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Review of literature on vibration control of inelastic 3D structures using tuned mass damper

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Abstract:
Vibration control of structures using several systems is common now-a-days. Tuned mass damper (TMD) is one of the passive control system used to reduce the vibrations of structure. Damping ratio is the one of the parameter of TMD and it is considered as the same as that of the structure. In this paper the effect of TMD is studied with different mass ratios and TMD configurations. This study was made to find the simplification of using TMD for controlling vibration of structure.
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Keywords — **Tuned mass damper, Active tuned mass damper, Harmonic absorber, Single-degree-of-freedom, Finite elements model**

I. INTRODUCTION

Tall buildings overshadow the skylines of major financial centres of the world, where high land costs and dense population have driven the demanding construction of tall commercial and residential accommodations. As a result, a number of landmark tall building projects are currently under construction in major cities, and the height record of world's tallest building became twofold in 30 years.

The increase in building height are often followed by more flexibility and insufficient inherent damping, magnifying the building's susceptibility to wind and earthquake-induced vibration, particularly in typhoon-prone cities. The wind and earthquake-induced dynamic response of such buildings needs to be considered in terms of loading and deflection during extreme storms and in terms of the effects of building motion on resider comfort during typhoons and other frequent strong monsoon wind events. Although recent novel developments in structural systems have permitted increased lateral wind loads to be successfully resisted, the wind and earthquake-induced building responses still have not been efficiently and economically dealt with, potentially causing discomfort to building resider and posing serious serviceability issues. Accordingly, the current design of many tall buildings often includes significantly more materials than are required for structural strength to satisfy occupant comfort requirements.

The present paper focuses on the performance evaluation of tuned mass dampers. The main objective is to study the effectiveness of these passive control techniques on vibration control of linear multi storied buildings under various loads, using numerical analysis. TMD is designed for multi-storeyed building and their performances are evaluated and compared.

A tuned mass damper (TMD), also known as harmonic absorber, is a device mounted in structures to reduce the amplitude of mechanical vibrations. Their application can prevent discomfort, damage, or outright, failure of the structure. TMD have been widely used for vibration control in mechanical engineering systems. In recent years, TMD theory has been adopted to reduce vibrations of tall buildings and other various civil engineering structures. Dynamic absorbers and tuned mass dampers are the realizations of tuned absorbers and tuned dampers for structural vibration control applications. The inertial, resilient, and dissipative elements in such devices are: mass, spring and dashpot (or material damping) for linear applications and their rotary counterparts in rotational applications. Depending on the application, these devices are sized from few ounces (grams) to many tons. Other configurations such as pendulum absorbers/dampers, and sloshing liquid absorbers/dampers have been realized for vibration mitigation applications. TMD is attached to a structure in order to reduce the dynamic response of structure. The frequency of the damper is tuned to a particular structural frequency so that when the frequency is excited, the damper will resonate out of phase with the structural motion. The mass is usually attached to the building via a spring-dashpot system and energy is dissipated by the dashpot as relative motion develops between the mass and the structure.

Fig -1: Tuned mass damper

In tall building the seismic forces result to huge deflections in the structure. So design engineers are forced to provide more materials to attain the structural strength. To control the seismic effect on the building proper design is necessary. But it will increase the cost of construction in a huge level. In recent years a new concept is adopted which is inserting dampers in the structure. The first study on this topic was done to reduce the rolling motion of ships. The first structure in which tuned mass damper was installed is the Centre point Tower in Sydney, Australia. So according to the previous studies proper design and installation of dampers will reduce the vibrations of the building and reduce the cost of construction. And it will increase the durability of the structure. But the design and the installation have some difficulties. It is depend on the structural properties.

II. LITERATURE REVIEW

The researches based on the tuned mass damper were started several years ago. And a lot of studies were completed based on the topic. The analytical studies gave the theoretical idea about the damper and mathematical studies based on software's proved the quality of Tuned mass damper on both concrete and steel structures. And it can use in every kind of structures. And in USA, Japan and Middle East some structures were already designed and built using several damping systems. So before doing this research some detailed studies should be carried out based on the previous studies on vibration analysis of tuned mass dampers**.**

