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Earthquake Excited Base-Isolated Structures Protected by Tuned Liquid Column Dampers: Design Approach and Experimental Verification

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Abstract

In this contribution a direct approach for optimal design of a Tuned Liquid Column Damper (TLCD) device attached to the base slab of a base-isolated structure is presented, aiming at reducing the seismic displacement demand of the base-isolation subsystem. Assuming white noise base excitation, for a wide parameter range a direct optimization procedure yields design charts for optimal TLCD quantities. The performance of the base-isolated structure equipped with optimally tuned TLCD device in comparison to the simple base-isolated one is evaluated both numerically and experimentally. In a numerical study the system is subjected to the 44 records of the FEMA P-695 far-field ground motion set. The experimental studies are conducted on a three-story small-scale base-isolated shear frame model. From the results it can be concluded that a TLCD effectively controls the seismic response of earthquake excited low-damped base-isolated structures.

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Keywords: Base-isolation; TLCD; Hybrid passive control; Optimal design

1. Introduction

The installation of a base-isolation subsystem between the foundation and the base slab is an effective means to reduce the vulnerability of relatively stiff structures against earthquake excitation. The base-isolation has low horizontal stiffness, aiming at decreasing lateral coupling of building and subsoil. Its vertical stiffness is, however, large to secure vertical load transfer from the building to the foundation. The base-isolation elongates the fundamental period of the system from the acceleration sensitive period domain into the displacement sensitive period domain, and thus, the internal structural forces are significantly reduced. The system displacements are mainly confined to the

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base-isolation subsystem, which is designed to accommodate this demand, whereas the above built structure behaves almost rigid.

The seismic displacements of the base-isolated system can be further reduced by application of a Tuned Liquid Column Damper (TLCD) or one of its varieties attached to the base slab, which rests on the base-isolators, as it was shown in [1,2]. In a TLCD a liquid column vibrates in a U-shaped container, and its natural frequency is basically a function of the column length only. It is, thus, particularly suitable for vibration mitigation of first-mode dominated systems with very low fundamental frequency such as base-isolated structures. When appropriately tuned to the fundamental frequency of the system whose dynamic response is to be mitigated, vibrational energy is transferred from the structure to the TLCD through the motion of the rigid TLCD container exciting the liquid column to vibrations. The dynamic response of the structure is reduced through the gravitational restoring force acting on the displaced TLCD liquid, and the energy is dissipated through viscous interaction of the liquid column and the rigid TLCD container. Compared to TMDs, TLCDs have some unique advantages such as low cost, easy installation and adjustment of liquid frequency, little maintenance needed, etc.

In a recent paper [3], the authors of the present contribution proposed an optimal design procedure for TLCDs aiming at seismic response control of base-isolated structures, verified in a comparative experimental investigation [4] on a small-scale model. In this paper the procedure described in [3] is briefly reviewed, and numerical and experimental outcomes are presented to show the beneficial effects of TLCDs for seismic response control of base-isolated structures.

2. Equations of motion

Consider an n dynamic degrees-of-freedom planar frame structure with $n \times n$ mass matrix $\mathbf{M}$, $n \times n$ damping matrix $\mathbf{C}$, and $n \times n$ stiffness matrix $\mathbf{K}$, let $\mathbf{x}$ be the $n \times 1$ vector of nodal structural deformations with respect to the base plate, and $\mathbf{r}$ the quasistatic influence vector. This multi-degrees-of-freedom (MDOF) structure is separated through a low-damped visco-elastic base-isolation from the foundation, with M_b denoting the mass of the base-plate, and C_b and K_b denoting the stiffness respectively damping of the isolation subsystem. The displacement of the base-plate with respect to the foundation is denoted as x_b. To the base-plate a U-shaped TLCD with constant cross-section is rigidly attached in an effort to reduce the displacement demand of the base-isolation. The motion of the liquid column with mass m_f is characterized by displacement u of the liquid surface. The equations of motion of this $(n + 2)$ degrees-of-freedom system subjected to the horizontal ground acceleration $\ddot{x}_g$ are derived in accordance to the assumptions and procedure outlined in [5], leading to

