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Real-Time Hybrid Simulation of Single and Multiple Tuned Liquid Column Dampers for Controlling Seismic-Induced Response

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ABSTRACT
Tuned liquid column damper (TLCD) is a special type of tuned liquid damper to dissipate energy of structures subjected to dynamic loads. Due to its geometric flexibility and low prime costs, TLCD is a good alternative over other damping measurements for slender structures. In this paper, the real-time hybrid simulation (RTHS) technique is employed to investigate the dynamic behavior of structures with TLCDs attached, which intend to simultaneously suppressing single and multiple modal responses. First, the verification of RTHS is demonstrated by means of a single TLCD controlling a single degree-of-freedom shear frame, and variations of structural parameters are also considered to study their effects on control efficiency. Then, the dynamic response of a 9-story benchmark building under the control of single and multiple TLCDs is further investigated. Reduction efficiencies of TLCDs are evaluated by comparing the results with those without TLCD. Results show that TLCD could play excellent performance to control seismic-induced responses.

KEYWORDS: *real-time hybrid simulation, tuned liquid column damper, reduction efficiency, multi-mode response*

1. INTRODUCTION

The structural vibration of tall and slender buildings that are subjected to wind or seismic loadings is a critical issue in civil engineering. Consequently, structural control technique is widely-used to suppress the structural vibration. Tuned liquid column damper (TLCD) is a type of passive control device that receives much attention because of its excellent absorption effect, low cost, and easy maintenance. A TLCD consists of a liquid-filled U-shaped tube container that is rigidly connected to a main structure. The frequency of the liquid in TLCD can be tuned to be to an eigenfrequency of the main structure by properly designing the geometry of the tube container. TLCD dissipates energy by combining the liquid movement, the restoring force caused by the impulse, and the damping force attributed to the inherent head loss characteristics.

The original concept of controlling structural vibration via TLCD was first proposed by Sakai et al. [1]; then, it experienced a developing process from single TLCD (STLCD) to multiple TLCDs (MTLCD). Most previous studies focused on theoretical and numerical analysis to investigate characteristics of TLCD, especially the nonlinear damping effect [2-5]. Parametrical studies are also extensively carried out to examine the effect of mass ratio, structural damping and stiffness, and geometrical sizes on the vibration reduction effectiveness of TLCD [1-3, 6]. In addition, numerous small-scale shaking table tests were conducted to evaluate the TLCD performance experimentally [4, 7-8]. However, these studies exhibit the following limitations: (1) for numerical simulation, though numerous techniques have been proposed to simulate the nonlinear damping force, the exact solution of motion of liquid remains difficult to be obtained; (2) for small-scale experiments, the relation between the scale effect and the nonlinearity is an issue; and (3) for conventional shaking table test, STLCD or MTLCD experiments for multiple degree-of-freedom (MDOF) or complex structures needs high requirement of experimental setup. Given this situation, a new approach must be developed for TLCD study in a convenient manner.

Real-time hybrid simulation (RTHS) is an emerging experimental technique for investigating the structural dynamic behavior by partitioning a structure into physical and numerical substructures [9]. The numerical substructure is numerically simulated in a computer, whereas the physical substructure is tested on a shaking table. RTHS has two unique advantages: (1) full- or large-scale models can be tested; and (2) nonlinear behavior of complex structures can be investigated. At present, RTHS has been utilized for the study of nonlinear damper devices. The performance of TLD for SDOF and MDOF structures was investigated comprehensively through RTHS [10-12].

In this paper, the application of TLCD on reducing structural vibration is extensively investigated through RTHS. Section 2 illustrates the RTHS framework for the structure-TLCD system. Section 3 first verifies the accuracy of RTHS by comparing responses of a single degree-of-freedom (SDOF) steel frame-TLCD system with those obtained from conventional shaking table test; then, studies the effects of key parameters of mass ratio, structural damping ratio and structural stiffness on STLCD effectiveness. The nonlinear behaviour of the STLCD is experimentally investigated as well. Section 4 conducts RTHS investigations to compare difference of control performance of TLCD for controlling single- and multiple-modal responses. Section 5 presents the conclusions.

