Journal of Advances in Science and Technology

Vol. IV, No. VII, November-2012, ISSN 2230-9659

AN EXPERIMENTAL STUDY OF TUNED MASS DAMPER TO CONTROL THE VIBRATION OF CONCRETE FLOORS

www.ignited.in

Journal of Advances in Science and Technology
Vol. IV, No. VII, November-2012, ISSN 2230-9659

An Experimental Study of Tuned Mass Damper to Control the Vibration of Concrete Floors

Bablu Bhattacharya

Research Scholar, CMJ University, Shillong, Meghalaya, India

Abstract – 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. Now-a-days several techniques are available to minimize the vibration of the structure, out of the several techniques available for vibration control, concept of using TMD is a newer one. This study was made to study the effectiveness of using TMD for controlling vibration of structure. At first a numerical algorithm was developed to investigate the response of a shear building fitted with a TMD. Then another numerical algorithm was developed to investigate the response of a 2D frame model fitted with a TMD. A total of three loading conditions were applied at the base of the structure. First one was a sinusoidal loading, the second one was corresponding to compatible time history as per spectra of IS-1894 (Part -1):2002 for 5% damping at rocky soil with (PGA = 1g) and the third one was 1940 El Centro Earthquake record with (PGA = 0.313g).

From the study it was found that, TMD can be effectively used for vibration control of structures. TMD was more effective when damping ratio of the structure is less. Gradually increasing the mass ratio of the TMD results in gradual decrement in the displacement response of the structure.

This paper deals with the optimum design of a tuned mass damper (TMD) for the mitigation of machineinducedertical vibration of structures. Theoretically, a TMD without damping tuning to the machine operating frequency will make optimum control performance. Considering zero damping is impossible, a new field-based design procedure and an adjustable vertically moving TMD (VTMD) are proposed. The VTMD is composed of variable mass blocks and changeable springs. A prototype of the VTMD was fabricated and tested on a simply supported beam and a reinforced-concrete floor of a school building. Both experimental results confirmed the control effectiveness and usefulness of the VTMD.

High levels of unwanted vibrations are normally occur in light, and (or) long span floor systems due to human activities such as walking or jumping. It causes annoyance and discomfort to the occupants. Hence, rectification measures would be required to minimize floor vibrational displacement amplitudes. This work is concerned with the development of a new innovative passive viscoelastic four arms damper. The mission of this damper is to reduce floor vibration.

---------------------------♦-----------------------------

INTRODUCTION

Vibration control is having its roots primarily in aerospace related problems such as tracking and pointing, and in flexible space structures, the technology quickly moved into civil engineering and infrastructure-related issues, such as the protection of buildings and bridges from extreme loads of earthquakes and winds.

The number of tall buildings being built is increasing day by day. Today we cannot have a count of number of low-rise or medium rise and high rise buildings existing in the world. Mostly these structures are having low natural damping. So increasing damping capacity of a structural system, or considering the need for other mechanical means to increase the damping capacity of a building, has become increasingly common in the new generation of tall and super tall buildings. But, it should be made a routine design practice to design the damping capacity into a structural system while designing the structural system.

The control of structural vibrations produced by earthquake or wind can be done by various means such as modifying rigidities, masses, damping, or shape, and by providing passive or active counter forces. To date, some methods of structural control have been used successfully and newly proposed methods offer the possibility of extending applications and improving efficiency.

The selection of a particular type of vibration control device is governed by a number of factors which include efficiency, compactness and weight, capital cost, operating cost, maintenance requirements and safety.

Tuned mass dampers (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 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 a few ounces (grams) to many tons. Other configurations such as pendulum absorbers/dampers, and sloshing liquid absorbers/dampers have also been realized for vibration mitigation applications.

TMD 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. 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.

