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EXPERIMENTAL SIMULATION OF COUPLED RESPONSE OF STRUCTURAL SYSTEMS USING THE SUBSTRUCTURE HYBRID SHAKE TABLE TEST METHOD

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SUMMARY

Development of the Substructure Hybrid Shake Table (SHST) test method based on the principle of the hybrid testing technique and the substructure technique in order to evaluate the real-time dynamic response of test structures and structural components is presented. This test method consists of the shake table test for the experimental substructure that is a part of the structural system and numerical computation for the numerical substructure. In this study, the reliability and accuracy of the SHST test method is secured by the compensation of the dynamic characteristics including the phase lag of the shaking table response using the application of digital filtering technique to the control system. The capability of the test method is demonstrated by two kinds of nonlinear dynamic interaction problems.

The first application is the validation problem of the performance of a Tuned Mass Damper installed to an existing RC bridge column as the countermeasure to the wind induced vibration. A scale model of the TMD is used as the experimental substructure and the test system stably and accurately performs the SHST tests even for the cases of nonlinear structural response range. The dynamic behavior of TMD can be successfully detected with the test method. The test system stably and accurately performs the SHST tests even for the cases of nonlinear structural response range.

The second application is the study on the dynamic behavior of liquid storage tank with seismic isolators with a bilinear hysteretic restoring force model. A cylindrical tank filled with water is treated as the experimental substructure, and the characteristics of the seismic isolators are numerically modeled in the computational part. The response of the isolated liquid storage tank is simulated with the test system, and the effect of isolation parameter is clearly shown in the comparison among the test cases.

INTRODUCTION

A dynamic test method which combines the shake table test and a numerical computation of the dynamic structural response has been proposed to experimentally evaluate the dynamic response of combined structural systems in a real-time basis. In this test concept, an on-line system of a shake table and a

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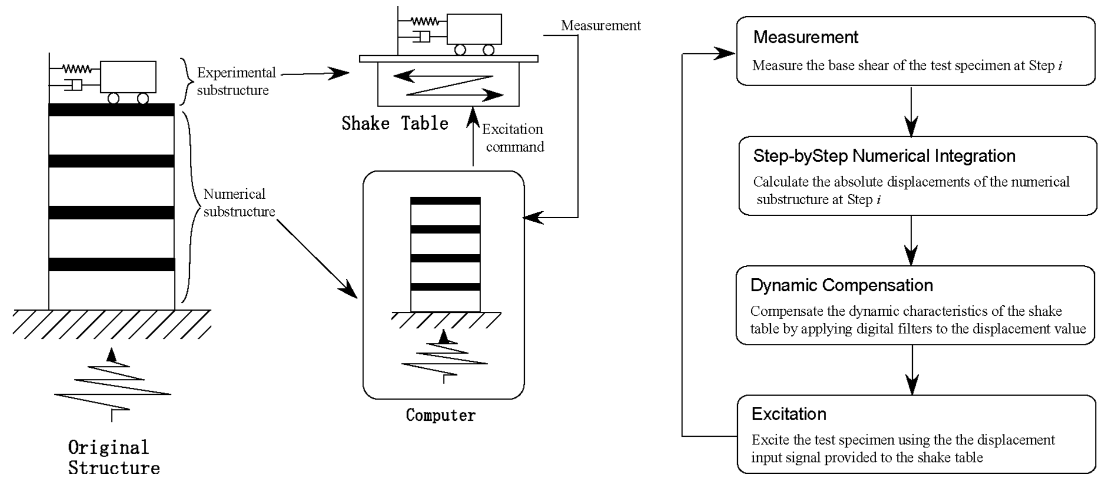
computer is operated so that the testing and the computation proceed simultaneously, exchanging the information each other. Since this test method deals with the structural system by dividing the system into a substructure for the shake table test and that for numerical computation, the test method based on this concept is referred to as the SHST Test (Substructure Hybrid Shake Table Test) in the present paper. The experimental aspect is similar to the conventional shake table test since a structural element of interest is dynamically excited by a shake table to verify the dynamic behavior. However, the SHST test method gives a great advantage to the researchers, by allowing consideration of the dynamic interaction of the test specimen with the other part, under a highly realistic excitation condition to the test specimen. It also is advantageous in economically achieving a testing environment for experimental verification of large-scale and complicated structural systems, even if it is not feasible to test the entire structural system using a shake table. For example, this test method is expected to be quite effective for the experimental performance verification of vibration control devices under the loading condition realized when the device is installed in the main structure.

The concept of the SHST Test method has been independently proposed by several research groups in different fields, including the authors [1]. Application of the test concept is attempted in various problem frameworks, including the verification of the secondary mechanical structures attached to main structures proposed by Horiuchi et al. [2], and the dynamic interaction problem between the foundation and the structure studied by Konagai et al. [3]. In the theoretical aspect, Igarashi et al. [4] derived the stability criteria and accuracy evaluation based on the transfer function representation of the test system. As the sophistication of the test methods and equipments are pursued and achieved by the efforts of many researchers, the attention and demand for the combination of real-time testing and simulation are growing.

In this study, in order to establish the SHST test method as a technique to experimentally validate the dynamic behavior and the response reduction effect of response control devices installed to structures, hypothetical verification tests are conducted to demonstrate the effectiveness of the test method. It is known that excitation amplitude errors and phase lags due to the dynamic characteristics of the shake table hardware are the major factors that considerably contribute to the deterioration of the accuracy of the test results [1] in this test method. Therefore, in constructing a SHST test system using a hydraulic shake table, a combination of the use of displacement control of the shake table hardware and dynamic compensation of the phase delay by digital filtering is used to ensure reliability and versatility of the test method. It is shown that even in the cases of using a nonlinear structural model in the computational substructure, the SHST test system based on the method proposed in the present paper allows to conduct tests with sufficient accuracy. Moreover, feasibility and the applicability of the test method in the nonlinear engineering application is examined by two kinds of tests; application to a Tuned Mass Damper (TMD)-RC bridge pier system, and application to liquid storage tanks with seismic isolators.