$$\begin{aligned}
&\left(M_b + m_f + \mathbf{r}^T\mathbf{M}\mathbf{r}\right)\ddot{x}_b(t) + \alpha m_f \ddot{u}(t) + \mathbf{r}^T\mathbf{M}\ddot{\mathbf{x}}(t) + C_b\dot{x}_b(t) + K_b x_b(t) = -\left(M_b + m_f + \mathbf{r}^T\mathbf{M}\mathbf{r}\right)\ddot{x}_g(t)\\
&\alpha\ddot{x}_b(t) + \ddot{u}(t) + \tfrac{1}{2L}\xi\left|\dot{u}(t)\right|\dot{u}(t) + \omega_f^2 u(t) = -\alpha\ddot{x}_g(t)\\
&\mathbf{M}\left(\mathbf{r}\ddot{x}_b(t) + \ddot{\mathbf{x}}(t)\right) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = -\mathbf{M}\mathbf{r}\ddot{x}_g(t)
\end{aligned} \tag{1}$$

The circular natural frequency $\omega_f = \sqrt{2g/L}$ of the stand-alone TLCD is a function of the gravitational acceleration g and liquid column length L composed of the vertical column length L_V and the horizontal column length L_H: $L = 2L_V + L_H$ [5]. ξ denotes the head loss coefficient, and geometric parameter $\alpha = L_H/L$ is the so-called length factor.

An MDOF structure resting on a well-designed base-isolation subsystem behaves virtually rigid, while the displacements are confined to the base-isolation. Thus, for preliminary design of a TLCD with optimal parameters it is reasonable to further reduce the entire base-isolated structure to a linear SDOF system equipped with a TLCD, as shown in Fig. 1(b). The equations of motion of this two-degrees-of-freedom system read as [3]

$$\begin{aligned}
&\left(1 + \mu_f\right)\ddot{x}_b(t) + \alpha\mu_f\ddot{u} + 2\zeta_b\omega_b\dot{x}_b(t) + \omega_b^2 x_b(t) = -\left(1 + \mu_f\right)\ddot{x}_g(t)\\
&\alpha\ddot{x}_b(t) + \ddot{u}(t) + \tfrac{1}{2L}\xi\left|\dot{u}(t)\right|\dot{u}(t) + \omega_f^2 u(t) = -\alpha\ddot{x}_g(t)
\end{aligned} \tag{2}$$

with the liquid ratio $\mu_f = m_f/M_{tot}$, where $M_{tot} = M_b + \mathbf{r}^T\mathbf{M}\mathbf{r}$ is the total system mass composed of the mass of base-isolation plate M_b and the total effective mass of the frame structure $\mathbf{r}^T\mathbf{M}\mathbf{r}$.

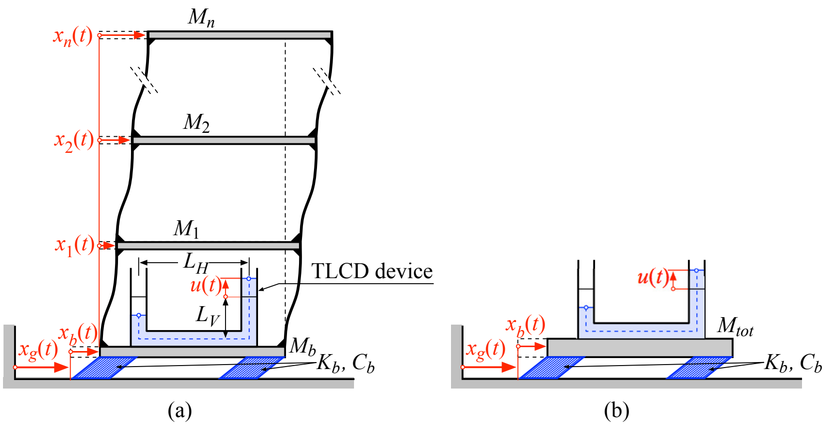

Fig. 1. (a) Base-isolated MDOF shear frame equipped with TLCD; (b) Base-isolated rigid structure equipped with TLCD (modified from [3]).

