BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LIX (LXIII), Fasc. 4, 2013
Secţia
CONSTRUCŢII. ARHITECTURĂ

VIBRATION CONTROL OF A FRAME STRUCTURE USING SEMI-ACTIVE TUNED MASS DAMPER

BY

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Received: July 19, 2013
Accepted for publication: July 31, 2013

Abstract. In this paper a three-storey building coupled with passive or semi-active tuned mass damper for reduction in the response of the structure to harmonic and seismic excitations is presented. Uncertainties in dynamic characteristics of a structure as well as the frequency content and intensity of the excitation may cause a deterioration of the performance of the passive tuned mass damper (TMD). For these reason a semi-active tuned mass damper (STMD) with variable damping is studied. Semi-active clipping control strategy is performed in order to optimize the performance of the STMD. The models are analyzed from numerical simulations point of view, for harmonic and seismic excitations. The OBTAINED results indicate that the efficiency of a STMD is better than that of passive TMD and comparable with that of an active tuned mass damper (ATMD).

Key words: Passive Tuned Mass Damper (TMD); Semi-Active Tuned Mass Damper (STMD); vibration control; variable damping.

1. Introduction

Passive tuned mass damper (TMD) is widely used to control structural vibration under wind load but its effectiveness to reduce earthquake induced vibrations. The first structure in which a TMD was installed appears to be

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Certerpoint Tower in Sydney, Australia. Also, the first major buildings using a TMD, in the USA, were the John Hancock Tower in Boston, completed in 1975 and the Citicorp Center in New York, completed in 1976. In Japan, the first TMD was installed in the Chiba Port Tower, followed by other installations (Housner *et al*., 1997).

Generally, inertial mass is attached near the top, through a spring and a viscous damping mechanism (*e.g.* fluid damper or visco-elastic damper) in order to absorb energy inputted into the structure and can be very effective if it's tuned to a natural frequency of the structure. The effective region of the TMD is limited to a narrow frequency band centering its tuned frequency. The very narrow band of suppression frequency and the sensitivity problem due to detuning are the inherent limitations of the passive TMD (Hartog, 1947). The advantages of passive TMD are simple, inexpensive and reliable to suppress the undesired vibrations of structural systems. A TMD, by definition, do not require external power for its operation.

Active structural control requires considerable amount of power for enhancing structural functionality and safety against natural hazards such as strong earthquakes and high winds. An active control device consists in an actuator able to generate a request force (Marazzi, 2002). This can be calculated with a great variety of control law (optimal control, acceleration feedback control, integral force feedback control, H_2 control, H_∞ control, PID, etc.), based on acceleration, speed, displacement or force measurement (Soong & Spencer, 2002). Energy cannot only be taken away with active control, but can also be inserted into the structure. Active tuned mass damper (ATMD) systems can provide significant reduction in building displacement and acceleration than that of passive TMD. Although the ATMD demonstrates superior performance, the active systems have the disadvantage of power failure during vibrations and great costs to implement such technologies.

Semi-active control systems are a class of active control systems for which the external energy requirements are smaller amounts than those of typical active control. A battery power, for instance, is sufficient to make them operative. Semi-active devices cannot add or remove energy to the structural system, but can control in real time parameters of the structure such as spring stiffness or coefficient of viscous damping. These control devices are often viewed as controllable passive devices.

As an extension of semi-active damping concept that has been successfully applied to a broad class of vehicle vibration isolation problems, a semi-active tuned mass damper (STMD) with variable damping has been proposed for structural vibration control (Pastia, 2004). Hovrat *et al*., (1983), investigated a STMD in order to control wind-induced vibrations in tall buildings. Simulations studies showed the proposed system is superior to conventional passively controlled and comparable to actively controlled system.

Pinkaew and Fujino, 2001, (Preumont, 2002), demonstrated the effectiveness of a STMD with variable damping under harmonic excitation using an optimal control law, which minimizes the quadratic performance index for the STMD. A three storey building coupled with passive or semi-active tuned mass damper for reduction in the response of the structure to harmonic and seismic excitations is presented.

