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Real-time hybrid shaking table testing method for the performance evaluation of a tuned liquid damper controlling seismic response of building structures

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Abstract

In this paper, a real-time hybrid shaking table testing method (RHSTTM) is experimentally implemented for evaluating the performance of a tuned liquid damper (TLD) controlling a seismically excited building structure. The RHSTTM does not require a physical building structural model in performing the experiment of a TLD–structure interaction system and it only uses a TLD and a shaking table. The structural responses of the interaction system are calculated numerically in real time using an analytical building model, a given earthquake record, and a shear force generated by the TLD, and the shaking table reproduces both the controlled and uncontrolled absolute acceleration of the TLD installed floor by modulating the feedback gain of the shear force signal measured by the load-cell positioned between the TLD and the shaking table. Comparison between the structural responses obtained by the RHSTTM and the conventional shaking table test of a single story steel frame with TLD indicates that the performance of the TLD can be accurately evaluated using the RHSTTM without the physical structural model. Finally, the uncontrolled and TLD-controlled structural responses of a three story structure are obtained by the RHSTTM in both time and frequency domains, showing that TLD can effectively mitigate the seismic responses of building structures.

1. Introduction

Investigation on the dynamic behaviors of large-scale civil engineering structures such as building and bridge by performing full scale test is very difficult or often practically impossible to be realized due to the size, weight, cost, etc. Therefore, the behavior of the whole structure is estimated generally based on the test results obtained by using a scale-down model or a critical part of the entire structure. Takanashi et al. [1,2] have firstly developed the pseudo-dynamic testing method, in which only a part of whole structure, particularly being expected to show nonlinearity, is manufactured and tested while the remainder showing linearity is

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numerically calculated. Because there exists propagation of experimental errors in pseudo-dynamic testing methods, the stability and accuracy of the numerical integration methods were investigated [3,4]. In these pseudo-dynamic testing methods, as implied in the name, the experimental part is not "dynamically" but "statically" excited under the loading condition which makes the testing part represent identical displacement response to that of the part in whole structure excited by considered dynamic load such as ground acceleration.

Recently, due to the improvement of the actuator performance and signal processing technology, not only the displacement but also velocity or acceleration component in dynamic loads can be realized in the experimental loading condition. A real-time hybrid testing method (RHTM) has been developed and applied to a lot of tests for the seismic performance assessment of large-scale structures. In the RHTM, both experiment and numerical parts are simultaneously implemented in the same manner as the pseudo-dynamic testing method, but the experimental part is not statically but dynamically excited [5].

This RHTM can be adopted for the performance evaluation of a base isolator or energy dissipation devices, which have been widely used for the vibration mitigation of large-scale structures vulnerable to wind or earthquake load. Pan et al. [6] have developed a mixed control algorithm utilizing displacement and force, and applied the RHTM to a base-isolated structure, of which behaviors were identified by dealing with base-isolation layer experimentally and the rest of the upper structure model numerically. Horiuchi et al. [7] compensated the time-delay effect caused mainly by analytical procedure in the RHTM. For its experimental verification, a small portion of a mass was separated from a mass–spring–dash-pot system and only the small portion of the mass was tested considering the effects of the other parts analytically. Iemura et al. [8] and Igarashi et al. [9] verified the effect of vibration control devices such as a tuned mass damper (TMD) and an active mass damper (AMD) installed in a structure excited by ground acceleration, using the real-time hybrid shaking table testing method (RHSTTM) in which the control devices were experimental parts and the remaining structural model was a numerical part. The acceleration signal of the moving mass of the devices was measured and used as input to the numerical model.

Tuned liquid damper (TLD) dissipates structural vibratory energy by tuning the frequency of the liquid sloshing to the one of the structure [10]. Its inherent damping results from wave breaking and the impact of liquid on the TLD container walls [11]. TLD has been generally applied to the control of wind-induced acceleration response [12], and recently, some investigations on the seismic control performance of the TLD have been made [13]. In order to describe the behavior of the TLD, linear model based on TMD analogy [14] and linear wave theory, nonlinear stiffness and damping model [15], and sloshing–slamming analogy [16,17] can be used. However, because any model has error in capturing the real dynamic characteristics of the control force generated by the TLD and furthermore the error increases for the case of non-stationary excitation such as earthquake, evaluation of the seismic control performance of the TLD only numerically has accuracy problem.

In this paper, the vibration control effect of a TLD for a building structure excited by earthquake load is experimentally evaluated through the RHSTTM. The RHSTTM does not require a physical building structural model in performing the experiment of a TLD–structure interaction system and it only uses a TLD which is known to have strong nonlinearity dependent on response amplitude, excitation frequency, and depth to length ratio [15]. The structural responses of the interaction system are calculated numerically in real time using the analytical structural model with the excitations of measured control force, user-defined base earthquake loads, and its state space realization incorporated in the integrated controller of the shaking table. Also, in order to minimize the distortion of the acceleration of the shaking table, the inverse transfer function of the shaking table is identified and its state space realization is implemented in the shaking table controller. The shaking table reproduces both the controlled and uncontrolled absolute acceleration of the TLD installed floor by modulating the feedback gain of the shear force signal measured by the load-cell positioned between the TLD and the shaking table. Comparison between the structural responses obtained by the RHSTTM and the conventional shaking table test of a single story steel frame with TLD is made in order to verify the accuracy of the RHSTTM and the uncontrolled and TLD-controlled structural responses of a three story structure are obtained by the RHSTTM in both time and frequency domains.

2. Real-time hybrid shaking table testing method

Fig. 1 depicts the conceptual illustrations of the RHSTTM for an n-degrees-of-freedom structural model which is excited by base acceleration and has a TLD at its top story. First, the whole control system is separated into the lower part structure, and the upper part TLD and the interaction force between the structure and TLD is considered. The TLD with the interacting force at its bottom is physically tested and the response of the structure with interacting force at the top floor and the base acceleration is numerically calculated by using the computer controlling motion of the shaking table. Measurement of interacting force is easily accomplished by installing a shear-type load-cell at the bottom of the TLD, as shown in Fig. 1. TLD-generated shear force is fed-back to the control computer. With this fed-back interacting force, the structural response of the story, where a TLD is installed, is calculated using the numerical part. The shaking table excites the upper TLD according to this calculated response. This process is carried out on real-time.

The numerical part with n-DOFs, which is subjected to the excitations of the measured control force, $i_e(t)$, and the input acceleration, $\ddot{z}_0(t)$, at its top and bottom, respectively, as enclosed in dotted line in Fig. 1, is calculated by

$$[M]\{\ddot{Y}_i(t)\} + [C]\{\dot{Y}_i(t)\} + [K]\{Y_i(t)\} = \{p(t)\}, \tag{1}$$

where $\{Y_i(t)\}$ is the absolute displacement at the ith$(i = 1\text{–}n)$ story, and the location vector of external forces with the length of n, $\{p(t)\}$ equals to $\{-i_e(t), 0, \ldots, 0, c_1\dot{z}_0(t) + k_1 z_0(t)\}^{\mathrm{T}}$, in which subscript "$e$" denotes the "experimentally" measured interacting force. Also, the structural mass, damping and stiffness matrices are represented by

$$[M] = \begin{bmatrix} m_n & & & \\ & m_{n-1} & & \\ & & \ddots & \\ & & & m_1 \end{bmatrix}, \quad [C] = \begin{bmatrix} c_n & -c_n & \\ -c_n & c_n + c_{n-1} & -c_{n-1} \\ \ddots & \ddots & \ddots \\ & -c_2 & c_2 + c_1 \end{bmatrix}, \quad [K] = \begin{bmatrix} k_n & -k_n & \\ -k_n & k_n + k_{n-1} & -k_{n-1} \\ \ddots & \ddots & \ddots \\ & -k_2 & k_2 + k_1 \end{bmatrix}. \tag{2}$$