Aly Mousaad Aly, Ferruccio Resta,Alberto Zasso,(2008)- Active control of a tall building subjected to wind loads is presented in this paper. A 48-story high-rise building (209 m height) equipped with two active mass dampers is used in this research. The structure is subjected to both across-wind and along-wind loads obtained for a rigid model (scaled 1:100) that was tested in the wind tunnel of Politecnico di Milano for two different configurations of the surrounding. The building alone is modelled dynamically using three-dimensional model with a total degrees-of-freedom of 144 (each floor has three degrees-of freedom: two lateral translations and one rotation about the vertical axis). The building considered in this study is a 48-story 209 meters steel tower. Finite elements model (FEM) for the building was done in [Aly et al., 2007]. In this study the in-plane motion of the structure in the x-direction is controlled using both the TMD and active tuned mass damper (ATMD). However, due to the fact that the control of the in-plane response in the x-direction will not effect on the in-plane response of the building in the y-direction, another TMD and ATMD are designed to control the lateral in-plane response in the y-direction. Following that the uncontrolled torsional response is re-added instantaneously to the two lateral responses to give the overall response in the two lateral directions. The building model was tested for a total number of 15 angles of wind attack and the pressure results were transformed into instantaneous pressure coefficients. And the response against wind pressure was recorded. Then TMD and ATMD is introduced and recorded the reduction of vibration. TMD in the x-direction is able to achieve an average reduction in the rms-displacements over all of the wind directions and the two configurations by 23.25% while the average reduction achieved by the TMD in the y-direction is 21.3%. The average reductions achieved by the ATMD in x and y-directions are 37.55% and 31.4% respectively. This means that both TMD and ATMD in the x-direction are achieving better performance in reducing rms-displacements than those in the y-direction with a smaller moving mass.

Mohamed Abdel-Rohman (1987). This paper investigates several methods of active control mechanism of tall buildings which are active tendon control, ATMD and active aerodynamic appendage mechanism. The tall building considered in this study is 305 m (1,000 ft) high, with a square cross section of 30.5 m (100 ft) width. The wind speed has been modeled to be the sum of a mean component and a fluctuating component. The fluctuating wind speed, u{t), has been calculated using the following relationships.

$$u(t) = \sqrt{2}\sum_{i=1}^{25}[2S_u(\omega_i)\Delta\omega]^{1/2}\cos(\omega_i t + \phi_i)$$

Then it results the first mode vibration. And this mode is used for the three mechanisms.

In the case of the ATMD, the actuator movements are represented by the relative sway between the damper and the building

One main disadvantage in using appendages is that an effective control occurs only when the appendage is perpendicular to the mean wind direction. In this section, the feasibility of this mechanism is studied assuming the appendage is always in a perpendicular direction to the mean wind direction.

The results of these studies have been summarized to indicate that using a combined active control mechanism would solve the problems raised when using only one control mechanism. The performance indices of several combined control mechanisms have been shown to indicate that for tall building control against wind, the combined active tendon and active TMD, when designed properly, would provide the solutions for many structural control problems.

James MW Brownjohn1, Ki-Young Koo(2010) This paper briefly reviews some provisions for predicting and assessing vibration serviceability for building sway, with reference to full-scale studies. this paper studies estimation of damping and effects on full-scale performance for two tall structures.

Tanaka et al. (1969) presented damping estimates for a set of buildings for micro-tremor and earthquake response (having amplitude differences of up to 1000). Using the best technology of the day they paid attention to likely errors and suggested trends for increased damping and decreased frequency. Davenport and Hill-Carroll (1986) presented experimental data based on single mode autocorrelation functions and steady state shaker test data and proposed some mechanisms for damping in tall buildings. Their results showed dependence on ratio of response amplitude to building height; one relationship for steel and one for concrete. A tall building and a tall chimney was modelled and analysed against wind forces in this paper. Both examples relate to vibration serviceability in wind, with some concerns about ultimate safety for the chimney. And they found that it has been possible to correlate damping levels with response to demonstrate clearly the nonlinear nature of damping forces and the case of the chimney the effect of the TMD on damping enhancement.

P.J. Carrato, and K. Santamont,(2012) This paper presents a structural design of The Ivanpah Solar Electric Generating Facility, located in San Bernardino County, California and the chosen solution to mitigate the cross-wind excitation. These towers are designed in accordance with the 2007 California Building Code and are classified as seismic design category C. The results of the wind tunnel study provided valuable insight into the behavior of this structure. The most significant result was that cross-wind excitation could produce substantial overturning moments on the tower. Overturning due to crosswind loads were predicted to be as much as three times that of the along wind load. After determining that stiffening the steel superstructure and designing the foundation for the cross-wind overturning moments was not practical, it was determined that using a TMD would be the most cost effective option. Use of tuned mass dampers to control vibration of structures is a well-established technology .Based on the results of the wind tunnel study, it was determined that a TMD providing at least 5% of critical damping for the fundamental mode of vibration of the tower would reduce the cross-wind response to an acceptable level.

