CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

A detailed report of the literature review carried out is presented in this chapter. The review is divided into three parts, namely, i) Optimization and effectiveness of TMD ii) Roof Top Frame as TMD and iii) Water tanks as TMD.

2.2 OPTIMIZATION

The effectiveness of the TMD depends on how effective the dynamic properties of the TMD are tuned to that of the structure to which it is attached. Hence optimization of the parameters is essential to enhance TMD’s performance. The following literature review presents the various optimization procedures derived for structures with TMD subjected to seismic excitation.

Warburton (1982) presents simple expressions for optimum absorber parameters for undamped one degree-of-freedom main systems subjected to harmonic and white noise random excitations with force and frame acceleration as input and minimization of various response parameters. It has been shown that when determining optimum parameters for an absorber which minimizes the vibration response of a complex system, the system may be treated as an equivalent single degree-of-freedom system if its natural
frequencies are well separated. The main mass responses are optimized with respect to damping of TMD (γ) and frequency ratio (α) for specified values of damping of structure and mass ratio (μ). The expression derived for random acceleration is,

\[ \alpha_{opt} = \frac{\sqrt{1 - \frac{\mu}{2}}}{1 + \mu} \]  

(2.1)

\[ \gamma_{opt} = \sqrt{\frac{\mu(1 - \frac{\mu}{4})}{4(1 + \mu)(1 - \frac{\mu}{2})}} \]  

(2.2)

For very small values of \( \mu \), \( \alpha_{opt} \) equals to 1, \( \gamma_{opt} \) becomes \((\mu)^{1/2}\) and optimum maximum response \( R_{opt} \) becomes \( \mu^{-1/2} \). As \( \mu \) increases \( \alpha_{opt} \) decreases. The expressions are derived from optimizing conditions, \( \frac{\partial(\sigma x^2)}{\partial \gamma} = 0 \) and \( \frac{\partial(\sigma x^2)}{\partial \alpha} = 0 \), where \( \sigma x^2 \) is the standard deviation. The author has concluded that the expressions can be used to obtain optimum parameters for absorbers attached to complex systems provided the optimization is with respect to an absolute, rather than a relative, quantity.

Villaverde (1985) presented numerous studies on the applicability of TMDs for seismic applications. It was found that TMDs performed best when the first two complex modes of vibration of the combined structure and damper have approximately the same damping ratios as the average of the damping ratios of the structure and the TMD. To achieve this the TMD should be in resonance with the main structure (\( \alpha = 1 \)), its damping ratio be \((\xi + \gamma)/2\), i.e., the average of the damping ratios of the structure and TMD independently and the relation between the parameters of the structure and the TMD is such that

\[ (\xi - \gamma)^2 \leq \phi^2 \mu \]  

(2.3)
Where $\xi$ is the damping ratio of the structure, $\mu$ is ratio of the mass of the absorber to the generated mass of the structure in a given mode of vibration (usually the fundamental mode) and $\Phi$ is the amplitude of the mode shape at the TMD location. $\Phi$, mass of the structure ($M$) and mass of the absorber ($m$) are computed using a mode shape that has been normalized to have a unit participation factor.

Jimmy Lee (1990) presents optimal mass ratios for minimizing the response of a structure exposed to earthquake or fluid flow type random excitations. A laminated beam treated as an equivalent one degree of freedom (Single DOF) main system vibrating in the fundamental mode was taken for the study. The effective main system response, $R$ is optimized with respect to $\gamma$, $\alpha$ and $\mu_{opt}$ for specified values of effective mass system damping and location of TMD along the length of the beam. The beam is subjected to Gaussian white noise force and Gaussian white noise base frame acceleration and the mean square displacement is minimized for vibration in the fundamental beam mode. The optimizing condition for mass ratio is $\frac{\partial R}{\partial \mu_{opt}} = 0$. In the optimized values presented by the authors, $\mu_{opt}$ takes values much larger than those considered in practical conditions.

Yozo Fujino and Masato Abe (1993) using the perturbation solutions, formulas relevant to designing the TMD for various types of loading are obtained; they are expressed as a function of mass ratio, tuning ratio, damping ratio of the TMD and damping ratio of the structure. The optimal parameters of TMD for random excitation controlling the displacement is given as

$$\alpha_{opt} = \frac{1}{1 + \mu} \quad \text{and} \quad \gamma_{opt} = \sqrt{\mu} / 2$$ (2.4)
The formulas are derived under the assumption that the mass of the TMD is small, i.e., \( \mu < 0.02 \). The authors concluded that although the limitations of the formulas are not extensively investigated, they can be used for the mass ratio \( \mu < 0.02 \) and the formulas for expressing the TMD effectiveness include the damping of the structure, most of the optimal TMD parameters are derived for \( \xi = 0 \). These should be used with care when \( \xi \) is not small, i.e., \( > 0.02 \).

