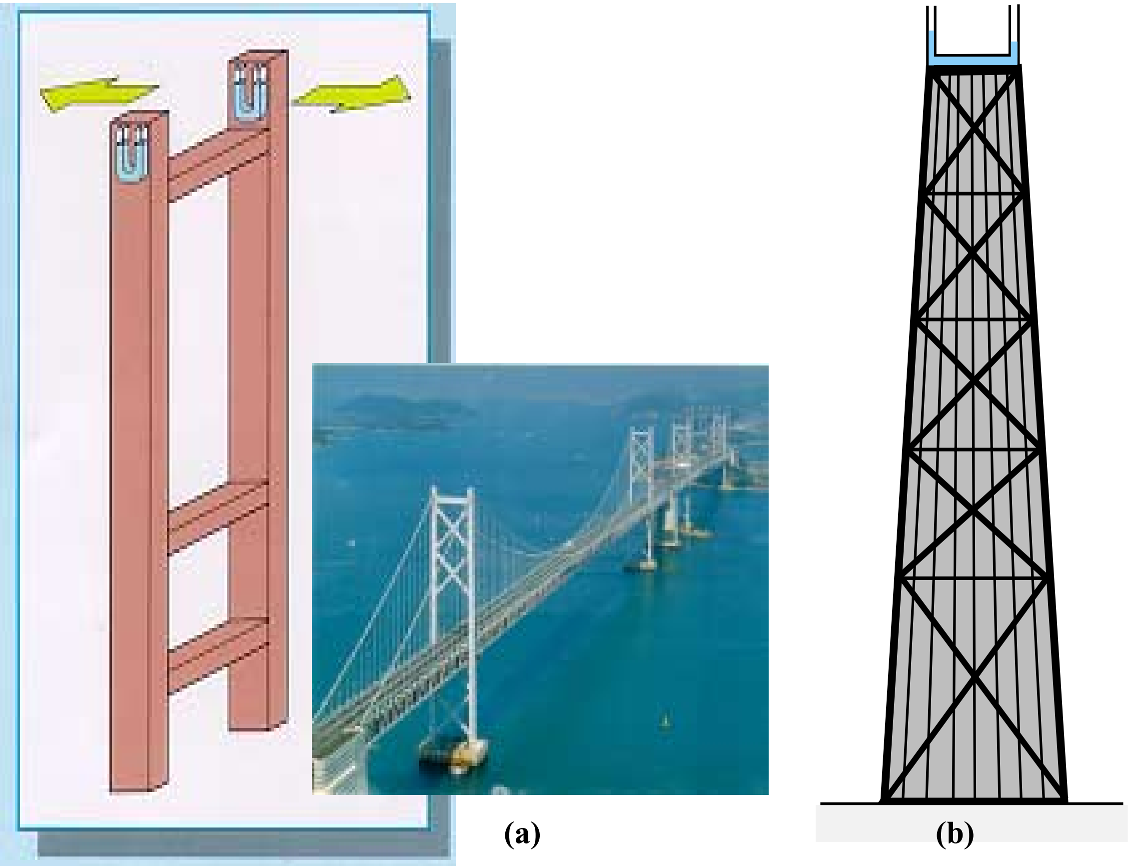
I strive for structural simplicity.... the technical man must not be lost in his own technology.
- Dr. Fazlur Khan

In this chapter various aspects dealing with design considerations, implementation details, cost analysis and reliability issues of liquid dampers are discussed. First, comparisons are made among different types of dynamic vibration absorbers (DVAs) in terms of their implementation and cost. Next, a risk-based decision analysis framework is presented to measure the risk of unserviceability in tall buildings and to provide a basis for choosing the optimal decision. Finally, some design guidelines for technology transfer are laid out in accordance with the research conducted and documented in earlier chapters.

8.1 Introduction

In previous chapters, analytical studies on liquid dampers and experimental validation on scale models have been discussed. However, the actual implementation of these dampers in full-scale structures needs careful consideration of certain practical design constraints. Furthermore, various players including the building owners, designers, architects and engineers need to be cognizant of the risks and related costs involved regarding various choices available to them for improving the serviceability of structures due to high winds and other loading conditions. This chapter addresses the design and implementation issues and also quantitatively justifies the use of the dampers within a risk-based decision analysis framework.

The full-scale implementation of liquid dampers in airport control towers and chimney masts was discussed in Chapter 1. However, future implementations in skyscrapers, bridge towers and offshore structures would require their integration into the overall system. Moreover, the adoption of semi-active TLCDs requires additional equipment and a more sophisticated set-up as compared to a passive system. Figure 8.1 show some of the implementation concepts in bridge towers and tall skyscrapers.



(a) (b)

Figure 8.1 Implementation ideas for tuned liquid dampers (a) bridge towers (b) tall buildings.

8.2 Comparison of various DVAs

There are various factors which influence the selection of a dynamic vibration absorber (DVA) for structures, namely: efficiency, size and compactness, capital cost, operating cost, maintenance, safety, and reliability. In this section, a comparison among three different types of DVAs, namely, the TMD, TLD and TLCD is made.

8.2.1 Implementation comparisons

Tuned Mass Damper (TMD)

The TMD system installed in the Citicorp building is a sophisticated system with a linear gas spring, pressure balance system, control actuator, power supply and electronic control system (Weisner, 1979). The different components used in a building-mounted TMD include in addition to the mass, gravity support system, and the spring system: a damping/active force generating system with a servo-valve and a hydraulic actuator; instrumentation including accelerometers, displacement transducers, pressure and temperature sensors; an electronic control system which turns TMD on and off automatically. Other parts of the TMD include restraint systems for TMDs including anti-yaw torque box, over-travel snubber system with reaction guides, and directional guides so that the mass block does not rotate during travel.

A TMD system needs to be designed in the face of several practical restraints. One of the main disadvantages in the TMD operation is that although it is theoretically a passive device, it needs electricity to operate. This is a problem since power could be lost during a high wind storm, a time when the TMD is expected to be operational (ENR, 1977). Figure 8.2 shows the actual TMD system installed in the Citicorp building in New York.

