17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

PRESENTING A NEW TYPE OF TUNED MASS DAMPER FOR VIBRATION CONTROL PURPOSES

M. Sadeghzadeh Nazari(1), K. Meguro(2), M. Numada(3)

(1) *Associate Professor (lecturer), Tokyo Institute of Technology, mehrdad.aa@m.titech.ac.jp*
(2) *Professor, The University of Tokyo, meguro@iis.u-tokyo.ac.jp*
(3) *Associate Professor, The University of Tokyo, numa@iis.u-tokyo.ac.jp*

Abstract

Tuned Mass Damper (TMD) systems have been applied to various structures from high-rise building and wind turbines to long-span bridges as a means to mitigate undesired vibrations due to winds or ground motions. However, applications of traditional TMDs have shown some performance limitations including lack of robustness to changes in the stiffness or mass of the controlled structure, lifespan and cost issues, and size restrictions. This paper presents a new type of TMD system that aims to reduce these limitations.

When the natural vibration frequency of a controlled structure, the dominant frequency of its base excitation, and the natural frequency of the controlling TMD are all the same, the effectiveness of the vibration control will be the highest. This is an ideal, but not a realistic case. In reality, however, excitations with a *range* of predominant frequencies may possibly resonate the controlled structure because the natural vibration period of the controlled structure may change. On the other hand, random input excitations such as winds or earthquakes are also not necessarily single-frequency waves to fully resonate the controlled structure. Yet, TMDs are conventionally designed to have a constant natural period. Therefore, in reality, an ideal tuning can never be achieved.

Considering the cost, there is generally no extra operational service cost after installation of passive TMDs because they do not use any kind of actuators or external energy resources. However, special technologies or components used in some TMD systems make them relatively costly. Another major concern for designers when it comes to using TMDs is the size limitation. It usually becomes impossible to fit a TMD within the normal story height in a building or provide enough room for the TMD to freely oscillate.

Accordingly, there is a need for a compact long-period TMD system with limited stroke. Such a TMD should preferably not use exclusive technologies so as to have a reasonable price. Besides, to provide a realistic and robust control for the structure, it may just offer a variable, yet narrow-band, natural oscillation period. In this paper, a new type of TMD system with such properties is introduced.

The paper first provides a brief review of the previous methodologies and body of research on Tuned Mass Damper systems, in particular, and other structural seismic control systems. The proposed TMD is then introduced and a simple experimental test is presented to show its performance.

Experimental results show the capability of the proposed TMD in mitigating the responses of a controlled structure. Since this compact TMD can maintain its long natural period with a smaller size as compared with conventional TMDs, it can be installed on different locations along a building height without occupying much space. It can be concluded that the proposed TMD system is a proper substitute for conventional TMDs. The problems faced in the experimental modeling of the proposed system have also been discussed.

Keywords: Tunes Mass Damper; Seismic Structural Control; Vibration Mitigation, Earthquake Excitation

1. Introduction

Various structures from high-rise building and wind turbines to long-span bridges and even launch vehicles apply Tuned Mass Damper (TMD) systems as a means to mitigate undesired vibrations. The source of such vibrations might be wind or ground motions. Traditional TMDs, however, have shown some performance limitations. In this paper, initially, an overall review of the previous research and methodologies on structural seismic control systems, in general, and more specifically on Tuned Mass Damper systems will be presented in an effort to clarify the need for the proposed Tunes Mass Damper System.

A new type of TMD system will next be introduced, and tested using a simple experimental model. Numerical solution to the free vibration of the proposed system will also be proposed.

2. Structural Vibration Control Methods and Tuned Mass Damper Systems

In earthquake engineering, vibration control is a set of technical means aimed to mitigate seismic impacts in building and non-building structures [1]. During the past couple of decades, developing and applying structural control techniques have attracted significant attentions. Accordingly, in the past three decades, severe efforts have been done in order to expand the theoretical concepts of structural control into a feasible reality. Now-a-days structural control is recognized as an accepted and appreciated part in the design process for important new structures as well as for the retrofitting of existing structures against earthquake and/or wind loads.

2.1 Structural Vibration Control Methods

Various vibration control devices and schemes have been studied up to the present time, each of them having their specific advantages and application targets. The main point of attention in many of the past research on structural control has been minimizing the inter-story drift, as a representative for the structural damage. However, if measures such as the structural responses, level of energy dissipation and damage of the structure, or selecting the proper control scheme for a structural system are to be taken into account [1], [2], [3], [4] other parameters should also be investigated. These parameters include the peak acceleration, hysteretic energy, RMS and peak of acceleration, RMS of drifts, control devices energy absorption, and etc. all of which representing the potential damage to the structure or the objects inside it. Moreover, using a wide range of strong ground motion excitations and proper statistical assessment methods are other effective issues [1], [5], [6], [7], [2], [4].

On the other hand, a variety of methods have been developed so far in order to produce proper control against wind and earthquake excitations. These techniques can be categorized into four main following groups:

I. Passive control
II. Active control
III. Semi-Active control
IV. Hybrid control

2.2 Tuned Mass Damper Systems

A Tuned Mass Damper (TMD) system is a structural control device used to reduce the amplitude of structural and mechanical vibrations in buildings and mechanical systems. Applications of TMDs in structures is mainly to reduce the unwanted vibrations due to wind or earthquakes and to prevent discomfort of the occupants as well as to increase the fatigue life of the structure [4]. Different types of TMD systems are available. The simplest one is the Passive TMD which includes a mass, a spring, and an energy dissipative device such as a damper [8].

