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Vibration Control using Tuned Mass Damper

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Abstract:— **Structures suffer excessive level of vibrations under the action of wind and earthquake loads, leading to structural failure. To ensure proper functioning of structures, vibration control devices are used. Tuned mass damper (TMD) is one such device, considered effective to control undesirable response of structure. The effectiveness of TMD is governed by proper tuning of its mass, damping and frequency. The present study comprises of two parts. The first part is an overview on the behavior of TMD and its application in wind and earthquake engineering. The second part discusses the effectiveness of elastoplastic TMD in seismic response reduction. The effect of yield level of TMD is studied for elastic main system. The resulting nonlinear equations of motion are solved numerically.**

Key word:-- **Elastoplastic, Tuned mass damper, Vibration control, Yield level.**

I. INTRODUCTION

Vibration control of structures comprises of active, passive and hybrid control system. Tuned mass damper is one of the passive controlling devicesused widely in vibration control.Despite the varied application of tuned mass dampers (TMDs), the fundamental theory used for vibration control is the one proposed by Den Hartog[1]. The damper frequency is tuned to a particular structural frequency which when excited, resonates the damper out of phase with structural motion.Several researches have been carried out to determine optimum damping and frequency of TMDs for different mass ratio. It includes researches done byFujino and Abe[2], Tsai and Lin [3],Rana and Soong [4], Hoang,Fujino, andWarnitchai [5]to name a few.

It is observed that most of these researches are on elastic TMD. Limited study has been done on elastoplastic TMD.Jagadish, Prasad and Rao [6] studied two storeyed bilinear structure with dynamic absorber concept in reducing seismic response. They studied the effect of frequency ratio and yield displacement ratio on ductility demand of bottom storey. Abe [7] proposed bilinearity in TMD for bilinear structures subjected to harmonic excitation. The initial yielding displacement of TMD is set as summation of modal deflection ratio and yield displacement of structure.

The objective of this paper is to study the performance of TMDs when subjected to wind and earthquake (EQ) forces. Different forms of TMDs is studied, namely: Traditional TMDs, Pendulum TMDs (PTMDs) and tuned liquid column dampers (TLCDs). In addition, a study is performed to investigate the effectiveness of elastoplastic tuned mass damper in reducing the earthquake response.

II. EQUATION OF MOTION AND OPTIMUM PARAMETERS

A schematic model of single degree of freedom system (SDOF) equipped with TMD is given in Fig.1.The equations of motion of structure-TMD system can be written as:

$$m\ddot{x} + c\dot{x} - c_d\dot{x}_d + kx - k_d x_d = f(t) \qquad (1a)$$

$$m_d(\ddot{x} + \ddot{x}_d) + c_d\dot{x}_d + k_d x_d = g(t) \qquad (1b)$$

The primes indicate derivative with respect to time t. Here, m, c and$k$ are the mass, damping coefficient and stiffness coefficient of the structure respectively; m_d, c_d and k_d are the mass, damping coefficient and stiffness coefficient of TMD; x is the relative displacement of the structure with respect to ground; x_d is the relative displacement of the TMD with respect to structure;$f(t)$ and $g(t)$ are the forces applied on the structure and TMD respectively, for wind forces: $f(t) \neq 0, g(t) = 0$; for earthquake forces both the masses are excited and $f(t) = -m\ddot{x}_g, g(t) = -m_d\ddot{x}_g, \ddot{x}_g$ is the acceleration of ground motion.

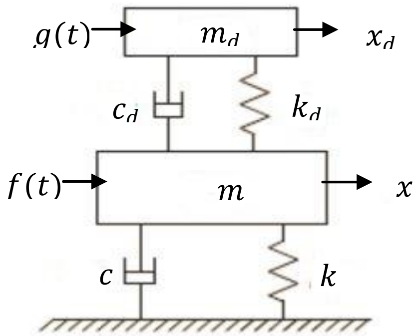


Fig. 1 Schematic model of the structure-TMD system

Den Hartog [1]developed optimum damper parameters for an undamped SDOF system subjected to harmonic excitation. For a SDOF system with natural frequencyω, damping ratio η and mass ratio μ, the frequency ratio f_{opt} and damping ratio η_{opt} of TMD subjected to wind excitation is given as:

$$f_{opt} = \frac{1}{1+\mu} \quad (2a)$$

$$\eta_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}} \quad (2b)$$

In case of harmonic base excitation, the optimum parameters are given as:

$$f_{opt} = \frac{1}{1+\mu}\sqrt{\frac{2-\mu}{2}} \quad (3a)$$

$$\eta_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}}\sqrt{\frac{2}{2-\mu}} \quad (3b)$$