2. RTHS FRAMEWORK OF STRUCTURE-TLCD SYSTEM

It is assumed that a STLCD is installed at the top of a shear-type SDOF structure to mitigate responses under base excitation, as shown in Fig. 2.1. The governing equations of the structure-TLCD system can be expressed as follows:

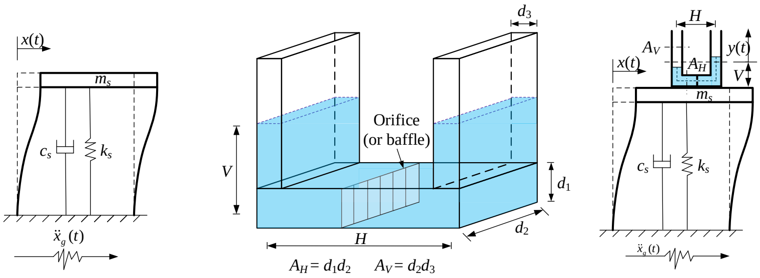

Figure 2.1 Structure-TLCD system

$$\begin{bmatrix} m_s+m_f & m_1 \\ m_1 & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix}+\begin{bmatrix} c_s & 0 \\ 0 & c_f \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix}+\begin{bmatrix} k_s & 0 \\ 0 & k_f \end{bmatrix}\begin{Bmatrix} x \\ y \end{Bmatrix}=-\begin{Bmatrix} m_s+m_f \\ m_1 \end{Bmatrix}\ddot{x}_g \tag{1.1}$$

where m_s, k_s, and c_s are the mass, stiffness, and damping of the structure, respectively. $m_f = \rho_w A_V L_2$, $m_1 = \rho_w A_V H$, $m_2 = \rho_w A_V L_1$ with $L_1 = 2V + \alpha H$, $L_2 = 2V+ H/\alpha$ where A_V and A_H are the vertical and horizontal cross-sectional areas of TLCD, respectively; $\alpha = A_V/A_H$ is defined as the cross-sectional area ratio; V and H are the lengths of the liquid in the vertical and horizontal directions, respectively; ρ_w is the density of the liquid in TLCD; x and y are the displacements of the structure and of the liquid in the vertical column, respectively; the upper dots in x and y represent time derivatives; $\ddot{x}_g$ denotes the ground acceleration; ξ and g are the head loss coefficient and the gravitational acceleration, respectively; $c_f = (1/2)\rho_w \alpha A_V \xi |\dot{y}|$ denotes the liquid damping; and $k_f = 2\rho_w A_V g$ is the stiffness of liquid. Then, the natural frequency of TLCD can be calculated by $f_f = 1/2\pi\sqrt{2g/L_1}$.

In RTHS, the prototype TLCD is modeled as the physical substructure and experimented in shaking table alone; while the main structure is numerically simulated in computer. The RTHS framework is displayed in Fig. 2.2. Herein, the equation of motion of structure in Eq. 1.1 can be written as

$$m_s\ddot{x}+c_s\dot{x}+k_s x = -m_s\ddot{x}_g \underbrace{-[m_f(\ddot{x}+\ddot{x}_g)+m_1\ddot{y}]}_{F_{TLCD}} \tag{1.2}$$

where F_{TLCD} is the measured force at the interface between the TLCD and the structure in RTHS. In this manner, the dynamic response of the emulated system can be obtained, avoiding additional solution for the nonlinearity equation of motion of the TLCD. In this paper, the Gui-λ method (λ = 11.5), a new explicit integration algorithm proposed by Gui et al. [13], is employed to solve Eq. 1.2 in real-time. The integration time-step is selected as Δt = 1/2048 s.

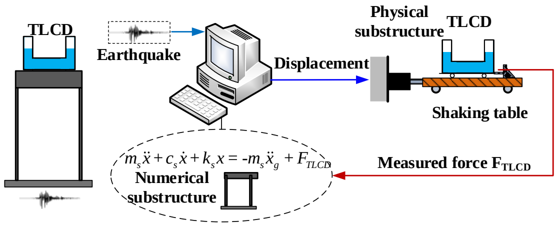

Figure 2.2 RTHS framework for TLCD experiments

3. RTHS OF SDOF STEEL FRAME-STLCD SYSTEM

3.1. Accuracy verification of RTHS system

In this section, the performance of a STLCD controlling dynamic responses of a SDOF steel frame is investigated through RTHSs and conventional shaking table tests. The accuracy of the RTHS system discussed in Section 2 is verified by comparing the results obtained from the two types of experimental methods. The experimental configurations are displayed in Fig. 3.1.