The large amount of energy in the structural system should not necessarily be always dissipated. Instead, a TMD changes the phase of vibration in order to reduce the amount of energy that goes into the structure. In fact, adding a TMD transforms the slightly-damped first mode of the uncontrolled system into two coupled and highly-damped modes of the controlled structure. The TMD is tuned to the structural mode of interest, so as to resonate out-of-phase with the structure, and therefore dissipate the vibration energy as heat by the damper. Therefore, by appropriately tuning the TMD to the fundamental vibration modes of the controlled structure, the TMD will significantly dissipate the structural vibration energy.

Generally, design of a TMD involves an optimization problem [8]. Optimization means the determination of TMD parameters in order to maximize the performance of the whole structure based on an objective function, or a performance criterion. It is desired to develop closed-form solutions which relate the mass ratio (ratio of the TMD mass to that of the structure), tuned frequency ratio (ratio of the TMD frequency to the structural natural frequency), and damping ratio. Selection of the performance criterion will be done based on a desirable level of a specific response in the structure (such as the roof acceleration).

The TMD systems include a relatively large masses and displacements. While selecting the mass ratio, some practical considerations must be taken into account. In large scale structures, the mass of the structure may exceed 100,000 tons [9]. With the mass ratio being generally about a fraction of the total structural mass, the structure’s capacity to contain such a mass becomes a practical challenge [8]. Therefore, mass ratios of TMD systems for large buildings typically fall below 1%. In some cases, spacing limitations will not permit application of traditional TMD configurations. This restriction has caused the application of alternative configurations, which include inverted pendulums, multi-stage pendulums, and also systems with laminated rubber bearings, mechanically guided slide tables, and hydrostatic bearings. To provide the stiffness for the TMD typically variable stiffness pneumatic springs or coil springs are being used.

The application of TMD systems is exclusively useful in long-period structures like tall buildings or suspension bridges, where external excitation conditions tend to be similar to resonant frequencies.

TMDs have been installed in many tall buildings, bridges, towers, smoke stacks, etc. to control responses [10]. The first structural TMD was apparently installed in the Centrepoint Tower in Sydney Australia [11]. In the United States many buildings have been equipped with TMDs, such as the Citicorp Center in New York City [12], the John Hancock Tower in Boston [13] and TransAmerica Tower in Sanfransisco [14]. The first TMD installed in Japan was in the Chiba Port Tower [15], [16]. As examples, Fig. 1 and Fig. 2, respectively, show the largest pendulum tuned mass damper in the world installed in Taipei 101 tower and the tuned mass damper installed in Tokyo Skytree in Tokyo, Japan.

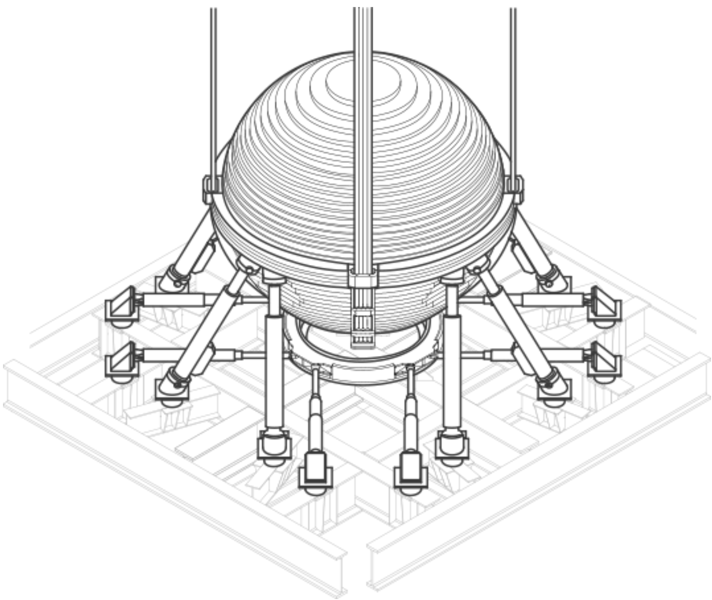

Fig. 1 – World’s largest pendulum tuned mass damper in Taipei 101 tower [17]

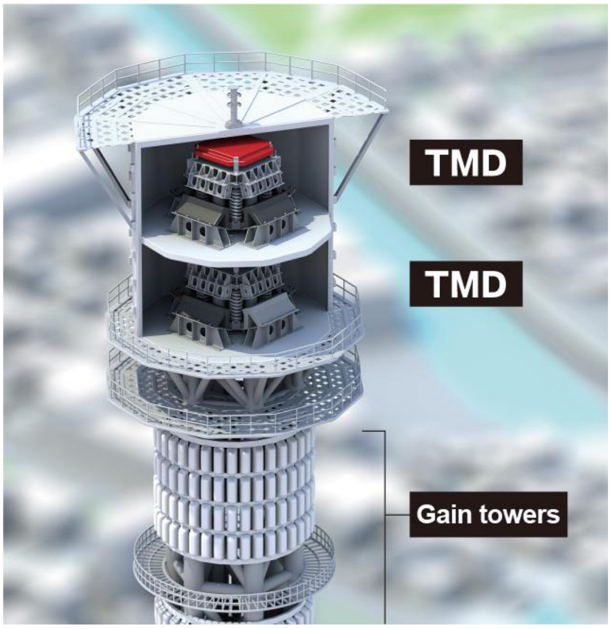

Fig. 2 – The tuned mass damper installed in Tokyo Skytree, Tokyo, Japan [18]

