確率的 方法에 의한 TLCD 減衰器의 地震에 대한 性能 評價

PROBABILISTIC SEISMIC PERFORMANCE EVALUATION OF TUNED LIQUID COLUMN DAMPERS

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ABSTRACT : 柔軟構造物의 受動制御 시스템인 TLCD 減衰器의 地震에 대한 性能 評價를 確率的 랜덤 振動 解析方法을 利用하여 研究하였다. 代表的 地震運動은 確率的 非正常 推計過程方法을 利用하였으며, TLCD 減衰器의 非線形 減衰力에 대한 計算은 等價線形技法을 利用하였다. 媒介變數에 대한 研究를 통하여 TLCD 減衰器의 性能 評價를 遂行하였다.

1. INTRODUCTION

The seismic performance of tuned liquid column dampers (TLCDs) for the passive control of flexible structures is investigated using random vibration analysis. A nonstationary stochastic process with frequency and amplitude modulation is used to represent the earthquake strong motion and an equivalent linearization technique is used to account for the nonlinear damping force in the TLCD.

Tuned liquid column dampers are effective vibration control devices for flexible, tower-like structures subjected to long-duration, periodic or harmonic excitations [1-3], and their potential application for earthquake mitigation has been recently explored [4-6]. However, the description of their performance for generalized earthquake loading is still lacking and their performance variability with respect to the design parameters and ground motion characteristics is not well established. In previous studies of TLCDs seismic performances, either time-history analysis or stationary random vibration analysis in the frequency domain were performed. The results obtained from these approaches may potentially be limited for a general description

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of the system's performance since they are strongly dependent on the particular ground motions considered when a time-history analysis is used, and the assumption of stationarity may not, in general, be a good approximation for earthquake loading.

A more realistic stochastic model of earthquake ground motions should be capable of representing their highly non-stationary nature. While several nonstationary stochastic ground motion models are available [7-9], the stochastic ground motion model with both frequency and amplitude modulation proposed by Yeh and Wen [10] is particularly well-suited for the random vibration analysis in the time-domain. Here, a time-domain random vibration analysis, together with a simple stochastic equivalent linearization technique are used to investigate the performance of TLCDs for the passive control of long period structures, such as tall buildings and cable-stayed bridges [2], under earthquake loading.

2. ANALYTICAL MODEL

A TLCD is a subsidiary vibration system consisting of liquid mass in a tube-like container attached to the primary structure as shown in Fig. 1. The restoring force resulting from the gravity forces acting on the liquid mass, and the damping effects resulting from the hydrodynamic head-loss when the liquid passes through an orifices smaller than the tube cross-section, reduce the vibration of the primary structure. In this respect, a TLCD may be regarded as an inertial vibration absorber. The equation of motion for the liquid

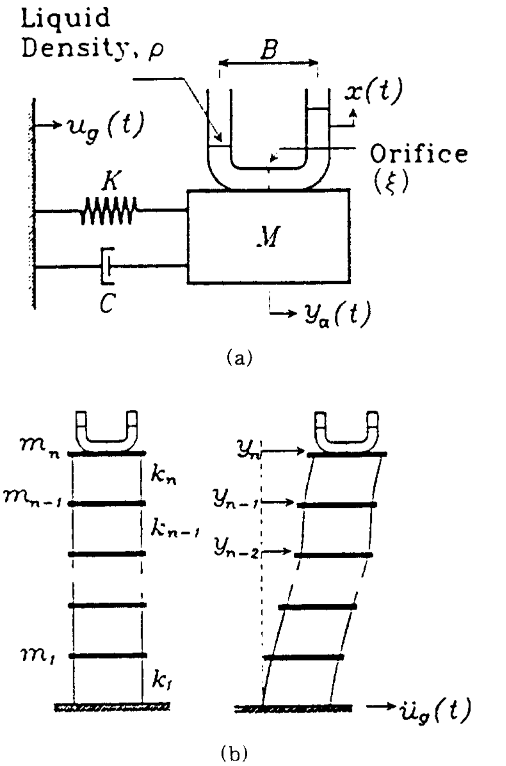

Fig. 1 (a) SDOF system with TLCD (b) MDOF shear-beam system with TLCD

oscillation subjected to an absolute acceleration, $\ddot{y}a$, of the container is given by [11]

$$\rho AL\ddot{x} + \frac{\rho A}{2}\xi|\dot{x}|\dot{x} + 2\rho Ag\,x = -\rho AB\ddot{y}_a \quad (1)$$

where $\ddot{y}_a = \ddot{u}_g + \ddot{y}$, for the SDOF structure($\ddot{y}_a = \ddot{u}_g + \ddot{y}_n$, for the MDOF structure), x is the vertical elevation change of the liquid surface, ρ, L, B and A are the density, length, width and cross-sectional area of the liquid column, respectively, and g is the gravitational acceleration. The constant ξ is the coefficient of head loss governed by the opening ratio of the orifice [12] at the center of the horizontal portion of the TLCD. The undamped natural frequency of the TLCD is $w_T = \sqrt{(2g/L)}$, which only depends on the length of the oscillating liquid mass.