To calculate the numerical part such as Eq. (1) by a control computer on real-time, it is transformed into the state-space representation given by

$$\begin{aligned} \{\dot{z}(t)\} &= [A_c]\{z(t)\} + [B_c]\{u(t)\}, \\ \{O(t)\} &= [C_c]\{z(t)\} + [D_c]\{u(t)\}, \end{aligned} \tag{3}$$

where the state variable vector, $\{z(t)\}$, with the length of $2n$ comprises the state variables,$\{\{y_i(t), \{\dot{y}_i(t)\}\}^{\mathrm{T}}$, in which the structural relative displacement, $\{y_i(t)\}$, equals to $\{Y_i(t)\} - z_0(t)$. The input vector, $\{u(t)\}$, with the length of 2 consists of $\{-i_e(t), \ddot{z}_0(t)\}^{\mathrm{T}}$. The output vector, $\{O(t)\}$, with the length of n corresponds to the

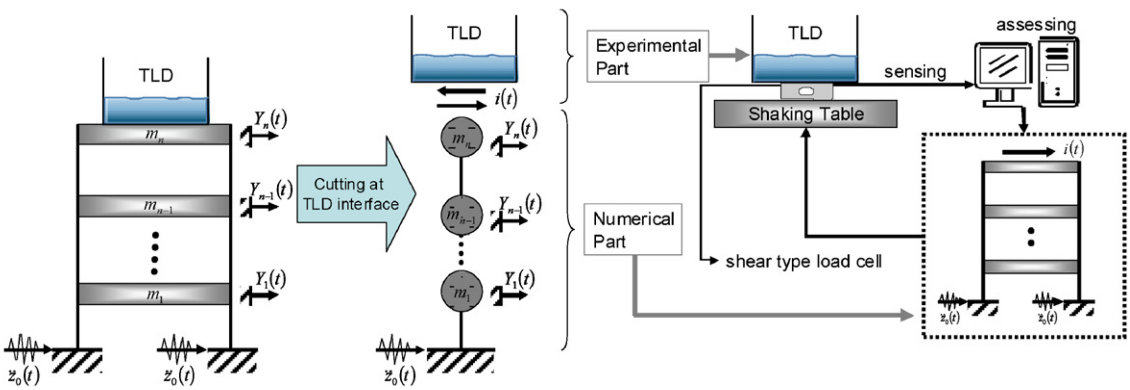

Fig. 1. Conceptual view of the real-time hybrid shaking table test.

structural absolute acceleration, $\{\ddot{Y}_i(t)\}$, itself. The matrices $[A_c]$, $[B_c]$, $[C_c]$ and $[D_c]$ with the sizes of $2n \times 2n$, $2n \times 2$, $n \times 2n$ and $n \times 2$, respectively, are expressed as follows:

$$[A_c] = \begin{bmatrix} [0]_{n\times n}, & [I]_{n\times n} \\ -[M]^{-1}[K], & -[M]^{-1}[C] \end{bmatrix}, \tag{4}$$

$$[B_c] = \begin{bmatrix} \{0\}_{n\times 1}, & \{0\}_{n\times 1} \\ [M]^{-1}\{b\}, & \{-1\} \end{bmatrix}, \tag{5}$$

$$[C_c] = \begin{bmatrix} -[M]^{-1}[K], & -[M]^{-1}[C] \end{bmatrix}, \tag{6}$$

$$[D_c] = \begin{bmatrix} [M]^{-1}\{b\}, & \{0\}_{n\times 1} \end{bmatrix}, \tag{7}$$

where [0] and $[I]$ are the zero and unit matrices, respectively, with the size of $n \times n$. $\{0\}$ and $\{-1\}$ are the vector whose components are 0 and -1, respectively, with the length of $n \times 1$. $\{b\}$ equals to $\{1, 0,\ldots,0\}^{\mathrm{T}}$ with the length of $n \times 1$.

3. Controller design

3.1. Experiment set-up

In order to experimentally verify the RHSTTM, an experimental system shown in Fig. 2 was set up in Seismic Retrofitting & Remodeling Research Center at the Dankook University, Seoul, South Korea. The TLD was uniaxially excited by the shaking table on which it was mounted. The shear-type load-cell was inserted between the TLD and the shaking table to measure the base shear force yielded by the horizontal motion of the TLD during the test. Also, an accelerometer was attached on the shaking table to monitor its motion. The data acquisition and implementation of the digital controller were conducted using a real-time digital signal processor (DSP). The primary tasks of the data acquisition board are the analog-to-digital (A/D) conversion of the measured force and acceleration data, and the digital-to-analog (D/A) conversion of the

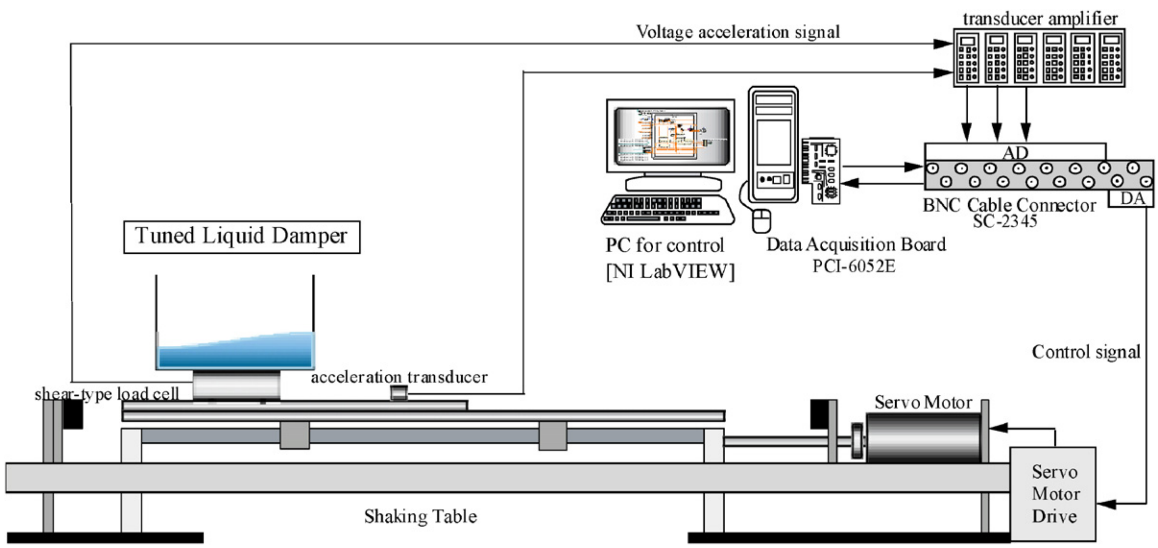

Fig. 2. Schematic diagram of experimental set-up.

reference signal computed by the control program LabVIEW [18]. An 8-channel data acquisition system was adopted using a NI PCI-6052E board and a NI SC-2345 B&C cable connector.

3.2. Shaking table dynamics

The motion of the shaking table shown in Fig. 2 is driven by the control signal that is sent from the control computer through DA channel of DAQ board. Without any compensation of the dynamic characteristics of the shaking table, the acceleration of the shaking table would not be as intended in their amplitudes and phases. An inverse transfer function of the shaking table, from the measured acceleration of the table to the reference signal within control computer, was used to cancel out the dynamic characteristics of the shaking table system and to control its motion with one's intention. At first, the transfer function, denoted as $G_e(s)$, from the reference signal to the shaking table acceleration, is obtained as shown in Fig. 3(a). Then, the inverse of the transfer function shown in Fig. 4 by the dotted line is incorporated in the control computer as a shaking table controller to eliminate the shaking table dynamics. In this paper, the approximation of the measured inverse transfer function was carried out using the 'invfreqs' command in MATLAB [19], which finds the real numerator and denominator coefficient vectors of the approximated transfer function in the form of fractional expression by adopting the damped Gauss–Newton method for iterative search to minimize the sum of the squared error between the measured and the approximated frequency response points [20]. The approximation result expressed in Fig. 4 by the solid line is given by the following fifth-order linear filter, and is considered in the control computer as a shaking table controller, as shown in Fig. 3(b)

$$G_n^{-1}(s) = \frac{0.6s^5 + 94s^4 + 10,746s^3 + 498,200s^2 + 167,124s + 108,216}{s^5 + 204s^4 + 15,900s^3 + 8252s^2 + 4676s + 405}, \tag{8}$$

where Laplace variable, s, equals to iω with imaginary constant, i.