Similar to other types of vibration control systems, Tuned Mass Dampers also come in different kinds. The purpose of developing different types of TMD systems is to overcome the limitations in each type. These limitations may be the TMD robustness to changes in the structural stiffness, the spatial limitations within the controlled structure, or the lifespan and cost of the TMD. Different types of TMD systems are categorized with a brief summary as follows:

I. Passive Tuned Mass Dampers

Passive control systems are characterized by not using external energy source. One of the limitations of the Passive TMD systems is their lack of robustness to detuning [19]. Outside of the TMD narrow tuned frequency band, its effectiveness gets diminished. Even a small deviation from the optimal tuning frequency may significantly deteriorate the performance. Therefore, the effectiveness of Passive TMD systems is dependent on the initial tuning accuracy, which can itself be affected by any subsequent structural detuning [20]. Apart from this significant limitation, since Passive TMD systems are relatively inexpensive systems they are still being used when properly tuned [4].

The three most typical kinds of Passive Tuned Mass Dampers are Translational TMDs (TTMD), Pendulum TMDs (PTMD) and Multiple TMDs (MTMD) which will be briefly explained hereafter.

I.1. Translational Tuned Mass Dampers (TTMD), in which the TMD mass is attached to the supporting structure by a set of springs and dampers, and moves either in one direction or in two perpendicular directions.

I.2. Pendulum Tuned Mass Dampers (PTMD), in which the TMD is in the form of a pendulum. The pendulum is consisted of a mass supported by a cable. The cable itself is pivoted about the point of attachment to the main structure. This type of TMD is generally less expensive than translational TMDs due to technical manufacturing simplicities.

I.3. Multiple Tuned Mass Dampers (MTMD), in which several small TMDs are used instead of a single larger mass, each tuned to a period close to the controlled structures' natural period [21]. Basically, Multiple TMDs are more robust against detuning conditions compared to traditional passive TMD systems.

II. Active Tuned Mass Dampers

In Active Tuned Mass Damper (ATMD) systems the forces applied to the structure from the TMD is controlled by controlling the motion of the TMD mass by the use of an external energy source such as an actuator. This design has two advantages. First, since any detuning will be compensated by the active feedback control, under detuning conditions, the performance of an ATMD system will be better than an equivalent passive TMD [22], [29]. Secondly, ATMD systems are capable of optimizing their transient response which is useful particularly for impact loads such as earthquake [8].

III. Semi-Active Tuned Mass Dampers

Active TMDs improve vibration control performance but they add to the energy requirement, maintenance costs, and complexity of the system [8]. Passive TMDs are rather simple systems, but lack robustness against detuning with the controlled structure and against multiple-frequency excitations [19]. Semi-Active TMDs combine the advantages of active and passive systems.

IV. Hybrid Tuned Mass Dampers

In a hybrid TMD system, under initial and typical loading conditions the TMD acts like a passive TMD. Once the structure response reaches a certain limit, the active part gets actuated. Manufacturing and design complexity of Active TMDs, significantly increase their financial costs compared to passive systems. Moreover, the energy required for the system significantly increases by addition of the actuator. To reduce this energy demand, hybrid TMD systems can be utilized [8].

2.3 Summary of Structural Control and Tuned Mass Damper Systems

As explained in more details throughout this section, in earthquake engineering, structural vibration control methods and tuned mass damper systems may be categorized as in the chart of Figure 2.9.

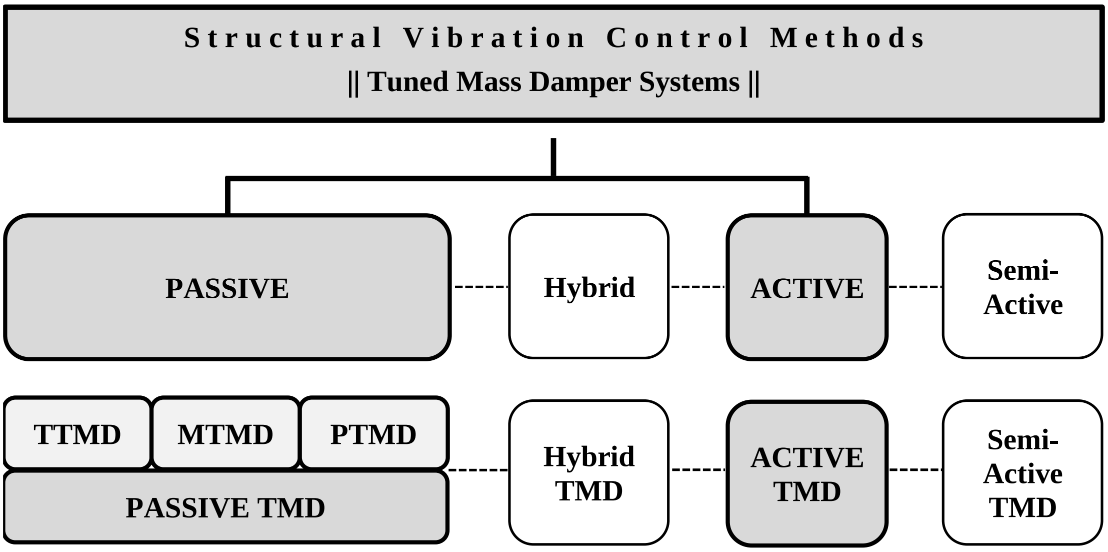

Fig. 3 – General categorization of structural vibration control methods and tuned mass damper systems