Using the values of f_{opt} andη_{opt}, stiffnessk_d and damping coefficientc_d of TMD can be determined as:

$$k_d = {f_{opt}}^2 \omega^2 m_d \quad (4a)$$

$$c_d = 2\eta_d f_{opt}\, \omega m \quad (4b)$$

To demonstrate the necessity of optimum parameters, a SDOF ($\omega = 1\text{Hz}, \eta = 2\%$) with TMD ($\mu = 10\%$) is subjected to harmonic base excitation$\ddot{x}_g = A\sin\lambda t$. Fig. 2 shows effect of damping on frequency response curve of main system.

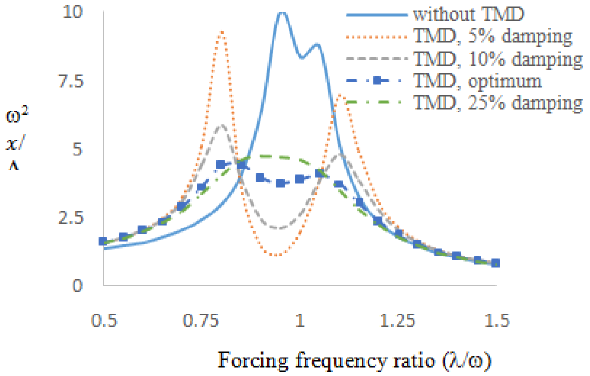


Fig. 2 Effect of dampingon frequency response curve of main system

Tuned mass dampers have the highest percentage of installation for response reduction compared to other devices. The earliest application of TMD is seen in 241 m John Hancock Building, Boston. It was installed in June, 1977 to protect the building against wind vibrations. Since then, TMDs have been installed in several high rise buildings, chimneys and other industrial units for protection against wind and earthquake forces. Recent applications of TMDs can be seen in Petronas Twin towers (1997), Malaysia; Taipei 101 Tower (2004), Taiwan; Shanghai World Financial Center (2007), Shanghai and ATC tower (2015), Delhi Airport. TMD application in bridges prevent vehicle induced or foot vibration as seen in Chao Phya Bridge (1985), Thailand and Millennium Bridge (2001), London.A detailed list of structures with the different types of TMD installed can be seen in Table 1 in chronological order.

Traditional TMDs require heavy weight and ample installation space.To remedy that, **Pendulum TMD** with mass hanging inside the building as shown in Fig. 3is installed. A cable supported PTMD gives same effect as of traditional TMD by adjusting the length (L) of cable. The damper stiffness and frequency ω_d of PTMD can be calculated as:

$$k_d = \frac{m_d\, g}{L} \;;\quad \omega_d = \sqrt{\frac{g}{L}} \quad (5)$$

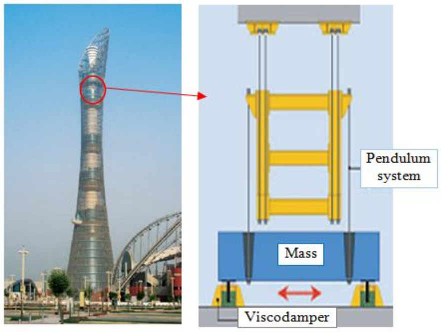


Fig. 3Aspire tower with TMD, Doha, Qatar [8]

Table I Structures fitted in with TMD, [5], [8], [9]