3. Optimal TLCD parameters

3.1. System response to random base-excitation

Assuming that the hybrid controlled system is subjected to random base-excitation in the form of a zero mean white noise process, the system response is also a stochastic process, however, non-Gaussian due to nonlinear TLCD damping. For instance, in [3] it is shown that the non-linear set of equations of motion Eqs 2 can be replaced by linear ones, subsequently written in matrix form with capital letters denoting the random response quantities,

$$\tilde{\mathbf{M}}\ddot{\mathbf{Z}} + \tilde{\mathbf{C}}\dot{\mathbf{Z}} + \tilde{\mathbf{K}}\mathbf{Z} = -\tilde{\mathbf{M}}\tilde{\mathbf{r}}\ddot{x}_g \tag{3}$$

where

$$\mathbf{Z} = \left[X_b(t)\ U(t) \right]^T \ ,\ \tilde{\mathbf{r}} = \left[1\ 0 \right]^T \ ,\ \tilde{\mathbf{M}} = \begin{bmatrix} 1+\mu_f & \alpha\mu_f \\ \alpha & 1 \end{bmatrix} \ ,\ \tilde{\mathbf{C}} = \begin{bmatrix} 2\zeta_b\omega_b & 0 \\ 0 & 2\zeta_f\omega_f \end{bmatrix} \ ,\ \tilde{\mathbf{K}} = \begin{bmatrix} \omega_b^2 & 0 \\ 0 & \omega_f^2 \end{bmatrix} \tag{4}$$

with ζ_f denoting the equivalent damping ratio of the TLCD, which is obtained by minimizing the mean square of the error between the original nonlinear system and the equivalent linear one with respect to ξ [3]. Excitation $\ddot{x}_g$ is modeled as a zero-mean stationary Gaussian white noise process with G_0 denoting its one-sided Power Spectral Density (PSD). Thus, the evolution of the response covariance matrix can be expressed in terms of the Lyapunov equation [3,6]

$$\dot{\Sigma}_{\mathbf{Q}}(t) = \mathbf{D}_{\mathbf{S}}\Sigma_{\mathbf{Q}}(t) + \Sigma_{\mathbf{Q}}(t)\,\mathbf{D}_{\mathbf{s}}^{\mathbf{T}} + \mathbf{G}_{\mathbf{S}}\mathbf{G}_{\mathbf{S}}^{\mathbf{T}}\pi G_0 \tag{5}$$

where $\mathbf{Q} = \left[\mathbf{Z}\ \dot{\mathbf{Z}} \right]^T$ is the vector of the state variables and $\mathbf{I_2}$ a 2×2 identity matrix. Covariance matrix $\Sigma_{\mathbf{Q}}(t)$, $\mathbf{D_S}$ and $\mathbf{G_S}$ read as

$$\Sigma_{\mathbf{Q}} = \begin{bmatrix} \sigma^2_{X_b} & \sigma^2_{X_bU} & \sigma^2_{X_b\dot{X}_b} & \sigma^2_{X_b\dot{U}} \\ & \sigma^2_U & \sigma^2_{U\dot{X}_b} & \sigma^2_{U\dot{U}} \\ sym & & \sigma^2_{\dot{X}_b^2} & \sigma^2_{\dot{X}_b\dot{U}} \\ & & & \sigma^2_{\dot{U}} \end{bmatrix} \ ,\ \mathbf{D_S} = \begin{bmatrix} \mathbf{0} & \mathbf{I_2} \\ -\tilde{\mathbf{M}}^{-1}\tilde{\mathbf{K}} & -\tilde{\mathbf{M}}^{-1}\tilde{\mathbf{C}} \end{bmatrix} \ ,\ \mathbf{G_S} = \begin{bmatrix} \mathbf{0} \\ \tilde{\mathbf{r}} \end{bmatrix} \tag{6}$$

Since only the steady state response statistics needs to be evaluated, in Eq. 5 the evolution of the covariance matrix is set to zero, i.e. $\dot{\Sigma}_{\mathbf{Q}}(t) = 0$. Then, after some algebra the solution of this equation for the variance of the steady state displacement of the base-isolation subsystem yields [3]

$$\sigma^2_{X_b} = \frac{\pi G_0}{4 z_{X_b}\omega_b^3} \ ,\ z_{X_b} = \frac{N_Z}{D_{ZX_b}} \tag{7}$$

