Reducing the Lateral Vibration of Light Weight Steel Structures Using the Concept of Tuned Mass Dampers

Hanan H. Eltobgy
Civil Engineering Department
Faculty of Engineering (at Shoubra), 108 Shoubra Str. Cairo / Benha University, Egypt
Hanan.altobgy@feng.bu.edu.eg

The need for new and better means of designing new structures and retrofitting existing ones from the damaging effects of severe environmental loadings has motivated civil engineers to develop innovative simple concepts of structural control to preserve the structural integrity of these buildings. One of the most effective concepts is the use of a tuned mass damper (TMD) to reduce the undesirable vibrations and enhance the response of the structure induced by wind or earthquake loads. The TMD is a passive energy absorbing device, consists of a mass, spring and a viscous damper attached to the structure. This system has proved to be significant in protecting environmental threats of large structures like towers, bridges and high rise buildings. Despite the fact that the TMD system has been successfully used for high-rise buildings, it needs a huge mass and a large room for installation at the top floor of the building, causing extra production cost and storage space problems. The present study aims to apply this concept for ordinary low-rise buildings making use of part of the building as the pendulum mass like water storage tanks located at top of the roof for these buildings. In this case the water tanks should be hung from the topmost story girder forming a pendulum. The damper of this type needs neither additional mass nor space because the building equipment is integrated into the damper. The study will develop a simple analytical technique which may be used by the designers to find out the optimum parameters of TMD that result in considerable reduction for the lateral vibrations.

1. Introduction

The use of lightweight, high strength materials, and advanced construction techniques have led to increasingly flexible and lightly damped structures, which may cause human discomfort, structural damage and even failure in extreme environmental loadings. Reducing structure vibrations caused by these environmental loadings is still representing serious design challenges for structural design engineers. The traditional approach is to increase the structural stiffness to reduce the excessive vibration. This approach is used by most of the design engineers despite the fact that it increases the cost considerably. Another significant approach is recently achieved based on enhancing the structural response by using a damping device to reduce the unwanted vibrations. This device is a pendulum-type tuned mass damper (TMD) which is proved to be practical and successful to high-rise buildings, (Nagase, 2000). The TMD that are installed at a point of maximum vibration have been implemented effectively for vibration control, (Wang et al., 2001; Wang and Lin, 2001; Marano and Greco, 2010). TMD have been used to reduce the seismic response of structures, (Miranda, 2005). The damper mass should be designed to have a natural frequency close to that of the primary structure. Then, the excess energy that is built up in the structure is dissipated by the TMD. The increasing cost of this method makes it difficult to be applied for ordinary buildings and limited its use to high rise towers only.

The present study will explain a simple and practical technique which may be applied to light weight moderate rise buildings (mostly made of steel) to reduce the undesirable

Proc. of the 10th Intl. Conf. on Advances in Steel Concrete Composite and Hybrid Structures
Edited by J Y Richard Liew and Siew Chin Lee

ISBN: 978-981-07-2615-7 :: doi:10.3850/978-981-07-2615-7_260

vibrations and enhance the response of the structure induced by wind or earthquake loads. This method will develop a simplified new damper using water storage tanks existed on top of most of the buildings as the moving mass of the damper. The proposed damper of this type will not cause remarkable extra cost as it will be part of the structure. The study will be extended to include a simple and convenient method for analyzing the structural system and to investigate the characteristics and effectiveness of the proposed technique.

2. System Description

The proposed device used for reducing the horizontal movements can be represented with a model consists of a tower with a mass pendulum suspended at the top of it. The suspended mass block should be allowed to sway in any direction. Enough suspenders should be designed to maintain the system stability. The device is simple and required no other mechanism for its operation. The mass block of the pendulum may be made as a solid mass or for practical applications may be designed as a suspended water storage tank. These tanks may help for the dynamic stability of the structure. It is recommended to use tanks with floating roofs to prevent the effect of sloshing waves.

The construction of these tanks is very simple and requires no special mechanisms. The tank should be installed near the center of the roof and will be suspended using cables at the tank corners with simple connections. The use of these cables will allow the mass block to sway freely in any direction. This system is simple, practical and requires no special maintenance.