Eq. (1) can be combined with the equation of motion for the structure, which is modeled as a n-degree of freedom linear-elastic shear-beam type structure. Accordingly, the equations of motion for the combined TLCD-structure system can be written

$$\begin{bmatrix} m & a \\ a^T & m \end{bmatrix} \begin{Bmatrix} \ddot{y} \\ \ddot{x} \end{Bmatrix} + \begin{bmatrix} c & 0 \\ 0 & c(t) \end{bmatrix} \begin{Bmatrix} \dot{y} \\ \dot{x} \end{Bmatrix} + \begin{bmatrix} k & 0 \\ 0 & k \end{bmatrix} \begin{Bmatrix} y \\ x \end{Bmatrix} = - \begin{Bmatrix} mJ \\ m_o \end{Bmatrix} \ddot{u}_g \qquad (2)$$

where m, c and k are the (n x n) mass, damping and stiffness matrices of the shear-beam structure except for the element m_{nn} in the mass matrix, which is the sum of the n-story mass and the TLCD mass ; y is a n-dimensional vector of the story displacements relative to the support ; J is a n-dimensional vector of ones ; a is a n-vector consisting of $[0 \cdots 0 \ m_0]^T$ where $m_0 = \rho AB$; $k = 2\rho Ag$; $m = \rho AL$; 0 is either a m-dimensional column or row vector of zeros as appropriate ; and, $c(t)$ is the velocity-dependent nonlinear damping term for the TLCD given by $(\rho A/2)\xi|\dot{x}|$.

Using normal mode approach [13] the displacement response vector for the structure can be approximated by

$$y \simeq \Phi_r q \qquad (3)$$

where Φ_r is a (n x m) truncated modal matrix containing those mode shapes of the structure that contribute most significantly to the response, usually, the first m mode shapes and frequencies, and q is a m-dimensional vector of generalized modal displacements. Substituting Eq. (3) into Eq. (2) and premultiplying the result by

$$\begin{bmatrix} \Phi_r^T & 0 \\ 0 & 1 \end{bmatrix} \qquad (4)$$

Applying the normal mode approach to the primary structure the combind system subjected to the ground acceleration, $\ddot{u}_g$, can be approximated as follow :

$$\begin{bmatrix} m^* & \Phi_r^T a \\ a^T \Phi_r & m \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ \ddot{x} \end{Bmatrix} + \begin{bmatrix} c^* & 0 \\ 0 & c(t) \end{bmatrix} \begin{Bmatrix} \dot{q} \\ \dot{x} \end{Bmatrix} + \begin{bmatrix} \dot{c}^* & 0 \\ 0 & k \end{bmatrix} \begin{Bmatrix} q \\ x \end{Bmatrix} = - \begin{Bmatrix} \Phi_r^T mJ \\ m_o \end{Bmatrix} \ddot{u}_g \qquad (5)$$

where m^*, c^* and k^* are the diagonal matrices, as a result of orthogonality. It is noted that classical damping is assumed for the structure with the added mass of the TLCD, but not for the combined structure TLCD system. Any number of significant modes, not necessarily in order, may be considered in Eq. (5)

3. STOCHASTIC EQUIVALENT LINEARIZATION

The TLCD response in nonlinear as a result of the drag-type force induced by the orifice as shown by the second term of Eq. (1). For the random vibration analysis, the equation of motion for the TLCD (Eq.(2)). is linearized as follows. First, the following equivalent auxiliary linear system is chosen to represent the original nonlinear system [14].

$$\rho AL\ddot{x}(t)+c_{eq}\dot{x}(t)+2\rho Agx(t) = -\rho AB\ddot{y}(t) \quad (6)$$

where c_{eq} is the equivalent linear damping coefficient for the TLCD. By minimizing the mean-square error between Eq. (1) and Eq. (6), and assuming that $x(t)$ is a Gaussian process [5]

$$c_{eq} = \sqrt{\frac{2}{\phi}}\, \rho A\xi\sigma_{\dot{x}} \quad (7)$$

where $\sigma_{\dot{x}}$ is the standard deviation of the liquid mass velocity $\dot{x}(t)$. Note that c_{eq} depends on $\sigma_{\dot{x}}$, which is not known a priori.

4. STOCHASTIC RESPONSE ANALYSIS

For the stochastic response analysis, the equation of motion for the structure-TLCD system are augmented with the filter equations for the ground motion and then written in a state-vector form, from which the response covariance matrix can be obtained [15]. The equations of TLCD structure, Eq. (2), are frist reduced to a frist-order system of equations, and augmented with appropriate filter equations which represent the frequency, intensity modulation and power spectrum of the stochastic ground motion. Symbolically, it is

$$\dot{Z} = GZ+b \quad (8)$$

where Z is the state vector and G is the system matrix.

Postmultiplying Eq. (4) by Z^T, adding the result to its transpose, and taking expected values, yields the following Liapunov matrix differential equation :

$$\dot{S} = GS+SG^T+B \quad (9)$$

The covariance matrix, $S=E[Z\ Z^T]$, contains all the mean-square response statics of interest for this study. Note that Eq. (9) is nonlinear because the constant c_{eq} for the TLCD, which appears in the G matrix, depends on $\sigma^2_{\dot{x}}$, which is part of the solution, S.