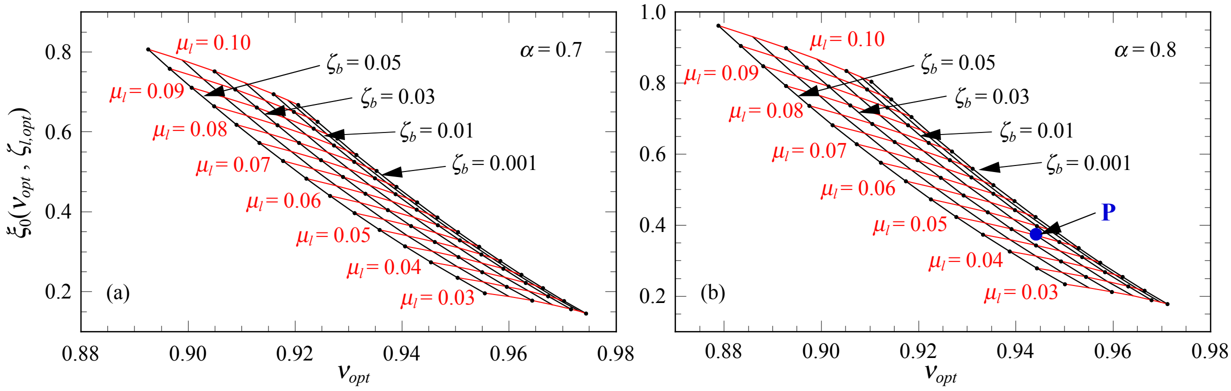

Fig. 2. Optimal design charts for ν_{opt} and $\xi_{0,opt}$; (a) $\alpha = 0.7$; (b) $\alpha = 0.8$ (modified from [3]).

with

$$N_Z = \zeta_b\zeta_f + \zeta_2^2\left(4\zeta_b^2 + \alpha^2\mu_f\right)\nu + 2\zeta_b\zeta_f\left[2\zeta_b^2 + \alpha^2\mu_f + \left(2\zeta_f^2 - 1\right)\left(1 + \mu_f\right)\right]\nu^2 + \zeta_b^2\left[\alpha^2\mu_f + 4\zeta_f^2\left(1 + \mu_f\right)\right]\nu^3 + \zeta_b\zeta_f\left(1 + \mu_f\right)^2\nu^4$$

$$D_{ZX_b} = \zeta_f\left(1 + \mu_f - \alpha^2\mu_f\right)^2 + \zeta_b\left[\alpha^4\mu_f^2 + 4\zeta_f^2\left(1 + \mu_f\right)^2\right]\nu + \zeta_f\left(1 + \mu_f\right)^2\left[4\zeta_b^2 + 3\alpha^2\mu_f + \left(4\zeta_f^2 - 2\right)\left(1 + \mu_f\right)\right]\nu^2 + \zeta_b\left(1 + \mu_f\right)^2\left[\alpha^2\mu_f + 4\zeta_f^2\left(1 + \mu_f\right)\right]\nu^3 + \zeta_f\left(1 + \mu_f\right)^4\nu^4 \tag{8}$$

where the so-called frequency tuning ratio $\nu = \omega_f/\omega_b$ has been introduced. The head loss coefficient ξ and the equivalent damping ratio ζ_f are related according to [3]

$$\xi = \frac{\xi_0\left(\nu, \zeta_f\right)}{\sqrt{G_0\omega_b}} \ , \quad \xi_0\left(\nu, \zeta_f\right) = 4g\zeta_f\sqrt{\frac{2\mu_f\left(\zeta_b + \gamma\zeta_f\right)}{\nu}} \tag{9}$$

3.2. Design charts for optimal TLCD parameters

In the design process, liquid mass ratio μ_f and length parameter α are usually predefined in advance. Thus, the only TLCD parameters that need to be determined are the frequency tuning ratio ν and the head loss coefficient ξ. Since Eq. 7 directly expresses the displacement variance $\sigma_{X_b}^2$ of the base-isolation subsystem of the reduced equivalent system according to Eq. 3 as a function of the excitation PSD G_0 and the system parameters, the optimal parameters can be found as the minimum of function [3]

$$\phi\left(\nu, \zeta_l\right) = \frac{1}{z_{X_b}} \tag{10}$$

It is seen that function ϕ does not depend on G_0 and the natural base-isolation system frequency ω_b. Application of a numerical minimization procedure provides the optimal TLCD parameters ν_{opt} and $\zeta_{f,opt}$, and further the optimal head loss coefficient ξ_{opt} respectively $\xi_{0,opt}$ through Eq. 9. The results of this procedure can be used to derive design charts in terms of ν_{opt} and $\xi_{0,opt}$ for different α values. Fig. 2 shows exemplary design charts for $\alpha = 0.7$ and $\alpha = 0.8$.