The SDOF steel frame, shown in Fig. 3.1, has the following structural parameters: mass m_s = 198.16 kg, natural frequency f_s = 1.526 Hz, and damping ratio ζ_s = 0.5%. Correspondingly, a STLCD system, made of plexi-glass, is designed to control the response of the SDOF steel frame. This STLCD consists three small TLCDs which have absolutely the same geometrical sizes (see Table 3.1). Finally, the natural frequency of the liquid in the STLCD is 1.527 Hz which is almost exactly the same as f_s; and the mass ratio for each small TLCD is μ = 0.79%, which results the total mass ratio of the STLCD to be μ_{total} = 2.37%.

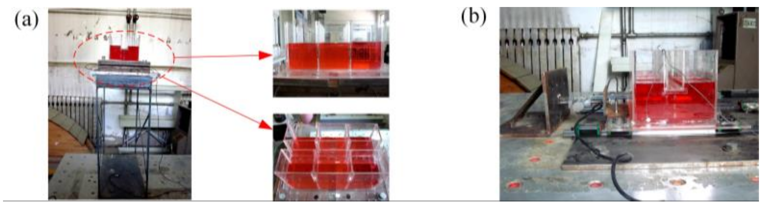

Figure 3.1 Configurations of STLCD experiments: (a) conventional shaking table test and (b) RTHS

Table 3.1 Parameters for each small TLCD in the STLCD system.

H (m)	V (m)	d_1 (m)	d_2 (m)	d_3 (m)	A_H (m^2)	A_V (m^2)	f_f (Hz)	μ (%)
0.111	0.051	0.0734	0.10	0.0734	0.00734	0.00734	1.527	0.79

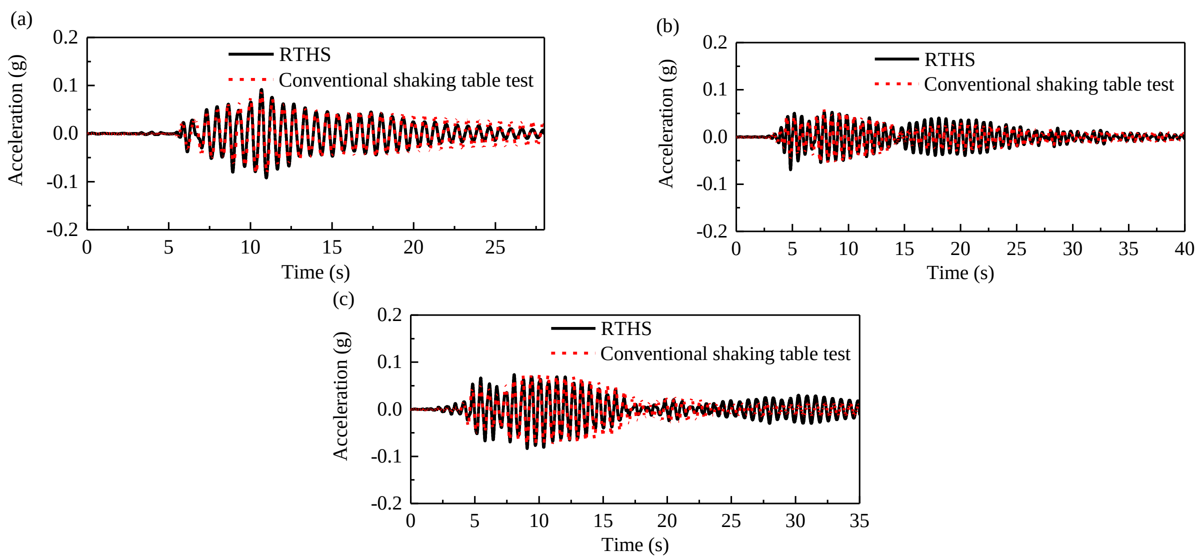

Figure 3.2 Comparison of the acceleration responses between the RTHS and the conventional shaking table test using (a) Kobe, (b) El Centro and (c) Taft earthquakes