3. Introducing the Proposed Tuned Mass Damper System, Different Components and the Adopted Terminology

This section explains the overall configuration of the proposed tuned mass damper system, its unique components, and the adopted terminology for the system. A specific name will be adopted for the proposed system. As well, the adopted terminology for different parts of the proposed TMD will be defined to be used throughout this paper.

The proposed tuned mass damper is composed of three main parts; (1) A concave hollow semi-cylindrical container (which will be called the Bowl throughout this text), (2) A hollow cylindrical mass which can freely roll inside the Bowl (to be called the Roller throughout this text) and (3) a piece of mass of any shape which is rigidly connected to the Roller (to be called the Eccentric mass). Hereon, we call the proposed Tuned Mass Damper system a “Tuned Roller Mass Damper (TRMD)”.

This TRMD system may be added to the controlled structure at appropriate location(s) such as on a floor of a building structure or on other floors. The common position for tuned mass dampers in buildings is on the top floors; however, distributed locations along the height of the building may also be selected according to different control strategies and purposes.

To make advantage of the system in two directions two options exist. One is to arrange a couple of the system in two perpendicular directions, which is recommendable for the control of asymmetric structures. This method is more efficient in case of asymmetric structures in which the natural vibration period of the structure is different in each orthogonal direction. Fig. 4 shows a sample arrangement scheme for the applying the proposed TRMD in a typical asymmetric structural plan.

The other way is to make use of spherical bodies instead of cylindrical geometries for the Bowl and the Roller. The latter choice may have some practical difficulties; however, it is not an impossible option. In this method, the total additional mass imposed to the structure for the control purpose will be less, although its usage will only be limited to symmetric structures.

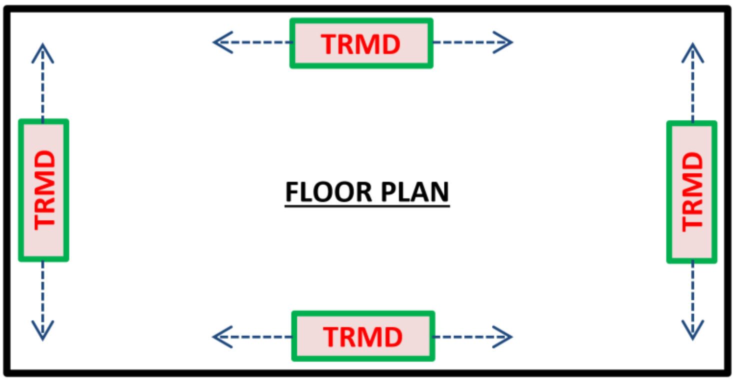

Fig. 4 – Plan view of a sample proposed TRMD arrangement in a typical asymmetric structural plan

In this section, the overall appearance and geometric shape of the proposed Tuned Roller Mass Damper was explained. Based on the exceptional dynamic properties of this system, it can have unique performance for mitigating structural vibrations. These characteristics will be discussed more throughout the following sections of this paper by numerical and experimental approaches.

4. Numerical Solution to the Natural Vibration Period of the Proposed TRMD System

One of the significant dynamic properties of any TMD system is its natural vibration period. In this section, it is intended to obtain the numerical solution to the natural free vibration of the proposed Tuned Roller Mass Damper (TRMD) system. Various parameters which are influential in the dynamic behavior of the proposed TRMD in natural oscillation will be introduced. In addition, the natural vibration periods of the system within specific values of these influential parameters will be calculated and presented in the form of a graph.

The behavior of the proposed system in natural situation is affected by a series of parameters. These parameters that affect the dynamic properties of the TRMD could be categorized into two types. The first group is those related to the masses, and the second group includes those regarding the geometry of the TRMD.

The pieces of mass which are effective in the dynamic behavior of the TRMD are the two masses of the Eccentric Mass (m1) and the Roller (m2). On the other hand, there are the geometric parameters that affect the dynamic behavior of the system. These parameters include: the radius of the Bowl (R), the inner radius of the Roller (ri), the outer radius of the Roller (ro), the radius of the Eccentric mass (r'), and the radial position of the Eccentric mass (r).

Therefore, the influential parameters could be generally listed as follows:
m_1 = mass of the ***Eccentric mass***
m_2 = mass of the ***Roller***
R = radius of the ***Bowl***
r_i = inner radius of the ***Roller***
r_o = outer radius of the ***Roller***
r' = radius of the ***Eccentric mass***
r = radial position of the ***Eccentric mass***

The natural vibration period of the TRMD, T, could be defined as the amount of time required for the Roller to travel from a specific initial position along the surface of the Bowl and return back to the similar rest position.

The position of the Roller along the surface of the Bowl could be determined by the parameter θ, which shows the angular position of the Roller in radians. Since the location of the Eccentric mass is correlated to that of the Roller, a single parameter is sufficient to define this location. The value of θ is measured at the center of the Bowl, and equals the angle between a vertical line passing through the center of the Bowl and a line which connects this center to the point of contact of the Roller and the Bowl.