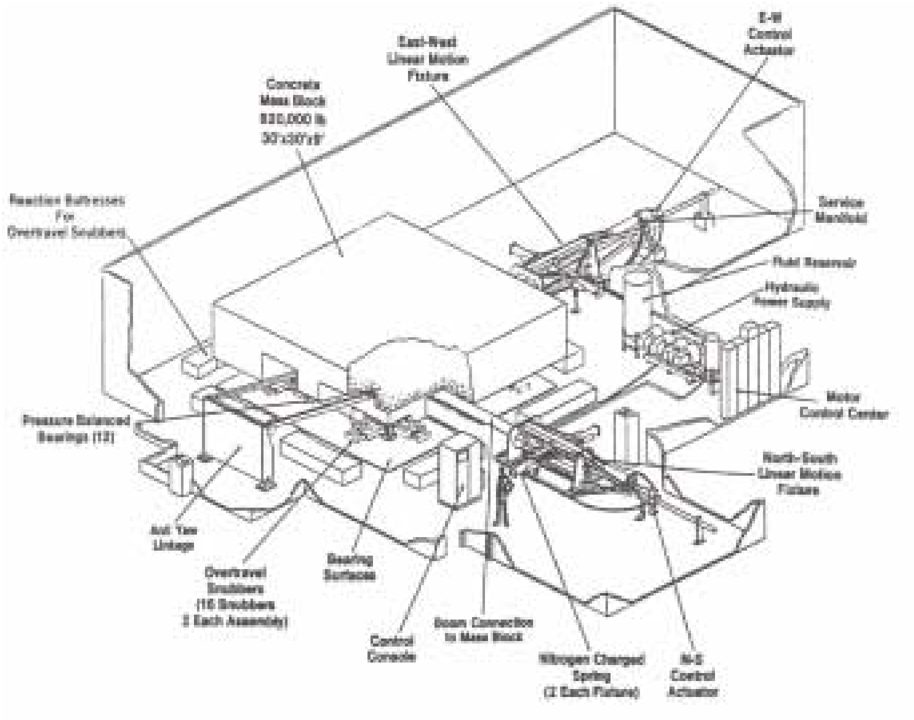
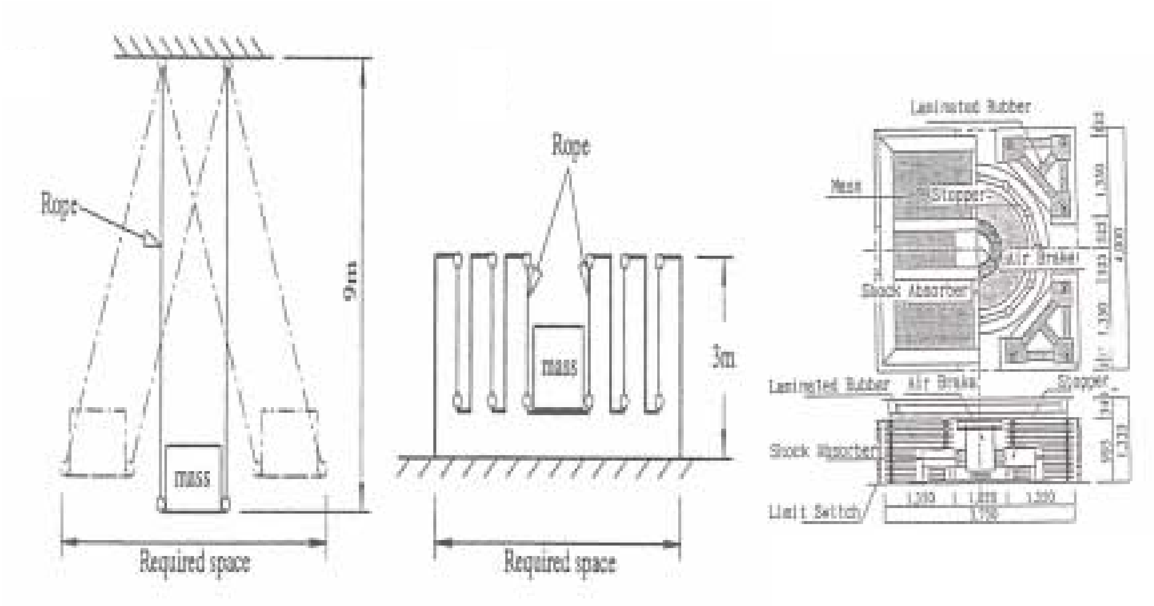


Figure 8.2 TMD system installed in the Citicorp Building, New York City (*taken from Wiesner, 1979*)

Modern TMDs, however, have been designed to accommodate these restraints. Pendulum-type TMDs with single and multi-stage suspensions have been devised. These pendulum-type dampers do not need power to operate. Multi-stage pendulum-type TMDs are advantageous for buildings with low frequency as the length of suspension can be quite large for single-stage pendulum-type TMD as shown in Fig. 8.3(a, b) (Yamazaki *et al.* 1992). Pendulum-type TMDs are usually augmented with coil springs for fine tuning. Mechanically guided slide tables, hydrostatic bearings, and laminated rubber bearings are used to provide low friction platforms. For TMDs with laminated rubber bearings, the bearings act as horizontal springs which eliminates the need for spring system. This type of system is shown in Fig. 8.3 (c). Innovative methods for integrating TMDs into existing buildings have been proposed by researchers. Mita and Feng (1994) proposed a mega-sub control system which utilize sub-structures in a mega-structure configuration to act as vibration absorbers. Similarly, researchers are considering the concept of a roof isolation system in which the top floor or roof of a structure act as mass dampers.

Recent notable TMD applications include the skybridge in the Petronas towers, Kaula Lumpur, Malaysia, where the legs of the bridge were found to be highly sensitive to vortex-induced excitations (Breukelman *et al.* 1998). A good overview of various types of TMD systems for reduction of wind response in structures is provided by Kwok and Samali (1995) and Kareem *et al*. (1999).



(a) (b) (c)

Figure 8.3 (a) Single-stage (b) multi-stage Pendulum-type TMDs (c) TMDs with laminated rubber bearings (taken from Yamazaki *et al.* 1992)

Tuned Liquid Damper (TLD)

Although the mathematical theory involved in accurately describing sloshing is complicated, TLDs are the most convenient to install and maintain due to the simplicity of the device. Furthermore, maintenance costs of these dampers are practically non-existent.

Due to their inherent simplicity, TLDs may be added to existing buildings as retro-fit solutions, even for temporary use if desired, e.g., during construction phases of a structure. A typical TLD may be designed in a variety of configurations ranging from rectangular tanks to stacks of circular tanks (Tamura, 1995).

The biggest advantage of liquid dampers is apparent in the case of tall buildings. In most commercial buildings, water supply is needed for day-to-day usage and for sprinkler tanks used for fire-fighting purposes. The maintaining of water pressure can be effectively done by placing water reservoir tanks on roof tops, where the water flows into plumbing with its own gravity. So, instead of maintaining a high water level using specialized pumping equipment, a water tank is an ideal cost-effective solution. On the other hand, in case of a TMD, the concrete/steel mass has no functional use.

Due to the nature of the system, a small error may be expected when measuring the still water level, which is the parameter that controls the fundamental sloshing frequency. However, an important advantage that the liquid damper has over a TMD is that for wide range of amplitudes of oscillation, particularly at higher levels, the system is not very sensitive to the actual frequency ratio between the primary and secondary systems. Another major advantage of liquid dampers is that no activation mechanism is needed for their operation. TMDs, for e.g., are designed to be activated at a certain threshold acceleration. However, no such activation mechanism is needed for liquid dampers.

Note that for small and medium amplitudes of oscillation, proper tuning of the system may considerably influence the response. Some installations of TLDs include baffles and/or metallic balls to dissipate energy. However, the exact amount of damping cannot be ascertained with these systems. Moreover, nonlinear frequency and damping characteristics inherent to these systems make them unsuitable for functioning as optimal devices.

