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Application of Tuned Mass Damper in Structures under Seismic Excitation – A Review

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Abstract: ***Tall Buildings are increasing day by day and one cannot have count of the number of low rise to high rise buildings built in the world. As safety of the Occupants is the prime factor of importance the structural stability and reliability has been the foremost concern of Civil and Structural Engineers. Most of the structures are found to have very low natural damping. In order to increase the damping capacity of a structure various mechanical means to increase damping are being considered in the era of high rise buildings. Structural vibrations produced by earthquake or wind can be controlled by different methods such as masses, damping, rigidity or shape and by providing active or passive counter forces. This paper makes an attempt to understand the present knowledge on Tuned Mass Damper in structural systems and their applications in earthquake engineering. The research work done by various researchers and their conclusions have been discussed in detail.***

Keyword: Tuned Mass Damper, Damping in Structures

1. Introduction

A tuned mass damper is a device consisting of a mass, a spring and a damper that is attached to a structure in order to reduce the dynamic response of the structure. The frequency of the damper is tuned to a particular structural frequency so that when that frequency is excited, the damper will resonate out of phase with the structural motion. Energy is dissipated by the inertial force of damper acting on the structure. A tuned mass damper is preferably placed where the deflections in the structure are great. The concept of Tuned Mass Damper was first introduced by Frahm in 1909 for reducing the rolling motion observed in ships and ship hull vibrations. Later on Ormondroyd and Den Hartog presented a theory for the TMD. In the book on mechanical vibrations Den Hartog has discussed in detail on optical tuning and damping parameters in 1940. The initial theory of tuned mass damper was applicable for an undamped single degree of freedom. TMD is used to reduce the action of earthquake in seismic area and to provide mitigation against wind forces. It is used to reduce the dynamic response of the structure. The frequency and the magnitude of the undesirable motion observed in the structure are measured. A model of an existing structure is developed and the TMD mass is determined and placed to meet the requirements for vibration mitigation. Prototype of TMD is tested to fine tune the design. The motion of the TMD on the structure is measured and the mitigation is achieved.

1.1Classification of Control Methods

Based on the Control mechanism implemented in TMD, Control methods are classified as Active Control, Passive Control, Hybrid Control and Semi- Active Control.

An Active control system is a system where forces are applied to the structure in a prescribed manner by using control actuators which are powered by an external power source. Energy can be added or dissipated from the structure by using these forces. The Signals sent to the Control actuators are measured with physical sensors (optical, mechanical, electrical, chemical and so on) and these signals are a function of the response system.

A Passive control system is a system in which no external power source is required for operation. Forces are developed in response to the motion of the structure and are imparted by passive control devices. Total energy remains inherently stable since it cannot increase.

A Hybrid control system is a combination of the active and passive control systems. For example, actively controlled actuators attached to a base isolated structure to improve the performance, distributed viscoelastic damping equipped in a structure and an active mass damper supplemented with it near the top of the structure.

Semi active control system is a kind of active control system where energy requirements are minimum compared to the typical active control system. Stability in bounded input and bounded output is ensured as these systems do not impart mechanical energy to the structural system.

2. Earlier Research Investigations

Hrovat *et al* (1983) presented a TMD known as SATMD with the varying controllable damping. Under Identical conditions when the structure is equipped with SATMD instead of TMD, the behavior of the structure is significantly improved. The parameters such as mass ratios, frequency ratios etc., do not influence the control design of SATMD. The TMD attached to the structure is tuned to the fundamental frequency of the structure which substantially reduces the first mode response of a structure. The higher modal responses may be only suppressed or amplified. The frequency related limitations of TMD in a structure. Each TMD is tuned to a different dominant frequency.

Setareh (1994) proposed a doubly tuned mass damper consisting of two masses connected in series to the structure.

Two different loading conditions were considered in this case such as harmonic excitation and random excitation of zero- mean white noise. The response reduction by using DTMD and the efficiency of DTMD is evaluated. From the analytical results it was concurred that although DTMDs are more efficient than single mass TMDs in the range of total mass ratios, they are only slightly more efficient than TMDs in the practical range of mass ratios (0.01-0.05).

Villaverde *et al* (1994) carried out a study on three different structures, in which the first one is a 2D two story shear building the second is a three-dimensional (3D) one-story frame building, and the third is a 3D cable-stayed bridge, using nine different kinds of earthquake records. Numerical and experimental results show that the effectiveness of TMDs on reducing the response of the same structure during different earthquakes, or of different structures during the same earthquake is significantly different; some cases give good performance and some have little or even no effect. This implies that there is a dependency of the attained reduction in response on the characteristics of the ground motion that excites the structure. This response reduction is large for resonant ground motions and diminishes as the dominant frequency of the ground motion gets further away from the structure's natural frequency to which the TMD is tuned. Also, TMDs are of limited effectiveness under pulse-like seismic loading.

