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Real-time hybrid simulation of full-scale tuned liquid column dampers to control multi-order modal responses of structures

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ABSTRACT

This paper aims to demonstrate the real performance of tuned liquid column dampers (TLCDs) in controlling seismic response of multi-degree-of-freedom (MDOF) structures based on the advantages of real-time hybrid simulation (RTHS). An RTHS framework is developed to carry out full-scale experiments of TLCD-structure-foundation system, and the application of multiple TLCDs to control single-order and multi-order modal responses of a nine-story benchmark building is investigated, respectively, as an example. Moreover, the effect of soil–structure interaction (SSI) on TLCD performance is examined, in which the finite and semi-infinite soil flexible foundations are simulated through a finite element model with 1160 DOFs embedding fixed and artificial boundaries, respectively. Results show that MTLCD is more effective than a single TLCD in suppressing structural responses; and the former is suggested to be used to control multi-order modal responses because of the uncertainty of the frequency content of earthquake excitations. The SSI effect significantly reduces TLCD performance, and the semi-infinite foundation may eliminate the control effect of TLCD due to the radiation damping effect. The parameters of the TLCD device should be regulated according to the characteristics of SSI-structure system when the SSI effect is unneglectable.

1. Introduction

To improve the performance of flexible structures subjected to seismic or wind loads, numerous structural control technologies are employed to dissipate structural energy. In general, such control can be categorized as follows according to differences in control strategy: passive, active, semi-active, and hybrid control [1]. Tuned liquid column dampers (TLCDs) [2] have recently garnered attention in the field of structural control as a type of passive control device. A traditional TLCD consists of a liquid-filled, U-shaped tube container that is rigidly connected to the main structure. Its natural frequency can be tuned to match the fundamental frequency of the main structure by properly setting the liquid length. Other TLCD modifications have also been proposed to improve the capability of this type of damper; these modifications include semi-active TLCDs with controllable orifices [3] or controllable frequency [4] and tuned liquid column gas dampers [5,6].

TLCDs dissipate energy by combining the action that involves liquid movement, the restorative force generated by gravity, and the damping force attributed to inherent head loss characteristics [2]. The damping term in the motion equation for TLCD is a nonlinear function of liquid velocity; thus, most theoretical studies on focus on conducting theoretical analysis of linearization solutions to obtain the equivalent damping term [7,8] as well as optimizing of TLCD parameters [9–11].

Experimental studies are commonly performed to investigate properties of TLCD as well as its structural control performance. Most experiments aim to identify the nonlinear dynamic characteristics of TLCDs [2,12] and to verify the numerical model for the nonlinear damping force [13]. Experimental investigations into TLCD effectiveness are also conducted with different types of liquid [14]. Given multi-degree-of-freedom (MDOF) structures, Min et al. [15] proposed a tuned liquid mass damper (TLMD) that functions as a TLCD and as a tuned mass damper in the direction orthogonal to the TLCD. The performance of a real TLMD in terms of controlling the responses of a practical five-story building was studied as well. Due to the capability of experimental setup as well as large sizes of TLCDs when tuning to low structure frequencies, it is difficult to perform MTLCD experiments using conventional shaking table tests. Shum and Xu [16] carried out experimental investigation of using MTLCDs to reduce torsional structural responses under harmonically forced excitations. The studied structure was a steel structure rotating around a pivot which could be seen as

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a single-degree-of-freedom (SDOF) system. Hence, a new experimental approach should be developed to comprehend the performance of TLCD given MDOF structures.

At present, the real-time hybrid simulation (RTHS) technique attracts considerable attention due to its unique advantages in relation to substructure analysis, including real-time loading, and to the investigation of rate-dependent behavior, among others [17,18]. RTHS is a virtual-actual experimental method that involves partitioning the structure for emulation into physical and numerical substructures, respectively. The numerical substructure is numerically simulated on a computer, whereas the remaining physical substructure is loaded through shaking tables or actuators. RTHS has been used to study nonlinear damper devices, such as passive elastomeric dampers [18], magnetorheological dampers [19], and tuned liquid dampers (TLDs) [20,21].