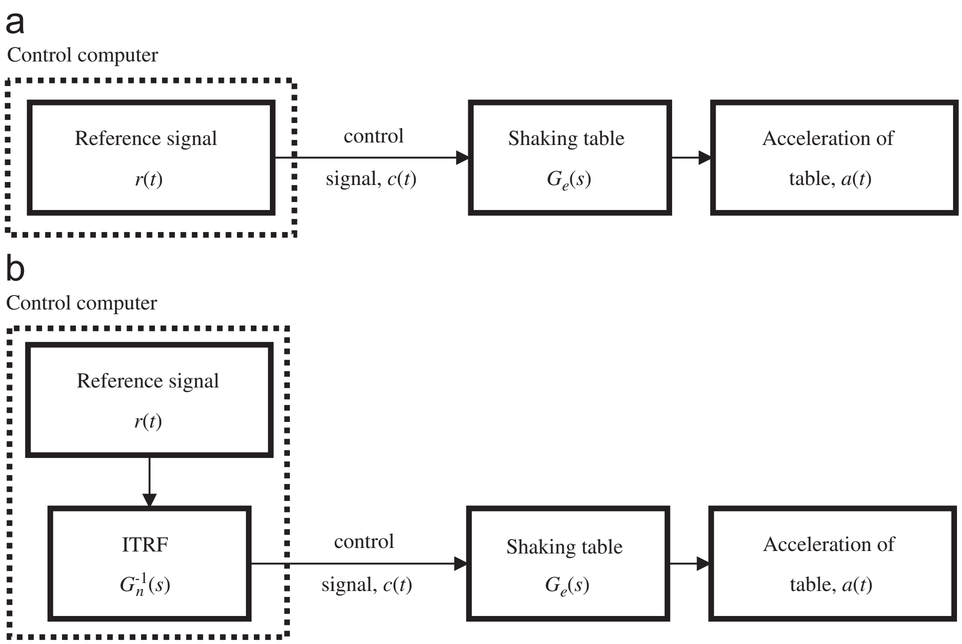

Fig. 3. Schematic diagram of shaking table controller: (a) definition of the transfer function of shaking table and (b) compensation using the inverse transfer function of shaking table.

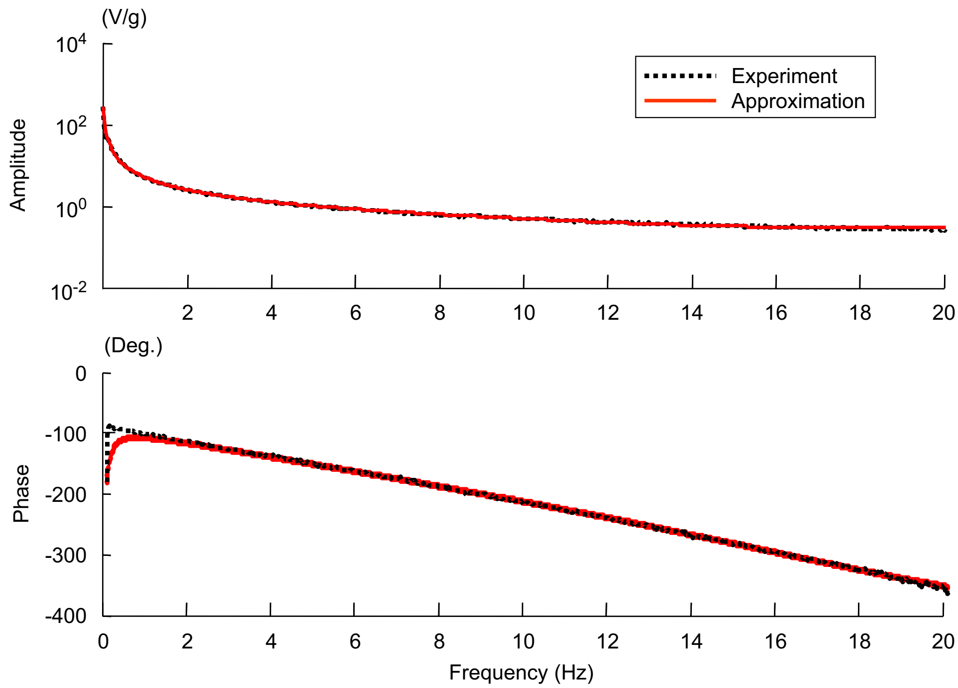

Fig. 4. Comparisons of the measured and the approximated inverse transfer function of shaking table.

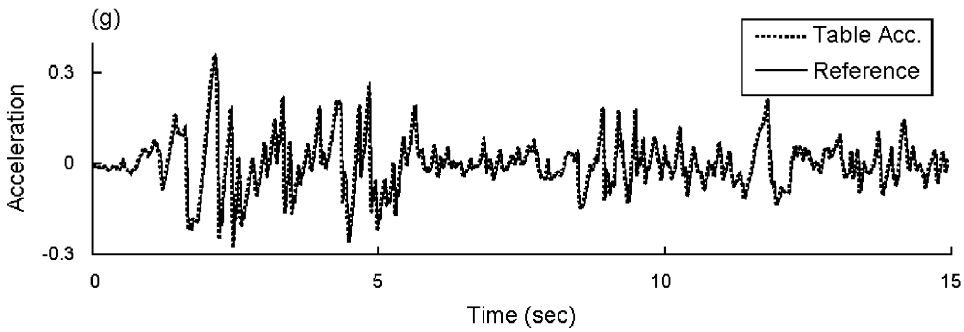

Fig. 5. Comparisons of the reference and the measured accelerations.

For its implementation in the control computer, Eq. (8) is converted into the following state space realization:

$$\begin{aligned}\{\dot{x}_s\} &= [A_s]\{x_s\} + [B_s]r(t),\\ c(t) &= [C_s]\{x_s\} + D_s r(t),\end{aligned} \tag{9}$$

where $\{x_s\}$, $r(t)$ and $c(t)$ are the state vector, the reference signal and the control signal of the shaking table, respectively. $[A_s]$, $[B_s]$, $[C_s]$ and D_s are the system matrix with the size of 5×5, the reference signal influence matrix with the size of 5×1, the output matrix with the size of 1×5 and the coupling coefficient between the reference and control signal, respectively.

In order to verify the shaking table controller performance, a down-scaled El Centro earthquake record is inputted to the approximated inverse transfer function of the shaking table as the reference signal. Then, the corresponding acceleration of the shaking table is measured. It is observed from Fig. 5 comparing between the

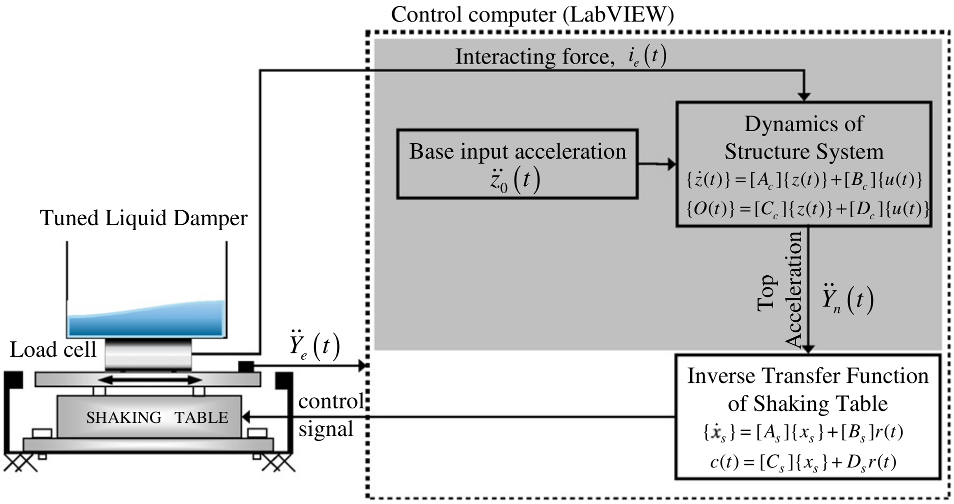

Fig. 6. Block diagram of the integrated controller for the real-time hybrid experimental system.