Tuned Liquid Column Damper (TLCDs)

Some of the main advantages of using TLCDs are the following:

1. The damping in the TLCD can be controlled through the orifice. The orifice opening ratio affects the headloss coefficient which in turn affects the effective damping of the liquid damper. Proportional valves can be actuated by a voltage signal obtained from a battery to obtain the required damping without the use of heavy power.
2. The TLCD can be tuned by changing its frequency by way of adjusting the liquid column in the tube. This is an attractive feature in case *re-tuning* becomes desirable in case of changes in the primary system frequency.
3. A mathematical model, which accurately describes the dynamics of the TLCD, can be formulated. This is an attractive feature for semi-active and active control.

TLCD has the advantage of convenient mathematical formulation, but suffers from the need for an appropriate tube length to satisfy the required frequency of oscillation. Therefore, it may be in conflict with the available space allocated to house it. One way of avoiding this is to introduce multiple TLCDs as discussed in Chapter 3. Figure 8.4 shows the schematic of an actual TLCD implementation similar to the prototype studied in the laboratory. Additional details are water level control system which has been introduced for tuning control. This means that changes in structural frequency can be compensated by changes in liquid level measured by a capacitance type wave gauge.

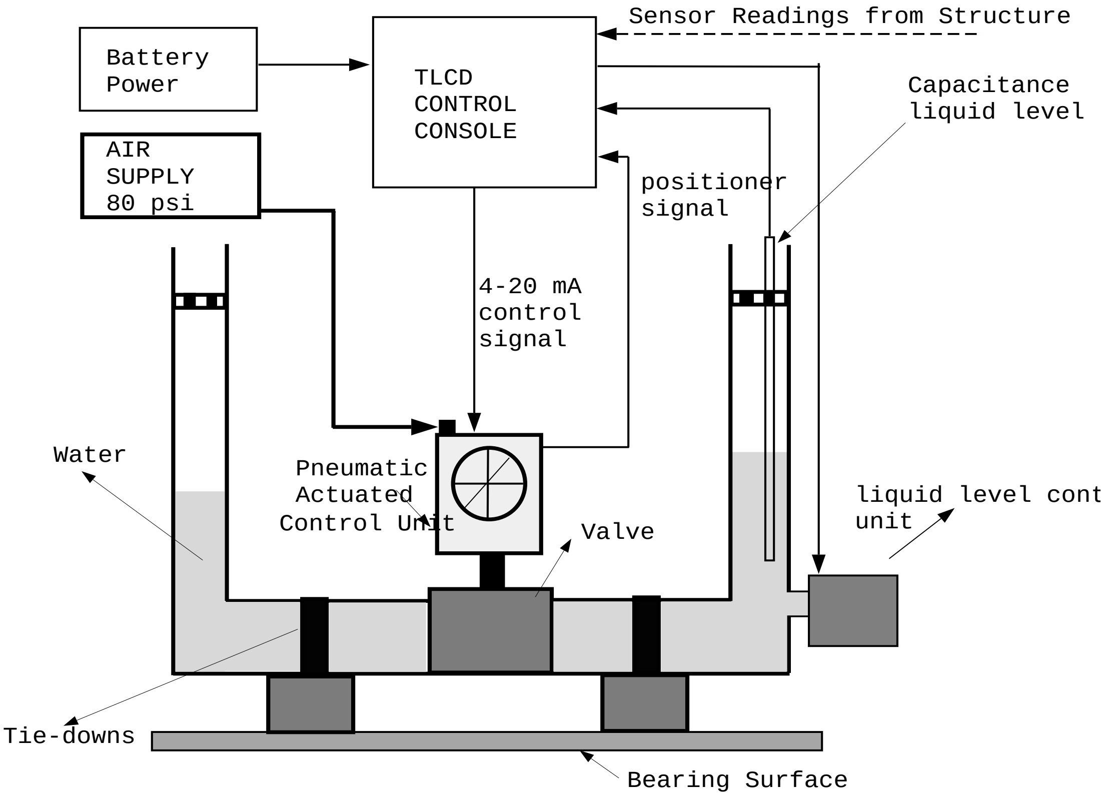


Figure 8.4 Equipment schematic for a building-mounted TLCD

8.2.2 Cost comparison

Damping devices are an efficient and cost effective means of reducing motion than traditional approaches of increasing structural mass and stiffness. The Citicorp building's TMD cost was about $1.5 million (costs in 1977, in 2001 this is roughly $5.0 million); however, it saved an overall structural cost of $4.0 million dollars that would have been spent to add some 28,000 tons of structural steel to add lateral stiffness to the frame and additional floor concrete to increase the mass of the structure (ENR, 1977). Typically, the capital cost of a conventional TMD system is in the vicinity of 1% of the total building cost. Table 8.1 lists some of the different components used in various systems. A preliminary analysis of the cost of a fully functional TLCD system has been estimated to be roughly 1/10 times the cost of an equivalent TMD system with similar performance in response reduction.

TABLE 8.1 Component comparison of different DVAs

Different cost components	TLDs	TLCDs	TMDs
Design and consulting fees	Very limited, simple design	Specialized design and consulting services needed	Specialized design and consulting services needed
Additional Construction	None, easy installation during construction stages	None, easy installation during construction stages	Local strengthening needed to support large amounts of spring and actuator forces Needs an over-travel snubber system
Mechanical components	None	Manual/actuated Valve Water level self-tuning control system	Nitrogen Springs/ laminated rubber bearings/ Hydraulic bearings Servo-valve hydraulic actuators Anti-yaw torque box, linear guideways Pendulum-type TMDs
Electronic components	None	Computer control system needed	Computer control system needed
Sensors	Liquid level sensor	Liquid level sensor Accelerometers Anemometer	Accelerometers Displacement transducers Pressure and Temperature sensors
Space	Take up a lot of valuable space, especially at the top of skyscrapers which is prime space, however water has functional use at the top of a skyscraper, in a TLP, etc.	Take up a lot of valuable space, especially at the top of skyscrapers which is prime space, however water has functional use at the top of a skyscraper, in a TLP, etc.	Definite savings in space as compared to the liquid dampers. However, Pendulum-type TMDs also require a large space for high-rise structures. This could be alleviated using multi-stage TMDs.
Power requirements	None	None (battery power)	Power required for some designs of TMDs.
Maintenace and operational costs	Very limited operational cost Regular cleaning of tanks and change of water (to prevent algae and fungi) is required	Control system maintenance Battery power Constant air supply needed for pneumatic actuator Cleaning of tanks and water is required	Control system maintenance Maintenance of mechanical components: nitrogen springs, hydraulic oil bearings, etc. Power supply needed Oil Supply needed Cooling water

8.3 Risk-based Decision Analysis

Serviceability is an important factor in the design of tall buildings under wind loading. There are primarily two types of adverse serviceability conditions caused by strong winds. The first is that excessive wind may cause large deflections in the structure causing architectural damage to non-structural members, for e.g., panels, cladding, etc., and affect elevator operation. The second is that the oscillatory motion may cause occupant discomfort or even panic. It is generally accepted that acceleration and the rate of change of acceleration (commonly known as *jerk*) are the main causes of human discomfort. Usually, the risk of unserviceability (i.e., excessive deflections or accelerations) is calculated assuming that failure occurs when the deflection or acceleration exceeds a certain specified value.