Allen J. Clark *et al* (1988) in his paper has discussed a methodology for designing multiple tuned mass damper for reducing building response motion. The technique is based on extending Den Hartog work from a single degree of freedom to multiple degrees of freedom. Simplified linear mathematical models were excited by 1940 El Centro earthquake and significant motion reduction was achieved using the design technique.

Performance of tuned mass dampers under wind loads **K.C.S. Kwok *et al* (1995).**The performance of both passive and active tuned mass damper (TMD) systems can be readily assessed by parametric studies which have been the subject of numerous research.. Few experimental verifications of TMD theory have been carried out, particularly those involving active control, but the results of those experiments generally compared well with those obtained by parametric studies. Despite some serious design constraints, a number of passive and active tuned mass damper systemshave been successfully installed in tall buildings and other structures to reduce the dynamic response due to wind and earthquakes.

A.N Blekherman *et al* (1996) proposes a passive vibration absorber to protect high-rise structural systems from earthquake damages. A structure is modelled by one-mass and n-mass systems (a cantilever scheme). Damping of the structure and absorber installed on top of it is represented by frequency independent one on the base of equivalent visco-elastic model that allows the structure with absorber to be described as a system with non-proportional internal friction. A ground movement is modelled by an actuator that produces vibration with changeable amplitude and frequency. To determine the optimum absorber parameters, an optimization problem, that is a minmax one , was solved by using nonlinear programming technique(the Hooke-Jeves method).

T.Shimazu and H.Araki *et al* (1996) in their paper have clarified the real state of the implementation of mass damper systems, the effects of these systems based on various recorded values in actual buildings against both wind and earthquake. The effects are discussed in relation with the natural period of buildings equipped with mass damper systems, the mass weight ratios to building weight, wind force levels and earthquake ground motion levels.

In the work done by **Fahim Sadek *et al* (1997)** has discussed the optimum parameters of TMD that result in considerable reduction in the response of structures to seismic loading . The criterion that has been used to obtain the optimum parameters is to select for a given mass ratio, the frequency and damping ratios that would result in equal and large modal damping in the first two modes of vibration. The parameters are used to compute the response of several single and multi-degree of freedom structures with TMDs to different earthquake excitations. The results show that the use of the proposed parameters reduces the displacement and acceleration responses significantly. The method can also be used for vibration control of tall buildings using the so-called _mega-substructure configuration‘, where substructures serve as vibration absorbers for the main structure.

G. W. Housner *et al* (1996) in his study provides a concise point of departure for those researchers and practitioners who wish to assess the current state of the art in the control and monitoring of civil engineering structures; and provides a link between structural control and other fields of control theory, pointing out both differences and similarities, and points out where future research and application efforts are likely to prove fruitful.

Byung-Wan Jo *et al* (2001) has adopted a three axis two degree of freedom system to reduce the structural vibration of a three span steel box bridge to model the mass effect of the vehicle; and the kinetic equation considering the surface roughness of the bridge is derived based on Bernoulli-Euler beam ignoring the torsional DOF. The effects of TMD on steel box bridge shows that it is not effective in reducing the maximum deflection , but it efficiently reduces the free vibration of the bridge. It proves that the TMD is effective in controlling the dynamic amplitude rather than the maximum static deflection.

Genda Chen *et al* (2001) studied the effects of a tuned mass damper on the modal responses of a six-story building structure. Multistage and multimode tuned mass dampers are then introduced. Several optimal location indices are defined based on intuitive reasoning, and a sequential procedure is proposed for practical design and placement of the dampers in seismically excited building structures. The proposed procedure is applied to place the dampers on the floors of the six-story building for maximum reduction of the accelerations under a stochastic seismic load and 13 earthquake records. Numerical results show that the multiple dampers can effectively reduce the acceleration of the uncontrolled structure by 10– 25% more than a single damper. Time-history analyses indicate that the multiple dampers weighing 3% of total structural weight can reduce the floor acceleration up to 40%.

T. Pinkaew *et al* (2002) has found that the effectiveness of TMD using displacement reduction of the structure to be insufficient after yielding of the structure, damage reduction of the structure is proposed instead. Numerical simulations of a 20-storey reinforced concrete building modelled as an equivalent inelastic single-degree-of-freedom (SDOF) system subjected to both harmonic and the 1985 Mexico City (SCT) ground motions are considered. It is demonstrated that although TMD cannot reduce the peak displacement of the controlled structure after yielding, it can significantly reduce damage to the structure. In addition, certain degrees of damage protection and collapse prevention can also be gained from the application of TMD.

Hua-Jun Li *et al* (2002) has considered the environmental loading to be a long-term non-stationary stochastic process characterized by a probabilistic power spectral density function. One engineering technique to design a TMD under a long-term random loading condition is for prolonging the fatigue life of the primary structure.