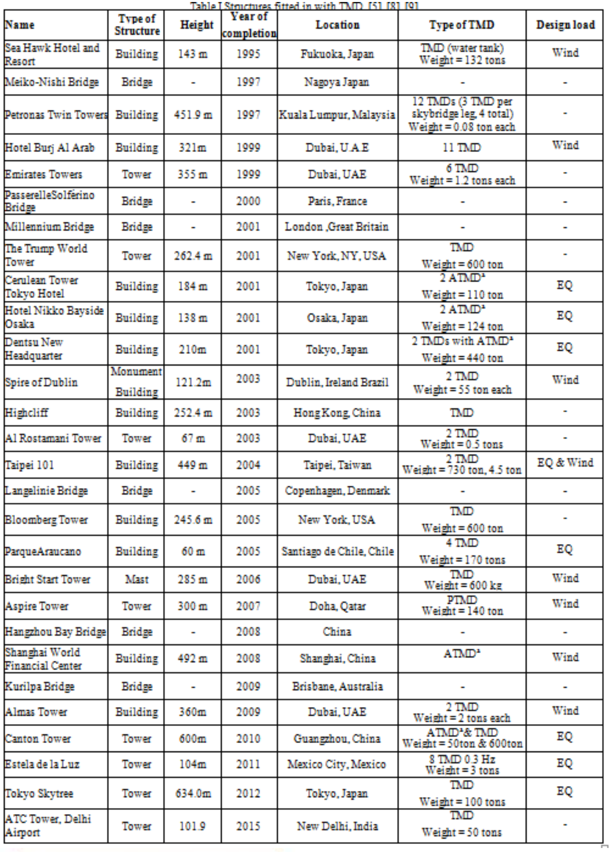
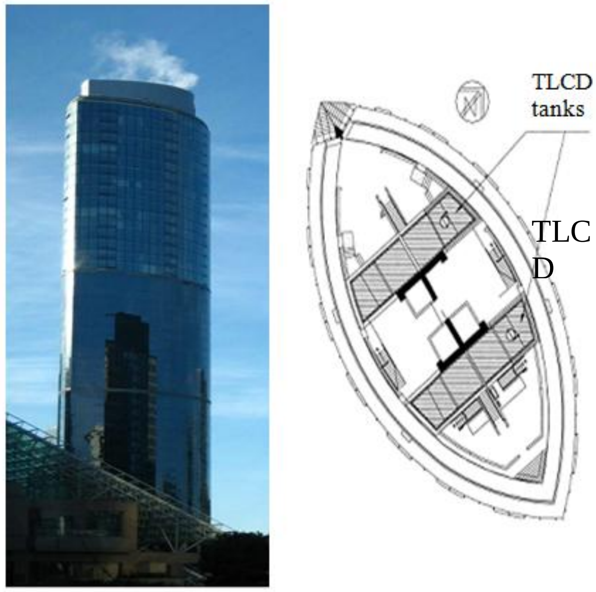


Table I Structures fitted in with TMD, [5], [8], [9]