The example considered in this chapter is merely for illustration purposes. However, the framework presented is quite general and could be applied to any system. The building considered is a 60 story, 183 m tall building with a square base of 31 X 31 m. The spectral characteristics of wind loads are defined in Li and Kareem (1990). In this example, designers and building owners are considering the option of adding liquid dampers for increasing the serviceability of this building under winds. Two types of TLCDs are considered for application in the along-wind direction. The first is a passive system with the frequency of oscillation of liquid tuned to the first mode frequency of the building while the damping is optimized for design level wind speed. The second is a semi-active system, in which an optimal level of damping is maintained at all levels of vibration.

In the case of passive system, the damping is assumed to be arising due to the friction in the tube. The headloss coefficient in this case is assumed to be equal to 1, which is typical of such a system. In the case of semi-active system, the optimal damping ratio of

4.5% is maintained at all levels of excitation by means of a controllable orifice using a gain-scheduled law as outlined in Chapters 5 and 7. The mass ratio (μ) is 1% and the tuning ratio (γ) is 0.99, which corresponds to a total mass of 280 tons and liquid column length of 12 meters. Multiple units of TLCDs of 1 m diameter can be used to accommodate the total weight of the damper and these may be distributed on the building roof.

The RMS acceleration response of the uncontrolled and controlled response using passive and semi-active systems is plotted as a function of the mean wind velocity at 10 meters height, U_{10} (Fig. 8.5). It can be seen from Table 8.2 that the dampers are effective in reducing the structural accelerations and displacements. In this analysis, the effect of bracing the structure is also examined. It has been assumed that the super-structure stiffness can be increased by a particular bracing system by 20%. Table 8.2 shows that the bracing system is quite effective in reducing displacement but not equally effective in reducing acceleration. Moreover, the bracing system increases significantly the overall building cost due to additional steel required for structural bracing.

From Table 8.2, it can be noted that there is an improvement of 10-25% in RMS acceleration response over the entire range of wind velocities using a semi-active system. The semi-active system realizes a 45% improvement over the uncontrolled system. This improvement justifies small additional cost associated with a semi-active system, for e.g., sensors, controllable valves, etc. This analysis is based on the assumption that all the system parameters are known with certainty. The parametric uncertainty and the resulting reliability of structural and loading parameters are treated in the following section.

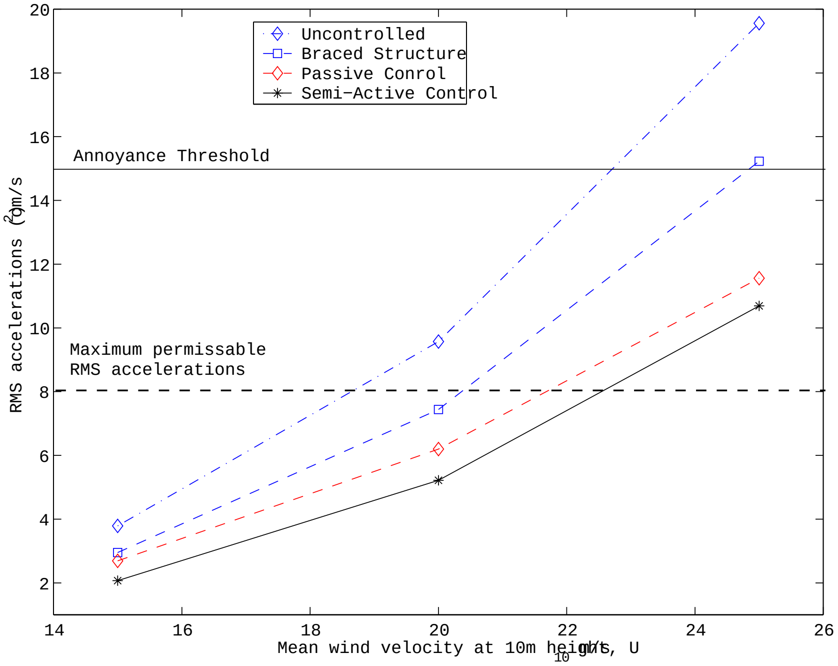


Figure 8.5 Variation of RMS accelerations of the top floor with increasing wind velocity

TABLE 8.2 Comparison of different systems for varying wind conditions

	RMS displacement $U_{10}=15\,m/s$ *(cm)*	*RMS displacement* $U_{10}=20\,m/s$ *(cm)*	*RMS displacement* $U_{10}=25\,m/s$ *(cm)*	*RMS acceleration* $U_{10}=15\,m/s$ *(cm/sec^2)*	*RMS acceleration* $U_{10}=20\,m/s$ *(cm/sec^2)*	*RMS acceleration* $U_{10}=25\,m/s$ *(cm/sec^2)*
Uncontrolled	2.37	5.97	12.19	3.79	9.57	19.56
Stiffened Structure	1.54 (30.4 %)	3.87 (35.1 %)	7.92 (35 %)	2.95 (22.1 %)	7.44 (22.2 %)	15.23 (22.1 %)
Passive system	1.73 (23.4 %)	3.93 (34.1 %)	7.17 (41.2 %)	2.69 (29 %)	6.20 (35.2 %)	11.56 (40.9 %)
Semi-Active System	1.26 (40.6 %)	3.18 (46.7 %)	6.49 (46.7 %)	2.07 (45.4 %)	5.22 (45.4 %)	10.69 (45.3 %)

8.3.1 Decision analysis framework

The decision making framework, shown in Fig. 8.6, is commonly composed of the following components: objectives of decision analysis; decision variables; decision outcomes; and associated probabilities and consequences. Each element of the analysis framework is described briefly here.

Objectives of Decision analysis: Decision analysis problems require an objective function(s) to be clearly defined. In our present example, the objective could be minimizing the total expected utility value.