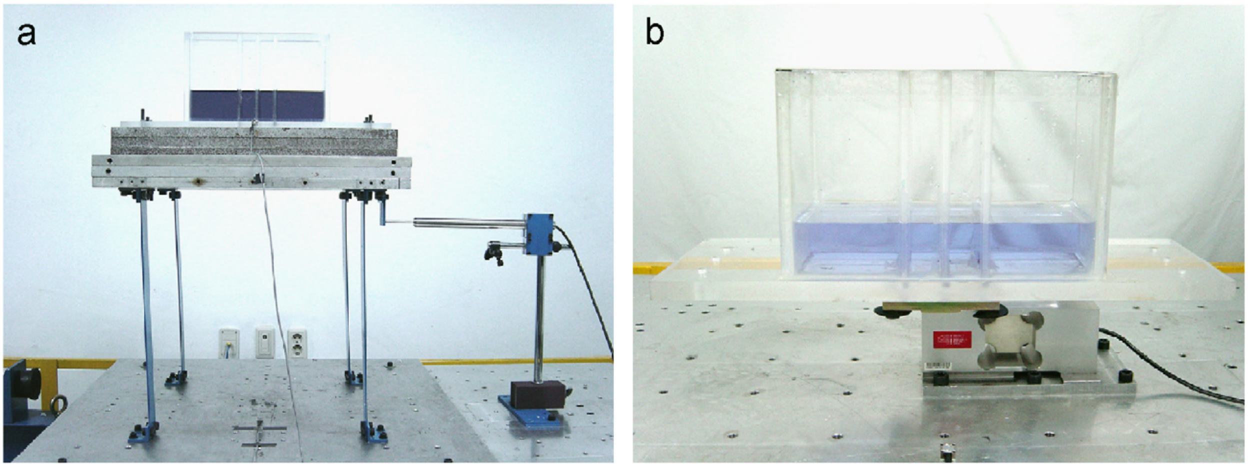

Fig. 7. TLD–structure interaction experimental system: (a) conventional shaking table test and (b) real-time hybrid shaking table test.

accelerations given by the reference signal and those measured from the shaking table that they agree well with each other.

3.3. Integrated controller of the numerical structural model and the shaking table

The numerical structural model and the shaking table dynamics discussed in the previous sections are integrated in the controller to implement the RHSTTM. Fig. 6 illustrates the block diagram for the RHSTTM. In the figure, the absolute acceleration is produced by the numerical structural model of Eq. (3) with two inputs of the measured interacting force, $i_e(t)$, and not the measured but the prescribed earthquake record signal, $\ddot{z}_0(t)$, as marked by the shaded area. The motion of the shaking table is driven by the controller using the inverse transfer function to minimize the error between the absolute acceleration, $\ddot{Y}_n(t)$, calculated as the top story response of the structure and the actual shaking table acceleration, $\ddot{Y}_e(t)$. Accordingly, the shaking table itself behaves as the top story of the structure, at which a TLD is installed, and excites the upper TLD that should be physically tested.

4. Experimental verification

4.1. A single story steel frame with a TLD

In this section, experimental verification of the RHSTTM is conducted for a single story steel frame with a TLD. First, the conventional TLD–structure interaction model shown in Fig. 7(a) is tested. Then, the RHSTTM shown in Fig. 7(b), which incorporates the single story steel frame in the numerical calculation, is performed and the results from the two testing methods are compared to each other.

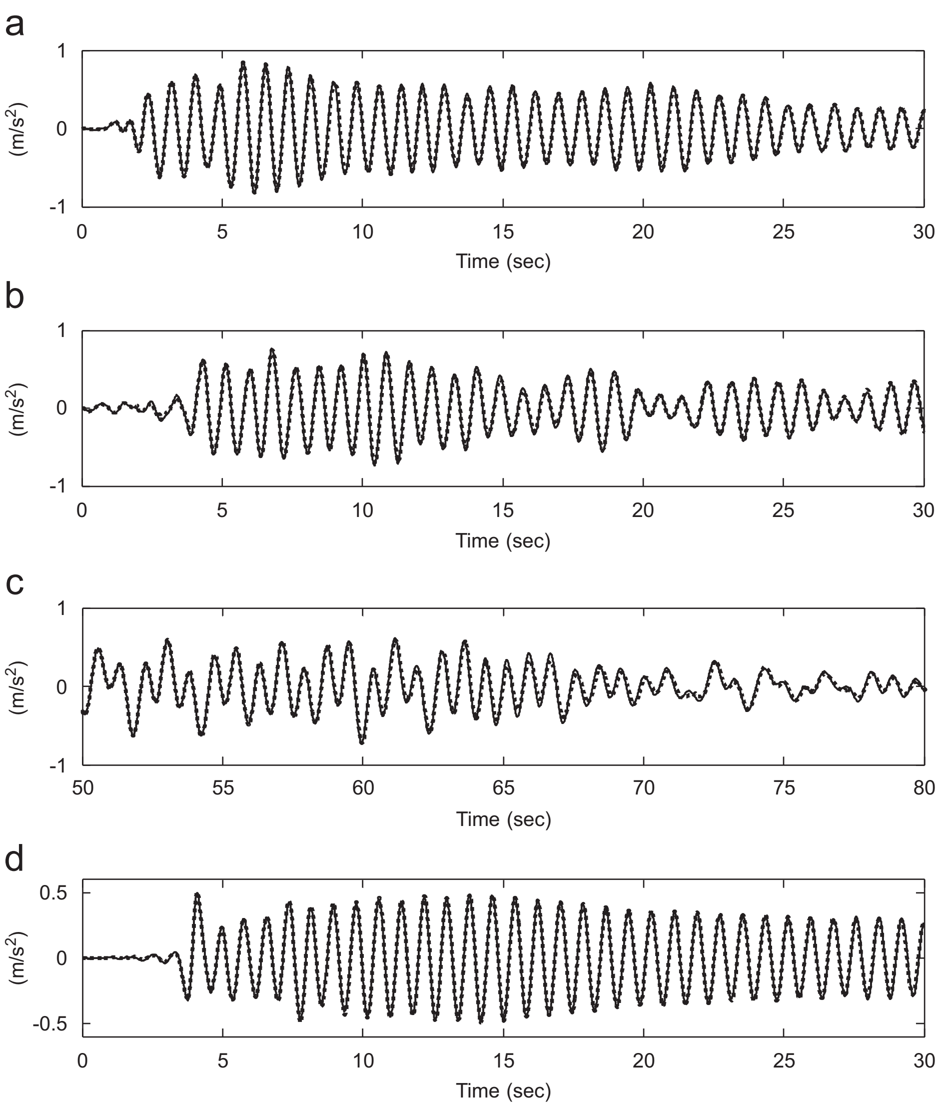

Fig. 8. Comparisons of the identified and measured structural accelerations (dotted line: identification, solid line: experiment): (a) El Centro earthquake, (b) Hachinohe earthquake, (c) Mexico city earthquake, and (d) Northridge earthquake.

Table 1
Identified structural parameters according to earthquake waves

Structural parameters	El Centro	Hachinohe	Mexico city	Northridge
Stiffness (N/m)	10,228	10,216	10,231	10,213
Damping (N s/m)	12.8	12.2	14.5	14.2

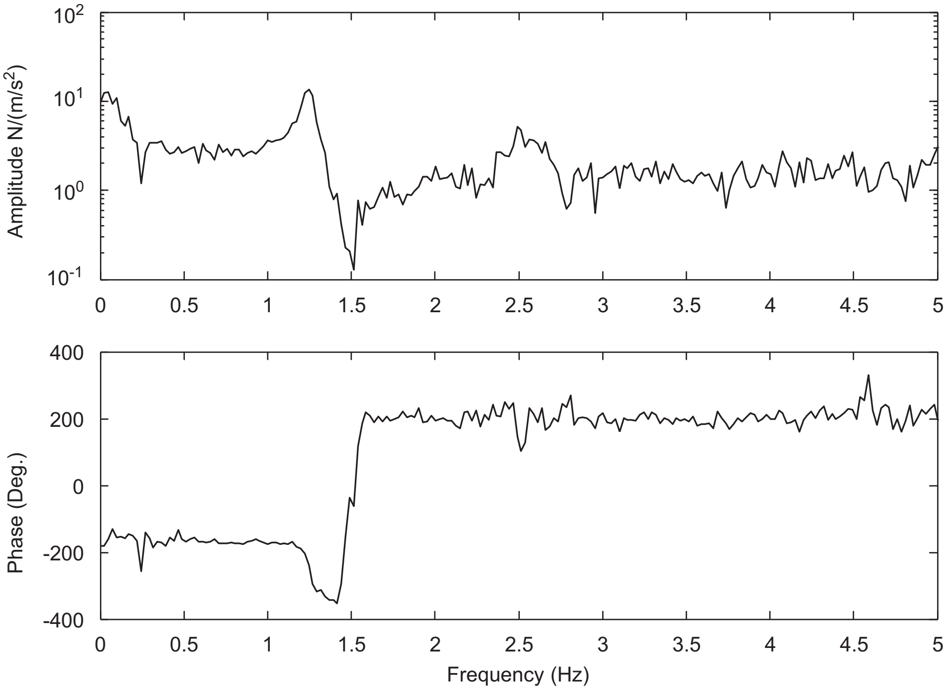

Fig. 9. TLD transfer function from the table acceleration to the base shear force.