Fahim Sadek et al (1995) presented the optimum parameters of TMD that result in considerable reduction in the response of structures to seismic loading. The criterion used to obtain the optimum parameters is to select, for a given mass ratio, the frequency and damping ratios that would result is equal and large model damping is the first two modes of vibrations. Curve fitting was used to find \( \alpha \) and \( \gamma \) in terms of \( \mu \) and \( \xi \).

For undamped structure,

\[
\alpha = \frac{1}{1+\mu} \quad \text{and} \quad \gamma = \sqrt{\mu(1+\mu)} \tag{2.5}
\]

For damped structure,

\[
\alpha = \frac{1}{1+\mu} \left[ 1 - \xi \sqrt{\frac{\mu}{1+\mu}} \right] \quad \text{and} \quad \gamma = \frac{\xi}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}} \tag{2.6}
\]

The optimum values are determined when the difference between the two damping ratios of critical modes is the smallest. The procedure was used for systems with damping ratios \( \xi = 0 \), 0.02 and 0.05 and mass ratios \( \mu \) between 0.005 and 0.15 with increments 0.005. It was found that the optimum TMD parameters result in approximately equal model damping ratios \( (\xi_1 \approx \xi_3) \).
greater than $(\xi + \gamma)/2$ and equal model frequencies ($\omega_1 \approx \omega_3$). The results indicate that higher the damping ratio of the structure, the lower is the tuning ratio and the higher is the TMD damping ratio. The higher the intrinsic damping in the structure, the larger is the mass required to achieve approximately the same level of response reduction. In comparison to the work done by Villaverde in 1985, Sadek has shown that if the tuning frequency, $\alpha$ is not equal to one, and takes a value around unity the response reduction is better when the system is subjected to seismic excitation.

Jangid in 1995 and 1999 studied the effectiveness of multiple tuned mass dampers (MTMD) and optimized the parameters for an undamped system subjected to harmonic base excitation. It has been shown that MTMD can be more effective than a single TMD with equal mass and damping ratio and the optimum parameters of the MTMD system are obtained for different mass ratio and number of dampers.

Lukkunaprasit and Wanitkorkul (2001) studied the effectiveness of TMD in vibration control of buildings under moderate ground shaking caused by long – distance earthquakes with frequency contents resembling the 1985 Mexico City (SCT) or the 1995 Bangkok round motion. Elastic-perfectly plastic material behaviour was assumed for the main structure, with linear TMD. The accumulated hysteretic energy dissipation affected by TMD was examined, and the ratio of hysteretic energy absorption in the structure with TMD to that without TMD is proposed to be used in conjunction with the peak displacement ratio, as a supplementary TMD performance index since it gives an indication of the accumulated damage induced in the inelastic structures. To investigate the performance of TMD buildings with periods 1.7, 1.8, 2, 2.15, 2.27, 2.6, 2.8 and 3 were subjected to the scaled Mexico and Bangkok excitations. The 2.27s period was included to match the predominant period of Bangkok earthquake excitation. The buildings were
equipped with Den Hartog TMDs with a generalized mass ratio of 6%. It was absorbed by the authors that over the building period range of 1.8-2.8s, the reduction in the dissipated energy is 40 per cent or more even though there is negligible reduction in the peak displacement response and TMD deteriorated in performance with increasing hysteretic energy dissipation.

Anupam Ahlawat and Ananth Ramaswamy (2004) proposed a genetic algorithm based integrated approach to optimize the total cost of building and the associated control device. Constraints for performance of the design include peak Interstorey drift and peak absolute acceleration of the floors. Idealized 3 plane frame equivalent models of 3 storey and 9 storey steel buildings have been considered. Building structure has been assumed to be linear elastic with Rayleigh damping. Mass of the building was lumped at floor levels. A TMD installed at roof of the building has been used as passive vibration control device. Four earthquake records, namely, Elcentro (1940, 0.35g), Hachinohe (1968, 0.23g), Northridge (1994, 0.84g) and Kobe (1995, 0.83g) was used as design excitations. Stiffness of the columns, mass, stiffness and damping of the TMD have been considered as design variable. Mass of TMD was taken as 5% the total mass of the structure. Results show that for 3 storey building example, optimal design is one without any TMD and for 9 storey building the best design is one with TMD of 4.4 % mass of the structure.