In order to obtain the natural vibration period of the TRMD one should consider the active forces in the system in natural situation. These active forces include some driving forces as well as some resisting forces caused by the gravitational acceleration together with the moment of inertia and damping effects (for simplicity, at this stage we neglect damping effects).

The governing equation of motion of the undamped proposed TRMD system during free oscillation may be determined as follows:

$$-m_2 g\, b + m_1 g\, d - \ddot{\theta}\left(I_{m1,O} + I_{m2,O}\right) = 0 \tag{1}$$

where,

$$I_{m1,O} = \frac{1}{2} m_1 \acute{r}^2 + m_1 \left(r^2 + r_O{}^2 + 2 r r_O \sin\left(\frac{\pi}{2} - \frac{R\theta}{r_O} - \theta\right)\right) \tag{2}$$

and,

$$I_{m2,O} = \frac{1}{2} m_2 \left(r_i^2 + r_O^2\right) + m_2 r_O^2 \tag{3}$$

In the above equations (1) to (3),
θ = relative angular position of the ***Roller*** (radians)
$\ddot{\theta}$ = angular acceleration of the ***Roller*** (second derivative of θ with respect to time)
m_1 = mass of the ***Eccentric mass***
m_2 = mass of the ***Roller***
d = effective gravitational force arm of the ***Eccentric mass***
b = effective gravitational force arm of the ***Roller***
$I_{m1,O}$ = moment of inertia of the ***Eccentric mass*** about the contact point, O
$I_{m2,O}$ = moment of inertia of the ***Roller*** about the contact point, O
g = gravitational acceleration

R = radius of the ***Bowl***
r_o = outer radius of the ***Roller***
r = radial position of the ***Eccentric mass***

By alternatively changing the values of variables in Eq. (1), the variations of the TRMD natural oscillation periods can be obtained through a comprehensive set of numerical calculations. In the graph of Fig. 5, a set of sample values of the TRMD natural undapmed vibration periods have been plotted against different values of the parameters influential on the TRMD natural vibration period. These parameters include: the mass of the Eccentric mass, m1, the mass of the Roller, m2, the radius of the Bowl, R, the outer radius of the Roller, ro, the radial position of the Eccentric mass, r, and also the initial release angle, θ0. However, the values of the radius of the Eccentric mass, r', and the inner radius of the Roller, ri, have been assumed constant as their variations has miner effects on the natural period values.

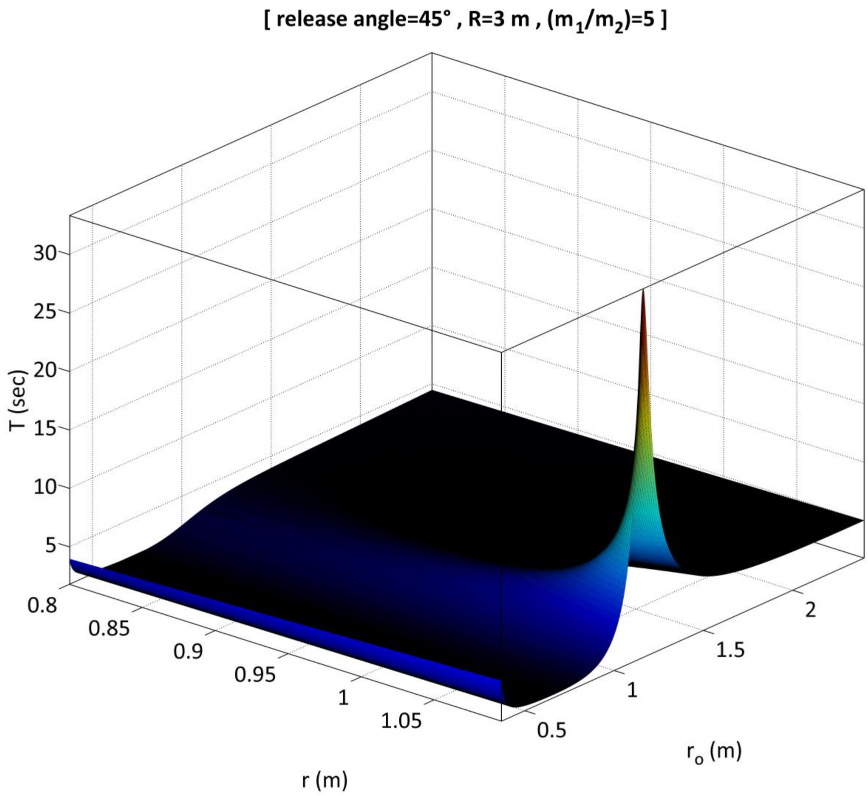

Fig. 5 – Variations of the TRMD natural period while θ0=45°, (m1/m2)=5 & R=3m

Such graphs could be an essential part of the TRMD design process. Considering all such graphs, designers could select the appropriate values of the influential parameters for each specific design purpose. Rationally, apart from considering the required oscillation time period, a good selection should avoid the sharp areas of the surfaces in the graphs. At these areas, minor manufacturing errors may significantly affect and change the desired time period, and thus, lead to malfunction.