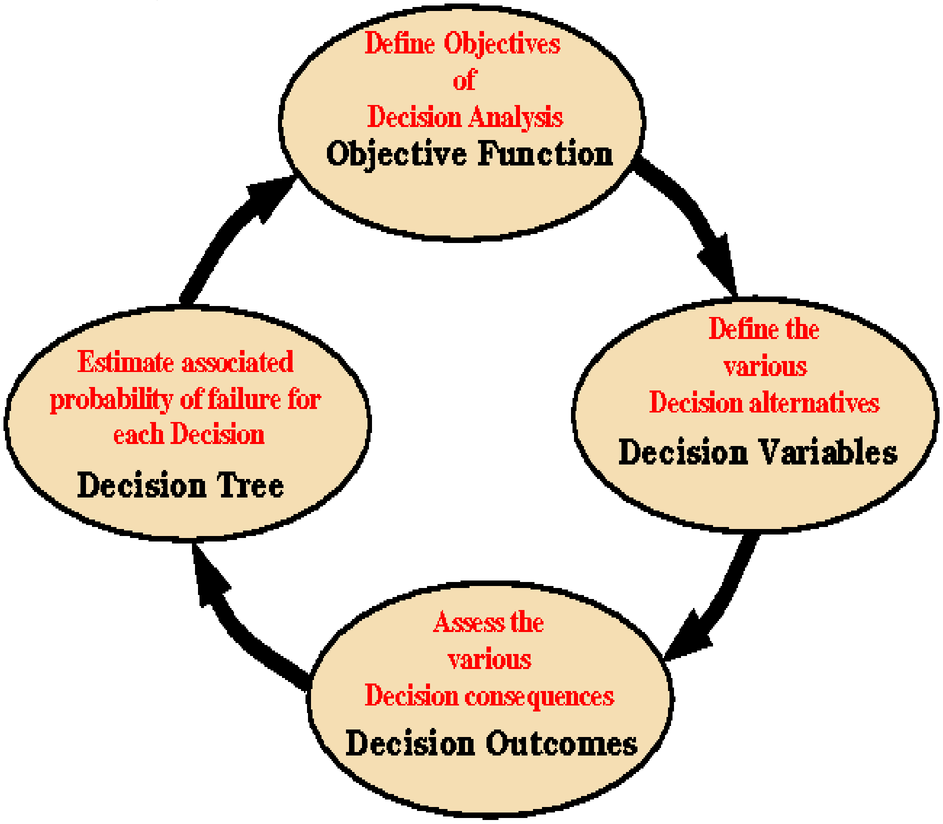


Figure 8.6 Elements of Decision analysis

Decision variables: These could be the various decision alternatives available to the decision maker. In our example, these could be the following alternatives available to the building owners:

1. Do not take any action to improve building serviceability.
2. Invest in traditional bracing/outrigger systems to increase the lateral stiffness. The net increase in the effective stiffness of the resulting structure due to the addition of bracing is given by a factor *kf* defined as the ratio of the stiffness of the structure with added bracing to the stiffness of the uncontrolled structure.

3. Install passive liquid dampers with optimal tuning ratio and optimal damping at design wind speed. This is a sub-optimal configuration of the TLCD since the damping is primarily due to friction in the tube and a fixed orifice which cannot be controlled.
4. Install semi-active TLCD system which maintains the optimal damping at all levels of response.

Decision outcomes: The various decision alternatives described above may have the following outcomes:

1. Building serviceability may be compromised severely leading to building shutdown. An important cost function to be considered is to account for the associated costs of an unserviceable structure brought about by business shutdown and loss of reputation.
2. Bracing systems and outrigger systems are expensive and are not as effective in reducing acceleration which is the primary metric used to assess serviceability problems.
3. The passive liquid damper devices are effective in reducing displacement and acceleration responses, however they perform optimally only at the design wind speed.
4. Semi-active system is more effective than the passive system, however, there are additional costs for controllable valves, computer control system, sensors and maintenance.

Associated Probabilities and Consequences: In the following sub-sections, methods to estimate the probabilities of failure and the associated costs/utility values of each decision are examined. Finally these are integrated into a risk-based decision analysis tree. The risk of an event is defined by the following traditional relationship:

$$Risk = \sum_i p_i(H, C_i) U(C_i) \tag{8.1}$$

where $p_i(H, C_i)$ is the probability of failure, H is the hazard, $U(C_i)$ is the utility function and C_i are the consequences. The impact of risk can be improved by either reducing the occurrence probability through system/component changes (which in our case refers to adding dampers) or by reducing the potential consequences.

8.3.2 Reliability Analysis

The structural reliability analysis is performed using limit states which are mathematical functions of a combination of random variables that describe whether the structure performs satisfactorily for the specific criteria it has been designed for. The design of damping systems needs to consider the model and physical uncertainties, for e.g., structural mass changes, damage to structure, hardening of concrete, loss of stiffness due to corrosion and fracture, stiffness changes in foundation, etc. Changes could also be inherent in the loading, for e.g., wind climate, change in surface roughness, etc. The damper is also not free from uncertainties, for e.g., decrease in its performance due to equipment wear and tear. Therefore, all these variables need to be considered in probabilistic terms for the reliability analysis.

For ultimate strength limit states, one is concerned about structural load and resistance, while for serviceability, the limit state represents the evaluation of a performance criteria. For design of very tall and slender structures under winds, it is usually the serviceability limit state which often governs the design. The limit state function is usually written as,

$$Z = g(X_1, X_2, \ldots, X_n) \tag{8.2}$$

and the probability of failure P_f for the component is defined as,

$$P_f = P(Z < 0) = P[g(X_1, X_2, \ldots, X_n) < 0] \tag{8.3}$$

$$P_f = \int_{g(\boldsymbol{X}) < 0} f_{\boldsymbol{X}}(\boldsymbol{X}) d\boldsymbol{X} \tag{8.4}$$

where $f_{\boldsymbol{X}}(\boldsymbol{X})$ is the joint probability density function of the *n*-dimensional vector $\boldsymbol{X}$ which describes the vector of random variables. In this case, the limit state function is a hyper-surface in the *n*-dimensional space and separates the fail and safe regions. Usually, standard reliability techniques, for e.g., First and second-order reliability (FORM and SORM) methods are used, wherein the limit state is linearized at the design point on the failure surface (Ditlevsen, 1999). This procedure involves transformation of the variables in the limit state equation to reduced normal variates which yields a new limit state equation in the reduced space. The probability of failure is then determined from the reliability index ($\tilde{\beta}$), which is defined as the shortest distance from the origin to the failure surface and is given by,

$$P_f = \Phi(-\tilde{\beta}) \tag{8.5}$$

The limit state equation for *drift serviceability* is commonly written as:

$$Z = \Delta_{all} - \Delta_{max} \tag{8.6}$$

where Δ_{all} is the allowable deflection, usually taken as = $H_b/400$ where H_b is the height of the building and Δ_{max} is the maximum deflection in the structure.

Similarly, for *comfort serviceability*, the limit state equation is written as,

$$Z = \sigma_{ma} - \sigma_{\ddot{x}} \tag{8.7}$$

where σ_{ma} is the maximum allowable RMS accelerations, which lies between 5-10 mg in the *perception* threshold range and 10-15 mg in the *annoyance* level range. In this study the focus is on the comfort considerations. Therefore, different values of σ_{ma} = 8, 10 and 12 mg have been considered. Random variables used in the analysis are listed in Table 8.3.

The distribution of wind velocity for a well behaved wind climate can be adequately modeled by a *Type 1* extreme value distribution. The other variables along with their statistical characteristics, i.e., probability distribution, and mean and coefficient of variation (COV) can be found in Rojiani (1978) and Kareem (1990). The probability of failure for the different systems under different mean wind velocities and different σ_{ma} is tabulated in Table 8.4.