C. C. Changl and Henry T. Y. Yang(1995) In this study, a form of a closed-loop complete-feedback control algorithm is proposed for the control of a building modeled as a single-degree-of-freedom (SDOF) system using an active tuned mass damper. The SDOF system is assumed to be under stationary Gaussian white noise ground excitation. The control force is calculated from the acceleration, velocity, and displacement feedbacks of the SDOF system and the active mass damper. The stiffness and damping constants of the tuned mass damper and the gain coefficients of the actuator are derived by minimizing the displacement variance of the SDOF system. The stability of the proposed algorithm is also discussed using the Routh-Hurwitz criterion. Monte Carlo simulations are performed to evaluate the performance of the active-tuned-mass-damper design on the examples of a SDOF system and a 10-story three-bay building frame. The control effects of the ATMD with optimal and non-optimal passive-control-device properties using velocity feedback are calculated and discussed. Comparisons are also made on the control efficiency between ATMD using velocity feedback and complete feedback. To evaluate the designs of TMD and ATMD discussed in this study, the control performance of a single-degree-of-freedom system and a 10 story, three-bay building frame were analyzed and discussed. The results of the standard deviations a xo' a yO' aXO~Xl' and 0";'1 are plotted against all for these two cases. It is seen that for the same level of reduction in SOOF responses (axtJ and ahJ, the control force all required is smaller for the case of complete feedback. This observation seems to suggest that the ATMO control using the optimal active tuned mass damper with complete feedback is more efficient than that of non-optimal active tuned mass damper with velocity feedback. It should be noted, however, that for both cases the reduction in the responses of a x and and a y is accompanied by the increase of TMD response characteristics, such as, the stroke Xo - l; and the absolute acceleration y1.

A closed-loop complete-feedback control algorithm was proposed for the control of a structure modelled as a single-degree-of-freedom (SDOF) system by using an ATMD. The SDOF system was assumed to be under Gaussian white noise stationary ground excitation. The control force was calculated from the acceleration, velocity, and displacement feedbacks of the SDOF system and the auxiliary mass. The passive properties and the gain coefficients of the actuator were derived by minimizing the displacement variance of the SDOF system. The stability of the proposed algorithm was also discussed using the Routh-Hurwitz criterion. Monte Carlo simulations were performed to verify and evaluate the performance of the ATMD design on the examples of a SDOF system and a l0-story three-bay building frame. The results show that control efficiency of the ATMD based on the velocity feedback depends on the passive-control-device properties assumed. Such a velocity feedback based ATMD cannot decrease the structural response when the control-device properties are optimal. The responses of the SDOF system could be reduced either by using velocity feedback on an ATMD with non-optimal parameters or by using complete feedback on an ATMD with optimal parameters.

K. T. Tse1; K. C. S. Kwok ; and Yukio Tamura,(2012) A series of wind tunnel pressure tests were conducted to determine the wind loads experienced by the studied building, which is considered to be wind-sensitive with its high aspect ratio and sharp corners of rectangular building form. The measured surface pressures were converted into layers of wind forces and used in the subsequent vibration analyses to determine the building tip displacement and acceleration responses. A drift optimization was performed successfully to redistribute the structural mass and stiffness to reduce the top deflection and inter story drifts to the allowable limits, and an Semi active tuned mass damper (STMD) was subsequently employed for the occupant comfort criteria. The bidirectional TMD was designed with natural frequencies slightly less than the building's first two natural frequencies and was equipped with MR dampers to provide additional controllable damping forces to significantly mitigate the acceleration responses. The maximum generated control forces were 35 kN, with a maximum stroke of 42 mm in x-direction, and 476 kN, with a maximum stroke of 526 mm in y-direction. Correspondingly, the standard deviation and peak responses were reduced by more than 50% and approximately 25%, respectively. To facilitate the decision making on the implementation of a control device in the design stage, a collaborative study with two construction companies was conducted to evaluate the capital and maintenance costs of the STMD. The results of the study showed that the total cost of the STMD is governed by the procurement and manufacture cost and is approximately 2% of the total building construction cost. The maintenance cost, which has been incorrectly perceived as a heavy lifelong burden, in fact contributes not more than 0.2% of the total building construction cost. A chart was subsequently developed to illustrate the initial estimation of the cost of an STMD by conducting a sensitivity analysis. The rate of change in STMD cost is found to be more substantial for a greater acceleration reduction level.