TMD systems are a practical well accepted strategy in the area of structural control for flexible structures, and particularly for tall buildings. It consists of added mass with properly tuned spring and damping elements, providing a frequency-dependent hysteresis that increases damping in the primary structure. The mechanism of suppressing structural vibrations by attaching a TMD to the structure is to transfer the vibration energy of the structure to the TMD and to dissipate the energy in the damper of the TMD. In other words, the frequency of the damper is tuned to a particular structural frequency so that when that frequency is excited, the TMD will resonate out of phase with the structural motion.

It is not always necessary to dissipate a large amount of energy. Instead, the TMD can reduce the amount of energy that goes into the system by changing the phase of the vibration. The addition of a TMD, in fact, transforms the lightly damped first mode of the uncontrolled structure into two coupled and highly damped modes of the 2-DOF modal system.

Compared to control devices that are connected to structural elements or joints, the TMD involves a relatively large mass and displacements. The method used to support the mass and provide precise frequency control is an important issue in the design of a TMD. Thus, the ultimate performance of the TMD system is limited by the size of the additional mass, where is typically 0.25~1.0% of the building's weight in the fundamental mode.

In some cases, spacing restrictions will not permit traditional TMD configurations. This limitation has led to the installation of alternative configurations, including multi-stage pendulums, inverted pendulums, and systems with mechanically-guided slide tables, hydrostatic bearings, and laminated rubber bearings. Coil springs or variable stiffness pneumatic springs typically provide the stiffness for the tuning of most types of TMDs. A number of TMDs have been installed in tall buildings, bridges, towers, and smoke stacks for response control against primarily wind-induced loads (Kwok and Samali 1995). In terms of TMD configuration there is also a large variety. The first structure in which a TMD was installed appears to be the Centrepoint Tower in Sydney Australia (Kwok and Macdonald 1990). There are some buildings in the United States equipped with TMDs or tuned liquid dampers (TLDs), the Citicorp Center in New York City (McNamara 1977) and the John Hancock Tower in Boston (Khan 1983) and TransAmerica Tower in Sanfransisco (Balendra et al. 1998). In Japan, the first TMD was installed in the Chiba Port Tower (Kawabata et al. 1990; Obtake et al. 1992), followed by installations in the Funade Bridge Tower, Osaka (Ueda et al. 1993), and in steel stacks in Kimitsu City (Soong and Dargush 1997), among others.

For flexible structures such as tall buildings, one of the classical dynamic vibrations damping device is the Tuned Mass Damper system. However, it is difficult to draw general conclusions explaining the effectiveness of the TMD for the structures including inelastic behavior due to the great variety of possible inelastic models. In some cases, the specified TMD produced a negative effect, i.e. it amplifies the response slightly. This poor performance is attributed to the ineffectiveness of the TMD, which has only linear properties and its inability to reach a resonant condition in the inelastic structure. It is also found, it requires a relatively large mass, and therefore, a large space for its installation and the corresponding clearance to accommodate such large displacements.

In recent decades, TMDs for reducing floor vertical vibration have received great research interest. Setareh and Hanson and Bell utilized a TMD device to control the vertical vibration induced by pedestrians in a museum, and Murray performed a similar study in a commercial building. Setareh used a ground-hook TMD to reduce the floor vibration during human activities. Yet, experimental studies on TMDs for suppressing machine-induced floor vertical vibrations remain rare. Thus, taking further steps to investigate and develop strategies in response to this particular aspect is urgently needed.

It is generally known that the optimum TMD damping and stiffness can be obtained through optimization of a prescribed performance index. Conventionally, adjustment of the optimum parameters of TMD, i.e. frequency ratio and damping ratio, is based on a given mass of the TMD. The optimum physical parameters, damping and stiffness coefficients, are then calculated for the manufacture of the TMD. In the case of using spring to provide restoring force, it needs making new springs, which is more expensive than purchasing commercially available products. The practical way is to select existing, regular springs to provide the required stiffness and then reversely calculating the required mass of the TMD.