TABLE 8.3 Random Variables used in Reliability analysis

Type	**#.**	***Random Variable***	***Probability Distribution***	***Mean***	***COV***
Structural Parameters	1	Mass matrix multiplier, $\tilde{m}$ (non-dimensional)	Normal	1.0	0.1
	2	Stiffness matrix multiplier, $\tilde{k}$ (non-dimensional)	Normal	1.0	0.25
	3	1st mode damping, ζ_s	Log Normal	1 %	0.35
Wind Load Parameters	4	Air density, ρ_a	Log Normal	1.25 kg/m^3	0.05
	5	Drag coefficient, C_d	Log Normal	1.2	0.17
	6	Power law exponent, $\tilde{\alpha}$	Log Normal	0.3	0.1
	7	Wind Velocity, U_{10}	Extreme Value Type 1	18, 20 m/s	0.1
Liquid Damper Parameters	8	Tuning ratio, γ	Normal	0.9870	0.1
	9	Coefficient of Headloss, ξ	Normal	1	0.1
	10	Optimal Damping, ζ_f	Log Normal	5.5 %	0.05

TABLE 8.4 Probability of Failure under different wind speeds

Probability of Failure (%)	***U_{10} = 18 m/s***		***U_{10} = 20 m/s***	
	σ_{ma} ***=8 mg***	σ_{ma} ***=10 mg***	σ_{ma} ***=10 mg***	σ_{ma} ***=12 mg***
Uncontrolled	39.34 %	14.21 %	44.43 %	29.87 %
Braced System	33.43 %	11.12 %	40.23 %	24.71 %
Passive System	14.86 %	3.66 %	23.17 %	8.79 %
Semi-Active Case	4.69 %	0.71 %	10.28 %	2.69 %

8.3.3 Cost and Utility Analysis

A generalized total expected cost function (for a period of *T* years) can be written as:

$$C_t = C_s + C_d + \int_0^T C_m(t)dt + \int_0^T C_f(t)dt \tag{8.8}$$

where C_s is the initial fixed cost of the structure, C_d is the initial fixed cost of the damper, C_m is the maintenance cost per unit year and C_f is the repair/business interruption cost per unit year. The estimation of these cost functions requires a detailed analysis of the system at hand. In particular, the cost which is hard to quantify is C_f because it is a function of several factors, e.g., local market value and real estate demand. For a simplified analysis, this can be written as:

$$C_f = TP_fC(E) \tag{8.9}$$

where *C(E)* is the cost of repair/ business interruption/ decreased employee productivity when an event *E* occurs. In this analysis, *C(E)* has been assumed to be equal to 10. Table 8.5 tabulates some general costs and utilities of a typical tall building. Most of these values are arrived at in an empirical way, however, the framework for more market value based cost analysis would remain the same.

TABLE 8.5 Costs and Normalized Utility Analysis

Type of system	*Fixed Costs (Cost of structure (C_s) same for all options)*	*Dollar values (% of Total cost of Structure C_s)*	*Utility*
Bracing	Amount of Steel, construction costs, loss of floor space	2.5%	5
Passive system	Cost of liquid tanks, loss of floor space, maintenance	0.5%	1
Semi-active system	Costs of liquid tanks, controllable valve, design and consulting fees, computer controlled system, maintenance	1%	2

8.3.4 Risk-based Decision Analysis

Figure 8.7 shows a typical decision tree used to examine the given problem in a systematic format. The decision tree includes decision and chance nodes. The decision nodes are followed by possible actions which the decision maker takes. The chance nodes are followed by outcomes that are beyond the control of the decision maker. The total expected utility for each branch is computed and the decision is selected such that the expected total utility function is minimized. As seen from Table 8.6, when the probabilities of failure are low, choosing semi-active dampers over passive dampers is not cost effective. However, in critically unserviceable structures, the semi-active scheme delivers better cost/utility benefits.

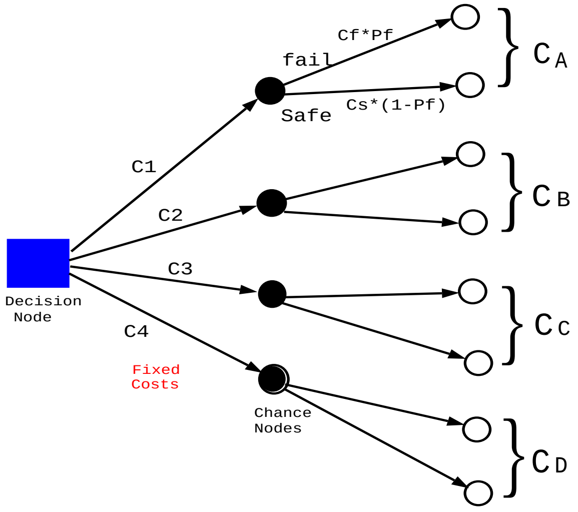


Figure 8.7 Decision Tree for Building Serviceability

TABLE 8.6 Utility analysis based on the decision analysis

Total Cost C_t	$U_{10} = 18$ m/s		$U_{10} = 20$ m/s	
	$\sigma_{ma} = 8$ mg	$\sigma_{ma} = 10$ mg	$\sigma_{ma} = 10$ mg	$\sigma_{ma} = 12$ mg
Uncontrolled (C_A)	7.86	2.84	8.88	5.97
Braced System (C_B)	11.68	7.24	13.08	9.94
Passive System (C_C)	3.97	1.73	5.63	2.75
Semi-Active Case (C_D)	2.93	2.14	4.05	2.53

8.4 Design of Dampers

8.4.1 Design Guidelines

Liquid

Usually water is the preferred liquid used in TLDs and TLCDs. It has been noted by Fujino *et al*. 1988 that the use of high viscosity liquids do not offer any advantage. This is because, for liquid dampers, there is an optimal level of damping that will provide the desired level of response reduction, therefore, higher liquid viscosity is not always effective.

Mass ratio (μ)

The mass ratio is dictated by the efficiency (defined as the ratio of response with control system to response of uncontrolled structure) of the dampers needed. For e.g., if an efficiency of 50% is required, then at least a mass ratio of 1% is needed. Practically, no more than 1% mass ratio is possible to be placed on the top of tall buildings. For example, TMD mass weighing up to 400 tons was installed in Citicorp Building. In case of TLDs and TLCDs, this implies more space requirement, therefore innovative schemes to integrate these into water storage tanks and fire-sprinkler tanks need to be designed.

Length ratio (α)

The length ratio determines the horizontal to total length of the liquid column. The length ratio also needs to be determined from an architectural point of view. For increasing length ratio, the efficiency of the damper increases. However, two things need to be considered. The vertical length of the tube should be high enough so that water does not spill out of the tube. Secondly, water should remain in the vertical portion of the U-tube at all times to provide continuity in the water column in the horizontal segment. This can be ensured by designing l and b such that,

$$max\{|x_f|\} \leq \frac{(l-b)}{2} \tag{8.10}$$

Tuning ratio (γ_{opt})

Typically, auxiliary devices are tuned to the first modal frequency of the structure. An acceptable design is obtained by ensuring a tuning ratio of almost unity for mass ratio of 1%. Exact values are provided for a variety of cases in chapter 3. In case the natural frequency of the structure changes by $\Delta\omega_s$, the length of the water column in the U-tube needs to be compensated by the following relation,

$$\Delta l = \frac{-4g}{(\gamma_{opt}\omega_s)^3}\Delta\omega_s \tag{8.11}$$

Damping ratio (ζ_{opt})

This is the damping ratio of the liquid damper. For a regular TMD, this represents the linear damping ratio. However, for liquid dampers the damping varies nonlinearly with amplitude. Based on design curves obtained in Chapter 3, a damping ratio of about 4.5% for mass ratio of 1% is recommended for optimal damping.