THE SUBSTRUCTURE HYBRID SHAKE TABLE TEST METHOD

The concept of SHST test is schematically shown in Fig. 1a. The SHST test method is a test strategy to examine the dynamic response of a structural system, where the shake table test is performed to a test specimen which is a part of the structural system, while the response of the rest of the system is numerically calculated by computers based on the measurement of the experimental part. The conventional pseudodynamic tests are not generally applicable to the structures that exhibit velocity-dependent response, namely viscous damping elements and mass effect. However, the SHST test uses the real-time excitation, thus allowing an accurate evaluation of the dynamic response of the structural components of this type. It is important to compensate the dynamic characteristics, especially the phase delay, of the input-output relationship of the shake table, to secure the reliability of SHST test. In this study, digital signal processing based on the digital filtering technique is used in the compensation of the input-output dynamics of the shake table, taking advantage of the implementation to the test controller based on the DSP system.



(a) Schematic of the test concept (b) Test algorithm with digital filter compensation

Fig. 1 The SHST (Substructure Hybrid Shake Table) Test

The test algorithms can be summarized in 5 steps (see Fig.1b): at each time step i, (1) Take a measurement of the base shear acting in the interface between the experimental part and the table (2) Calculate the response of the numerical substructure after Δt using the step-by-step numerical integration scheme, based on the measurement and the ground acceleration input. (3) Apply the digital filter for the dynamic characteristics compensation to the displacement response value obtained from the numerical computation, and obtain the output of the filter. (4) Use the filter output as the input displacement command signal to the shake table, and move the table (5) Return to step (1) incrementing $i \rightarrow i+1$.

The most important part of the study to achieve a successful test is the design of the appropriate digital filter in step (3), which will be described in detail later.

THE TEST SYSTEM

General

A SHST Test system was developed using a hydraulic shake table. The shake table is shown in Fig.2 and

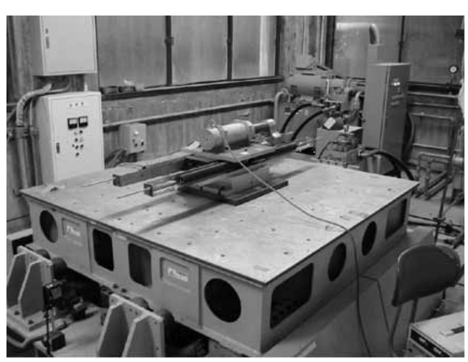


Fig. 2 Shake table for SHST test system development

Table 1 Specifications of the shake table

Table dimensions	1.5m X 1.5m
Max. weight	2.0 tf
Max. excitation force	29.4 kN
Excitation	horizontal, one-direction
Max. table displ.	+/- 100mm
Frequency range	DC-30 Hz
Type	hydraulic servo mechanism

the specification is summarized in Table 1. In order to develop the SHST test system, the shaking table was combined with a PC-DSP (Digital Signal Processor) system as the hardware controller, which calculated the command signal to the shake table based on the measurement data obtained through A/D and D/A interfaces on a real-time basis. The time step interval of 1msec and the backward Euler method was employed as the time integration scheme with minimal amount of computation to ensure the system stability.

In the SHST test, a load sensor was installed between the contact surfaces of the table and the test specimen for the measurement of the base shear of the experimental substructure. The acceleration of the test specimen was measured via acceleration pick-ups, and the shake table displacements were monitored through laser displacement sensors. The test system setup is shown in Fig. 3.

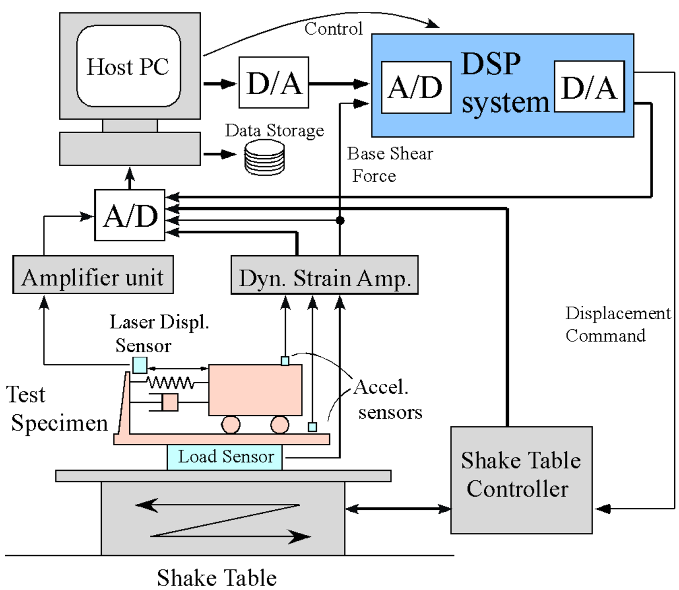


Fig.3 SHST Test System

Dynamic compensation of shake table dynamics by digital filters

The ideal transfer function of the digital filter to compensate the input-output characteristics of the shake table is equal to the inverse of the transfer function for input command signal to the shake table output. In this case, the complete cancellation of the shake table dynamics including time delay in the output is achieved. However, such a digital filter with the perfect frequency response is hard to obtain in real cases.

In this study, the transfer function of the shake table is obtained by the measurement of the dynamic response of the shake table for random signals containing the frequency contents of 0.1-5 Hz for the design of the digital dynamic compensator. It is assumed that the transfer function of the input displacement command signal to the shake table displacement response can be expressed as a rational function with limited orders, for which the coefficients can be determined using the parameter fitting strategy. The FIR (Finite-Impulse-Response) filter structure is chosen for the compensation filter, since it is observed that the transfer function of the shake table in the displacement control mode can be well represented by an approximate function which can be compensated by a 4th-order FIR filter. The filter becomes an FIR filter with a phase lead (because the filter is for cancellation of the phase lag), which is known to generally show amplification characteristics in the higher frequency range, rendering the test system unstable. Therefore, the two-stage filtering scheme combining two types of digital filters is used, where an IIR (Infinite-Impulse-Response) digital filter with low-pass characteristics is employed as the pre-conditioner to the signal provided to the FIR compensation filter.