Bakre and Jangid in 2004 presented the optimum parameters of multiple tuned mass dampers (MTMD) for suppressing the response of base-excited damped main system and observed that MTMD is more effective than single tuned mass damper.

Bakre and Jangid in 2007, presented optimum parameters of TMD system attached to a viscously damped single degree – of – freedom main
system for various combinations of excitation and response parameters. The authors have concluded that the optimum damping ratio of the TMD is not much influenced by the damping of the main system but the optimum tuning frequency of TMD is significantly affected by the damping of the main system.

From the literature of optimization of TMD the following observations are made

(i) The effectiveness of the Tuned Mass Dampers (TMD) depends on the proper tuning of the characteristics of TMD to that of the structure.

(ii) Structures with different time period respond to same earthquake in different manner.

(iii) The mass ratio assumed by researchers takes values much higher than practical considerations.

Hence the dynamic parameters of the TMD, i.e., the mass ratio $\mu$ (i.e., ratio of TMD mass to modal mass of the structure), frequency ratio or tuning ratio (i.e., ratio of frequency of TMD to frequency of structure) and damping ratio $\gamma$ of the TMD need to be evaluated for structures with different time period.

2.3 ROOF TOP FRAME AS TMD

The Tuned Mass Damper (TMD) requires large space for their installation. To undergo large deflection the TMD requires space. To address this issue researchers have carried out work on roof top frame and roof isolation systems. A detailed report of the research carried out to address implementation issues is presented in the following sections.
Jerod Johnson et al. (2005) presents the author’s presents a feasibility study for placing a tuned mass damper in the form of a steel moment resisting frame on the roof of relatively stiff structures to reduce seismic acceleration response. Six exciting structures ranging from three to nine stories, originally designed to meet UBC seismic zone 3 lateral force originally were studied. 2 D frame was taken for the analysis. The time period of the structures varied from 0.35 to 1.06 sec. Five earthquake data, namely, Imperial Valley (1940, 0.32 g), Loma Prieta (1989, 0.54 g), Kobe (1995, 0.84 g) and San Fernando (1971, 1.17 g) were selected to encompass a broad range of seismic response. The added mass was taken as a fraction of the total mass of the structure (m/20) and stiffness by a fraction of the total stiffness (k/20). Analysis was done using nonlinear static pushover analysis. The roof top frame was allowed to behave in non-linearly. The analyses results are presented for a braced frame with time period 0.7 sec. The mass of the roof top frame, based on the design was approximately 11.6% of the mass of the original building. The results indicate that adding mass in conjunction with a steel moment resisting on the roof results in the elongation of the fundamental period of structures. The results show that one roof top frame design for a structure may not reduce the structural response for all possible unrelated ground motions. They concluded that the design of the roof top tuned mass damper frame could result in reduction of the seismic acceleration response, which translates to safer structures when used as a retrofit measure, or a more economical design if used in new construction.

Robertto Villaverde and Gilberto Mosqueda (1999) presents details of the results from analytical and experimental studies conducted with a small-scale laboratory model to assess the feasibility and effectiveness of using roof isolation system. The roof isolation system entails the insertion of flexible laminated rubber bearings between a building’s roof and the columns that support this roof, and the installation of viscous dampers that are
connected to the roof and a structural element below the roof. It is based on the concept of a damped vibration absorber and on the idea of making the roof, rubber bearings, and viscous dampers respectively constitute the mass, spring, and dashpot of such an absorber.

The model considered in the analytical and experimental studies is a 2.44-m high, five-storey, moment-resisting steel frame, with a fundamental natural frequency of 2.0 Hz. It was built by welding its square columns to base plates, welding its longitudinal and transverse rectangular beams to the columns, and welding its rectangular secondary beams to the longitudinal beams. Its floor and roof plates were supported freely by all the beams, but were restrained against lateral motion by special keys welded to the inferior face of the plates. In the experimental study the frame is tested with and without the proposed roof isolation system on a pair of shaking tables under a truncated version of one of the accelerograms from the 1985 Mexico City earthquake.