Yang Runlin *et al* (2002) in his study has focused on determining the instantaneous damping of the semi-active tuned mass damper with continuously variable damping. An off-and- towards-equilibrium (OTE) algorithm is employed to examine the control performance of the structure/SATMD system by considering damping as an assumptive control action. Two numerical simulations of a five-storey and a ten-storey shear structures with a SATMD on the roof are conducted. The effectiveness on vibration reduction of MDOF systems subjected to seismic excitations is discussed.

Devendra P. Garg *et al* (2003) investigated the advances made in the area of vibration suppression via recently developed innovative techniques (for example, constrained layer damping (CLD) treatments) applied to civilian and military structures.Developing theoretical equations that govern the vibration of smart structural systems treated with piezo-magnetic constrained layer damping (PMCLD) treatments; and developing innovative surface damping treatments using micro-cellular foams and active standoff constrained layer (ASCL) treatments. The results obtained from the above and several other vibration suppression oriented research projects being carried out under the ARO sponsorship are also included in this study.

Bijan Samali, Mohammed Al-Dawod *et al* (2003) have described the performance of a five-storey benchmark model using an active tuned mass damper (ATMD), where the control action is achieved by a Fuzzy logic controller (FLC) under earthquake excitations. The advantage of the Fuzzy controller is its inherent robustness and ability to handle any non-linear behaviour of the structure. The simulation analysis of the five-storey benchmark building for the uncontrolled building, the building with tuned mass damper (TMD), and the building with ATMD with Fuzzy and linear quadratic regulator (LQR) controllers has been reported, and comparison between Fuzzy and LQR controllers is made. In addition, the simulation analysis of the benchmark building with different values of frequency ratio, using a Fuzzy controller is conducted and the effect of mass ratio, on the five-storey benchmark model using the Fuzzy controller has been studied.

Nawawi Chouw *et al* (2004) has presented the influence of a tuned mass damper on the behaviour of a frame structure during near-source ground excitations. In the investigation the effect of soil-structure interaction is considered, and the natural frequency of the tuned mass damper is varied. The ground excitations used are the ground motion at the station SCG and NRG of the 1994 Northridge earthquake. The investigation shows that the soil-structure interaction and the characteristic of the ground motions may have a strong influence on the effectiveness of the tuned mass damper. But in order to obtain a general conclusion further investigations are necessary.

Nadathur Varadarajan *et al* (**2004)** has investigated the effectiveness of a novel semi-active variable stiffness-tuned mass damper ~SAIVS-TMD! for the response control of a wind-excited tall benchmark building is investigated. The benchmark building considered is a proposed 76-story concrete office tower in Melbourne, Australia. Across wind load data from wind tunnel tests are used in the present study. The objective of this study is to evaluate the new SAIVS-TMD system, that has the distinct advantage of continuously retuning its frequency due to real time control and is robust to changes in building stiffness and damping. The frequency tuning of the SAIVS-TMD is achieved based on empirical mode decomposition and Hilbert transform instantaneous frequency algorithm developed by the writers. It is shown that the SAIVS-TMD can reduce the structural response substantially, when compared to the uncontrolled case, and it can reduce the response further when compared to the case with TMD. Additionally, it is shown the SAIVS-TMD reduces response even when the building stiffness changes by 15%.

A. Ghosha, B. Basu *et al* (2004) has studied the properties of the structure used in the design of the TMD that are evaluated considering the structure to be of a fixed-base type. These properties of the structure may be significantly altered when the structure has a flexible base, i.e. when the foundation of the structure is supported on compliant soil and undergoes motion relative to the surrounding soil. In such cases, it is necessary to study the effects of soil-structure interaction (SSI) while designing the TMD for the desired vibration control of the structure. In this paper, the behaviour of flexible-base structures with attached TMD, subjected to earthquake excitations has been investigated. Modified structural properties due to SSI has been covered in this paper.

Chien-Liang Lee *et al* (2006) has proposed An optimal design theory for structures implemented with tuned mass dampers (TMDs) . Full states of the dynamic system of multiple-degree-of-freedom (MDOF) structures, multiple TMDs (MTMDs) installed at different stories of the building, and the power spectral density (PSD) function of environmental disturbances are taken into account. The optimal design parameters of TMDs in terms of the damping coefficients and spring constants corresponding to each TMD are determined through minimizing a performance index of structural responses defined in the frequency domain. Moreover, a numerical method is also proposed for searching for the optimal design parameters of MTMDs in a systematic fashion such that the numerical solutions converge monotonically and effectively toward the exact solutions as the number of iterations increases. The feasibility of the proposed optimal design theory is verified by using a SDOF structure with a single TMD (STMD), a five-DOF structure with two TMDs, and a ten-DOF structure with a STMD.