Based on a det of comprehensive studies (which cannot be presented here due to the limitation of paper length), it can generally be observed that higher values of Eccentric Mass Ratios result in longer natural periods. Also, when the radius of the Bowl gets larger, the natural period values tend to become longer. Moreover, when the Eccentric mass gets farther from the center of the Roller, the periods tend to get longer.

5. Simple Experimental Model

The experimental model is a small prototype which has been prepared so as to give a general understanding and estimation of the performance of the proposed TRMD, its feasibility and effectiveness in mitigating the free vibration oscillations of a structural model. The experiments performed on this model will be discussed by introducing the setup of this model, explaining the procedure of the experiment and discussing the observed results.

5.1 Experimental Setup and General Configurations

The experimental setup is composed of two main parts attached to each other: (1) A Single-Degree-of-Freedom (SDOF) mass-spring-damper system (called the "Primary Structure" in this paper) representing the main structure whose vibration is going to be controlled, and (2) the Tuned Roller Mass Damper that should be applied to the Primary Structure in order to mitigate its vibrations.

The Primary Structure is composed of a specific vibrating mass quantity, equal to M, which oscillates by the means of a number of springs, with an overall stiffness equal to K, attached to it. Its overall damping may be denoted as C. The source of this damping is basically the inherent damping generated by the environmental frictions, springs' inherent damping, etc.; however, no separate damper device is applied in the experiments.

The Primary Structure is once equipped with a TRMD, and the other time, vibrates alone without the application of any kind of control device.

The total Primary Structure moving mass (M) in the experimental model is equal to 9.210 kg. Two springs with a total average stiffness (K) of 103 N/m have also been used to oscillate this mass. Geometric dimensions of the TRMD for this model may be listed as below:
Radius of the Bowl, R = 0.15 m
Inner Radius of the Roller, ri = 0.042 m
Outer Radius of the Roller, ro = 0.045 m
Radius of the Eccentric mass, r' = 0.02 m
Radial Position of the Eccentric mass, r = 0.02 m.

The mass of the Eccentric Mass (m1) equals 0.900 kg, while the mass of the Roller (m2) is 0.060 kg. Accordingly, the TMD mass ratio (m/M) may be calculated as to be 0.10, while the Eccentric Mass ratio (m1/m2) equals 15.