For the numerical structural model used in RHSTTM, the single story steel frame is assumed to be a SDOF mass–damping–spring system. The structure has 0.6 m of width, 1.0 m of height and 169.7 kg of measured floor mass. El Centro, Hachinohe, Mexico city and Northridge earthquake waves were realized by the shaking table and the resulting absolute accelerations of the floor and the shaking table were measured. The system identification was conducted using the measured absolute accelerations. The identified and measured structural accelerations in the time domain match very well as shown in Fig. 8. The identified structural damping and stiffness coefficients slightly vary according to input earthquake waves, as shown in Table 1. The averaged damping and stiffness coefficients are 13.4 N s/m and 10,222 N/m, respectively, which correspond to 0.5% of damping ratio and 1.23 Hz of structural natural frequency. The TLD shown in Fig. 7 has the size of 31 (cm) $\times$ 14 (cm) $\times$ 20 (cm). The level of water in the TLD was adjusted to have 3.4 cm that is theoretically calculated based on the linear wave theory [10] for the TLD to have fundamental sloshing frequency tuned to the identified structural natural frequency. As a result, the mass ratio of the TLD to the structure is about 1.3%. To confirm whether the numerically calculated frequency of the TLD is modulated to the structural one, the transfer function shown in Fig. 9, from the shaking table acceleration to the shear force by the TLD, was obtained by using the white noise excitation. It is observed in Fig. 9 that the TLD has the sloshing frequency of 1.25 Hz which is very close to the structural natural frequency of 1.23 Hz.

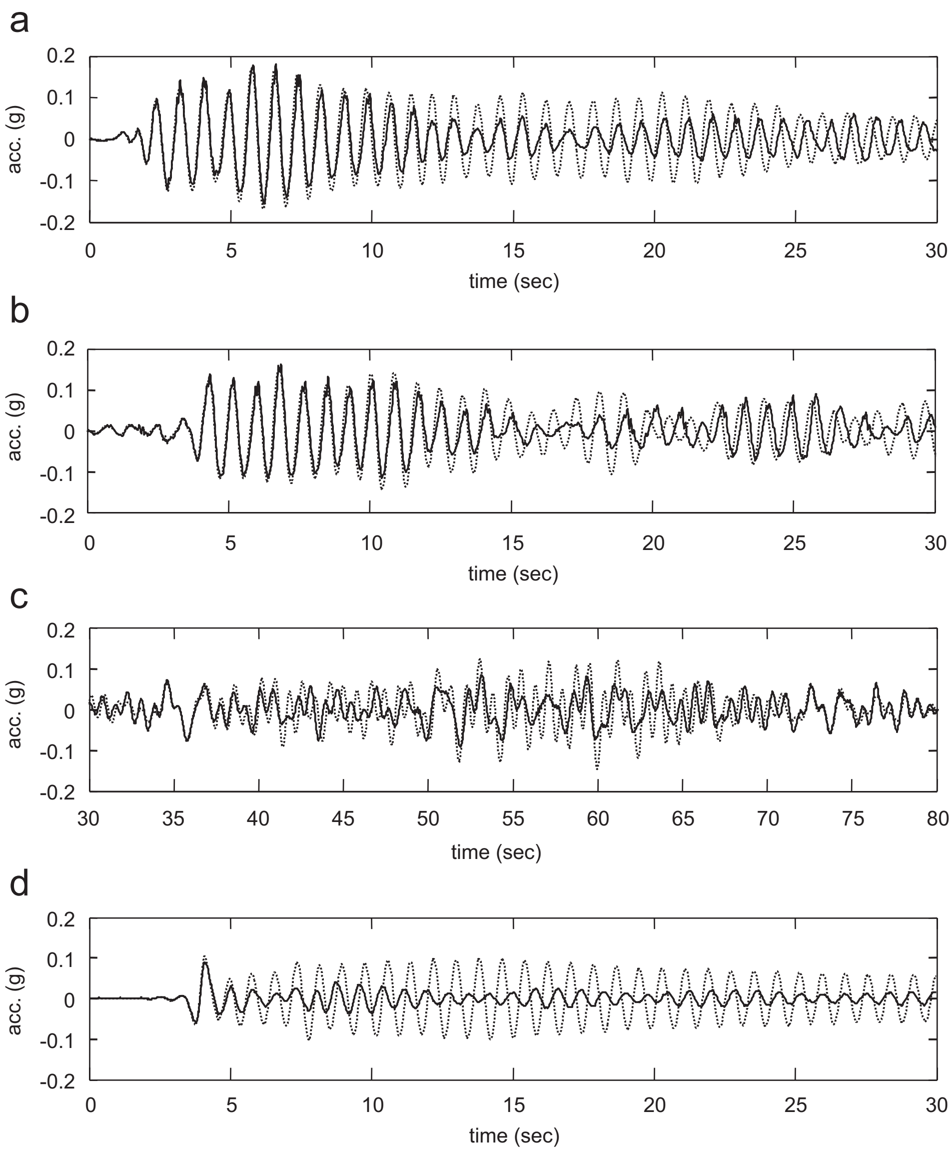

Fig. 10. Structural acceleration in the time domain measured from the conventional shaking table test of TLD–structure interaction system (dotted line: without control, solid line: with control): (a) El Centro earthquake, (b) Hachinohe earthquake, (c) Mexico city earthquake, and (d) Northridge earthquake.

At first, the conventional shaking table test shown in Fig. 7(a) is performed to investigate the seismic response control performance of the TLD. Previously mentioned four earthquake records are scaled to have the peak acceleration of 100 gal and used to excite the TLD–structure system. Figs. 10 and 11 show the measured structural acceleration responses in the time and frequency domains, respectively. Especially, the spectral data shown in Fig. 11 is obtained from taking the Fourier transform of the entire time history data including the transient responses. It is observed from Fig. 10 that generally acceleration in the latter part of the total response history is significantly reduced. This is typical tendency in the structural response controlled by a tuned mass-type control device, since it makes effect when the structural response is governed by the fundamental mode after initial strong impulse like component has passed. In the response to Mexico-city