Three ground motions, namely Kobe, El Centro, and Taft, are selected as the ground accelerations. Taken into account the movement of the liquid in STLCD and the safety of the steel frame, the peak acceleration of each ground motion is scaled to 0.025 g. Fig. 3.2 gives the comparison of the acceleration responses at the top of the SDOF steel frame that obtained from the RTHS and the conventional shaking table test, respectively. Good agreement between the conventional shaking table test and RTHS can be observed. Fig. 3.3 presents the quantitative peak and RMS acceleration values, as well as the error results between these two experiment methods. The peak acceleration errors for the Kobe, El Centro and Taft earthquakes are 4.44%, 10.17%, and 13.89%, respectively; the corresponding RMS acceleration errors for the Kobe, El Centro and Taft earthquakes are 6.89%, 5.56%, and 3.85%, respectively. These results demonstrate that the RTHS can capture the dynamic response of STLCD controlled system effectively.

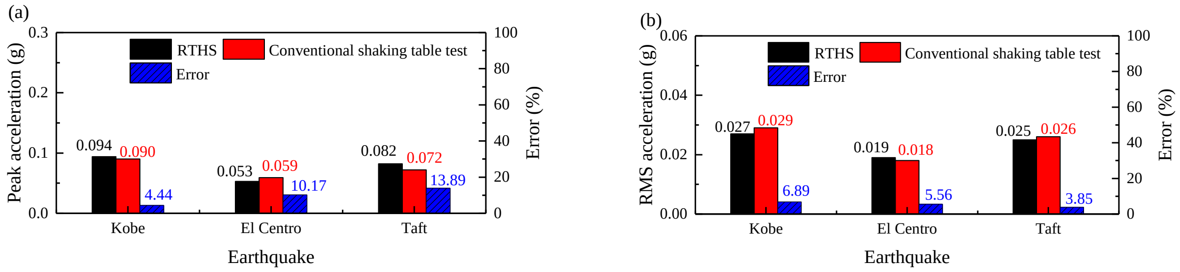

Figure 3.3 Error comparison between the RTHS and the conventional shaking table test

3.2 Parametric studies

In this section, a series of RTHSs is conducted to investigate the effects of structural parameters and excitation parameters on the reduction efficiency of STLCD by exploiting the convenient adjustment of RTHS parameters. It should be noted that the dynamic responses of the pure SDOF steel frame without TLCD control in this section are provided by numerical simulations solved by Gui-λ method (λ = 11.5) [13].

3.2.1. Mass ratio

Mass ratio is a crucial parameter when designing the TLCD. In this section, six values of μ (μ = 0.79%, 1.58%, 2.37%, 3.16%, 3.95%, and 4.74%) are considered. The case wherein μ = 2.37% is discussed in Section 3.1.

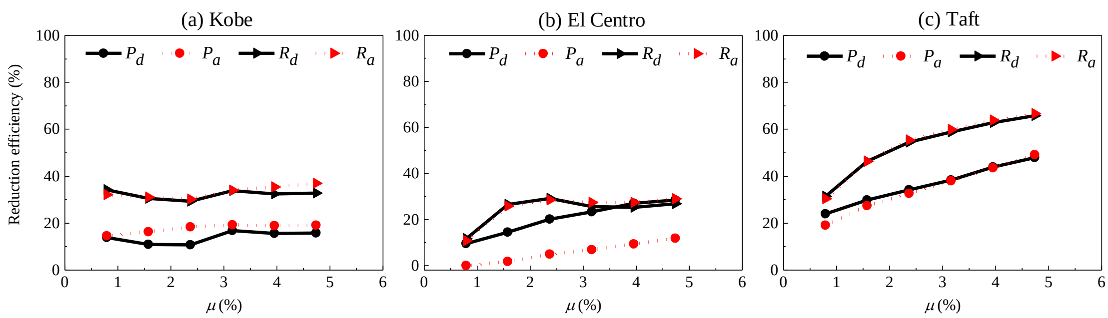

Figure 3.4 Comparison of reduction efficiency of TLCD under different mass ratios (P_d: peak displacement; P_a: peak acceleration; R_d: RMS displacement; R_a: RMS acceleration)

As shown in Fig. 3.4, the RTHS results obtained with the STLCD are compared with the numerical results in the absence of TLCD. For the three ground motions, the reductions of both the peak and RMS responses (displacement and acceleration) increase with μ increasing. It is worth noting that the reduction for smaller mass ratios (i.e., no more than 3.16%) have more significant growth than those for larger mass ratios (i.e., more than 3.16%). These results imply that a large mass ratio may not correspond to an equally high reduction efficiency. Hence, a range of μ from 2% to 3% is recommended as the optimum value from a practical view.