The first study of the application of the Tuned Mass Damper (TMD) for the control of floor vibrations was performed by Lenzen (1966) who used an absorber mass of about 2% of the floor mass. Allen and Swallow (1975) used TMD in the form of a steel box loaded with concrete blocks.

Allen and Pernica (1984) designed a special simple tuned mass damper consisting of wooden planks with weights on top for the reduction of annoying vibrations due to walking. Setareh and Hanson (1992*a*, 1992*b*) used TMD to control the floor vibrations due to dancing in an auditorium floor. Webster and Vaicajtis (1992) used TMDs to control the annoying vibrations of a long-span cantilevered composite floor system due to human movements. Bell (1994) used a TMD to control annoying vibrations of a museum floor due to walking. Shope and Murray (1995) and Rottmann (1996) used TMD to control walking vibrations in office floors. All previously mentioned studies use viscous damping mechanisms as the media for vibrational energy dissipation. Saidi *et al.* (2007, 2008) have developed a viscoelastic TMD using the principle of constrained damping developed by Mead and Markus (1975). Saidi *et al* converted the conventional viscous damping mechanism into a viscoelastic one and examined the effectiveness of the developed TMD when attached to a laboratory size simply supported steel beam. Good agreement is found between the analytical, numerical and experimental solutions. The present study is a continuing research to that of Saidi *et al*. It is a numerical study on the effectiveness of a new four arms viscoelastic damper in suppressing the unwanted vibration of a heavy concrete floor. The floor is excited by a walking person of 94 kg. The walking is simulated as a time variant function following the model of Murray *et al* (1997).

THE EXPERIMENTS

The test floor is a hollow-core concrete element pin supported at both ends. The distance between the supports of the one-way spanning element is about 11 m, and the width of the element is about 1.2 m. The weight of the element amounts to more than 5,000 kg.

As the floor-strip is pin-supported, its fundamental mode (the first vertical bending mode) is well separated from other modes of vibration, and in tests this mode is excited. It is the damping ratio of the fundamental mode which is determined in tests. This is done by bringing the element into free decaying vibrations by applying an impact load at midspan, and from recordings of floor vertical displacement response (by LVDT's positioned at floor midspan), the damping ratio of the floor is identified using the logarithmic decrement method.

Without any chairs or humans atop the test floor its undamped frequency was found to be 5.8 Hz and the damping ratio was found to be around 0.25 %cr. Six test sequences were carried out, and they are denoted A, B, C, D, E, and F.

The first two test sequences are described below:

A. One rigid office chair atop the floor strip at midspan

B. One swivel chair atop the floor strip at midspan

In these tests, floor damping was determined with different numbers of sandbags placed in the seat of the chairs. Each sandbag had a weight of 40 kg, and after doing a test without a sandbag, first one, then two, three and finally four sandbags were placed in the seat. In the presentation of results, the sandbag weight is denoted *m*, and floor damping was thus determined for values of *m* of 0, 40, 80, 120, and 160 kg. This provides insight into how the value of *m* influences floor damping for the two different types of chairs. In tests with the swivel chair, a number of different swivel chairs were used so as to investigate variability in results (for *m* = 80 kg) from chair to chair. All swivel chairs were of the same type of construction. The swivel chairs employed in tests are perhaps 15 years old and are not provided with modern damping devices between seat and wheel frame. The wheel frames of the chairs carry five wheels. The rigid office chair is a standard four-legged office chair used at Aalborg University in meeting rooms, whereas the swivel chair is the type used by students at their desks.

In test sequences C and D not only a single chair was used. These tests involved:

C. Up to four office chairs atop the floor strip at midspan

D. Up to four swivel chairs atop the floor strip at midspan

In these tests, three or four chairs were positioned on the floor strip at the same time, and the chairs were each carrying either 80 kg of sandbag (2 sandbags) or no sandbags. The tests were made in the way that first one chair carried 80 kg (*m* = 80 kg), then two chairs carried 80 kg each (*m* = 160 kg), and then three chairs carried 80 kg each (*m* = 240 kg), etc. This procedure allows for investigating how floor damping is influenced when the sandbag mass is split (carried by more than one chair), which also accommodates a higher total sandbag mass than what is possible to carry by a single chair.