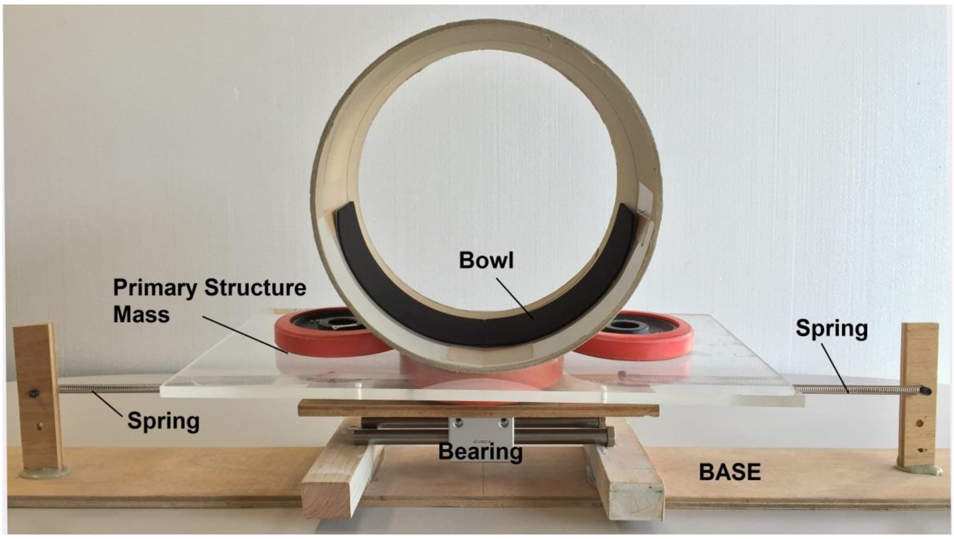

Fig. 6 – Front view of the experimental setup without TRMD

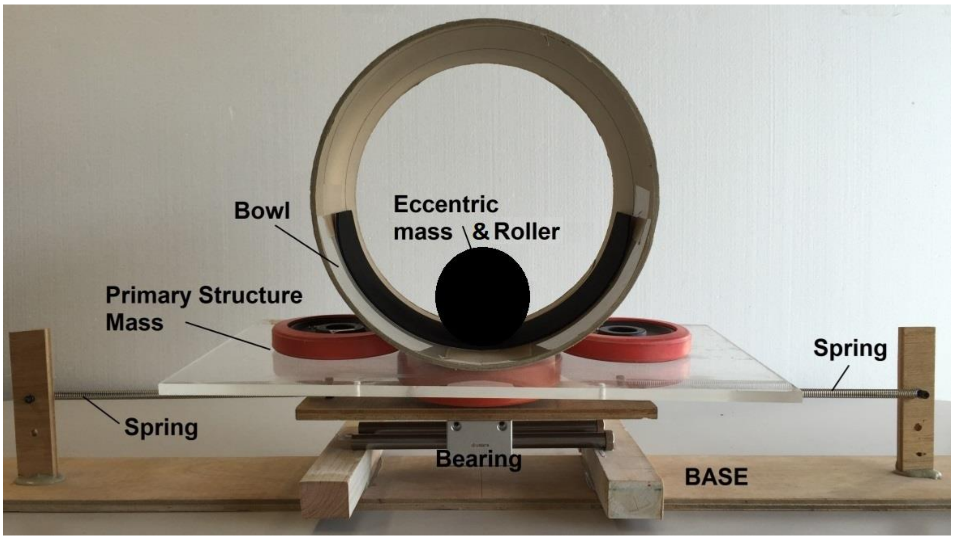

Fig. 7 – Front view of the experimental setup with TRMD

The experimental setups have been shown in Fig. 6 and Fig. 7. A free vibration test has been performed for the two different cases; one for the Primary Structure alone, and the other one for the Primary Structure equipped with the TRMD. For this purpose, the Primary Structure has been pulled along the springs to a specific displacement of 8 centimeters from its rest position and quickly released so as to show a free vibration. During the tests, the acceleration time history of the Primary Structure has been recorded by two accelerometers attached to the Primary Structure.

5.2 Experimental Results and Discussions

The acceleration time-history responses recorded by the accelerometers during the free vibration test of the model number 1 have been plotted in Fig. 8. Fig. 9 shows the velocity time-history responses calculated by integrating the corresponding acceleration responses. In these figures, the graphs are plotted for both of the cases in which the Primary Structure is equipped or is not equipped with the TRMD system.

As it can be seen from the response graphs, when the TRMD system is applied, both of acceleration and velocity responses of the Primary Structure have notably decreased. This reduction can be observed not only considering the responses amplitudes, but also considering the total vibration durations. The duration of free vibration of the Primary Structure in case when it is equipped with the TRMD system, has become relatively shorter compared to that when the Primary Structure oscillates without any control device. These all imply the desired additional damping effect caused by the proposed TRMD system to the overall system.

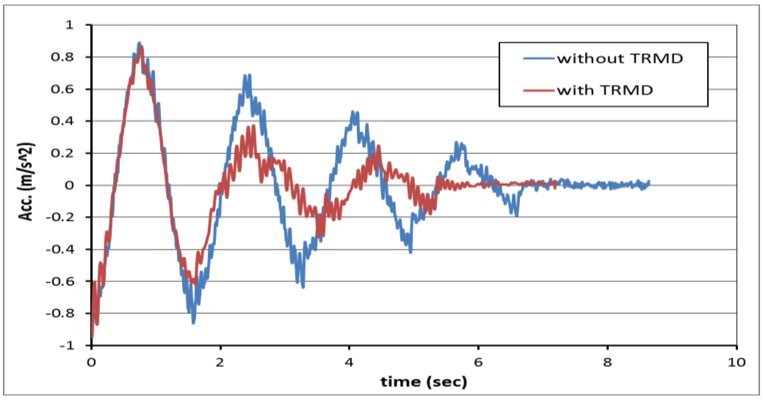

Fig. 8 – Experimental acceleration time-history responses of the Primary Structure with and without the application of TRMD

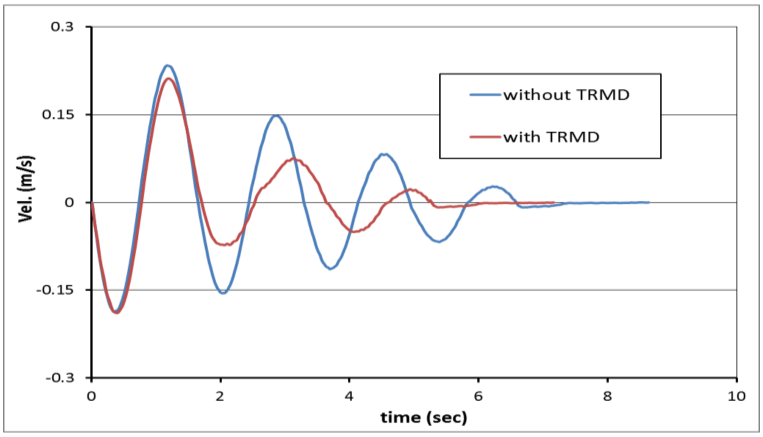

Fig. 9 – Experimental velocity time-history responses of the Primary Structure with and without the application of TRMD

However, the graphs show that the amount of response reduction within the first two peaks of the curves is minor. This can be explained considering the method of the experiment. In the beginning of the experiment, the Primary Structure has been pulled up to a maximum displacement position while the TRMD has been in its neutral position. According to the natural period of the applied TRMD, it can take some time for the TRMD to oscillate with acceptable phase difference relative to the Primary Structure. This time lag causes the delayed response reduction observed in Fig. 8 and Fig. 9.

6. Conclusions

In this paper, a new type of TMD system called "Tuned Roller Mass Damper" was introduced, and tested using a simple experimental model. Numerical solution to the free vibration of the proposed TRMD was also proposed. Previous methodologies and body of research on Tuned Mass Damper systems and other seismic control systems were also briefly reviewed.

It was explained that this system can have a unique performance for mitigating undesirable seismic structural vibrations based on its exclusive dynamic properties. Geometric dimensions and masses of different parts of the proposed TRMD are the main parameters affecting the dynamic behavior of the system. The closed-form solution to the natural vibration of the proposed TRMD system was shown in terms of the influential parameters under natural condition as well as under dynamic excitation. This allowed the computer simulations, dynamic analyses, and numerical modeling of the system. Also, in the design process of a TRMD, all these parameters should be simultaneously taken into account.