The control performance of TLD/TLCD has been studied through RTHS by the authors of this paper. Wang et al. [21] proposed a methodology for full-scale TLD experiments and implemented the RTHS of multi-story structures with single TLD. Zhu et al. [22] studied the control effect of single TLCD on SDOF structures, and the performance of multiple TLCD (MTLCD) on SDOF structural control was also preliminarily investigated using single shaking table. This paper develops the methodology of full-scale MTLCD experiments by using multiple shaking tables: (1) based on the advantages of sub-structuring technique in RTHS, STLCD/MTLCD experiments on controlling dynamic responses of a nine-story benchmark building are investigated in full scale; (2) the application of MTLCD on multiple modal responses control by using twin shaking tables is proposed and experimentally verified by RTHSs; and (3) the SSI effect considering both fixed and artificial foundation boundaries on TLCD performance is also investigated through RTHSs.

2. RTHS framework for structure–MTLCD systems

2.1. Governing equations of the structure–MTLCD systems

Fig. 1 displays an MDOF structure equipped with an MTLCD system consisting of n TLCDs. For the ith TLCD, ρ_ω is the liquid density; V_i and H_i are the vertical and horizontal liquid length, respectively; A_{Vi} and A_{Hi} are the areas of vertical and horizontal liquid columns, respectively; δ_i is the coefficient of head loss; y_i, $\dot{y}_i$ and $\ddot{y}_i$ are the displacement, velocity and acceleration of inside liquid, respectively. The displacement, velocity and acceleration of the DOF connected to the TLCDs are denoted by x_N, $\dot{x}_N$ and $\ddot{x}_N$, respectively. The equilibrium equation of the liquid relative motion can be expressed as [10]:

$$m_{1i}\ddot{x}_N + m_{2i}\ddot{y}_i + c_{fi}\dot{y}_i + k_{fi}y_i = -m_{1i}\ddot{x}_g,\ |y_i| < V_i \tag{1}$$

where $m_{1i} = \rho_w A_{Vi} H_i$; $m_{2i} = \rho_w A_{Vi}(2V_i + H_i/\eta_i)$; $\eta_i = A_{Vi}/A_{Hi}$; $c_{fi} = (1/2)\rho_w (A_{Vi}^2/A_{Hi})\delta_i|\dot{y}_i|$ is the damping term for the ith TLCD; $k_{fi} = 2\rho_w A_{Vi} g$ is the stiffness term for the ith TLCD; $\ddot{x}_g$is the input ground acceleration; g is the acceleration of gravity. The equilibrium equation of the DOF connected to the TLCDs can be expressed as [10]:

$$(m_{sN} + m_{f,total})\ddot{x}_N + \sum_{i=1}^{n} m_{1i}\ddot{y}_i + c_{sN}(\dot{x}_N - \dot{x}_{N-1}) + k_{sN}(x_N - x_{N-1}) = -(m_{sN} + m_{f,total})\ddot{x}_g \tag{2}$$

where m_{sN}, c_{sN} and k_{sN} are the mass, damping and stiffness of the DOF connected to the TLCDs. $m_{f,total} = \sum_{i=1}^{n} m_{fi} = \sum_{i=1}^{n}\rho_w A_{Vi}(2V_i + H_i/\eta_i)$ is the total mass of n TLCDs. Then, the governing equations of structure–MTLCD system motion can be expressed in a matrix form as