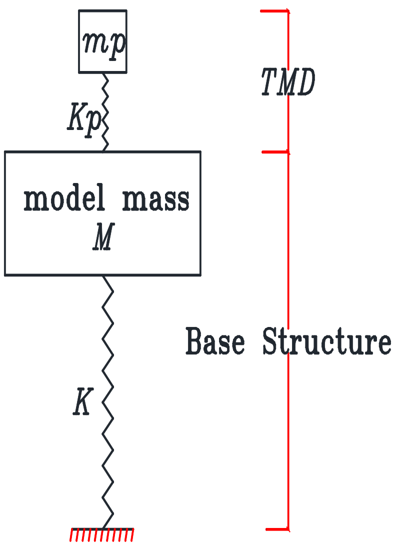

Figure 1: Operating principle of the TMD mounted on the top of a main structure.

3. Modeling and Analysis

The analytical model for calculating the seismic response of tall buildings with the pendulum in place is shown in Fig. 1. The pendulum can be treated as an equivalent mass-spring system attached to the top of the building. The stiffness of the spring is given by Eq. (1), (Tsiatas and Daly, 1994)

$$k_p = \frac{m_p\, g}{l} \tag{1}$$

Where m_p is the mass of the pendulum is, l is the vertical distance between the pendulum mass and it's hanging points (or vertical distance of the pendulum) and g is the acceleration due to gravity.

The structural tower may be modeled using equivalent prismatic beam elements. By employing n elements for the tower, the stiffness equation of the tower structure can be formed by Eq. (2), (Paz, 1991)

$$\begin{bmatrix} K_{uu} & K_{u\theta} \\ K_{\theta u} & K_{\theta\theta} \end{bmatrix} \begin{Bmatrix} u \\ \theta \end{Bmatrix} = \begin{Bmatrix} F_u \\ F_\theta \end{Bmatrix} \tag{2}$$

Where u and θ are the vectors for the nodal lateral displacement and rotations of the tower, F_u and F_θ are the corresponding applied force vectors to u and θ respectively, and K_{uu}, $K_{u\theta}$, $K_{\theta u}$, $K_{\theta\theta}$ are the sub-matrixes for the global stiffness of the tower obtained by superposing the stiffness matrixes of the elements. Rotational earthquake excitations can be neglected, thus $F_\theta = 0$. The horizontal earthquake excitations is the considered excitations, thus Eq. (2) reduces to Eq. (3);

$$K_u u = F_u \tag{3}$$

Where K_u can be expressed by Eq. (4)

$$K_u = K_{uu} - K_{u\theta} K_{\theta\theta}{}^{-1} K_{\theta u} \tag{4}$$

The complete form of K_u can be expressed by Eq. (5)

$$K_u = \begin{bmatrix} k_{u11} & k_{u12} & \cdots & k_{u1n} \\ k_{u21} & k_{u22} & \cdots & k_{u2n} \\ \cdots & \cdots & \cdots & \cdots \\ k_{un1} & k_{un2} & \cdots & k_{unn} \end{bmatrix} \tag{5}$$

The distributed mass of the tower can be represented by the lumped mass system where each floor is represented by a lumped mass positioned at the node. The conventional mass lumping technique can be used to calculate the values of the lumped masses.

The pendulum system may be modeled by a shear medium with lumped mass rested on the top floor of the building. The stiffness of the medium is equal to that of the equivalent mass-spring system for the pendulum as per Eq. (6), (Bruch et al., 1994).

$$\frac{GA}{l} = k_p \tag{6}$$

On the basis of the above modeling, the stiffness matrix of the whole system of tower with the pendulum on top of it, K_T, is expressed by Eq. (7)

$$K_T = \begin{bmatrix} k_{u11} & k_{u12} & \dots & k_{u1n} & 0 \\ k_{u21} & k_{u22} & \dots & k_{u2n} & 0 \\ \dots & \dots & \dots & \dots & \dots \\ k_{un1} & k_{un2} & \dots & k_{p+}k_{unn} & -k_p \\ 0 & 0 & \dots & -k_p & k_p \end{bmatrix} \tag{7}$$

The mass matrix of the whole system is given by Eq. (8)

$$M_T = diag\{m_1, m_2, \dots, m_{n1}, m_p\} \tag{8}$$

Where m_i (i=1, 2, …n) are the equivalent lumped masses located at the nodes of the elements of the tower at each floor.