Number of Dampers

The number of dampers depends on various factors such as the available space, shape and sizing of the damper units. In case of multiple dampers, it was shown in Chapter 3 that by increasing the number of dampers does not necessarily improve better performance concomitantly. A typical number of 5 units is usually adequate. Kareem and Kline (1995) conducted numerical studies on multiple dampers with non-uniform mass distribution and non-uniform frequency spacing. They concluded that such systems did not offer any useful advantage over systems with uniform mass distribution and frequency spacing.

Orientation of the liquid dampers

For structures with different fundamental frequencies in the two major directions, tuning may be accomplished by using rectangular tanks or TLCDs. With proper design of the damper dimensions, fundamental frequencies in both directions may be tuned. This is important since the theory is based on tanks subjected to only a uni-directional excitation. For structures with the same fundamental frequency in the two principal directions, a circular tank may be used.

8.4.2 Control Strategy

As discussed in section 5.2, gain-scheduling is an ideal control policy for maintaining optimal damping in TLCDs. Sensors on the buildings (accelerometers, liquid level sensor, or anemometer) estimate the excitation level, which is used to adjust the headloss coefficient based on a pre-computed look-up table.

Comparing Fig. 5.1 and Fig. 8.8, one can draw analogies wherein the *look-up* table is the gain-scheduler, the controllable valve of the TLCD is the regulator, and the head loss coefficient is the parameter being changed. The external environment is the wind loading acting on the structure and the process represented by the combined structure-TLCD system.

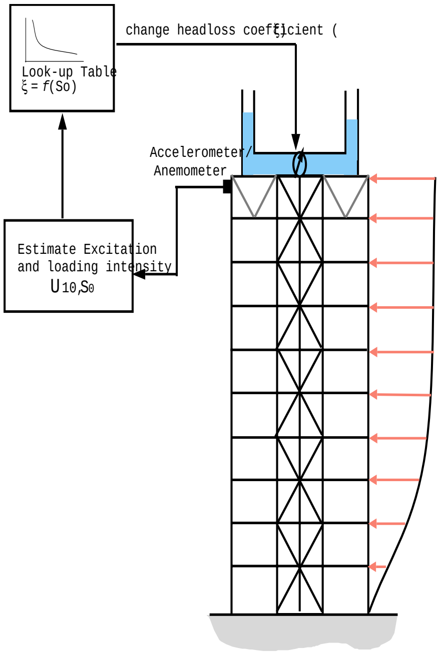


Figure 8.8 Semi-active control strategy in tall buildings

8.4.3 Design Procedure

Structural Characteristics

The first step in the design of the dampers is to gather adequate knowledge of the natural modes and damping of the structure being considered for control. The structural characteristics are determined either at the design stage by analysis or for existing buildings by monitoring full-scale data or a combination of both techniques. The first method involves a FEM analysis of the structural system. The second relies on analyzing full-scale measurements from instrumented buildings. The response power spectral density provides an estimate of the natural frequency and damping in the structure. Usually, it is advisable to conduct full scale testing in order to obtain ambient or forced building response before installing dampers. This is because FEM models usually not reliable for accurate estimates of frequencies due to difficulties in modeling accurate boundary conditions, e.g., soil-structure interactions, and other nonlinear effects.

Loading Characteristics

The wind, earthquake or wave loading characteristics have to be determined from site characteristics and hazard maps. Wind tunnel experiments are also needed for critical projects to investigate the characteristics of wind force acting on the building and to estimate the structural response. This analysis is done during the design stages of the structure. In this section, we will discuss alongwind loading only, although the acrosswind and torsional directions can be handled accordingly if the spectral information is available (Aerodynamic load database, www.nd.edu/~nathaz/database/index.html). The loading spectra for alongwind excitation can be defined as

$$\frac{nS_{vv}(z,n)}{u_o^2} = \frac{200f}{(1+50f)^{\frac{5}{3}}} \tag{8.12}$$

where $f = \frac{nz}{U(z)}$; $U(z)|_{z>10m} = 2.5u_o ln\left(\frac{z-z_d}{z_o}\right)$; $u_o = U_{10} \big/ \left(2.5 ln\left(\frac{10-z_d}{z_o}\right)\right)$; z_o = surface roughness length; z_d = zero plane displacement; U_{10} = mean wind velocity at 10m height. The coherence function required for the cross-spectrum is given as

$$coh = exp\left(\frac{-n[C_v^2(z_1-z_2)^2 + C_h^2(x_1-x_2)^2]^{\frac{1}{2}}}{\frac{1}{2}[U(z_1)+U(z_2)]}\right) \tag{8.13}$$

where (x_1, z_1) and (x_2, z_2) are the coordinates of the nodes, C_v and C_h are the coherence decay coefficients in the vertical and horizontal directions. The multiple-point representation may be simplified for line-like structures, e.g., buildings, towers, in which the spatial variation of wind fluctuations are only implemented for one spatial dimension. The wind force at a certain level j is obtained as,

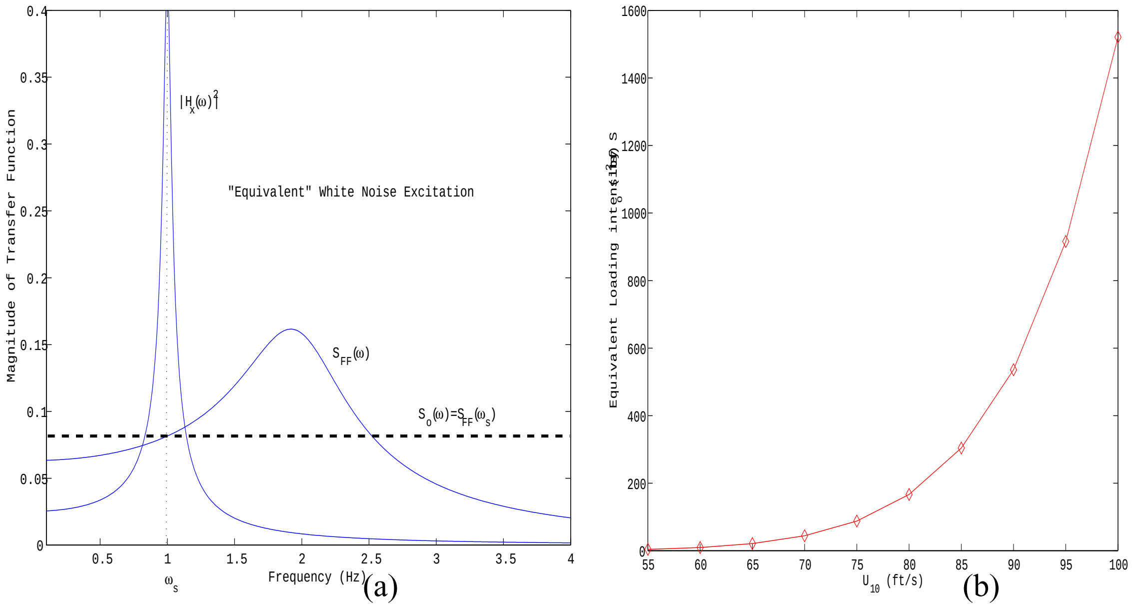
$$F_j(t) = 0.5\rho_a A_{bj} C_{Dj} (U(z_j) + v_j)^2 \tag{8.14}$$

where A_{bj} is the tributary area exposed to wind, C_{Dj} is the drag coefficient at the j^{th} floor and ρ_a is the air density. From Eq. 8.14, one can also obtain the spectra of the loading, given as: $S_{FF}(\omega, z) = (\rho_a A_{bj} C_{Dj} U(z))^2 S_{vv}(\omega, z)$.