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = \mathbf{F} \tag{3}$$

where $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ denote the mass, damping, and stiffness matrices of the structure–MTLCD system, respectively; $\mathbf{F}$ represents external force; and $\mathbf{X}$ indicates the displacement vector. These matrices take the following forms:

$$\mathbf{M} = \begin{bmatrix} m_{s1} & 0 & 0 & \cdots & \cdots & \cdots & 0 \\ 0 & \ddots & 0\ \mathbf{M_s} & \cdots & \cdots & \cdots & 0 \\ 0 & 0 & m_{sN}+m_{f,total} & m_{11} & m_{12} & \cdots & m_{1n} \\ \vdots & \vdots & m_{11} & m_{21} & 0 & \cdots & 0 \\ \vdots & \vdots & m_{12} & 0 & m_{22} & \cdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & m_{1n} & 0 & \cdots & 0 & m_{2n} \end{bmatrix},\quad \mathbf{C} = \begin{bmatrix} c_{s1}+c_{s2} & -c_{s2} & 0 & \cdots & \cdots & \cdots & 0 \\ -c_{s2} & \ddots & -c_{sN}\ \mathbf{C_s} & \cdots & \cdots & \cdots & 0 \\ 0 & -c_{sN} & c_{sN} & 0 & \cdots & \cdots & 0 \\ \vdots & \vdots & 0 & c_{f2} & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & 0 & \ddots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & c_{fn} \end{bmatrix},$$
$$\mathbf{K} = \begin{bmatrix} k_{s1}+k_{s2} & -k_{s2} & 0 & \cdots & \cdots & \cdots & 0 \\ -k_{s2} & \ddots & -k_{sN}\ \mathbf{K_s} & \cdots & \cdots & \cdots & 0 \\ 0 & -k_{sN} & k_{sN} & 0 & \cdots & \cdots & 0 \\ \vdots & \vdots & 0 & k_{f2} & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & 0 & \ddots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & k_{fn} \end{bmatrix},\quad \mathbf{F} = \begin{Bmatrix} m_{s1} \\ \vdots\ \tilde{\mathbf{M}}_\mathbf{s} \\ m_{sN}+m_{f,total} \\ m_{11} \\ m_{12} \\ \vdots \\ m_{1n} \end{Bmatrix}\ddot{x}_g,\quad \ddot{\mathbf{X}} = \begin{Bmatrix} \ddot{x}_1 \\ \vdots \\ \ddot{x}_N\ \ddot{\mathbf{x}} \\ \ddot{y}_1 \\ \ddot{y}_2 \\ \vdots \\ \ddot{y}_n \end{Bmatrix},\quad \dot{\mathbf{X}} = \begin{Bmatrix} \dot{x}_1 \\ \vdots \\ \dot{x}_N\ \dot{\mathbf{x}} \\ \dot{y}_1 \\ \dot{y}_2 \\ \vdots \\ \dot{y}_n \end{Bmatrix},\quad \mathbf{X} = \begin{Bmatrix} x_1 \\ \vdots \\ x_N\ \mathbf{x} \\ y_1 \\ y_2 \\ \vdots \\ y_n \end{Bmatrix} \tag{4}$$

where $\mathbf{M_s}$, $\mathbf{C_s}$, and $\mathbf{K_s}$ denote the mass, damping, and stiffness matrices of the numerical substructure, respectively. The natural frequency of the ith TLCD is calculated by

$$f_{fi} = \frac{1}{2\pi}\sqrt{\frac{2g}{L_{1i}}} \tag{5}$$

where $L_{1i} = 2V_i + H_i\eta_i$. It is clear in Eq. (5) that the TLCD is suitable only for controlling structures with low fundamental frequency. When a structure with high fundamental frequency is considered, L_{1i} is quite small which will bring much hard for the design of TLCD.

In general, the state of MTLCDs is categorized into two types. In the first type, the designed TLCD is used to control the first-order modal response [10], as shown in Fig. 2(a). To clearly explain the frequency setting of each TLCD in MTLCD, the number of TLCD units (denoted by n) is assumed to be odd, and the frequencies of TLCD units are assumed to be uniform distributed. Hence, the difference of frequency between two adjacent TLCD units, denoted by Δf, is the same. The tuning frequency of MTLCDs is determined with the center frequency of $\bar{f} = (f_{f1} + f_{fn})/2$and the frequency interval of $\Delta f = f_{fi+1} - f_{fi},\ i = 1, \ldots, n-1$.