In the analytical study, the frame was analyzed with and without such a system and under the same ground motion except that the ground motion accelerations are properly magnified to study the effectiveness of the roof isolation system when the frame is stressed beyond its linear range of behavior. In the experimental study, the reduction factors are of the order of 30 per cent. In the analytical study, the maximum floor displacements were reduced, on average, by 84, 67, 37, and 41 per cent. It is found that the suggested device effectively reduces the seismic response of the frame, although the extent of this reduction depends on how large its non-linear deformations are. Based on these findings, it is concluded that the proposed roof isolation system has the potential to become a practical and effective way to reduce earthquake damage in low- and medium-rise buildings. Further since it has been found in previous studies by the author that an effective
vibration absorber requires a mass of the order of 7 per cent of the total mass of the building where it is installed, this means that without an added mass the proposed isolation system can only be effective for buildings with up to about 15 stories. In like manner, it is important to note that the applicability of the system is limited to buildings which are not closely surrounded by neighboring buildings at their roof level. That is, buildings that has the sufficient clearance to permit the unrestricted motion of the bearings.

Villaverde (2000) has suggested using a portion of a building’s mass as the mass of the absorber. He has suggested the use of laminated electrometric bearings of the type being currently employed in base isolated buildings. More specifically, he has proposed to form a vibration absorber using the roof of a building. The building selected for the investigation corresponds to an existing commercial building located in Sherman Oaks, California and designed around 1964. The building has 13 stories, 2 basements, a pile foundation, a rectangular plan 22 meters (72 feet) wide and 58 meters (189 feet) long, and is structured with moment-resisting reinforced concrete frames. The mass and damping constant of the vibration absorber (roof isolation system) for the building under investigation was determined by means of the formulas given by Villaverde (1985) and absorber’s damping ratio calculated from the relation given by Sadek (1995). Because of the different natural frequencies of the building along its longitudinal and transverse directions, different bearing and damping characteristics need to be considered along each of these two directions. In the longitudinal direction and in its fundamental mode, the building without its roof has a fundamental natural frequency of 0.481Hz, a generalized mass of 12,756Mg, and a unit-participation-factor mode shape amplitude at roof level equal to 1.27. The absorber-to-building mass ratio was equal to 0.085, the absorber frequency and damping ratios along that direction are 0.897 and 0.38, respectively. In the transverse direction, the building without its roof and also
in its fundamental mode had a natural frequency equal to 0.435Hz, a
generalized mass equal to 12,558Mg, a unit-participation-factor mode shape
amplitude at roof level equal to 1.29, and an absorber-to-building mass ratio
equal to 0.086. The absorber frequency and damping ratios for the building’s
transverse direction were equal to 0.894 and 0.39, respectively. The ground
motion selected for the analysis was the acceleration time history recorded
during the 1994 Northridge earthquake at the ground level of the building
under investigation and along its transverse direction.

It was seen that the roof isolation system keeps all members within
their linear elastic range of behavior and all interstory drifts within the
allowable limit. On average the roof isolation system reduces the interstory
drifting of the building by 35.7 percent in the longitudinal direction and 39.8
percent in the transverse direction. The author concluded that the proposed
scheme to build a vibration absorber with a building’s roof is effective, is
constructible and has the potential to become an attractive way to reduce
structural and non-structural earthquake damage in those buildings for which
their roof weight is a significant percentage of their total weight; that is, low
and medium-rise buildings.

Peter Nawrotzki (2006) presents Tuned- Mass Control Systems
(TMCS) to suppress vibrations in buildings subjected to seismic excitations.
Experimental and analytical investigations have been carried out to verify the
effectiveness of the model. A multi-storey building equipped with a tuned-
mass system on the rooftop was taken for the study. The additional mass
consists of reinforced concrete and rests on helical steel spring devices with
integrated dampers. The quantity of the additional mass was chosen according
to the target control efficiency; usual values for these purposes were found in
the range of 1.5 - 4 % of the total building mass and damping ratio of TMD, 5
to 20%. The peak forces are reduced by 40 % and hence, the damage causing
energy becomes considerably smaller. The damage causing energy was reduced from 10.5 to 2.5 units by activating the TMCS. The authors concluded that, a remarkable decrease of the structural frequencies by seismic effects can be avoided with a proper layout of the tuned-mass system.

The literature on Implementing of TMD shows that

(i) TMD installation in the form of Roof top frame or roof isolation system can solve implementation issue of requirement of space. Further, the roof space is free and may be used for other installations.

(ii) It is an ideal method of retrofitting, since the buildings usage need not be affected during the installation.

(iii) The mass of the roof top systems used by previous researchers takes values around 10% except Peter Nawrotzki (2006) who has taken the value upto 4%. Higher values reduce the response of the buildings but increase the dead weight.