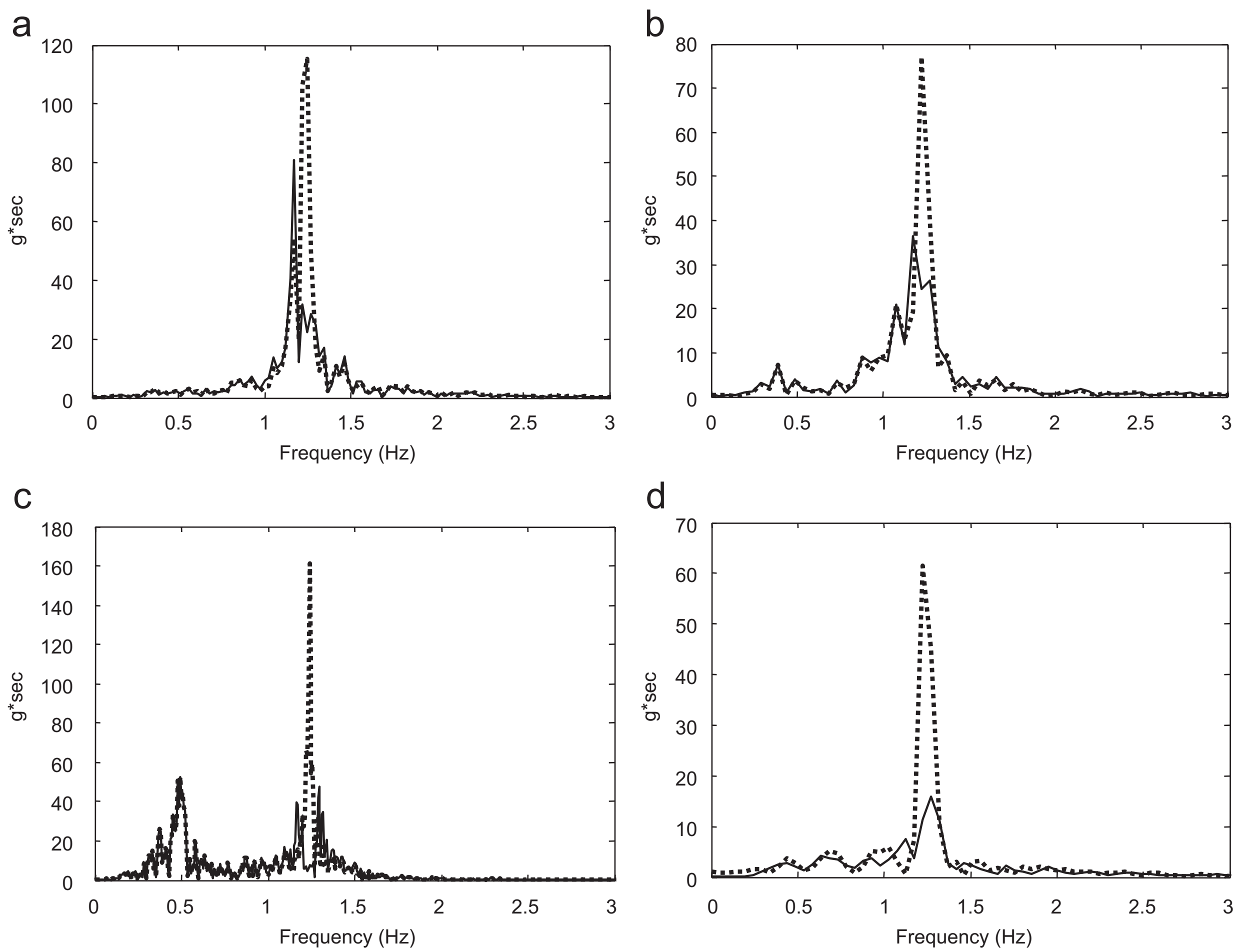

Fig. 11. Structural acceleration in the frequency domain measured from the conventional shaking table test of TLD–structure interaction system (dotted line: without control, solid line: with control): (a) El Centro earthquake, (b) Hachinohe earthquake, (c) Mexico city earthquake, and (d) Northridge earthquake.

earthquake excitation, as shown in Fig. 11(c), the first peak corresponding to the major frequency component of earthquake itself is not controlled, but the response in the region of the TLD modulation frequency is reduced to nearly zero.

Then, the RHSTTM is applied with the experimental set-up shown in Fig. 7(b). For its implementation for the controlled case, the identified structural parameters are reflected in the numerical part expressed by the shaded region in the integrated controller shown in Fig. 6. The continuous filters are converted into discrete ones with a time interval of 0.01 s. Figs. 12 and 13 compare the controlled accelerations obtained by performing the conventional and the RHSTTM in time and frequency domains, respectively. The effectiveness of the RHSTTM is verified from the fact that the experimental results from two methods coincide well with each other on the whole. The small discrepancies existing in the controlled responses subjected to El Centro and Hachinohe earthquakes are considered to result from the underestimation of damping coefficients in the numerical structural model since averaged parameters for the four earthquake data were used. Also, it is known from Table 2 that the error between the conventional method and the RHSTTM has amplitude of $0.0002(g)$–$0.0095(g)$ in the root mean square (rms) responses according to the earthquake excitations is observed.

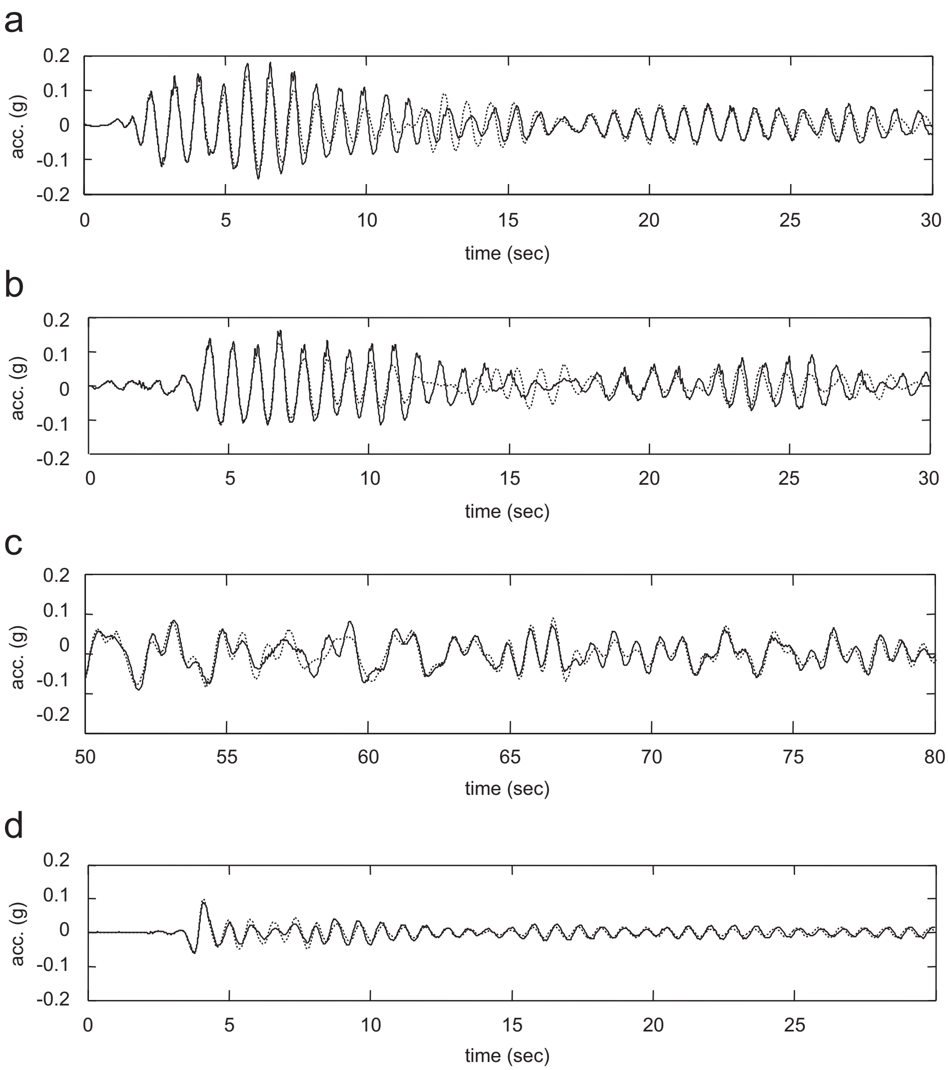

Fig. 12. Comparisons of controlled structural accelerations in the time domain (dotted line: conventional shaking table test, solid line: real-time hybrid shaking table test): (a) El Centro earthquake, (b) Hachinohe earthquake, (c) Mexico city earthquake, and (d) Northridge earthquake.

4.2. A three story structure with a TLD

The control performance of a TLD installed in a three story structure is investigated by using the RHSTTM. The structure is assumed to be a three story shear-type model, which has identical story properties as follows: $m_i = 128.8\,\mathrm{kg}$, $c_i = 13.52\,\mathrm{N\,s/m}$, $k_i = 33908\,\mathrm{N/m}$ for $i = 1,2,3$. The structure has natural frequencies of 1.15, 3.22 and 4.65 Hz. The TLD discussed in the previous section is used and its water level is modulated to 4.6 cm in order for the TLD to have sloshing frequency of 1.15 Hz. As a result, the mass ratio of the TLD to the structure is about 2%. The four earthquake waves used for the excitation of the single story steel frame were scaled to have peak acceleration of 40 gal. The uncontrolled structural responses were obtained by removing the feed back loop of the TLD-generated interacting force, which causes the numerical structural model to be excited only by the base earthquake motion.