2. Description of the Frame Structure

The frame structure constructed inside the ELSA laboratory has three storeys. It consists of a steel frame with floors constituted by sheet metal and concrete properly connected. The inter-storey high is 2 m because the scale was considered 2/3 of a real structure. The structure has been tested with dynamic and pseudodynamic techniques. Without entering into details, the mass, stiffness and damping matrices that will be used in the analytical model are as follow:

$$\mathbf{M} = \begin{bmatrix} 5{,}000 & 0 & 0 \\ 0 & 5{,}000 & 0 \\ 0 & 0 & 5{,}000 \end{bmatrix}, \text{ [kg]},$$

$$\mathbf{K} = \begin{bmatrix} 45{,}774{,}000 & -25{,}936{,}000 & 647{,}000 \\ -25{,}936{,}000 & 36{,}260{,}000 & -17{,}555{,}000 \\ 647{,}000 & -17{,}555{,}000 & 12{,}600{,}000 \end{bmatrix}, \text{ [N/m]},$$

$$\mathbf{C} = \begin{bmatrix} 5{,}854 & -3{,}547 & 1{,}347 \\ -3{,}547 & 5{,}073 & -1{,}571 \\ 1{,}347 & -1{,}571 & 2{,}273 \end{bmatrix}, \text{ [Ns/m]}.$$

With the above matrices, the identified natural frequencies and the damping ratios are reported in the following Table 1.

Table 1
Frequencies and Damping Ratios

Frequencies	f_1, [Hz]	f_2, [Hz]	f_3, [Hz]
	3.018	10.29	19.09
Damping ratios	ξ_1, [%]	ξ_2, [%]	ξ_3, [%]
	0.8	0.32	0.8

These low values of the damping ratio are normally for a steel structure. The modal matrix of the structure is:

$$\Phi = \begin{bmatrix} 0.2756 & 1 & -1 \\ 0.7168 & 0.7550 & 0.9138 \\ 1 & -0.8169 & 0.3794 \end{bmatrix}.$$

3. Equations of Motion

The equations of motion of lumped mass frame structure at which it's considered a TMD, installed at its top may be written as

$$\begin{cases} \mathbf{M}\ddot{X} + \mathbf{C}\dot{X} + \mathbf{K}X = \begin{bmatrix} 0 \\ 0 \\ c_{sa}\dot{x}_{tmd} + k_{tmd}x_{tmd} \end{bmatrix} + \begin{bmatrix} -m_1\ddot{x}_g + P_1 \\ -m_2\ddot{x}_g + P_2 \\ -m_3\ddot{x}_g + P_3 \end{bmatrix}, \\ m_{tmd}\ddot{x}_g + c_{sa}\dot{x}_{tmd} + k_{tmd}x_{tmd} = -m_{tmd}(\ddot{x}_g + \ddot{x}_3), \end{cases} \tag{1}$$

where: $\ddot{x}_g$ represents the horizontal components of a recorded ground acceleration and $\{P\}$ is a vector containing the horizontal harmonic forces.

4. Design of Optimal TMD and STMD

TMD can be very effective if it's precisely tuned on the resonance frequency, which we want to reduce it. The structural mode of vibration to be controlled with TMD is the first because the other two modes give a negligible contribution to the total response. The ratio, μ, between the mass of the TMD and of the system should be chosen typically between 1/100 and 1/10. The classical formula givin in many handbooks for optimal tunning of the tuned mass damper as function of mass ratio μ is

$$f_{tmd} = \frac{f_1}{1+\mu} \text{ and } \xi_{\text{opt}} = \sqrt{\frac{3\mu}{8(1+\mu)^3}}, \tag{2}$$

where f_{tmd} is the optimum natural frequency of the damper and ξ_{opt} – the optimum damping ratio of the damper.

Considering $\mu = 0.0105$, the following characteristics of the optimal TMD were assumed (Table 2).

Table 2
Dynamic Characteristics of the Optimal TMD

m_{tmd} = 157.2 kg	k_{tmd} = 55,371 N/m	ξ_{opt} = 6.18%

With these optimal values, the frequency responses of the displacement at the 3th level of the structural model with optimal TMD and with TMD set for μ = 0.01, are showed in Fig.1.