The preconditioning IIR filter is the 3rd order Butterworth IIR filter with the pass band of 10Hz and the stop band 50Hz, which is represented by

$$y_n - 2.79987 y_{n-1} + 2.61928 y_{n-2} - 0.81849 y_{n-3} = 10^{-3} \cdot (0.114 x_n + 0.341 x_{n-1} + 0.341 x_{n-2} + 0.114 x_{n-3}) \quad (1)$$

where n is the discrete time step (time interval Δt=1ms), x_n is the filter input and y_n is the filter output. On the other hand, the compensation FIR filter can be expressed as

$$H(z) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_m z^{-m} \quad (2)$$

where z^{-1} is the operator to represent the one-step delay, i.e. $z^{-1} = e^{i\omega\Delta t}$. The frequency response function of the ideal compensation filter can be estimated by using the data of the shake table displacement input signal x_n and measured response displacement y_n , as $\hat{P}_{xy}(\omega)/\hat{P}_{yy}(\omega)$, where $\hat{P}_{yy}(\omega)$ is the estimated power spectrum of y_n and $\hat{P}_{xy}(\omega)$ is the estimated cross spectrum of x_n and y_n. Based on these estimates, the optimal coefficients b_0, b_1,...,b_m satisfying the minimization criterion below is calculated using the iterative search algorithm by the damped Gauss-Newton method[4)5)].

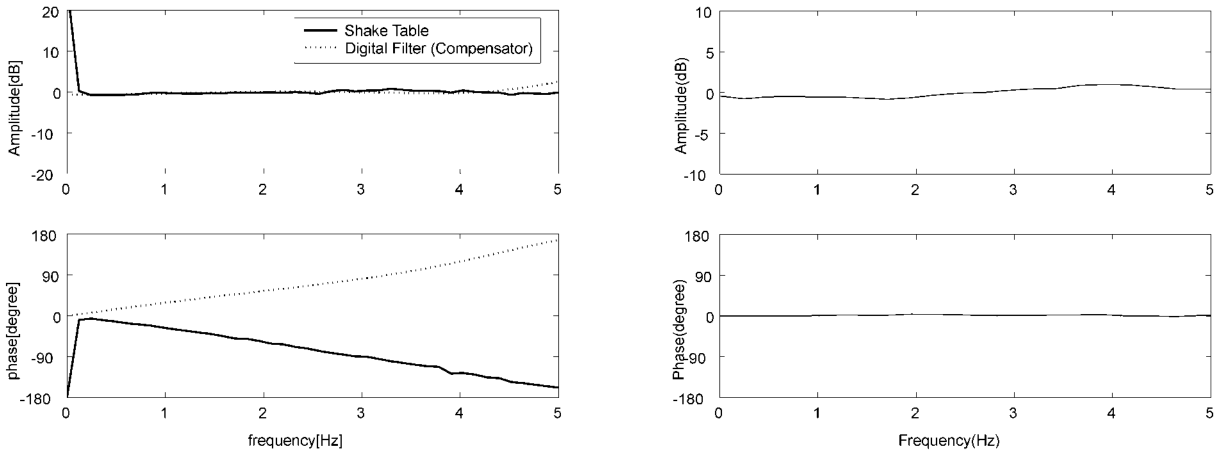
$$\left| H(z) - \frac{\hat{P}_{xy}(\omega)}{\hat{P}_{yy}(\omega)} \right|^2 \to \min \quad (3)$$

Only the frequency range of excitation 0.1-5Hz is required to be considered in calculation of the minimization criterion used in the iterative search. The result of the determination of the compensation FIR filter is represented by

$$y_n = 10^5 \cdot (0.33571 x_n - 1.32145 x_{n-1} + 1.95403 x_{n-2} - 1.28640 x_{n-3} + 0.31816 x_{n-4}) \quad (4)$$

In Fig. 4a, the frequency response of the shake table and that of the compensation filter are plotted with solid lines and dotted lines, respectively. The frequency response characteristics of the shake table are considerably well-behaved so that the amplitude is almost constant and the phase lag is nearly proportional to the frequency for the entire frequency range considered, partly because the displacement control mode is used in the shake table control. It follows that a high level of compensation can be expected with the use of simple digital filters.

The result of the compensation using a random noise input is shown in Fig.4b. It is shown that the dynamics, including the phase lag, of the shake table in the frequency range up to 5Hz is successfully compensated with the digital filters. With the success of the compensation, the phase delay problem is regarded as mostly solved for the purpose of the application to the SHST test system.