In the last section, the gain-scheduled control was derived for different loading intensities. In order to extend it to wind excited structures, one needs to find relationship between the wind force spectra, $S_{FF}(\omega)$, and an "equivalent" white noise excitation. For small values of ζ_s, one can approximate $S_{FF}(\omega)$ by a equivalent white noise S_o, which is the value of $S_{FF}(\omega)$ at the natural frequency of the structure (Lutes and Sarkani, 1997). This is shown schematically in Fig. 8.9(a) where using the following relationship:

$$S_o(U_{10}) = S_{FF}(\omega_s) \tag{8.15}$$

The equivalent white noise for an example case where ω_s = 1 Hz is given in Fig. 8.9 (b).



(a) (b)

Figure 8.9 (a) Equivalent white noise concept (b) Variation of equivalent white noise with wind velocity.

Damper Sizing

Once the structural and loading characteristics have been determined, the designer can begin design of the damper. The optimum design parameters are discussed in Chapter 3. All symbols, unless explained here, refer to the earlier notations. The length of the water column is given by,

$$l = 2g/\omega_f^2 \tag{8.16}$$

where $\omega_f = \gamma_{opt}\omega_s$.

The cross sectional area of the damper can be obtained by,

$$A = \frac{\mu M_1}{\rho l} \tag{8.17}$$

and for a spatially distributed single TLCD,

$$A_i = \frac{\mu M_1}{N\rho l} \tag{8.18}$$

where N is the number of units and M_1 is the generalized first modal mass of the structure. In case of multiple TLCDs, the length of liquid column and the cross sectional area of each unit are given by,

$$l_i = 2g/\omega_{fi}^2 \tag{8.19}$$

$$A_i = \frac{\mu M_1}{N\rho l_i} \tag{8.20}$$

Next, from the wind loading excitation information, the headloss coefficient can be determined as follows,

$$\xi_{opt} = \frac{2\zeta_{opt}\sqrt{gl}\pi}{\sigma_{\dot{x}_f}} \tag{8.21}$$

where $\sigma_{\dot{x}_f}$ is given by:

$$\sigma^2_{\dot{x}_f} = S_0(U_{10})\int_0^{\infty} H_{\dot{x}_f F}(\omega)d\omega \tag{8.22}$$

The valve sizing should be selected such that the entire range of desired values of ξ can be covered. This can be ensured by relating the headloss coefficient to the valve conductance, C_V for different angles of valve opening (see Appendix A.3). Typically, for most applications a headloss coefficient between the range of 1-100 should be adequate.

8.4.4 Technology

Actuated Valves

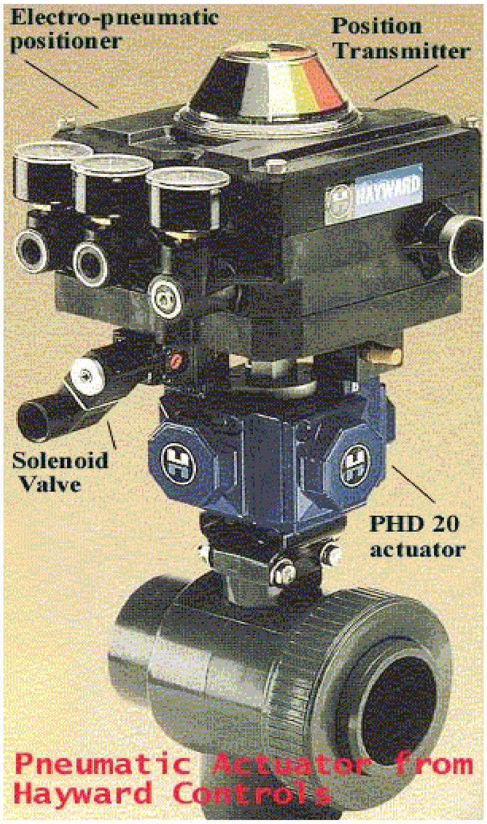


Figure 8.10 Electro-pneumatic valve (*courtesy Hayward Controls*)

Actuated valve technology has improved in the last few years. Electro-pneumatic valves are available with an option of a position transmitter which can be used for controlling the valve. Figure 8.10 shows the actuator commercially available, which is a pneumatically actuated ball/butterfly valve with an additional solenoid valve for modulating the valve opening. The electro-pneumatic positioner uses a 4-20mA signal to change the valve position. The positioner modulates the flow of supply air (at 80 psi) and converts the input signal to a 3-15 psi air pressure for proportional modulation of the valve. The headloss characteristics for the valve are described in Appendix A.3.

Tubing Systems

Clear PVC piping systems are the best choice for the TLCD tube construction. This is because they are rugged and durable, yet allow easy maintenance and visibility of the liquid.

Sensors

A capacitance type liquid level sensor is needed to determine the liquid level in the TLCD. This is important for tuning the TLCD to the building frequency. This needs to be done on a regular basis because changes in structural frequency may take place due to aging or stiffness degradation of building characteristics which can lead to mis-tuning of the system. Additionally, accelerometers and anemometers for estimating the loading characteristics are needed. These are commercially available from a variety of vendors. It should be noted that accelerometers chosen should have good frequency characteristics in the low frequency region (< 1 Hz). This is because the response of tall buildings is primarily concentrated in this low frequency band.

Control System Software and Hardware

With advances in control system implementation hardware, a computer controlled system running on auxiliary power is quite affordable these days. A typical computer running a data acquisition and control implementation software can be set up very cheaply. The system can also be configured to include remote control using TCP/IP system which enables off-site users to monitor the system, which eliminates the need for an on site operator.

8.5 Concluding Remarks

This chapter discussed the design consideration and implementation details of liquid dampers. Different dynamic vibration absorbers, namely TMDs, TLDs and TLCDs are compared in terms of implementation and costs. Next, a probabilistic framework for decision analysis concerning the serviceability of a building has been presented. Both deterministic and reliability-based analyses confirm the attractiveness of the passive and semi-active liquid dampers in reducing acceleration response and the associated probabilities of failure. The decision analysis framework presented here would facilitate building owners/designers to ensure adequate life-cycle reliability of the building from a serviceability viewpoint at a minimum cost. Finally, some design guidelines for technology transfer are laid out based on research work presented in earlier chapters.