Maria Q. Feng,Akira Mika (1995) In this paper, a new method of vibration control for tall buildings is presented, which takes advantage of the mega sub structural configuration and does not require additional mass or active control devices. An innovative vibration-control system, which takes advantage of the mega-substructure configuration, was proposed for tall and super tall buildings. This mega-sub control system was designed in such a way that the vibration energy (kinetic energy) of the mega structure due to wind or earthquake loads can be transferred into the substructures and then dissipated in the substructures by conventional damping devices. This control system does not require any additional mass as seen in the conventional mass damper systems. The difficulties in the vibration control of tall buildings associated with their high rigidity and slenderness can be overcome by the proposed mega-sub control system. The optimum values of parameters such as the frequency and damping ratio of the substructure were derived for a simplified model of a mega substructure. The dramatic effectiveness of the mega subsystem in controlling building vibration responses to improve human comfort and structural safety was demonstrated through analytical and numerical studies. The simplicity and effectiveness make this unique control system extremely attractive for its future implementation in tall and super tall buildings.

Matt Jackson,David M Scott(2010) The design example studied here is 250 West 55th Street, a new 40-story office tower in New York City, developed by Boston Properties, and designed by Skidmore Owings and Merrill. As is typical for New York City office towers, the building has a steel frame with a steel braced core, and composite floors. The design includes a hat truss with outriggers connected to the core, located in the roof top mechanical level. The design was initially based on ASCE-7 wind loads, and checked against the New York City Building code. At lower levels there was significant shielding from other existing buildings, reducing the loads substantially; however, the shape of the tower was found to be susceptible to cross wind vibrations and was also subject to some buffeting from surrounding tall buildings. It was decided that adding damping was the more cost effective option. Because the actual loads (and hence deflections) were lower than expected, it was possible to further reduce the stiffness of the structure whilst still meeting conventional drift limits, provided further supplemental damping was added to meet the acceleration limits. Beyond this limit the damping could be increased further; however, unless the benefit of the damping was taken in the calculation of the wind loads, the drift would have been increased. A tuned mass damper system was also briefly considered, however this would have required the loss of valuable real estate at the top of the tower, would have had a higher initial capital cost and ongoing maintenance cost. It also would not have allowed for the 500 tons of material savings.

The damped outrigger system can offer similar levels of damping to a tuned mass or liquid damper, with lower capital cost, reduced space takings and reduced maintenance. When compared to other distributed damping systems, the location of the dampers are optimized to provide maximum damping in the primary modes, thus reducing the number of dampers, and reducing initial cost and inspection costs.

H. Kim, J.-W. Park, D.-K. Kim, S. Hwang(2011) In this paper, an identification method of the dynamic properties of secondary mass dampers based on the force vibration test is presented. Decoupled equations of motion are derived from a coupled equation of motion of building and damper. The decoupled equations of motion are then applied to the system identification of secondary mass dampers using the response of dampers as an input and the response of the building as an output. For the verification of the proposed method, the dynamic properties of a TMD and a Tuned liquid column damper (TLCD) installed on a SDOF system are identified through numerical examples. Further, the method is applied to the identification of an actual TMD and TLCD installed in buildings using free vibration responses.

The equation of motion of an SDOF system with a TMD can be easily constructed treating the TMD as an additional DOF added to the SODF system. The natural frequency and damping ratio of TMD can be obtained. the dynamic properties of the building can be easily obtained from a transient vibration test applying any typical system identification techniques (Ljung, 2007). In the transient vibration test, the movement of TMD should be restrained in order not to provoke any interaction with the building. This condition, however, is often difficult to satisfy in practice. Accordingly, it would be useful if the approximate dynamic properties of the building could be directly identified from an in-situ experiment.

TLCD and Tuned liquid damper (TLD) are similar to a TMD in principle except that a TLD uses liquid (usually water) as a secondary mass body. That is, liquid acts as a moving mass and the liquid sloshing movement absorbs the building's energy if the sloshing frequency is tuned to the natural frequency of the building. In addition to this similarity, a TLD has the advantages of cheap installation cost and ease of maintenance compared to a TMD. Because the control performance of a TLD is close to that of a TMD, it has been increasingly used in practice. The damping force of a TLCD is not linear unlike a TMD since the absolute value of velocity is included in the damping coefficient.