Hence the implementation of roof top system with mass ratio less than 1.5% for systems subjected to seismic excitation have to be evaluated.

2.4 WATER TANK AS TMD

The following sections present a brief review of the literature on Tuned Liquid Dampers (TLD) used to suppress vibrations. The procedures adopted to arrive at the dynamic parameters of the TLD have been briefed.
Kareem and Sun (1987) presented a perturbation based procedure to represent the modal properties of a system comprising of a fluid-containing appendages attached to a multi-degree-of-freedom system in terms of the individual dynamic properties of the primary and secondary system. The modal properties were arrives at by utilizing the mode shapes of the combined system. The primary system is modeled as a lumped mass multi-degree of freedom system. An equivalent lumped mass model of the sloshing fluid is used to represent the secondary system. The boundaries of the appendage are assumed to be rigid, which precludes any dynamic fluid-structure interaction. The modal frequency of the tank depends on its dimension in the direction of motion. The dimension of the water tank was assumed such that the second tank mode was tuned with the fundamental building mode. The mass ratio was taken as the mass of the sloshing fluid to building mass plus the water mass associated with the rigid body mode. The water level in the tank was varied and the results suggest that the water level, if not too shallow, has no significant effect on the combined frequency of the system. The procedure is validated using a 10-storey building in which the water tank is located either at the top of the building or the fifth floor, subjected to El Centro earthquake data. The dynamic response analysis suggests that an optimally tuned tank may act as a tuned mass damper in reducing the response of the building. The percentage reduction in response is proportional to the ratio of the fluid appendage to the building and its dimension. The fluid damping also influences the response of the combined system.

Sun and Fujino (1994) presented an analytical model for a TLD using a rectangular tank filled with shallow liquid (1/2 > h/L > 1/20 - 1/25) is presented by the authors. It was assumed that the free surface is continuous; hence the model was valid as long as no breaking of waves occurs in the TLD. To account for breaking of waves two coefficients was introduced into
the equation of motion. The response of a SDOF structure fitted with a TLD was experimentally studied subjecting the model to sinusoidal excitation. The TLD tank used for experimental studies had a length of 390mm and filled with 30mm of water. The frequency of the water in the tank was matched with the frequency of the structure. The mass ratio was taken as 1.05% and structures damping 0.32%. It was found that the TLD is very satisfactory for suppressing structural vibrations.

Sun et al (1995) has expressed TLD properties using a TMD analogy, i.e., by effective (or equivalent mass) mass, frequency and damping. Experiments were conducted using a shake table under sinusoidal base motion with various amplitudes and frequencies. Prototype-sized TLD were used in the experiment to avoid hydrodynamic similitude problems. The wave height and the base shear force in the TLD were measured. A virtual mass and a virtual damping for a TLD attached to an undamped linear SDOF structure were calculated and then amplitude-dependent equivalent mass, frequency and damping were obtained using the TMD analogy.

Dorothy Reed et al (1998) studied the behavior of TLD under large amplitude excitation. Experimental investigations were carried out by the authors. Tanks of various configurations were tested under small and large amplitude sinusoidal excitation. The fundamental natural frequency of the water sloshing motion was calculated based on the linear water wave theory. The results suggest that nonlinear tuning of the tanks is appropriate; that the tanks are robust in dissipating energy over a wide frequency range, particularly for large amplitude excitation. Because of this robustness and hardening spring behaviour, the design damper frequency (if it is evaluated by the linearized wave theory) must be tuned at the value lower than that of the structural response frequency.
TLD’s have been installed in many structures across the world to suppress vibrations. The TLD’s installed are provided separately instead of being directly embodied from the water tank. Hence the TLD and the water tank tend to duplicate their installation space and load.

The literature shows that the mass of water alone was taken for mass ratio (mass of TMD to mass of structure) calculation and weight of tank was not included and the tank used for all study did not include staging for the tank. Hence in the present work the mass ratio and frequency ratio includes water, walls and roof of tank, beams and columns supporting the tank. A procedure to find the optimum water level in the tank to reduce the peak response has been presented.

2.5 SUMMARY

A brief review of the literature has been presented under three divisions as, optimization, roof top frame as TMD and water tank as TMD. From the literature, it is observed that the optimum parameters of TMD for structures with different time period has to be derived, since structures with different time period behave in a different manner to the same earthquake. And based on the optimized values, implementation of TMD, in the form of Roof Top Frame and Water Tank need to be investigated.