(a) Frequency responses of the shake table and the filter

(b) Frequency response of the compensated shake table

Fig. 4 Effects of dynamic compensation with respect to the frequency response

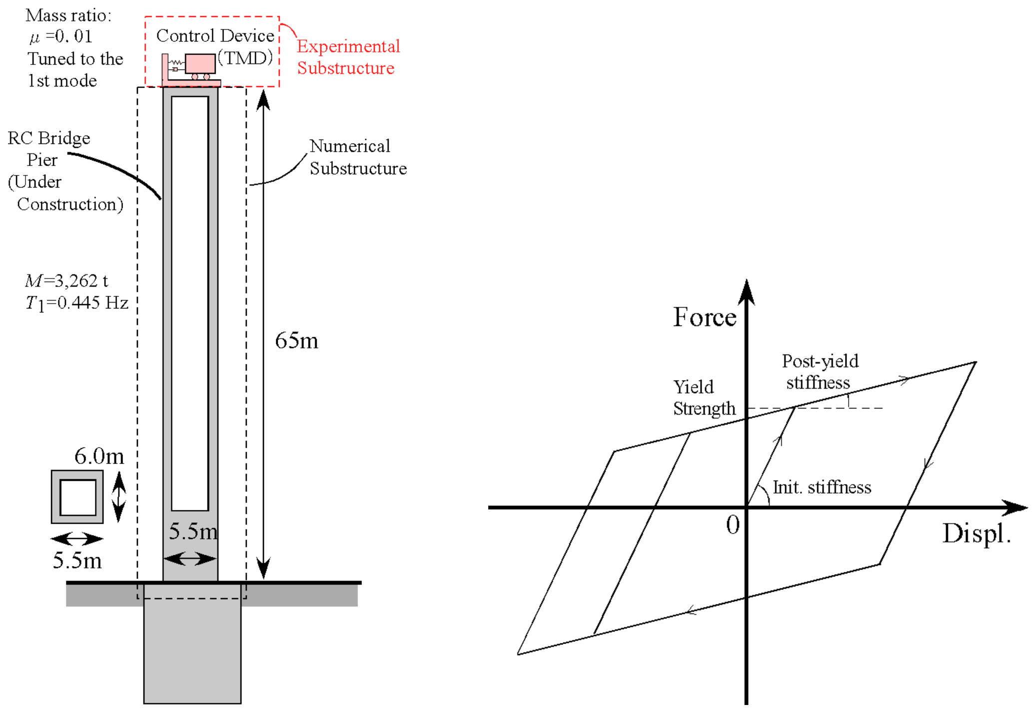
TEST OF TMD APPLICATION TO A BRIDGE PIER

Premise

As a case study of the application of the SHST test method, a series of tests assuming a validation problem of a vibration control device installed to a real-scale structure were conducted. The hypothetical test structure, shown in Fig.5, is a tall bridge pier elected from the ground in the middle of the construction process of the bridge, and a TMD is installed on the top of the pier as a temporary measure to control the wind-induced vibration. The purpose of the test is the verification of performance and safety of the TMD and the pier in case of a strong earthquake excitation. The height of the assumed pier is 65.0m, and the dimensions of the cross section are 5.5m X 6.0m; a hollow core cross section (web thickness=1.0m) is assumed except for the top 5.0m length along the height. The effective mass of the pier is 3262t, and the 1st mode natural frequency is 0.445Hz. The mass of the TMD is assumed to be 1% of the pier's mass, and the natural frequency is tuned to the 1st mode of the pier. A model of the TMD for verification is prepared and the HSST test is performed using the TMD model as the experimental substructure and treating the pier as the numerical substructure. The bilinear restoring force model (Fig. 5b) is assumed to consider the nonlinearity of the pier restoring force, and the ratio of post-yield stiffness / initial stiffness is assumed to be 0.05.

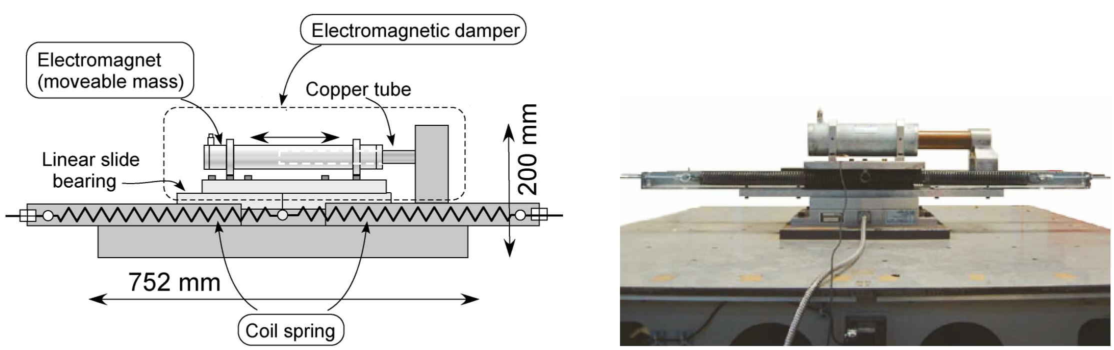
Test Specimen

A tuned mass damper with the viscous damping mechanism of an electromagnetic damper, (which is referred to as a "electromagnetic mass damper" in this paper), shown in Fig.6, is used as the test specimen for the SHST tests. An electromagnet is supported by a linear sliding bearing so that the electromagnet can smoothly moved in one direction; coil springs installed between the base and the electromagnet provide stiffness, and electromagnetic damper consisting of the electromagnet and a copper tube placed inside the electromagnet generates viscous damping force. With the mass of the moveable electromagnet, the



(a) Model structure: Pier-TMD system (b) Bilinear model for the nonlinearity of the Pier

Fig. 5 Hypothetical example of control device verification test using SHST system



(a) Dimensions and layout (b) Side view

Fig. 6 Test model: electromagnetic mass damper specimen

electromagnetic mass damper acts as a SDOF vibration system, which can work as a TMD. The mass of the moving part is 35.40kg, and the natural frequency of the system is 2.03Hz. The damping ratio can be changed within the range from 0.5% up to 8%, with the adjustment of the input electric current supplied to the electromagnet.

Equations of motion for the structural system

The input displacements to the shake table are calculated as follows: The base of the pier is supported by the grounds, and the response of the pier is mainly due to the flexural deformation. The equation of motion for the pier is expressed by Eq.5.