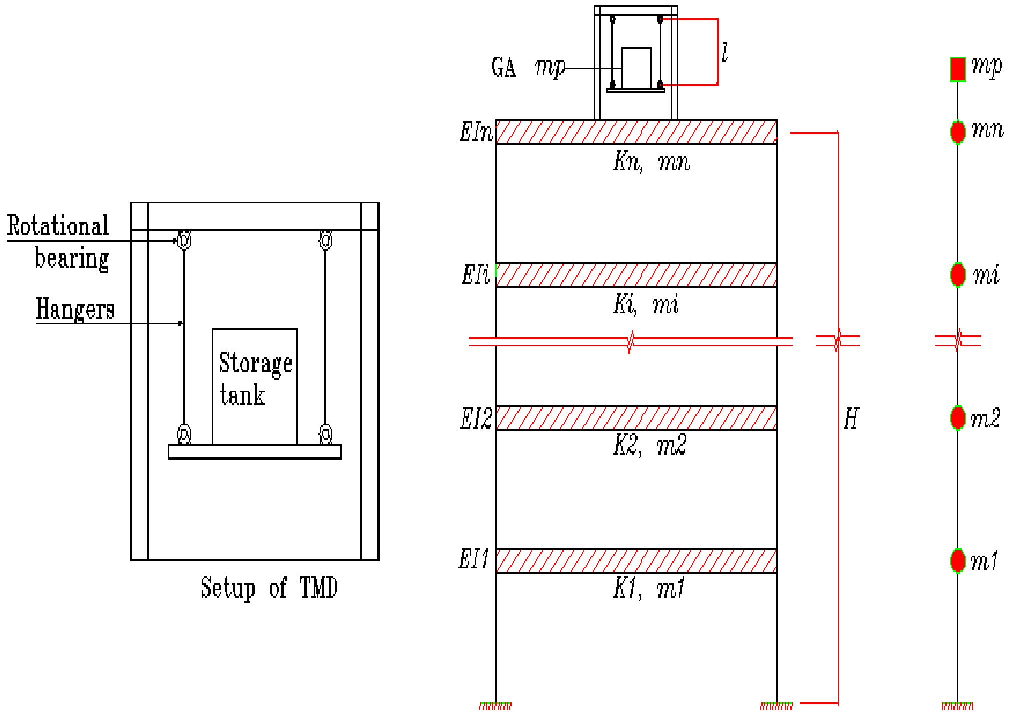

Figure 2: Analysis model for the building with the pendulum on top floor.

4. Dynamic Characteristics of Pendulum

It is known from the structural dynamics (Paz and Leigh, 2004), that the natural frequency of the pendulum should be as close to the fundamental frequency of the structure as possible in order to achieve the most favorable reduction in structural vibrations induced by external excitations. Based on this, Eq. (9) is adopted to determine the vertical length of the pendulum for reducing the seismic response of the tower.

1/2À g/l = f_1 (9)

Where the left hand side of the equation is the natural frequency of the pendulum and the right hand side of the equation is the fundamental frequency of the tower. From the previous equation, the vertical length of the pendulum can be adopted as per Eq. (10)

$$l = (\frac{1}{2\pi})^2 g \tag{10}$$

It can be demonstrated that the imposed (live) loads for most of the high rise buildings are less than the dead loads and consequently the fluctuations of the natural frequencies, especially the fundamental one, of the building may be neglected.

5. Numerical Investigation

To illustrate numerically the effectiveness of the proposed procedure in reducing the lateral vibrations, three buildings with 5, 10 and 15 stories are analyzed. Each of them consisted of a simple steel rigid frame. Assuming that the weight of each building above the ground is from 0.7 to 0.8 t/m^2. The weight of each floor is taken as M=200 ton. Each storey is assumed to have a height of 4.0 m. The weight of the storage tank used for domestic use for each building depends on different variables but it ranges from 0.02 to 0.08 of the building total weight.

The structural properties are assumed to be uniform along the length and height of each building. Each building is modeled as a shear building and therefore may be represented by a spring- mass system. The stiffness of each storey is calculated and found to be 4.75x10^6 Kg/m. The fundamental natural frequency for each building is calculated. A tuned mass damper is considered using different mass ratios (from 0.02 to 0.10). The parameters of the tuned mass damper are calculated as previously explained.

In order to investigate the effectiveness of the proposed method a comparison is made between the maximum top displacement of each building subjected to horizontal excitation with and without the incorporation of the pendulum device. The calculation of the horizontal drift for each building is considered by the mode superposition approach. The results are shown in Fig. 3, in which U_s and U_b are the maximum top drift for each building with and without the pendulum device respectively.

The results demonstrated that the lateral vibrations of light weight steel buildings may be significantly reduced by incorporating the mass pendulum device. However, it can also be found that the reduction is gradually lost as the mass of the pendulum increases. It can also be demonstrated that the lower the building, the larger is the mass required to reduce the horizontal vibrations.