Test sequence E:

E. Single swivel chair atop the floor strip at various positions

In this test sequence a randomly selected swivel chair was placed at different positions on the floor strip carrying a sandbag mass of 80 kg, and for each position floor damping was identified. The different positions were chosen such that floor damping could be mapped as a function of the distance from floor support.

Test sequence F involved humans, so as to establish a reference for the damping introduced by chairs:

F. Humans sitting atop the floor strip at midspan

Floor damping was determined in situations were one, two and three persons sat on the floor strip.

The individuals were asked to assume this posture during the entire phase of decaying vibrations. Each individual was weighted prior to the tests, such that the total mass (*m*) of the crowd was known. Thereby, it was possible to relate estimates of floor damping to the total mass of the crowd of people. For all test conditions, a series of free decay tests were made allowing a series of estimates of floor damping to be produced. For simplicity, the result section only presents mean values of floor damping (obtained under similar conditions).

DESCRIPTION OF THE PROPOSED TMD SYSTEM

A tuned mass damper (TMD) 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 damper inertia force acting on the structure. The TMD concept was first applied by Frahm in 1909 (Frahm, 1909) to reduce the rolling motion of ships as well as ship hull vibrations. A theory for the TMD was presented later in this study by Ormondroyd and Den Hartog (1928), followed by a detailed discussion of optimal tuning and damping parameters in Den Hartog's book on mechanical vibrations (1940). The initial theory was applicable for an undamped SDOF system subjected to a sinusoidal force excitation. Extension of the theory to damped SDOF systems has been investigated by numerous researchers.

Significant contributions were made by Randall et al. (1981), Warburton (1981, 1982), Warburton and Ayorinde (1980), and Tsai and Lin (1993). structures. A rigorous theory of tuned mass dampers for SDOF systems subjected to harmonic force excitation and harmonic ground motion is discussed next. Various cases, including an undamped TMD attached to an undamped SDOF system, a damped TMD attached to an undamped SDOF system, and a damped TMD attached to a damped SDOF system, are considered. Time history responses for a range of SDOF systems connected to optimally tuned TMD and subjected to harmonic and seismic excitations are presented. The theory is then extended to MDOF systems, where the TMD is used to dampen out the vibrations of a specific mode. An assessment of the optimal placement locations of TMDs in building structures is included. Numerous examples are provided to illustrate the level of control that can be achieved with such passive devices for both harmonic and seismic excitations.

Two dampers were added to the 60-story John Hancock Tower in Boston to reduce the response to wind gust loading. The dampers are placed at opposite ends of the fifty-eighth story, 67 m apart, and move to counteract sway as well as twisting due to the shape of the building. Each damper weighs 2700 kN and consists of a lead-filled steel box about 5.2 m square and 1 m deep that rides on a 9-m-long steel plate. The lead-filled weight, Laterally restrained by stiff springs anchored to the interior columns of the building and controlled by servo-hydraulic cylinders, slides back and forth on a hydrostatic bearing consisting of a thin layer of oil forced through holes in the steel plate. Whenever the horizontal acceleration exceeds 0.003g for two consecutive cycles, the system is automatically activated. This system was designed and manufactured by LeMessurier Associates/SCI in association with MTS System Corp., at a cost of around 3 million dollars, and is expected to reduce the sway of the building by 40 to 50%.

NUMERICAL ANALYSIS

To illustrate the effectiveness of the proposed tuned mass viscoelasic damper, a reinforced concrete beam is used for modeling the vibrating floor (primary system). The 9.5 m long, heavy concrete beam is simply supported at its ends and simulates a proportion of a typical long span floor construction. The properties of the beam are: effective mass = 3091 kg, natural frequency, *fn* = 4.4 Hz and it has a damping ratio. The data (above) used in the modeling of the vibrating floor is taken from a real laboratory structure located at the Civil Engineering Department, University of Melbourne, Australia. The reason for using this data is that it will be used in a future paper that concern with experimental investigations.