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{\dot{u}\}=-[M]\{1\}\ddot{z}_g-\{f\}F_{TMD} \tag{5}$$

where $\{u\}$ is the displacement vector, $[M]$, $[C]$, $[K]$ are the mass, damping and stiffness matrices, respectively, zg is the ground motion, FTMD is the force that acts on the pier from the TMD. The vectors $\{1\}$ and $\{f\}$ denote the force location vectors which have the value of unity for the components corresponding to the force locations, and zero value otherwise. It is assumed that the first mode response of the natural frequency 0.445Hz dominates the dynamics of the pier and the higher mode response is negligible. The first mode coordinate of the pier response $q_1(t)$ is governed by Eq.6.

$$\ddot{q}_1+2h_1\omega_1\dot{q}_1+\omega_1{}^2q_1=-\beta_1\ddot{z}_g-\gamma_1F_{TMD} \tag{6}$$

where ω_1 and h_1 are the first mode natural circular frequency and the first mode damping ratio, respectively, and β_1 and γ_1 are the "participation factors" defined by

$$\beta_1=\frac{\{\phi_1\}^T[M]\{1\}}{\{\phi_1\}^T[M]\{\phi_1\}}\ ,\ \gamma_1=\frac{\{\phi_1\}^T\{f\}}{\{\phi_1\}^T[M]\{\phi_1\}} \tag{7}$$

in which $\{\phi_1\}$ is the first mode shape vector. In this case, the pier deformation is assumed to be represented by $\{u\}=\{\phi_1\}q_1$. It follows that the top displacement of the pier u_{top} can be computed by $u_{\mathrm{top}}(t)=\phi_{1\,\mathrm{top}}q_1(t)$, which is then used as the shake table displacement after adding the ground displacement.

Scaling law

Due to the capacity limitation of the shake table hardware, appropriate test model scales in the SHST tests are determined based on scaling laws. The scaling factor with respect to time is denoted by S_t, and the one with respect to length is S_x , i.e.

$$t=S_t\,t_m\ ,\ x=S_x\,x_m \tag{8}$$

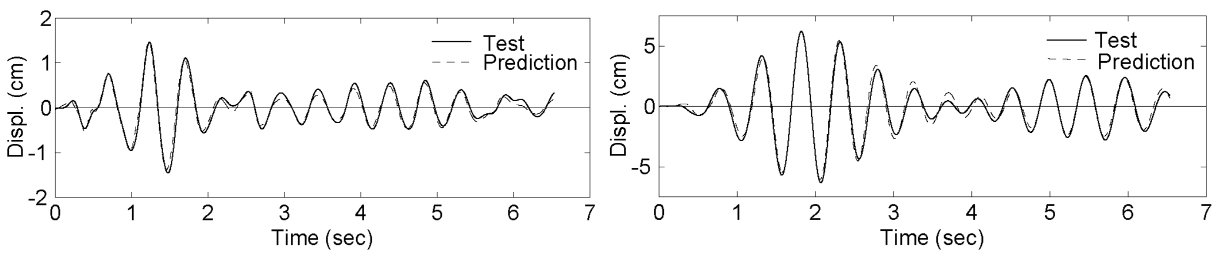
where t and x are the time and the length (displacement) in the full-scale problem, respectively, and the variables with subscript 'm' denote that the variables correspond to the scale model used in the test. It can be easily shown that the scaling relationships with respect to other parameters including the load F, velocity v, acceleration a, stiffness K, damping coefficient C, and mass M can be easily derived from the above two scaling factors as

$$t_m=\frac{1}{S_t}t\ ,\ F_m=\frac{1}{S_x{}^2}F\ ,\ x_m=\frac{1}{S_x}x\ ,v_m=\frac{S_t}{S_x}v\ ,\ a_m=\frac{S_t{}^2}{S_x}a\ ,\ K_m=\frac{1}{S_x}K\ ,\ C_m=\frac{1}{S_xS_t}C\ ,\ M_m=\frac{1}{S_xS_t{}^2}M \tag{9}$$

If the scale factors S_t = 4.59 and S_x = 26.47 are employed, the scale model of the TMD which should be prepared as the test specimen are of natural frequency 2.03Hz, and the moveable mass should be 35.40kg. Since those conditions are exactly matched with the electromagnetic mass damper specimen, it is hypothesized that the test specimen is designed so that the scaling law is satisfied with the actual TMD device to be installed.

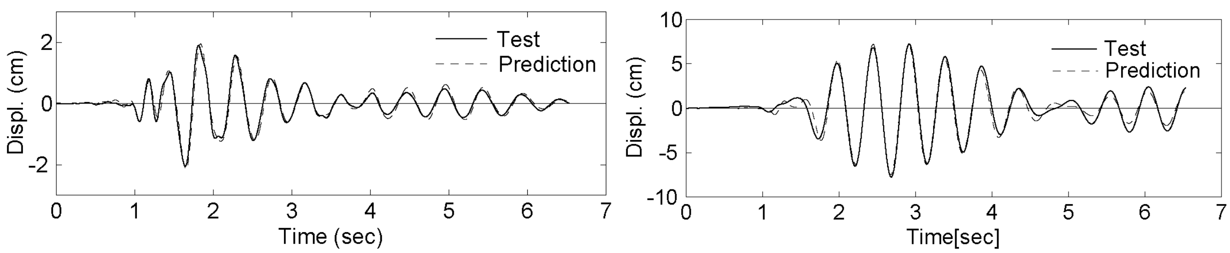
Pier and TMD response

The TMD response from the test using the ground acceleration input of the El Centro NS component is shown in Fig. 7. The analytical result is obtained by calculating the numerical integration of the equation of motion for the pier-TMD system. The result is shown in the same scale of the HSST tests i.e. the same scale as the measurement in the experiment. Since the yield displacement of the pier (top displacement) corresponding to the scaled model is 2.497cm, this result implies that the pier's response for the El Centro input remains within the elastic range. The test results and the analysis show remarkably good agreement, in particular the errors in the peak displacements of the pier are less than 0.1 %. The test results for the input of the Kobe JMA record (Hyogo-ken Nanbu Earthquake) is shown in Fig.8. The pier response of the Kobe JMA input case also is within the elastic range. The agreement between the test and analysis is good as well.