3.2.2. Structural damping ratio

The structural damping ratio ζ_s is examined in this section. Four ζ_s with values of 0.5%, 2%, 5%, and 8% are selected to conduct the RTHSs. All of the parameters in this section are the same as those presented in Section 3.1, with the exception of ζ_s.

It can be seen from Fig. 3.5 that the control efficiency in both the peak and RMS responses decrease as ζ_s increases. A significant decrease of reduction efficiencies occurs when ζ_s ranges from 0.5% to 2%; after this range, the reduction efficiencies are almost unchanged. It is concluded that the performance of STLCD is more sensitive given low structural damping ratios than given high structural damping ratios. Hence, the STLCD may be effective only for structures with low damping ratios in the range of 0.5%-2%.

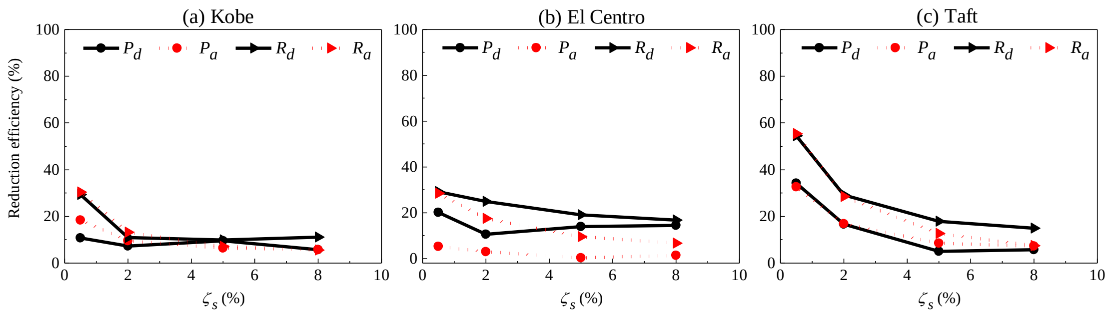

Figure 3.5 Comparison of reduction efficiency of the STLCD under different structural damping ratios

3.2.3 Structural stiffness

Because of degradation effect, temperature effect or soil conditions, the stiffness reduction of structure may happen, which may induce performance variation for TLCD. Under this background, the effect of structural stiffness on the reduction efficiency of the STLCD is discussed in this section by evaluating the control performance when uncertainty in the structural stiffness exists. The variation ratios of $\Delta k_s = \pm 20\%$ for the structural stiffness are considered.

Fig. 3.6 compares the corresponding performance indices of the STLCD. It is clear that the effectiveness of the STLCD strongly depends on the variation of structural stiffness and the frequency content of the excitation. Hence, when designing TLCD, the tuning ratio of TLCD should be guaranteed to ensure its performance.

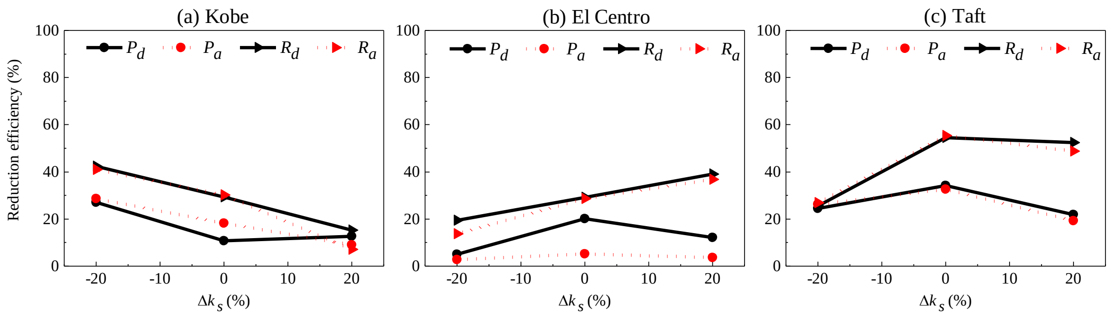

Figure 3.6 Comparison of reduction efficiency of TLCD under variation of structural stiffness

3.2.4 Load level of the ground motion input

The nonlinear behavior of TLCD is a well-known phenomenon which directly determines the performance of TLCD. Considering the maximum displacement of the STLCD, the three ground motions with peak values of 0.0125 g, 0.025 g, 0.0375 g, and 0.05 g are taken into account, respectively. It should be noted that the RTHSs with the peak acceleration of 0.025 g have been carried out in Section 3.1.