These design charts can be used to efficiently identify optimal TLCD parameters ν_{opt} and ξ_{opt}. For instance, assume that length ratio $\alpha = 0.8$, damping ratio of the base-isolation $\zeta_b = 0.02$, and liquid mass ratio $\nu = 0.05$. The point corresponding to these parameters in the design chart Fig. 2(b) is denoted as **P**. Then, the optimal parameters corresponding to this point are identified as $\nu_{opt} = 0.944$ and $\xi_{0,opt} = 0.368$. Substituting these outcomes and G_0 into Eq. 3 yields the optimal head loss coefficient ξ_{opt}.

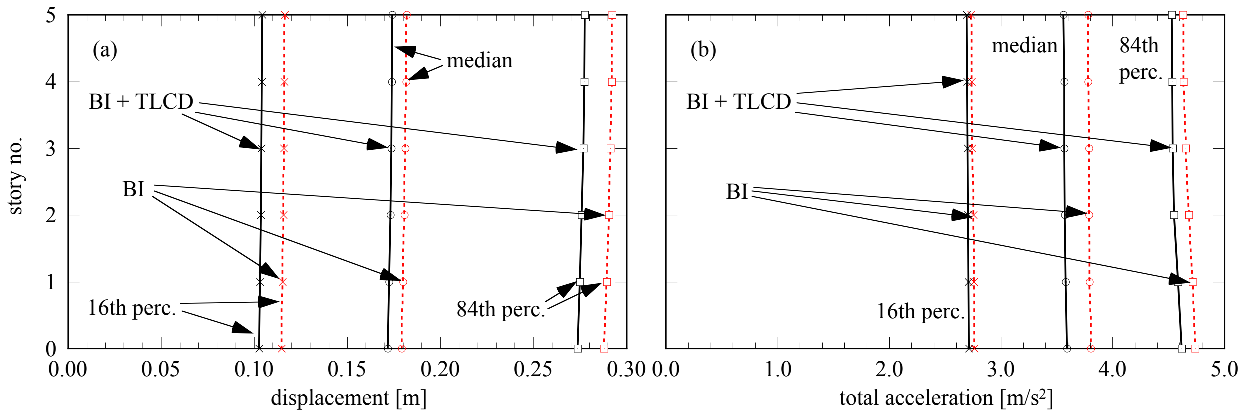

Fig. 3. Statistical response of hybrid controlled structure (BI+TLCD - black solid line) and base-isolated structure (BI - red dashed line) subjected to the 44 FEMA P-695-FF records: (a) Peak floor displacement relative to the ground; (b) Peak floor total acceleration.

4. Numerical application

As an example problem a planar base-isolated five-story shear frame structure used in [7] subjected to a set of recorded ground motions is considered. Each story has a mass $M_i = 3500kg$, a story stiffness $K_i = 35 \cdot 10^6 N/m$, and a dashpot damping coefficient $C_i = 35 \cdot 10^3 Ns/m$. The base-isolation subsystem with mass $M_b = 3500kg$ has a natural frequency $\omega_b = 3.16 rad/s$ and a damping ratio $\zeta_b = 0.02$. The response of this structural system, and alternatively equipped with a TLCD at the base, to the 44 recorded far-field ground motions of the FEMA P-695-FF set described in [8], which originate from severe seismic events of moment magnitude between 6.5 and 7.6 recorded on NEHRP site classes C (soft rock) and D (stiff soil), was computed through direct numerical solution of the pertinent equations of motion of the complete systems (Eqs 1) using a forth order Runge-Kutta algorithm. Assuming a TLCD with mass ratio $\mu_l = 5\%$ and length ratio $\alpha = 0.8$, the optimum design parameters obtained by the proposed simplified approach are $\nu_{opt} = 0.944$ and $\xi_{opt} = 45.54$, based on the one-sided PSD $G_0 = G_{\ddot{X}_g}(\omega_b)$ of the FEMA P-695-FF record set.