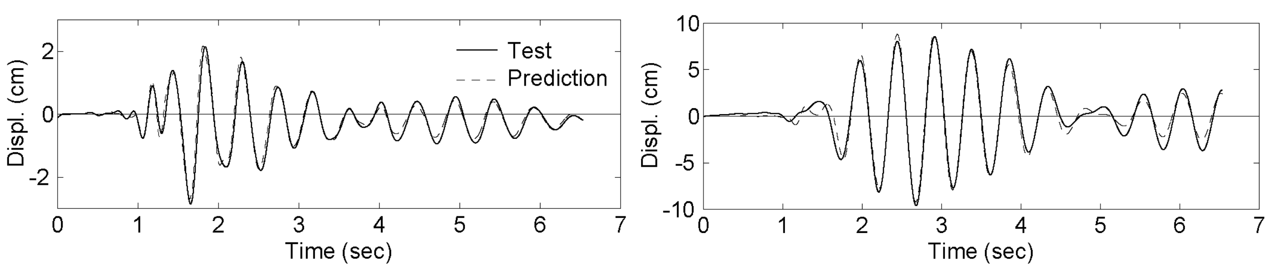
(a) Top displacement of the pier (=shake table disp.) (b) Displacement of TMD auxiliary mass

Fig. 7 Test result: El Centro NS input



(a) Top displacement of the pier (=shake table disp.) (b) Displacement of TMD auxiliary mass

Fig. 8 Test result: Kobe JMA NS input



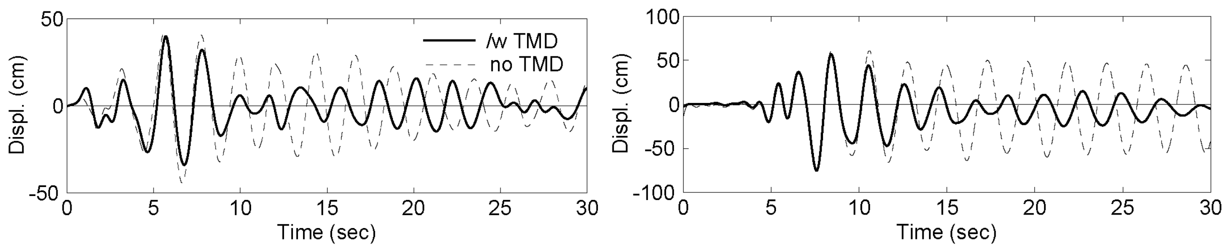
(a) Top displacement of the pier (=shake table disp.) (b) Displacement of TMD auxiliary mass

Fig. 9 Test result: Kobe JMA NS input (scale factor=1.3)

In Fig.9, the test result for the case the Kobe JMA record with increased amplitude (scale factor=1.3) is shown. The peak displacement exceeds the assumed yield level of the pier approximately 1.8 seconds after the start of the test, and an inelastic response is induced. Even in the nonlinear response range, the test result and the analysis show a good agreement, indicating that the method is applicable to nonlinear problems.

Dynamic response reduction effect of TMD

The obtained top displacement time history of the pier represented in the scale of original problem is shown in Fig.10. The response of the case with the TMD is compared with the case without TMD. Although the maximum displacement that appears immediately after the initiation of the record is not much affected by the TMD installation, the greatly reduced tail part response can be observed in the figure. This is a typical behavior which is predicted and experienced in the use of a TMD, especially of the auxiliary mass of 1% ratio to the main structure. This example shows that the SHST test method is effective in measuring the dynamic behavior of the type of devices used in this example.



(a) El Centro NS input case

(b) Kobe JMA NS input (scale factor = 1.3) case

Fig. 10 Reduction of top displacement response of the pier (full-scale representation)

TEST OF SEISMICALLY ISOLATED LIQUID STORAGE TANKS

General

As the second example of the application of the test method, the SHST test of seismically isolated liquid storage tanks are conducted. In this section, a brief summary of the tests is described, with the particular emphasis on the issues and features of test methods peculiar to the case of liquid storage tanks.

As suggested by the past and recent experience on the damage of liquid storage tanks due to earthquakes, the seismic performance and safety of liquid storage tanks against strong earthquakes have continuously been an important issue. Seismic isolation of liquid storage tanks, in which the tank structure is supported by isolation bearings, is one of the proposed and actually applied measures to secure the safety of such facilities for strong earthquakes. The aim of the seismic isolation concept to the liquid storage tanks is protect the tank from the structural damage due to short period components of the seismic input and the coupled fluid-structure interaction response. Due to the elongation of natural periods, the acceleration response induced by the earthquake ground motion and the resulting dynamic force acting to the structure is reduced. It implies that with the application of the seismic isolation system to the liquid storage tanks, the reduction of seismic actions, including the dynamic loads to the tank walls, base shear and the overturning moments are expected. However, sloshing due to long period components of earthquake ground motions is one of major concern in the liquid storage tank response, as is the case in judging the effect of seismic isolation to the tank. It has been reported in the past research that the seismic isolation of liquid storage tanks can increase the amplitude of sloshing under seismic excitation in some cases. Therefore, the merits and adverse effects of the seismic isolation of liquid storage tanks should be investigated for the application in practice.

The concept of the application of SHST test method to the isolated liquid storage tanks is illustrated in Fig. 11. A model of a tank with water as the stored liquid is used as the experimental substructure, and the response of the base supporting part and the seismic isolators is treated as the numerical substructure. This type of test allows the verification of real-time dynamic response of the isolated tank system with fluid, which can be nonlinear in nature. The clear advantage of the application of the SHST test method to the investigation of isolated liquid storage tanks is that various cases of design parameters of the seismic isolators can be easily tested with the software setting.

Test Setup

The test setup is shown in Fig. 12. A liquid storage tank model containing water is used as the test specimen and is installed on the shake table with the load sensor under the specimen, as in the TMD tests described in the previous section. Dimensions and weights of the tank model are summarized in Table 2. The depth of water used in the tests is 20 cm, resulting in the sloshing natural period of 0.88 sec.