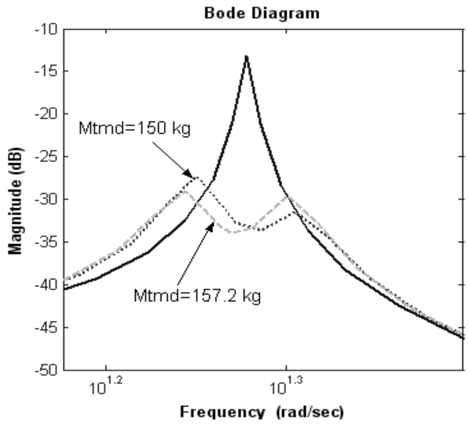

Fig. 1 – Comparison in frequency responses of the structural model without, with optimal TMD and with TMD set for μ = 0.01.

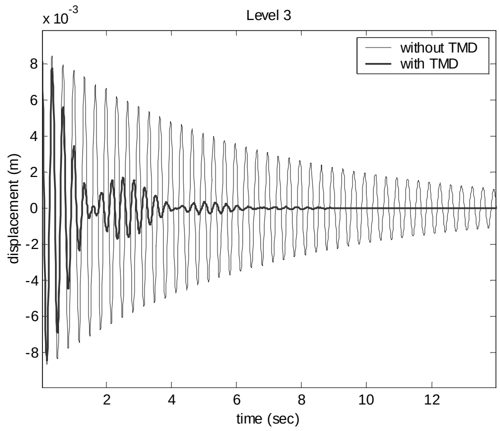

Fig. 2 – Free vibration responses of the structural model without and with optimal TMD.

Fig. 2 illustrates free vibration responses in controlled case with optimal TMD and uncontrolled, when the structure is assumed to have the initial displacement of 0.003 m, 0.006 m and 0.009 m for first, second and third floors, respectively.

In case of semi-active tuned mass damper it's consider a variable orifice device in order to control the damping coefficient of the TMD. The variable damping devices comprise a hydraulic cylinder with a controllable by-pass valve and can be fashioned from a conventional damper with provision for fast modulation of the damping coefficient. The damping characteristics of a variable orifice can be controlled between two damping values (low damping when the valve is completely opened and high damping when the valve is completely closed) by varying the amount of flow passing through the by-pass pipe from one chamber of the piston in the other. If the valve is open, the damping can be virtually reduced to zero if the by-pass is large enough. In the intermediate position the device produces a specific damping dissipation. The adjustment of the valve can be made usually electromechanically (*e.g.*, servo valve or solenoid valve). It can be assumed that the cylinder of semi-active device is attached by to the building mass, and the piston is connected to the TMD, which acts as a dynamic absorber.

For the passive mode of operation, the valve is stationary and partial open, which corresponds to the standard passive scheme. During semi-active mode of operation electrical signals from a control computer initiate the control valve action. Thus, different damping levels are produced depending on the valve position.

The adjustment of the time-depending damping coefficient, $c(t)$, can be produced by the semi-active damping law (Pinkaew & Fujino, 2001; Preumont, 2002) as

$$c_{sa} = \frac{f_c}{\dot{x}_{tmd}}, \text{ for } x_{tmd} \neq 0, \tag{3}$$

where: f_c is desired control force computed by an active control strategy. The function $f_c / \dot{x}_{tmd}$ saturates between $c_{\min}$ = 10 N.s/m and $c_{\max}$ = 750 N.s/m. The variation of c_{sa} occurs only when the term $f_c / \dot{x}_{tmd}$ lies within a variable range. Otherwise is set to either the minimum or maximum value. For this reason the control law is similar to the continuous clipping control strategy. The control is accomplished by measuring the actual relative velocity of the STMD and the acceleration of the third storey of structure.

The required force is computed according to the Fig. 3 and has the relationship as follow:

$$f_c = g m_{tmd} \ddot{x}_3, \tag{4}$$

where g is control gain. There is considered an actuator, which acts on the tuned mass damper. This actuator is not attached by the structure mass and for this reason the control system is called ideal active tuned mass damper (ATMD) in order to help us to design a semi-active control law. Dyke *et al.*, (1996), experimentally demonstrated efficiency to use a control strategy, which weights the acceleration of the structure in order to design an active tuned mass damper. In that case the actuator had interaction with the structure.