Figure 3 shows the profiles of the median, 16th and 84th percentiles of the peak response quantities of the base-isolated structure with (black solid lines) and without (red dashed lines) TLCD. It is apparent that the optimized TLCD device directly connected to the base-isolation subsystem decreases the relative displacement demand (Fig. 3(a)) by 5 to 10%. The total statistical peak accelerations are less affected by the TLCD, and reduced between 2.5 and 5%, as seen in Fig. 3(b). It is thus shown that the application of a TLCD optimized based on the assumption of stationary white noise process further reduces the structural seismic peak response considering the actual non-stationary nature of real ground motions.

5. Experimental verification

For experimental verification of the proposed design approach for the TLCD attached to a base-isolated structure, in the laboratory of the Unit of Applied Mechanics at the University of Innsbruck a small-scale structural model was investigated. This model consists of a base-isolated three-story shear frame equipped with a TLCD. Fig. 4 shows a photo of the experimental model and a sketch of the corresponding mechanical model with overall dimensions. The natural frequencies of the three-degrees-of-freedom frame without base-isolation are $f_{s1} = 7.4Hz$, $f_{s2} = 21Hz$ and $f_{s3} = 36Hz$. Natural frequency and damping ratio of the base-isolation are $f_n = 1.35Hz$ and $\zeta_b = 0.022$ respectively. The TLCD with a length ratio $\alpha = 0.7$ and a liquid mass ratio $\nu_f = 0.03$ is tuned to optimal frequency ratio $\nu_{opt} = 0.97$, as it can be identified from the design chart shown in Fig. 2(a). That is, the optimal frequency of the TLCD is $\omega_f = 1.31Hz$. The equivalent viscous damping coefficient $\zeta_f = 0.08$ of the stand-alone TLCD was determined in a free-vibration test. The base of the model was subjected to chirp sine signal and the response acceleration recorded. For further details on the experimental model and on test set-up it is referred to [4].

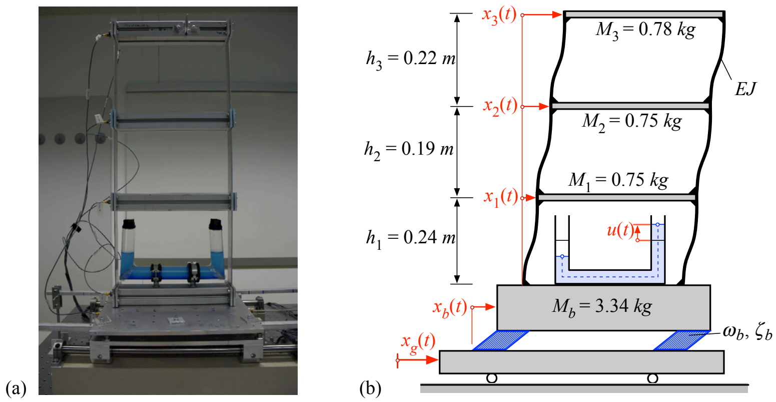

Fig. 4. Three-story base-isolated small-scale frame equipped with TLCD. (a) Photo; (b) Mechanical model.

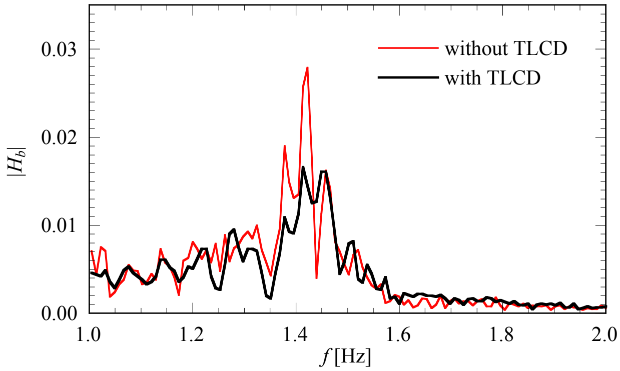

Fig. 5. Displacement transfer function of the base plate.

Fig. 5 shows the displacement transfer function of the base plate of the base-isolated structure equipped with optimally tuned TLCD (black line), and alternatively, without TLCD (red line). This result proves that the application of the TLCD reduces significantly the displacement demands of the base-isolation.

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