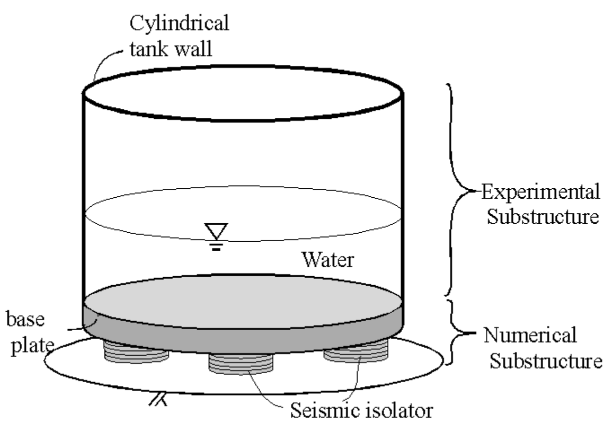


Fig. 11 Concept of the application to the seismically isolated liquid storage tanks

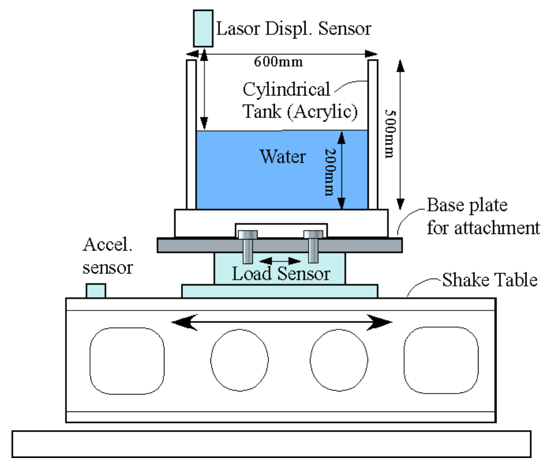


Fig. 12 Test setup for the liquid storage tank SHST tests

Table 2 Liquid storage tank model dimensions

Outer Diameter	600 mm
Wall Thickness	6 mm
Inner Radius	294 mm
Height	500 mm
Weight	161.7 N
Weight (incl. all attachments)	602.7 N

Fig.13 Liquid storage tank model on the shake table

Numerical modeling

The most critical issue in the application of the SHST test to the seismically isolated liquid storage tanks is the stability of the test control. Because of large mass ratios (ratio of the mass of experimental part to that of the numerical part) and extremely small damping of the liquid in the experimental part, the system becomes quite susceptible to dynamic instability, resulting in test failure. In order to overcome this difficulty, the models for the SHST test are especially chosen so that the mass of the supporting base part of the tank is included in the numerical integration to make the ratio of the mass in the experimental part to that of the numerical part smaller. In this case, the inertia force induced by the mass of the supporting base part of the tank in the experimental substructure is subtracted from the base shear measurement from the load sensor installed between the tank and the shake table.

Considering the purpose of the test as the demonstration of the SHST test for combined fluid-structure system, the liquid storage tank model is treated as the 'full-scale' specimen, so that scaling of the test specimen is not considered in this example. The restoring force characteristics of the seismic isolator of the tank are assumed to be the bilinear model as shown in Fig. 14, in which three cases of yielding load P_y with the same post-yield stiffness are illustrated. The value of 500 kg is used as the hypothetical mass of the supporting base part in the numerical substructure.

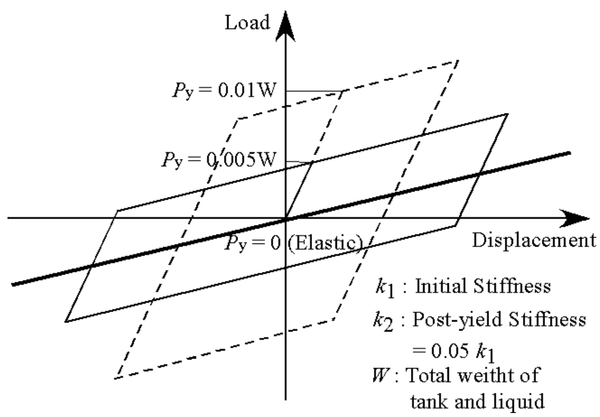


Fig. 14 Bilinear restoring force model for the seismic isolators

Test results

In the series of the tests, the El Centro record NS component scaled to 10% acceleration of the original is used as the input ground motion. Representative test results are shown in this section. In the model of the seismic isolators, the post-yield stiffness k_2 is selected so that the corresponding natural period is 1.4 sec. The test results of three cases of the yielding force P_y=0, 0.005W, and 0.02W (W: total weight of the tank) are shown in Figs.15, 16 and 17, respectively, along with the response of the tank without seismic isolators experimentally obtained by conventional shake table test using the ground motion input shown in Fig. 18. In these figures, solid lines represent the test result, and dashed lines indicate results of simplified dynamic response analysis using a 2-DOF model of the isolated tank based on Housner's model with the damping ratio of 0.001.

Considering that the amplitude of the input ground motion is 1/10 of the original El Centro record, P_y= 0.005W corresponds to case in which the factor of the yielding force of the isolators to the weight of the supporting structure is 5%, and P_y= 0.02W corresponds to the factor of 20%, for the input of the original El Centro record.

Each figure indicates the time histories of the measured base shear, displacement of the isolators, and water surface level at the edge. As can be seen in those figures, the test results and the simple simulation results show acceptable agreement in most cases, although subtle differences in amplitude and phase can be observed. Since the simulation of the sloshing behavior of the liquid part is conducted using a simple linear modeling, small errors in the damping parameters and nonlinearity can introduce this discrepancy.

The test result reflects the difference of the response due to the parameter setting. Among the three cases, P_y=0.05W in Fig. 16 gives the considerably fast decay of the response in terms of the base shear and the water surface levels compared with the other two cases as well as the non-isolated case. Amplitude growth of the base shear response after the main shaking phase should be noted for the cases of P_y=0 and P_y=0.02W. These observations can be explained by the effective energy absorption by the seismic isolators in the case of P_y=0.005W, which contributes to the damping of liquid response.