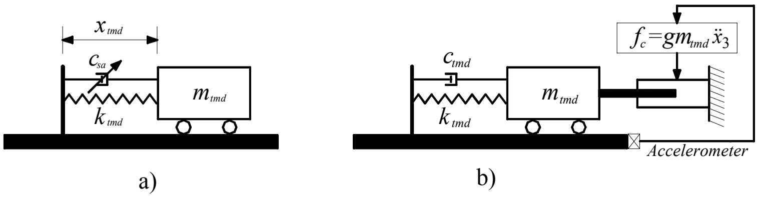

Fig. 3 – *a* – Configuration of semi-active tuned mass damper (STMD); *b* – ideal active tuned mass damper (ATMD).

5. Numerical Results

The frame system has been modelled with Simulink and several simulations has been performed using as input El Centro earthquake acceleration and harmonic excitation. The detailed scheme of tuned mass damper model, for all cases (passive, active and semi-active), is shown in Fig. 4.

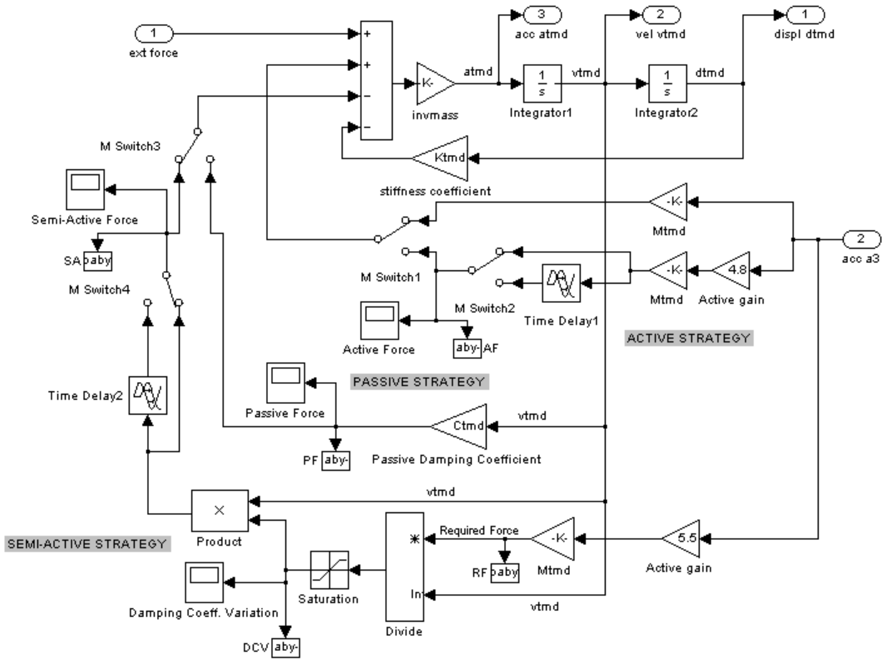

Fig. 4 – Simulink scheme for simulation of TMD, STMD and ideal ATMD.

Figs. 5,...,8 show the comparisons among the time history displacement responses of the structure in the uncontrolled case and controlled one with passive and semi-active TMD under El Centro simulated earthquake and harmonic excitation. The harmonic forces excitation is used at the frequency $\omega = 18.965$ rad/s (corresponding with the first natural frequency of the structure); the force amplitude is F = 1,000 N. It's supposed that the force acts at the level of each floor in horizontal direction.

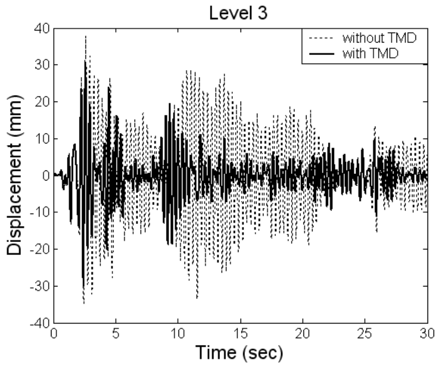

Fig. 5 – Comparison between displacement responses of structure without and with TMD under El Centro earthquake.