Fig. 3.7 plots the comparison of reduction effectiveness of the STLCD under the three ground motions with different peak accelerations. As the peak acceleration of the input ground motion is increased from 0.0125 g to 0.025 g, the reduction efficiency of the STLCD, especially for the aspect of RMS response, is improved for the three ground motions; while with the peak acceleration increasing from 0.025 g to 0.05 g, the reduction efficiency of the STLCD decreases rapidly. This observation illustrates that the performance of TLCD is amplitudedependent, demonstrating that the nonlinear behavior of TLCD is of significance in structural control of vibrations with high amplitudes.

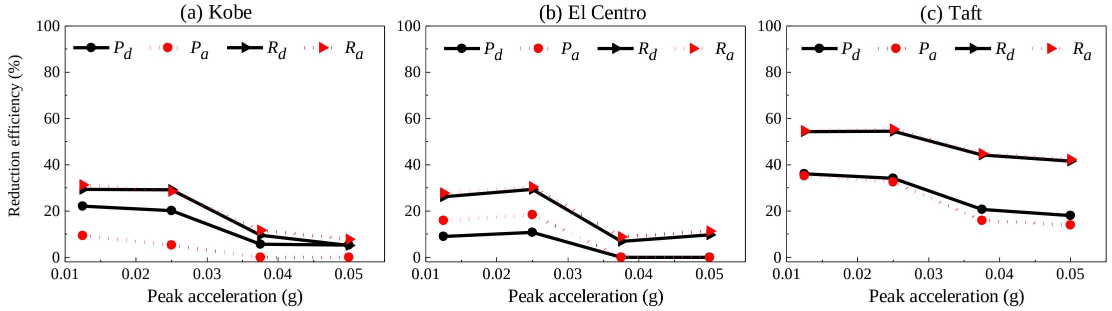

Figure 3.7 Comparison of reduction of the STLCD under the three ground motions with different peak values

4. RTHS OF A 9-STORY BENCHMARK BUILDING-TLCD SYSTEM

A 9-story benchmark building [14], designed for the SAC Phase II Steel Project to provide a clear basis to evaluate the efficiency of various structural control strategies, is used as the studied model. The schematic view of this building is shown in Fig. 4.1. Ohtori et al. [14] proposed a finite element model to describe this model, while Maghareh et al. [15] simplified this model to be a shear-type model system with 9 DOFs. In this study, this shear-type model is employed to simplify the numerical simulation in RTHS.

In this shear-type model, the mass and stiffness matrices can be founded in paper [15]. The modal damping with damping ratio of 2% is applied. The natural frequencies of the 9-story benchmark building are 0.449 Hz, 1.178 Hz, 1.975 Hz, 2.737 Hz, 3.436 Hz, 4.013 Hz, 4.573 Hz, 5.332 Hz and 6.122 Hz. The total mass of the structure is 9.90×10^6 kg. Considering the bearing capability of shaking table, the mass scale is assumed as $C_m=10^4$, while the time scale and acceleration scale are assumed to be $C_t = C_a = 1$. Under this condition, the dynamic responses obtained from experiments are exactly the same as those obtained from prototype structures.

Correspondingly, two types of TLCD, named TLCD-A and TLCD-B, are designed to control the first two modal responses of this benchmark building. The parameters and pictures of these two types of TLCDs are shown in Table 4.1 and Fig. 4.1, respectively. Two experiment configurations are considered: (1) Configuration #1 uses one TLCD-A to control the first modal response, and (2) Configuration #2 uses one TLCD-A and three TLCD-B to control the first two modal responses. Hence, the mass ratio for these two configurations are 2.2% and 3.5%, respectively. Considering the first two order mode shapes have the maximum displacement at the top of the structure, both TLCD-A and TLCD-B are installed at the roof. For Configuration #2, the RTHS is carried out by setting TLCD-A and TLCD-B on two shaking tables. Noted that only one TLCD-B is fixed at a shaking table, and the measured force will be multiplied by 3 to obtain the corresponding feedback force for 3 TLCD-B.