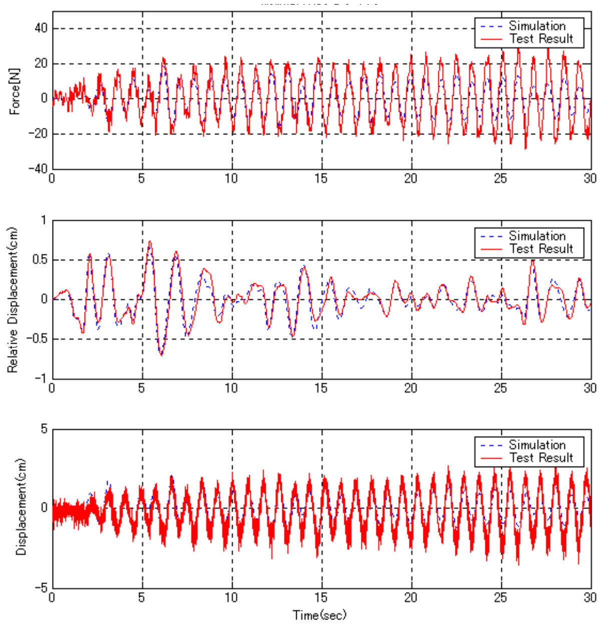


Fig.15 Test result: P_y = 0 (elastic isolator)

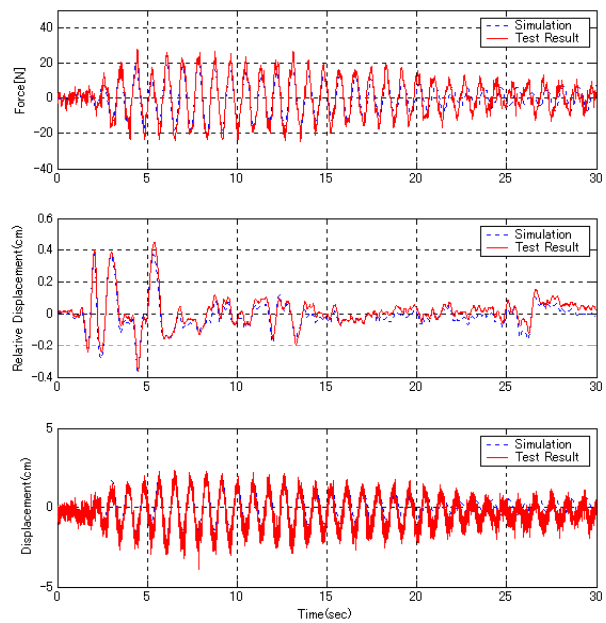


Fig. 16 Test result: P_y=0.005W

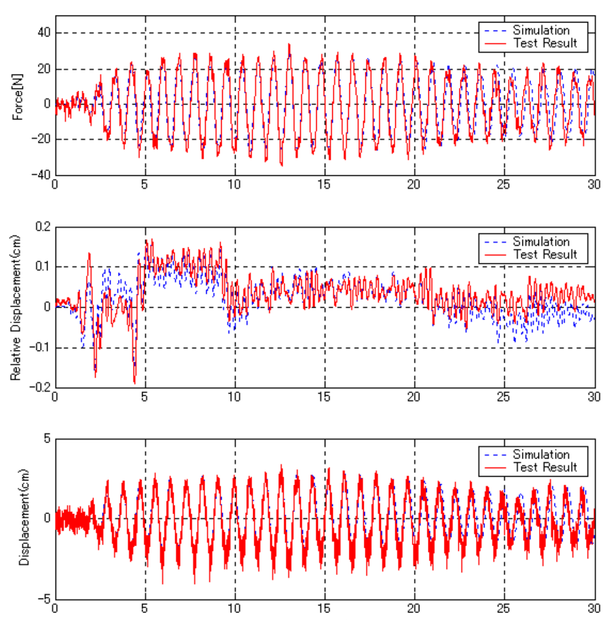


Fig. 17 Test result: P_y=0.02W

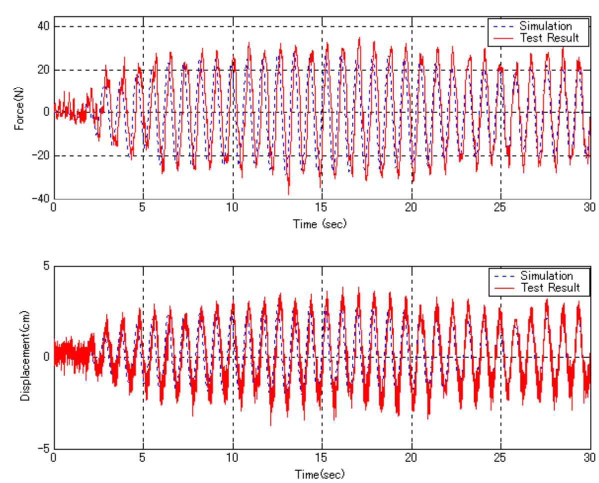


Fig.18 Response of the tank without seismic isolation

CONCLUSIONS

Conclusions obtained from the research described in this paper can be summarized as follows:

(1) In order to develop a SHST (substructure hybrid shake table) test system, which combines the shake table test for the experimental substructure and numerical computation for the numerical substructure, the dynamic characteristics including the phase lag of the shaking table response are compensated by using the displacement control and the application of digital filtering technique to the control system.

(2) The capability of the test method is demonstrated by the application to a validation problem of the performance of a TMD (tuned mass damper) installed to an existing RC bridge column as the countermeasure to the wind induced vibration. A scale model of the TMD is used as the experimental substructure and the test system stably and accurately performs the substructure hybrid shake table tests even for the cases of nonlinear structural response range.

(3) The TMD test result shows that the dynamic response of the RC column is well within the elastic range even with the strong seismic input of Kobe JMA record, and the behavior of the TMD can be successfully detected with the test method. The SHST test method is expected to be an effective test method for the purpose of control device verification tests.

(4) A series of SHST tests are conducted to simulate the response of seismically isolated liquid storage tanks under seismic excitation. The test setup is achieved by placing a liquid storage tank model on the load sensor and the shake table, and the bilinear restoring force model is assumed in the numerical substructure for the isolator response simulation. It is verified that the SHST test method allos the verification of the base shear and the action of the liquid to the tank structure, displacement of the isolators, and sloshing behavior of the stored liquids.

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