In order to make sure that the fundamental frequencies of the concrete floor (primary system) and the viscoelastic damper (secondary system) are matching to each other, an FE (Ansys11) harmonic analysis is performed on each system with an arbitrary values for the amplitude harmonic excitation and dissipation loss factor. The aim is to produce modal pictures for these systems.

The newly developed four arm damper is equivalent to a four oscillators system attached at the mid point of the floor by a steel bracket. The mass of the bracket is small compared to the heavy floor therefore has no effect on the vibration characteristics of the floor.

A finite element transient analysis is performed on the coupled system using Ansys11 finite element package. The floor is excited by the periodic force (walking) of the form. Results of the transient bending response of the floor are monitored for the cases:

1. Empty concrete floor (no damper attached)

2. The 0.25% mass ratio, four arms damper attached to the concrete floor

3. The 1% mass ratio single arm damper attached to the concrete floor.

INVESTIGATION OF VIBRATION SOURCES

The dominant source of the observed vibration at L-19 of SX1 is AHU 18-1; when this unit was switched off, little vibration was perceptible even when standing directly above AHU 18-3. At the other end of the building on the same floor, the vibration from AHU 18-2 and 18-4 was also perceptible, but of lower magnitude and less likely to lead to such extreme complaints.

One test determined that a (horizontal) system resonance occurred at 230rpm. This is equivalent to 3.8Hz which indicated that the spring isolators under the fans were not correctly loaded. The project specification nominated 50mm deflection coil steel springs with a natural frequency of 2Hz. The 3.8Hz resonance may be a lateral (viz horizontal) mode, although since coil springs are normally less stiff horizontally than vertically, we suspected this was a measure of vertical resonance, and was too high.

Several attempts were made to dynamically balance the fans and adjust the drive belt drive tension; however there was no resulting appreciable change in vibration.

As the source of vibration was directly related to AHU's 18-1 and 8-3, the investigations were directed at identifying potential vibration transmission paths to the building structure and in particular to the L-19 floor slab above.

Following one inspection the following fundamental actions were recommended:

- Frequency banding to restrict fan operation outside the critical range of interest.
- All AHU 18-1 supply air ductwork should be suspended by combined spring and neoprene rubber hangers with a deflection of at least 50mm. Any identified bridging of isolators by incorrectly aligned hanger rods or hangers were corrected.
- The roof of the AHU enclosure had to be installed so that there was no direct connection between the AHU roof panels and the L-19 floor slab above. If connected by rigid hangers including wire or chain, then vibration isolators were required
- The walls of the AHU enclosure could not run full height from the floor of L-18 to the underside of L-19 above. Any structural elements that breached between the two that were attached to the AHU enclosure had to be decoupled using flexible isolated connections
- Where the supply air duct passed through the AHU enclosure penetration a clearance of 50mm was required on all sides to prevent transmission of duct borne vibration to the AHU walls.

TMD STRUCTURE

The proposed TMD building system concept can be defined as an extension of the conventional TMD system, but using a large mass ratio. Due to the large mass ratio, the upper portion may experience large displacement. To avoid excessive lateral motion or stroke of the tuned mass, the upper portion can be interconnected by the combined isolation system of rubber bearings and a viscous damper (for the PTMD passive version) or a resetable device (for the resetable SATMD proposed here).

When the building frame is implemented with the proposed TMD (PTMD or SATMD) system, the upper portion is supported by rubber bearings attached on the top of the main frame's columns.

The overall mechanism of suppressing structural vibration induced by an earthquake is to transfer the vibration energy of the structure to the isolated upper storey. The transferred energy is dissipated at the isolation interface so that seismic force of the entire superstructure can be reduced. Thus, the overall effectiveness depends on the amount of energy transferred or the size of the tuned mass, and the ability of the isolating elements (viscous damper or resetable device) to dissipate that energy via the relative motions at the interface.