Figs. 14 and 15 compare the uncontrolled and controlled accelerations of the third story structural model in time and frequency domains, respectively, which is realized by the shaking table through the RHSTTM. It is

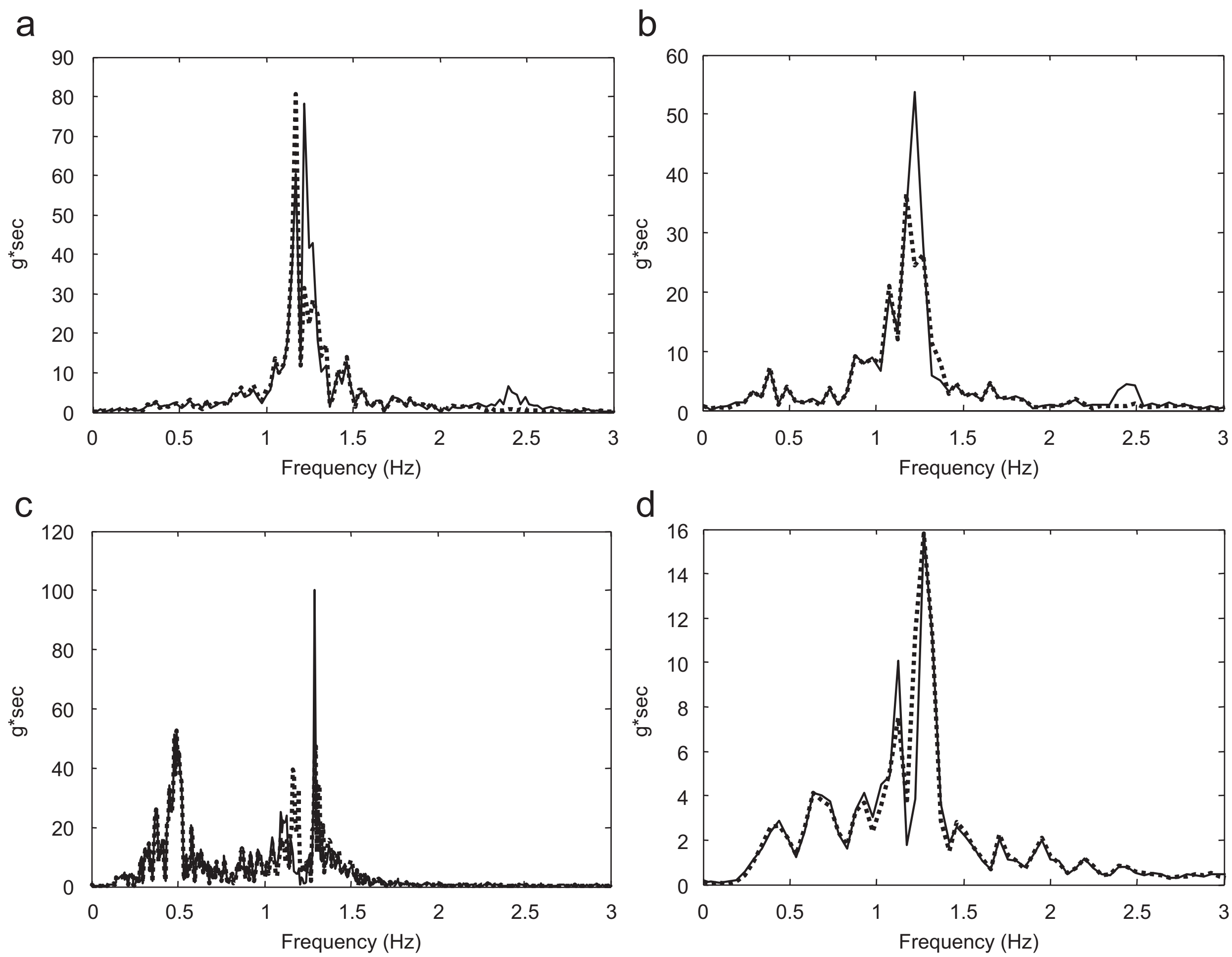

Fig. 13. Comparisons of controlled structural accelerations in the frequency domain (dotted line: conventional shaking table test, solid line: real-time hybrid shaking table test): (a) El Centro earthquake, (b) Hachinohe earthquake, (c) Mexico city earthquake, and (d) Northridge earthquake.

Table 2
Controlled RMS structural accelerations according to methodologies

Methodologies	El Centro	Hachinohe	Mexico city	Northridge
Conventional method (g)	0.0352	0.0353	0.0185	0.0165
RHSTTM (g)	0.0397	0.0448	0.0192	0.0167

observed that the structural accelerations are significantly reduced by the TLD, especially in the region of the fundamental frequency. Table 3 indicates that the acceleration is reduced by 4–30% in peak and by 18–60% in rms responses. It is also identified in Fig. 15(d) that the TLD lessens the additional second mode response of the structure. Fig. 16 shows the typical sloshing and slamming behaviors of the water in the TLD tanks during the experiment, which occur in the small and large amplitude of the water motion, respectively [16,17].

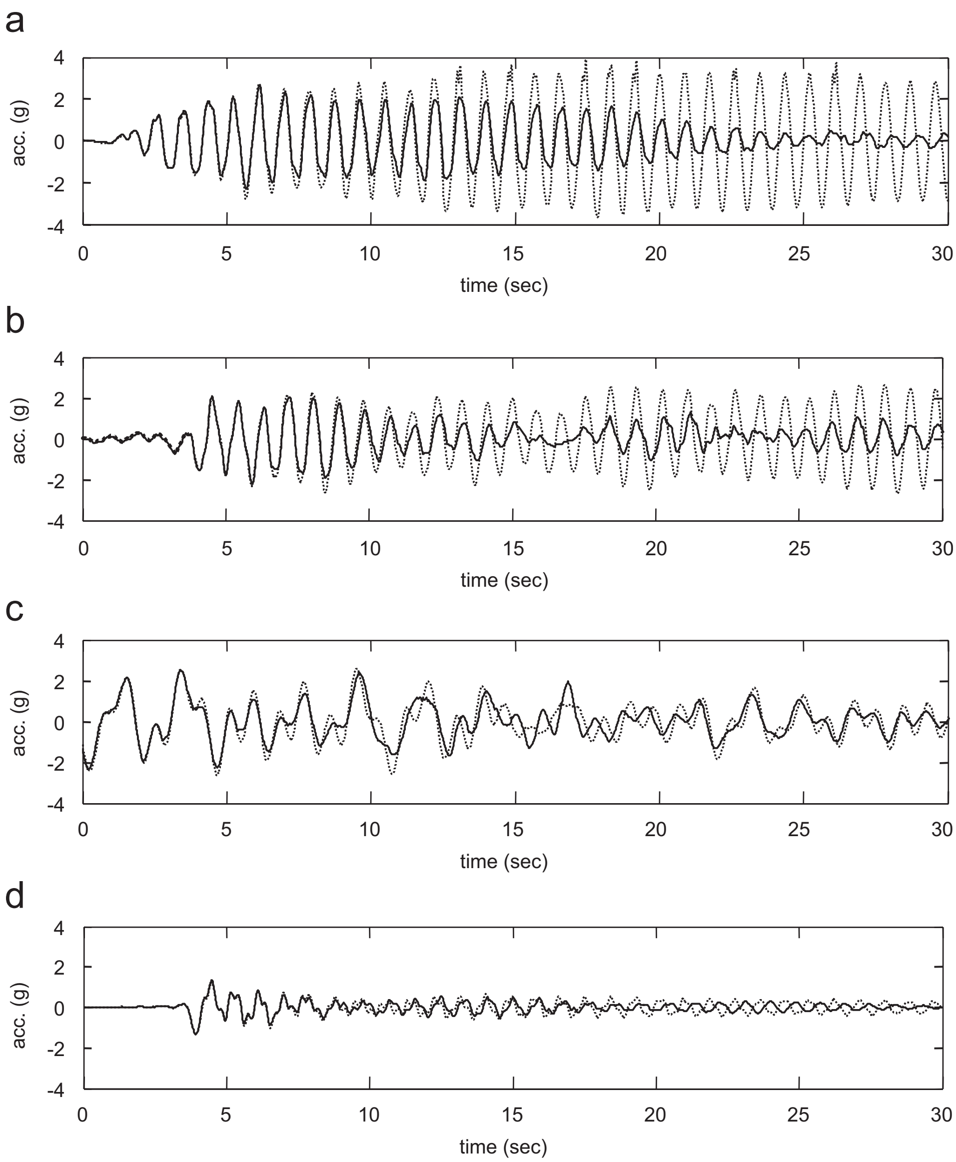

Fig. 14. Absolute accelerations in the time domain, measured from the top story of MDOF structure with a TLD by the real-time hybrid shaking table test (dotted line: without control, solid line: with control): (a) El Centro earthquake, (b) Hachinohe earthquake, (c) Mexico city earthquake, and (d) Northridge earthquake.