Mehdi Setareh *et al* (2007) has used a semi-active magneto-rheological device in a pendulum tuned mass damper PTMD system to control the excessive vibrations of building floors. This device is called semi-active pendulum tuned mass damper SAPTMD. Analytical and experimental studies are conducted to compare the performance of the SAPTMD with its equivalent passive counterpart. An equivalent single degree of freedom model for the SAPTMD is developed to derive the equations of motion of the coupled SAPTMD-floor system. A numerical integration technique is used to compute the floor dynamic response, and the optimal design parameters of the SAPTMD are found using an optimization algorithm. Effects of off-tuning due to the variations of the floor mass on the performance of the PTMD and SAPTMD are studied both analytically and experimentally. From this study it can be concluded that for the control laws considered here an optimum SAPTMD performs similarly to its equivalent PTMD, however, it is superior to the PTMD when the floor is subjected to off-tuning due to floor mass variations from sources other than human presence.

K. K. F. Wong *et al* (2008) investigated the energy transfer process of using a tuned mass damper TMD in improving the ability of inelastic structures to dissipate earthquake input energy is investigated. Inelastic structural behaviour is modelled by using the force analogy method, which is the backbone of analytically characterizing the plastic energy dissipation in the structure. The effectiveness of TMD in reducing energy responses is also studied by using plastic energy spectra for various structural yielding levels. Results show that the use of TMD enhances the ability of the structures to store larger amounts of energy inside the TMD that will be released at a later time in the form of damping energy when the response is not at a critical state, thereby increasing the damping energy dissipation while reducing the plastic energy dissipation. This reduction of plastic energy dissipation relates directly to the reduction of damage in the structure.

Y.Q. Guo, W.Q.Chen *et al* (2008) presented the formulations of the reverberation matrix method (RMM) for the dynamic analysis of space structures with multiple tuned mass dampers (MTMD). The theory of generalized inverse matrices is then employed to obtain the frequency response of structures with and without damping, enabling a uniform treatment at any frequency, including the resonant frequency. For transient responses, the Neumann series expansion technique as suggested in RMM is found to be confined to the prediction of accurate response at an early time. The artificial damping technique is employed here to evaluate the medium and long time response of structures. The free vibration, frequency response, and transient response of structures with MTMD are investigated by the proposed method through several examples. Numerical results indicate that the use of MTMD can effectively alter the distribution of natural frequencies as well as reduce the frequency/transient responses of the structure. The high accuracy, lower computational cost, and uniformity of formulation of RMM are also highlighted in this paper.

Maryam Bitaraf *et al*(2010) has studied the application of semi-active control strategies for seismic protection of buildings with MR dampers **.**Magneto-rheological (MR) dampers are semi-active devices that can be used to control the response of civil structures during seismic loads. They are capable of offering the adaptability of active devices and stability and reliability of passive devices. One of the challenges in the application of the MR dampers is to develop an effective control strategy that can fully exploit the capabilities of the MR dampers. This study proposes two semi-active control methods for seismic protection of structures using MR dampers. The first method is the Simple Adaptive Control method which is classified as a direct adaptive control method. The controller developed using this method can deal with the changes that occur in the characteristics of the structure because it can modify its parameters during the control procedure. The second controller is developed using a genetic-based fuzzy control method. In particular, a fuzzy logic controller whose rule base determined by a multi-objective genetic algorithm is designed to determine the command voltage of MR dampers.

In the work done by **Chi-Chang Lin *et al*.(2010)** on Vibration control of seismic structures using semi-active friction multiple tuned mass dampers . There is no difference between a friction-type tuned mass damper and a dead mass added to the primary structure if static friction force inactivates the mass damper. To overcome this disadvantage, this paper proposes a novel semi-active friction-type multiple tuned mass damper (SAF-MTMD) for vibration control of seismic structures. Using variable friction mechanisms, the proposed SAF-MTMD system is able to keep all of its mass units activated in an earthquake with arbitrary intensity. A comparison with a system using passive friction-type multiple tuned mass dampers (PF-MTMDs) demonstrates that the SAF-MTMD effectively suppresses the seismic motion of a structural system, while substantially reducing the strokes of each mass unit, especially for a larger intensity earthquake.

3. Conclusion

It is very evident that with certain drawbacks, TMD can be successfully used to control vibration of the structure and are very effective tool to protect the structures from various lateral forces, like Wind loads, Seismic effects.. Although TMD is more effective in reducing the displacement responses of structures with low damping ratios, it is less effective for structures with high damping ratios. Current trends in construction industry demands taller and lighter structures, which are also more flexible and having quite low damping value. This increases failure possibilities and also, problems from serviceability point of view. Several techniques are available today to minimize the vibration of the structure, out of which concept of using of TMD is also one among them.

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