In this paper, an identification method for the dynamic properties of secondary mass dampers based on the forced vibration test is presented for the case that the pre-assembled test in a factory is impractical. Decoupled equations of motion are derived from a coupled equation of motion of building and damper. These decoupled equations of motion can be applied to general system identification methods using the responses of the building and damper. For the verification of the proposed method, the dynamic properties of a TMD and a TLCD install12345ed on a SDOF system were identified through numerical examples, and the method was applied to the identification of an actual TMD and TLCD installed in buildings using free vibration responses. The results of the numerical study and the forced vibration test show that the proposed method is effective in the identification of TMD and TLCD based on the forced vibration test.

Zhiqiang Zhang, Guowei Zhou, Aiqun Li1,, Xiaofeng "Bill" Zhang(2011) In this paper a 3-D finite element model was developed in MIDAS in order to study the dynamic behaviour of the structure, and to provide a basis for the settings of the damper parameters. The space beam element is used to model concrete and steel beams and columns. The shell element is used to model floor slabs, taking account of in-plane and out-of-plane deformations. The cable element is used for the cable hanging the bowl. the corridor shows significant vertical vibration in every mode. Therefore, the vertical vibration is significant for the corridor. The main task of controlling the vibration of the corridor under walking excitation is to reduce vertical vibrations. Tuned mass damper (TMD), as a passive control technology, has been successfully used in control of wind-excited vibration in high-rise structures. Numerical studies have shown that TMD can also effectively reduce the vertical vibration of long-span structures. To maximize the effect of vibration control, the frequency of TMD shall be set near the free vibration frequency of the structure to be controlled. However, the damping effect of TMD is very sensitive to the fluctuations of the free vibration frequency, and there are always discrepancies between the actual free vibration frequencies of the structure and the calculated ones as a result of structural analysis errors and construction variations. Damping effect of TMD will be affected by these factors. More importantly, for the vibration modes lower than the mode being controlled, TMD has a good curbing effect to their response. For the modes higher than the one being controlled, TMD has little damping effect or may even amplify them. Given these characteristics, Clark (1988) proposed the concept of MTMD, which aims at a certain range of frequencies to be controlled, resolving the TMD system of a certain frequency bandwidth into multiple sub-TMD systems to improve the stability of the control system.

When the vertical natural frequency of the structure is close to the walking frequency, the resonance response is significant. In order to meet the human comfort requirements, the vibration control should be implemented. TMDs need to be deployed in the vicinity of the peaks of the mode shape corresponding to the frequency to be controlled to achieve the most vibration control effects. TMDs perform the best when tuned to the excitation frequencies. They are less effective to other vibration modes. To control more vibration modes, each group of TMDs should be located at the peaks of the corresponding mode shape. Grouping TMDs into different frequencies within the controlling frequency range.

Thakur V.M and Pachpur P.D (2012) In this research TMDs used as soft story which is considered to be made up of RCC, constructed at the top of the building. A six storied building with rectangular shape is considered for analysis. Analysis is done by FE software SAP 2000 by using direct integration approach. TMDs with percentage masses 2% & 3% are considered. Three different recorded time histories of past EQ. are used for the analysis. Comparison is done between the buildings with TMD and without TMD. Simple TMD with optimum frequency ratio, provided in the form of soft storey at building top is found to be effective in reducing seismic response of building.

III. CONCLUSION

From the above literatures we can conclude that depending upon the structural parameters and depending on the seismic characteristics of that region the type of damping system will change. That is number of dampers to be provided and the frequency to set will change. And also the position of damper depends on the response of the structure due to the wind or seismic load. Various studies were conducted based on the use of single tuned mass damper and multiple tuned mass dampers. In all the studies of multiple tuned mass damper the dampers are designed from the frequencies of the other modes of vibration other than the first modes of vibration and also no studies were conducted in order to reduce the mass acting on the single beam in case of single tuned mass damper installed on the top of the building. This thesis mainly concentrated on the distribution of mass of the single tuned mass damper to multiple tuned mass dampers which is installed at different floors of the structure. From this literature study it is concluded that if we are using the proper damping system and design of the TMD with quality, it will change the structural response. But we need to find the most economical and correct design and configuration of the TMDs for the structure. Sometimes only one TMD will be enough for the structure or may be sometimes multiple TMDs are needed. So by this literature study we got a path for our research and the findings from these studies should be considered.

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