5. NUMERICAL EXAMPLES

Since TLCDs are expected to be effective for long period structures, their seismic performance is evaluated below for stochastic ground motion models with long-period components and for long period structures. The parameters for the stochastic ground motion models are selected such that its mean response spectrum approximates the response spectrum for the ground motion record of the 1985 Mexico City earthquake (S60E-SCT). A shear-beam type structural model is considered to represent a 30-story building. The ratio of the TLCD mass to the entire building mass, μ, and the ratio B/L, are kept constant and equal to 0.02 and 0.7, respectively, and the TLCD is tuned to the fundamental mode of the structure(w_1=2.0 rad/sec). The first five modal responses are considered in the analysis. The response quantities considered are the absolute acceleration response and the interstory drift (or interstory shear force), which are the important response quantities for the serviceability and safety criteria, respectively. These quantities can be conveniently calculated from the covariance matrix, S.

It is observed that the displacement response is dominated by the fundamental

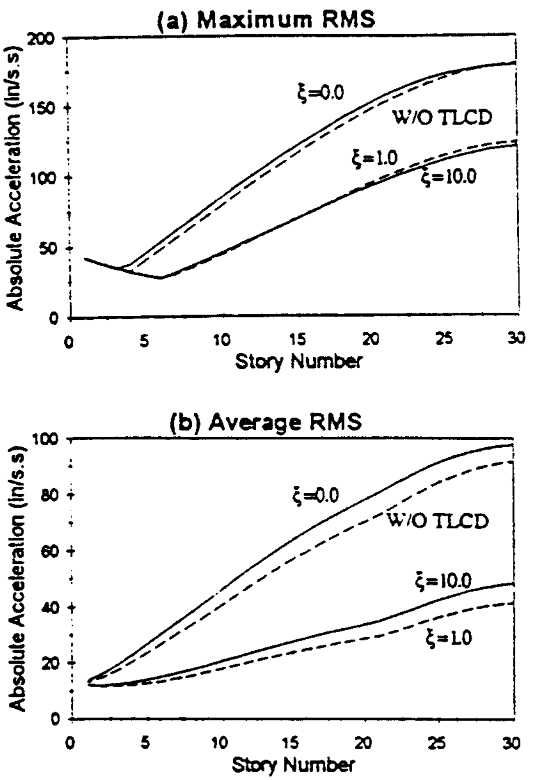

Fig. 2 Absolute acceleration

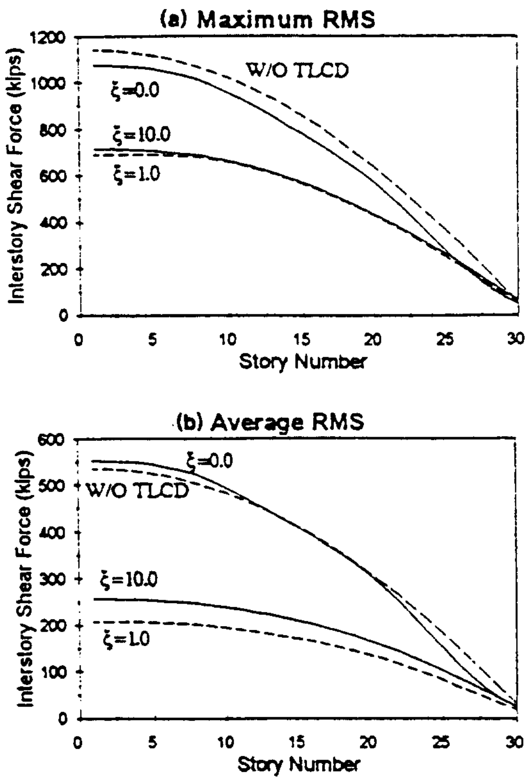

Fig. 3 Interstory shear force distribution

mode, which is effectively reduced by the TLCD. While the higher mode responses of structure with TLCD are larger than the responses without TLCD, the higher mode contribution is relatively small and this effect is not significant. The TLCD response statistics are also computed. It is noted that TLCD response becomes excessive for a coefficient of head loss $\xi < 10$. The maximun and temporal average values of the absolute acceleration and interstory shear force distributions are calculated by considering the first five modal responses, and are shown in Fig. 2 and Fig. 3. It is observed that the TLCD is effective in reducing the absolute acceleration response and the interstory shear forces for both $\xi=1.0$ and $\xi=10.0$.

6. CONCLUSIONS

The seismic performance of TLCDs are evaluated using time-domain nonstationary random vibration analysis. It is shown that TLCDs are promising devices to reduce earthquake-induced motions in long period structures.

Potential advantages of TLCDs over the conventional inertial devices are that the system is inexpensive and requires minimum maintenance, is well suited for temporary use, its vibration characteristics are well defined and can be easily modified and water storage already available in tall buildings can be utilized without introducing excessively large added mass.

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