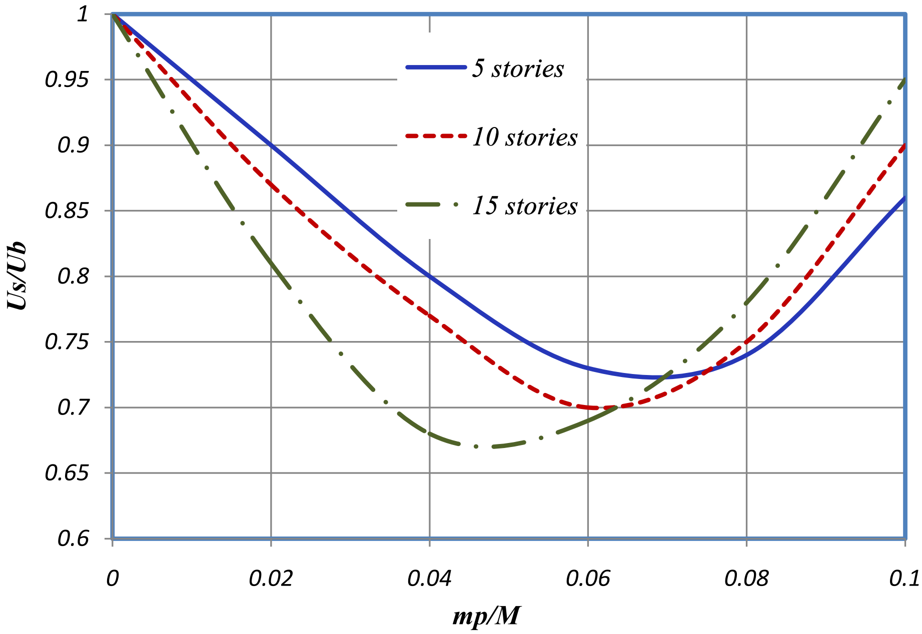

Figure 3: Effectiveness of the pendulum system.

6. Conclusion and Recommendations

The numerical studies showed that the lateral vibrations of light weight steel structures equipped with elevated water tanks on the top floor as a simple pendulum device may be significantly reduced. In practice it is preferable that the pendulum mass is as small as possible. The damper of this type needs neither additional mass nor space, so it is practical, economical and it may be used to protect ordinary buildings from excessive vibrations. A parametric study is made to show the required parameters of the TMD and its effectiveness. From the study results, the following conclusions are drawn:

- A reduction of about 35% of the building drift may be achieved by applying the proposed technique.

- It is found that the optimum value for the mass ratio for the studied buildings ranges from about 0.04 to 0.07. The increase of damper mass than this value will be not effective and may cause bigger drifts.

- It can also be concluded that the proposed method is more efficient for high rise buildings and the mass ratio is increased for low rise buildings.

References

[1] Bruch, J.C., Jr., Sloss, J.M., Sadek, I.S., Adali, S. and Richter, A., (1994), *Vibration control and actuator locations to minimize the dynamic response of beams, First World Conference in Structural Control*, WA1 23-32 , Los Angeles, California, USA.

[2] Marano, G.C., and Greco, R., (2010), *Optimization criteria for tuned mass dampers for structural vibration control under stochastic excitation, Journal of Vibration and Control*, pp.1-10.

[3] Miranda, J. C., (2005), *On tuned mass dampers for reducing the seismic response of structures, Earthquake Engineering Structure Dynamics*, Vol. 34, pp. 847–865.

[4] Nagase, T., (2000), *Earthquake Records Observed in Tall Buildings with Tuned Mass Damper, 12th World Conference on Earthquake Engineering*, Vol., 1893, pp. 1-8

[5] Paz, M., (1991), *Structural Dynamics Theory and Computation*, Van Nostrand Reinhold, New York.

[6] Paz, M. and Leigh, W., (2004), *Structural dynamics theory and computation, updated with SAP2000*, Springer, New York.

[7] Tsiatas, G., and Daly, K., (1994), *Controlling Vibrations with Combination viscous/friction mechanisms, First World Conference on Structural Control*, Los Angeles, California, USA, Wp4, pp. 3-11.

[8] Wang, A. P., Fung, R. F., and Huang, S. C., (2001), *Dynamic analysis of tall building with a tuned mass damper device subjected to earthquake excitation, Journal of Sound and Vibration*, Vol. 244.

[9] Wang, A. P., and Lin, Y. H., (2001), *Vibration control of tall building subjected to earthquake excitation, Journal of Sound and Vibration*, Vol. 299, pp. 757-773.