The experiments revealed the effectiveness of the proposed TRMD system. The structure controlled by the TRMD showed a better performance than the uncontrolled structures under natural free vibration. However, different dimensions of the system and also the selected values for stiffness and masses had not been selected to be the optimum ones. Some of these issues which need to be investigated through further studies, include: calibrating the dynamic properties of the system so that it performs optimally, testing the proposed system while the Primary Structure is subject to dynamic input ground excitations, and checking the robustness of the proposed TRMD system.

The proposed TRMD system offers two main advantages at the same time which make it an exclusive and unique passive TMD device: its compactness, and its capability to provide long natural periods. The compactness of the TRMD denotes its ability to fit within limited normal building story height as well as the ability of the TRMD control mass to split into arbitrary smaller discrete portions. The latter capability enables the choice of different arrangements of the TRMD on each level of the structure under control, besides the choice to prevent excessive control mass amounts on a single level and vertical mass irregularity.

7. References

[1] Soong, T. and Constantinou, M. C, (Editors), (1994). Passive and Active Structural vibration Control in Civil Engineering. *Springer-Verlag* Wien-New York

[2] Setareh, M. Ritchey, J.K., Baxter, A.J., and Murray, T.M. (2006). Pendulum Tuned Mass Dampers for Floor Vibration Control. *Journal of Performance of Construction Facilities*, 20(1), pp.64-73

[3] Roffel, A.J., Lourenco, R., Narasimhan, S., and Yarusevych, S. (2011). Adaptive Compensation for Detuning in Pendulum Tuned Mass Dampers. *Journal of Structural Engineering*, 137(2), pp.242-251

[4] Kareem, A., Kijewski, T., and Tamura, Y. (1999). Mitigation of Motion of Tall Buildings with Specific Examples of Recent Applications. *Wind and Structures*, 2(3), pp.201-251

[5] Tamboli, A., Joseph, L., Vadnere, U., and Xu, X. (2008). Tall Buildings: Sustainable Design Opportunities. In: *Council on Tall Buildings and Urban Habitat, CTBUH 8th World Conference*, Dubai, March 3-5

[6] Conner, J.J. (2003). Introduction to Structural Motion Control.. *Pearson Education Inc.*

[7] https://www.wikipedia.org/

[8] Huang, X., Elliott, S. J., and Brennan, M. J. (2003). Active isolation of a flexible structure from base vibration. *Journal of Sound and Vibration*, 263(2), 357-376

[9] Barbat, A. H., Rodellar, J., Ryan, E. P., and Molinares, N. (1995). Seismic performance of a new nonlinear active base isolation system. *Proceedings of the 10th European Conference on Earthquake Engineering*, Vienna, Austria, 2781

[10] Scruggs, J. T., Taflanidis, A. A., and Beck, J. L. (2006). Reliability-based control optimization for active base isolation systems. *Structural Control and Health Monitoring*, 13(2-3), 705-723

[11] Jalihal, P., Utku, S., and Wada, B. K. (1994). Active base isolation in buildings subjected to earthquake excitation. *Proceedings of the International Mechanical Engineering Congress and Exposition*, Chicago, IL, USA, Nov. 6-11, 381-388

[12] Yang, J. N., Agrawal, A. K., Samali, B., and Wu, J.-C. (2004). Benchmark problem for response control of wind-excited tall buildings. *Journal of Engineering Mechanics*, 130(4), 437-446

[13] Inman, D. J. (2001). Smart structures and materials 2001: Damping and isolation. *Proceedings of SPIE - The International Society for Optical Engineering*, Newport Beach, CA, 493

[14] Kwok, K. C. S., and Samali, B. (1995). Performance of Tuned Mass Dampers under Wind Loads. *Engineering Structures*, 17(9), 655-667

[15] Kwok, K. C. S., and Macdonald, P. A. (1990). Full-scale measurements of windinduced acceleration response of Sydney tower. *Engineering Structures*, 12(3), 153

[16] McNamara, R. J. (1977). Tuned mass dampers for buildings. *Journal of Structural Division*, Vol. 103(9), 1785–1798

[17] Khan, F. R. (1983). 100 Storey John Hancock Center, Chicago: A case study of the design process. *Engineering Structures*, 5(1), 10-14

[18] Balendra, T., Wang, C. M., and Rakesh, G. (1998). Vibration control of tapered buildings using TLCD. *Journal of Wind Engineering and Industrial Aerodynamics*, 77-78, 245-257

[19] Kawabata, S., Ohkuma, T., Kanda, J., Kitamura, H., and Ohtake, K. (1990). Chiba Port Tower. Full-scale measurement of wind actions Part 2. Basic properties of fluctuating wind pressures. *Journal of Wind Engineering and Industrial Aerodynamics*, 33(1-2), 253-262

[20] Obtake, K., Mataki, Y., Ohkuma, T., Kanda, J., and Kitamura, H. (1992). Full-scale measurements of wind actions on Chiba Port Tower. *Journal of Wind Engineering and Industrial Aerodynamics*, 43(pt 3), 2225-2236

[21] http://www.tokaibane.com/

[22] Igusa, T., and Xu, K. (1994). Vibration Control Using Multiple Tuned Mass Dampers. *Journal of Sound and Vibrations*, 175(4), pp.491-503