CONCLUSION

The investigations of the paper quantified how chairs carrying sandbags influenced damping characteristics of a floor strip with a frequency of 5.8 Hz. It was found that swivel chairs with sandbags in their seats added much damping to the floor strip (to its fundamental mode, first vertical bending mode), and that the “swivel chair with sandbag”-damper added most damping when located at midspan of the floor strip. It was also shown that persons sitting on the floor strip added much damping, and that floor damping depends on the size of the crowd of people present atop the floor.

The damping added by an optimally tuned TMD with a mass of 80 kg was shown to be higher than the damping added by a single person sitting at midspan and higher than the damping added by the swivel chair with 80 kg of sandbag in the seat. Nevertheless, the results indicate that passive damping sources such as humans and swivel chairs carrying humans can add much damping to the floor.

The TMD has the advantage that it can be tuned and targeted to solving a specific vibration problem, basically for any floor frequency. This is not the case for the swivel chair carrying sandbags. Its performance in mitigating floor vibrations for a specific floor is by default dictated by the mechanical characteristics of the chair having fixed characteristics. As long as the mechanical characteristics of the chair are unknown it is quite difficult to predict how the swivel chair would perform in mitigating vibrations on a floor with a natural frequency different from that used in the present tests. It might perform even better or it might perform worse on other floors. Empty floor modal mass and damping would also be parameters influencing the damping capacity of swivel chair(s), but this is also the case for the TMD.

In any case it is not expected that swivel chairs will be used as a permanent solution for solving vibration problems in flooring-systems (for a number of reasons, although the chairs are cheap and readily at hand), but they might, for some floors, be considered for use as a temporary remedial measure taking the top of excessive vibrations until permanent and reliable solutions are found. At least the results of the investigations suggest that the swivel chair has an inherent damping capacity that can be brought into play when loaded by sandbags, which might be useful to have in mind.

The numerical study of this paper has presented the development of a new geometry of a tuned mass viscoelastic damper. The new damper is composed of four arms each of which represents a separate viscoelastic elastic damper with the same value of natural frequency as that of the treated floor. The total mass ratio of the new damper is equivalent to that of a single arm.

The effectiveness of the new damper when attached to a 9.5 m long simply supported, heavy concrete beam is almost similar to that of the single arm that has the same mass ratio. The new system is equivalent to four oscillators system attached at one point on the floor.

The auto tracking TMD is a new innovative and unique method of controlling vibration in structures from variable speed devices where other methods of vibration control such as replacement of equipment or increasing floor stiffness are not feasible.

The present paper studies the seismic behavior on tall buildings structure through using the TMD system. The purpose of the study is to investigate TMDs device that not only provides adequate energy dissipation by different models, but also is easy to install and tested. In addition, these are not like cross-bracings which may be undesirable in the field of aesthetically and architecturally.

REFERENCES

- Clark J. Allen(1988).‖Multiple passive TMDs for reducing earthquake induced building motion‖. *Proceedings of ninth world conference on Earthquake Engineering Tokyo Kyoto Japan,Vol.5*
- Nashif. A., Jones, D., and Henderson, J. (1985). —Vibration damping.‖ *John Wiley & Sons, New York, N.Y.*
- K. Cunefare,(2000) —State-switched absorber for vibration control of point-excited beams‖, *Proceedings of ASME International Mechanical Engineering Conference and Exposition, Vol. 60, pp. 477–484*
- Baz (1998), —Robust control of active constrained layer damping‖, *Journal of Sound and Vibration 211 pp467–480.*
- McNamara, R. J. (1977) *“Tuned mass dampers for buildings.” Journal of Structural Division, 103(9), pp1785–1798.*
- Roberts, J. B., and Spanos, P. D. (1985). Random vibration and statistical