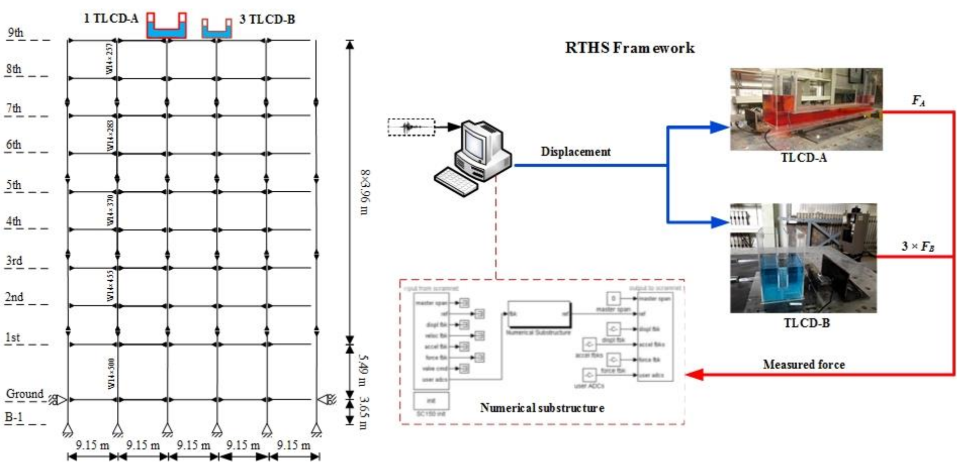

Figure 4.1 RTHS framework for the TLCD controlled system

Table 4.1 Parameters for TLCDs

Name	H (m)	V (m)	d_1 (m)	d_2 (m)	d_3 (m)	A_H (m^2)	A_V (m^2)	f_f (Hz)	μ (%)
TLCD-A	1.3	0.15	0.0773	0.18	0.1225	0.0139	0.0221	0.459	2.20
TLCD-B	0.1	0.12	0.06	0.177	0.06	0.0108	0.0108	1.188	0.43

The three ground motions used in Section 3 is reemployed to excite the structure, in which the peak acceleration is scaled to 0.05 g. Fig. 4.2 compares the displacement and acceleration responses in frequency domain at the top of the structure without TLCD control, with TLCD-A control and with TLCD-A + TLCD-B control. Fig. 4.3 provides the comparison of reduction effectiveness. For Kobe and El Centro earthquakes, the TLCD-A shows excellent reduction for the displacement responses but less good reduction for the acceleration responses. This is because that the acceleration response of the second-order mode is relative strong. For Taft earthquake, the second-order mode response is mainly excited so that the efficiency of TLCD-A is not as well as that under Kobe and El Centro earthquakes. When both TLCD-A and TLCD-B are applied, it is observed that the second-order mode responses are reduced significantly, especially for the acceleration responses under Kobe and El Centro earthquakes, and both displacement and acceleration responses under Taft earthquake.