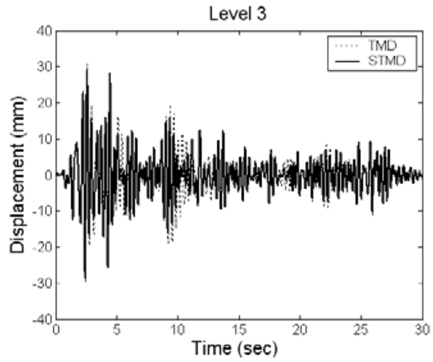

Fig. 6 – Comparison between displacement responses of structure with TMD and STMD under El Centro earthquake.

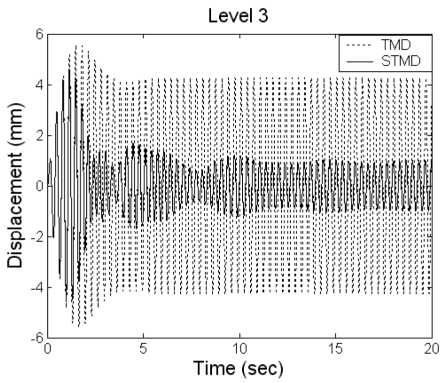

Fig. 7 – Comparison between displacement responses of the structure with optimal TMD and STMD under harmonic excitation.

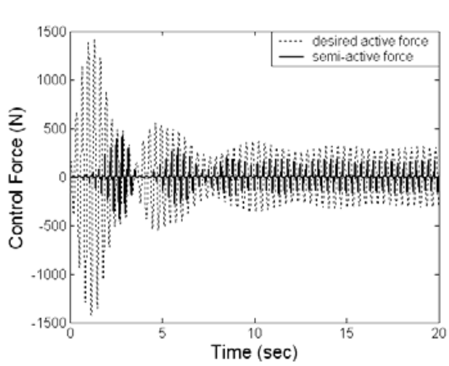

Fig. 8 – Comparison between desired active control force and actual semi-active control force.

The control gain is g = 4.8 for the active case. In the semi-active case the gain is g = 5.5 for achieving the desired active force that is used in order to optimize the damping coefficient, c_{sa}. The curves show that significant displacement reduction can be achieved with STMD than with passive TMD under harmonic excitation. In steady state response, this reduction is approximately 70%. Fig. 7 illustrates the time history of the semi-active damping force and the active force. It's seen that the semi-active force acts like a large impulse force. However, the STMD, which utilizes the modulation of damping to achieve the performance of an active system, cannot supply the energy into the system because the dashpot always dissipates the energy. Therefore, for the first 1.5 s, the damping of the STMD is set to minimum in order to maximize the energy transfer from structure.

6. Conclusions

In this study a new semi-active tuned mass damper (SATMD) was developed according to the proposed modeling. The STMD performance has been compared with those of passive and active TMD systems. The results of numerical simulations indicate that the STMD can substantially improve the response of the structure around the tuning frequency over the conventional passive TMD.

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CONTROLUL VIBRAŢIILOR UNEI STRUCTURI ÎN CADRE
CU DISIPATOR CU MASĂ ACORDATĂ SEMIACTIV

(Rezumat)

Este prezentată o clădire cu trei etaje cuplată cu dispator pasiv sau semi-activ cu masă acordată pentru reducerea răspunsului structurii la excitaţii armonice şi seismice. Incertitudinile caracteristicilor dinamice ale unei structuri, precum şi conţinutul de frecvenţă şi intensitate a excitaţiei poate provoca o deteriorare a performanţei disipatorului pasiv cu masă acordată (TMD). Din aceste motive se studiază un disipator semi-activ cu masă acordată (STMD), cu amortizare variabilă. În scopul de a optimiza performanţa STMD se aplică strategia de control semi-activ 'clipping'. Modelele sunt analizate din punct de vedere al simulărilor numerice pentru excitaţii armonice şi seismice. Rezultatele indică faptul că eficienţa STMD-lui este mai bună decât cea a TMD-lui şi comparabilă cu cea a disipatorului activ cu masă acordată (ATMD).