linearization‖. *John Wiley & Sons, New York, N.Y.*

- Wong K.K.F(2008) ―Seismic Energy Dissipation of Inelastic Structures with Tuned Mass Dampers‖ *Journal of Engineering Mechanics*, *Vol. 134, No. 2*
- Shimazu T, Araki H(1996) ―Survey of actual effectiveness of mass damper systems installed in buildings‖. *Eleventh world conference on Earthquake Engineering*, *Paper no.809*
- Yan, N., Wang, C. M., and Balendra, T. (1999). ―Optimal damper characteristics of ATMD for buildings under wind loads.‖ *Journal of Structural Engineering,125(12), pp1376–1383.*
- Webster, A. c., and Vaicaitis, R. (1992). "Application of tuned mass dampers to control vibrations of composite floor systems." *Engineering. Journal, 29(3), pp116-124.*
- TakewakiI (2000).‖Soil-structure random response reduction via TMD-VD simultaneous use‖ *Computer Methods in Applied Mechanics and Engineering 190, pp 677-690*
- Alexander Nicholas A, Schilder Frank(2009) ―Exploring the performance of a nonlinear tuned mass damper‖ *Journal of Sound and Vibration 319 pp 445–462*
- Ellis, B.R., and Ji. T., *Human-structure interaction in vertical vibrations*, Proceedings of the ICE: Structures and Buildings, Vol. 122, pp.1-9, 1997
- Ellis, B.R., *On the response of long-span floors to walking loads generated by individuals and crowds*, The Structural Engineer, Vol. 78 (10), pp. 1-25, 2000
- Setareh M, Hanson RD. Tuned mass dampers to control floor vibration from humans. Journal of Structural Engineering (ASCE) 1992; 118(3):741–762.
- Bell DH. A tuned mass damper to control occupant induced floor vibration. Proceedings of the 18th Annual Meeting of the Vibration Institute, Willowbrook, IL, 1994; 181–185.
- Murray TM. Tips for avoiding office building floor vibrations. Modern Steel Construction 2001; 41:24–31.
- Setareh M. Floor vibration control using semi-active tuned mass dampers. Canadian Journal of Civil Engineering 2002; 29:76–84.
- Lin CC, Hu CM, Wang JF, Hu RY. Vibration control effectiveness of passive tuned mass dampers. Journal of the Chinese Institute of Engineers 1994; 17:367–376.
- Lin CC, Wang JF, Ueng JM. Vibration control identification of seismically-excited MDOF structure—PTMD systems. Journal of Sound and Vibration 2001; 240:87–115.
- Lin CC, Ueng JM, Huang TC. Seismic response reduction of irregular buildings using passive tuned mass dampers. International Journal of Engineering Structures 2000; 22(5):513–524.
- Wang JF, Lin CC, Chen BL. Vibration suppression for high speed railway bridges using tuned mass dampers. International Journal of Solids and Structures 2003; 40:465–491.
- Ueng JM, Lin CC, Wang JF. Practical design issues of tuned mass dampers for torsionally coupled buildings under earthquake loadings. The Structural Design of Tall and Special Buildings 2008; 17:133–165.
- 12. Wowk V. Machinery Vibration: Measurement and Analysis. McGraw-Hill: New York, 1991; 202–204.
- J. P. Den Hartog, *Mechanical Vibrations*, McGraw-Hill, New York, NY, USA, 4th edition, 1956.
- A.C. Webster and R. Vaicaitis, "Application of tuned mass dampers to control vibrations of composite floor systems," *Engineering Journal/American Institute of Steel Construction Third Quarter/1992*, pp. 116–124, 1992.
- K. I. Al-Hulwah, *Floor vibration control using three degree of freedom tuned massdampers*, Ph.D. thesis, The School of Engineering, University of Dayton, 2005.
- J. W. Smith, *Vibration of Structures Application in Civil Engineering Design*, Chapman and Hall, 1988.