5. Concluding remarks

In this study, a real-time hybrid shaking table test was conducted to verify the seismic control performance of the TLD installed in the building structures. The TLD installed at the top floor of the structure is physically tested, and simultaneously numerical calculation is carried out for the assumed analytical structural model. Comparison between the structural responses obtained by the RHSTTM and the conventional shaking table test of a single story steel frame with TLD indicates that the performance of the TLD can be accurately evaluated using the RHSTTM without the physical structural model. Finally, the uncontrolled and TLD-controlled structural responses of a three story structure are obtained by the RHSTTM in both time and

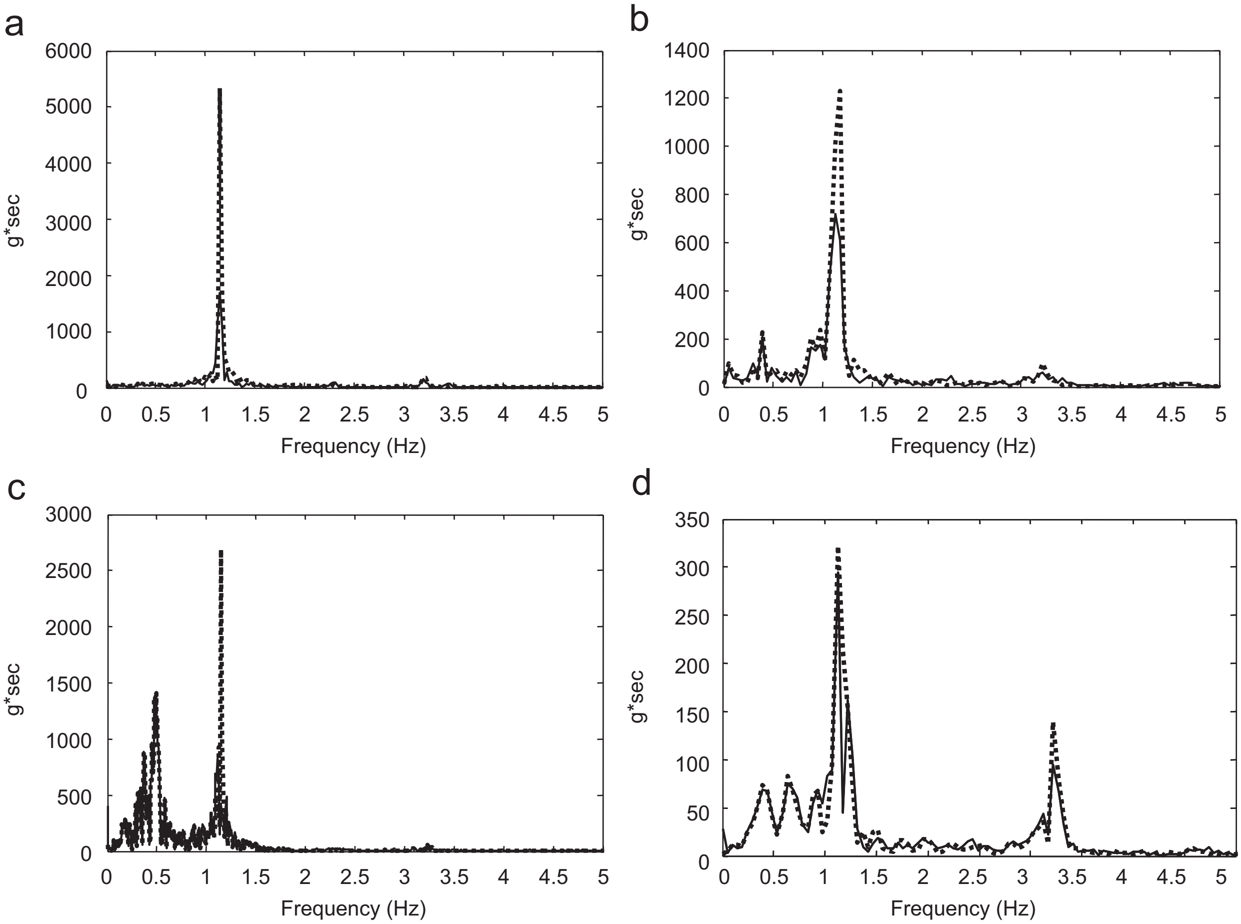

Fig. 15. Absolute accelerations in the frequency domain, measured from the top story of MDOF structure with a TLD by the real-time hybrid shaking table test (dotted line: without control, solid line: with control): (a) El Centro earthquake, (b) Hachinohe earthquake, (c) Mexico city earthquake, and (d) Northridge earthquake.

Table 3
Uncontrolled and controlled responses of a combined TLD–MDOF structure system

Responses (*g*)	El Centro	Hachinohe	Mexico city	Northridge
Peak acceleration				
Uncontrolled	3.85	2.71	2.63	1.34
Controlled	2.69	2.19	2.52	1.34
RMS acceleration				
Uncontrolled	1.91	1.36	0.54	0.33
Controlled	0.74	0.66	0.45	0.27

frequency domains, showing that TLD can effectively mitigate the seismic responses of building structures and the RHSTTM can reproduce the dynamic behavior of TLD–structure interaction systems for both the uncontrolled and controlled case. The RHSTTM can be also applied to the performance evaluation of tuned liquid column damper which has strong inherent nonlinearity.

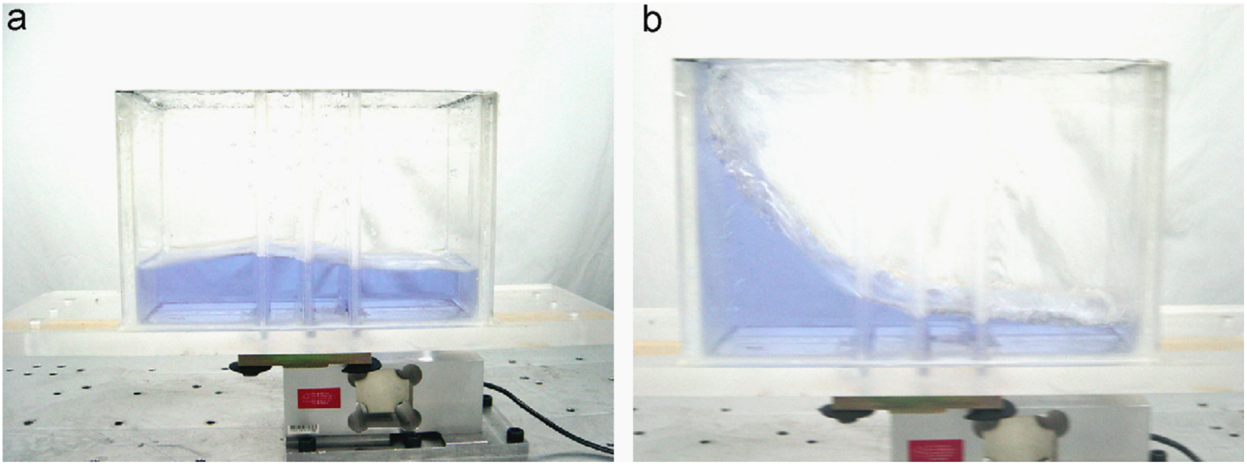

Fig. 16. Behaviors of a TLD under the earthquake motion: (a) sloshing of TLD and (b) slamming of TLD.

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