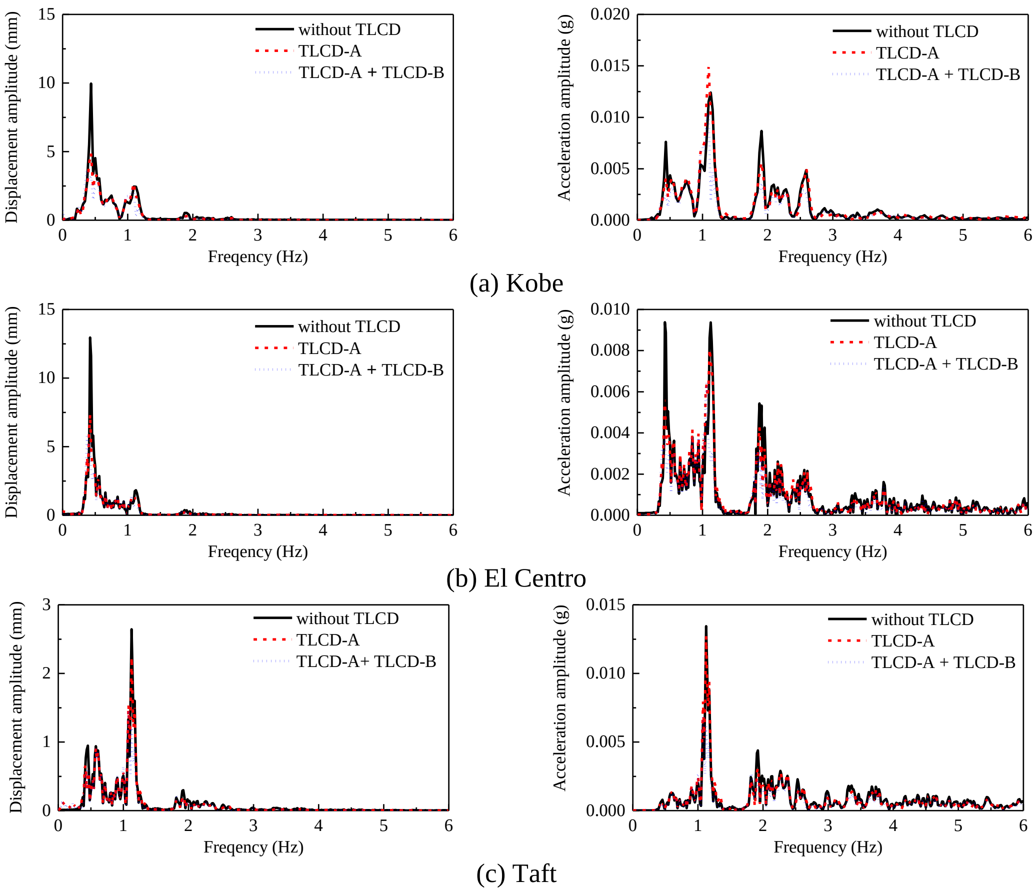

Figure 4.2 Comparison of Fourier spectrums of responses (left: displacement; right: acceleration) between the TLCD-A for one order mode control and TLCD-A + TLCD-B for two order modes control

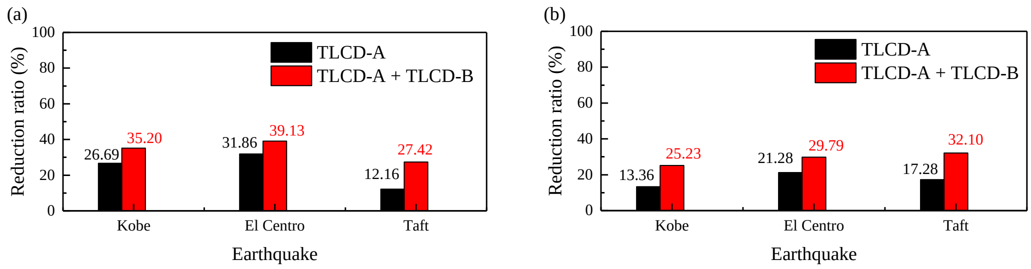

Figure 4.3 Comparison of reduction for RMS responses between the TLCD-A (a) and TLCD-A + TLCD-B (b)

5. CONCLUSIONS

In this paper, the RTHS is employed to investigate the performance of TLCD for controlling the seismic-induced structural responses. The TLCD is physically experimented, and the structure is assumed as the numerical substructure and analytically simulated. Comparison of the dynamic responses between the RTHS and the conventional shaking table test of the SDOF steel frame-STLCD system verifies that the RTHS could achieve satisfactory accuracy. It is found that the STLCD shows a superior performance when the mass ratio is set in the range of 2%-3% and when the structural damping ratio is lower than 2%. The uncertainty of structural stiffness changes the structural frequency which results in the performance variation of STLCDs under different earthquakes. In addition, the reduction effectiveness of the STLCD could be improved with the increase of the peak acceleration of earthquake inputs. By contrast, this effectiveness may be lost when earthquake inputs are relatively strong. For RTHSs of the 9-story benchmark building installed with TLCDs, it is concluded that using MTLCD to control multi-modal responses is an effective manner to mitigate both displacement and acceleration responses.

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