Name	Type of Structure	Height	Year of completion	Location	Type of TMD	Design load
Sea Hawk Hotel and Resort	Building	143 m	1995	Fukuoka, Japan	TMD (water tank) Weight = 132 tons	Wind
Meiko-Nishi Bridge	Bridge	-	1997	Nagoya Japan	-	-
Petronas Twin Towers	Building	451.9 m	1997	Kuala Lumpur, Malaysia	12 TMDs (3 TMD per skybridge leg, 4 total) Weight = 0.08 ton each	-
Hotel Burj Al Arab	Building	321m	1999	Dubai, U.A.E	11 TMD	Wind
Emirates Towers	Tower	355 m	1999	Dubai, UAE	6 TMD Weight = 1.2 tons each	-
PasserelleSolférino Bridge	Bridge	-	2000	Paris, France	-	-
Millennium Bridge	Bridge	-	2001	London ,Great Britain	-	-
The Trump World Tower	Tower	262.4 m	2001	New York, NY, USA	TMD Weight = 600 ton	-
Cerulean Tower Tokyo Hotel	Building	184 m	2001	Tokyo, Japan	2 ATMD^a Weight = 110 ton	EQ
Hotel Nikko Bayside Osaka	Building	138 m	2001	Osaka, Japan	2 ATMD^a Weight = 124 ton	EQ
Dentsu New Headquarter	Building	210m	2001	Tokyo, Japan	2 TMDs with ATMD^a Weight = 440 ton	EQ
Spire of Dublin	Monument Building	121.2m	2003	Dublin, Ireland Brazil	2 TMD Weight = 55 ton each	Wind
Highcliff	Building	252.4 m	2003	Hong Kong, China	TMD	-
Al Rostamani Tower	Tower	67 m	2003	Dubai, UAE	2 TMD Weight = 0.5 tons	-
Taipei 101	Building	449 m	2004	Taipei, Taiwan	2 TMD Weight = 730 ton, 4.5 ton	EQ & Wind
Langelinie Bridge	Bridge	-	2005	Copenhagen, Denmark	-	-
Bloomberg Tower	Building	245.6 m	2005	New York, USA	TMD Weight = 600 ton	-
ParqueAraucano	Building	60 m	2005	Santiago de Chile, Chile	4 TMD Weight = 170 tons	EQ
Bright Start Tower	Mast	285 m	2006	Dubai, UAE	TMD Weight = 600 kg	Wind
Aspire Tower	Tower	300 m	2007	Doha, Qatar	PTMD Weight = 140 ton	Wind
Hangzhou Bay Bridge	Bridge	-	2008	China	-	-
Shanghai World Financial Center	Building	492 m	2008	Shanghai, China	ATMD^a	Wind
Kurilpa Bridge	Bridge	-	2009	Brisbane, Australia	-	-
Almas Tower	Building	360m	2009	Dubai, UAE	2 TMD Weight = 2 tons each	Wind
Canton Tower	Tower	600m	2010	Guangzhou, China	ATMD^a& TMD Weight = 50ton & 600ton	EQ
Estela de la Luz	Tower	104m	2011	Mexico City, Mexico	8 TMD 0.3 Hz Weight = 3 tons	EQ
Tokyo Skytree	Tower	634.0m	2012	Tokyo, Japan	TMD Weight = 100 tons	EQ
ATC Tower, Delhi Airport	Tower	101.9	2015	New Delhi, India	TMD Weight = 50 tons	-



(a) (b)

Fig. 4 (a) Wall center, Vancouver. (b) cross-section [10]

Other form of TMD which is used most commonly is Tuned liquid column damperas shown in Fig. 4where the mass of damper is substituted by liquid, mainly water. The water is put in a tube with an orifice on the horizontal part which provides variable damping. The shape of the tube can be modified according to the available space for installation. The sloshing of water in the tank counteracts the external forces.

IV. ELASTOPLASTIC TUNED MASS DAMPER

In this section, the effect of yielding of tuned mass damper on the elastic main system response is studied. The objective of this study is to determine the parameters where TMD suffers large inelastic deformation while reducing the damage of main system.In elastic TMD,force-deformation relation is linear while in elastoplastic TMD, force-deformation relation is nonlinear. Fig. 5 shows a typical deformation cycle of elastoplastic system with loading, unloading and reloading curve, as described in [11].

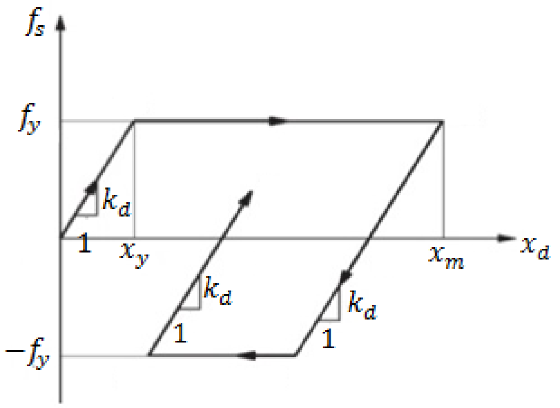


Fig. 5 Force-deformation curve of elastoplastic TMD

The system yields at yield displacementx_y, beyond which plastic deformation occurs. The yield strength is same on the sides. Unloading starts from a point of maximum deformationx_m and reloading starts from a point of minimum deformation. The slope of loading, unloading and reloading curve is same as initial elastic stiffness. The resisting force thus no longer remains single valued but depends upon the displacement and velocity of previous state.Thus, the equations of motion of structure-elastoplastic TMD system subjected to base excitation can be written as:

$$m\ddot{x} + c\dot{x} - c_d\dot{x}_d + kx - f_s(x_d, \dot{x}_d) = -m\ddot{x}_g \text{(6a)}$$

$$m_d(\ddot{x} + \ddot{x}_d) + c_d\dot{x}_d + f_s(x_d, \dot{x}_d) = -m_d\ddot{x}_g \text{(6b)}$$

Where $f_s(x_d, \dot{x}_d)$ is the restoring force.These nonlinear equations are numerically solved by Newmark beta method, linear acceleration approach as explained in [11].

The yield level or yield strength ratio for elastoplastic TMD [12] is defined as:

$$f_{\bar{y}} = \frac{f_y}{f_o} = \frac{x_y}{x_m} \qquad (7)$$

Where f_y is yield strength and f_0 is the maximum elastic force.

The effect of yielding of TMD is studied on the same example of Fig. 2. Frequency response of main mass with elastoplastic TMD and elastic TMD are plotted in Fig. 6.It is observed that elastoplastic TMD reduces main mass response up to a certain yield level.While the response of TMD increases with reduced yield levelas shown in Fig. 7.

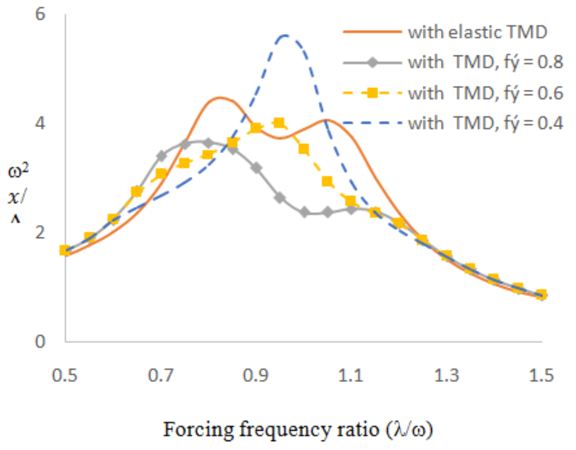


Fig. 6 Effect of yield level on main system response

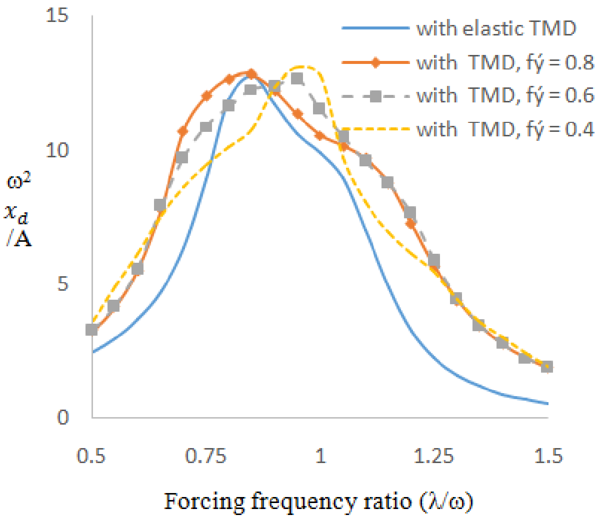


Fig. 7Effect of yield level on TMD response

V. CONCLUDING REMARKS

A discussion on the working mechanism of TMD is presented. This paper also presents different forms of TMD and their application in wind and seismic response control.It is noted that TMDs are being increasingly used for wind oscillations as well as earthquake response control. A numerical study is performed to establish the effectiveness of elastoplastic TMD for elastic main system. The steady state response due to harmonic base excitation is calculated byNewmark beta method.The proposed elastoplastic TMD having optimum parameters same as elastic TMD is found to be more effective in reducing the structural response.

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