REAL-TIME HYBRID EXPERIMENTAL SIMULATION SYSTEM USING COUPLED CONTROL OF SHAKE TABLE AND HYDRAULIC ACTUATOR

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ABSTRACT :
The proposed hybrid loading test method using a shake table and a hydraulic actuator is intended for the application such as evaluation of real-time dynamic response of structural systems under strong seismic excitation. The test method consists of the shaking table test, and dynamic loading test using a dynamic actuator for the specimens that are parts of the structural system considered and numerical computation for the other part. The coupled time delay effect of the shake table and the hydraulic actuator is analyzed using the transfer function approach and numerical stability analysis, and the successful implementation of the test method based on the dynamic compensation of the delay effects of the loading equipments using digital filters is demonstrated by a series of verification tests.

KEYWORDS:
Hybrid simulation, real-time pseudo-dynamic test, seismic isolation, liquid storage tank, seismic damper

1. INTRODUCTION

The real-time hybrid loading test method (Igarashi et al 2000, 2003), which is used to evaluate the dynamic response of structural systems that includes structural components with known dynamic behavior and those having response property of interest. In this test method, the structural system is divided into a numerical substructure and a experimental substructure; response calculation of the numerical substructure with computers and dynamic loading test of structural elements using test equipments such as dynamic actuators are synchronously executed on a real-time basis by controlling the test procedure using the information of both processes.

In this study, a real-time hybrid loading test method simultaneously using two different kinds of test equipment, a shake table and a hydraulic actuators, is developed, in order to extend the scope of application of this test technique to categories of more complicated structural systems. The proposed hybrid experimental simulation test method using a shake table and a hydraulic actuator is intended for the application such as evaluation of real-time dynamic response of structural systems under strong seismic excitation. The real-time test using of mixed loading test equipments has already been attempted to some extent (for example, Spencer et al, 2004). In this study, emphasis is made on condition for the feasibility of such test systems based on the stability analysis, while the effect of phase delay time of the loading due to the loading equipments to the behavior of the total system is examined. A test system considering the application to the testing of liquid storage tanks with seismic isolation is developed, and accuracy and reliability of the test system combined with phase delay compensation by means of a digital filter is confirmed by verification tests.

2. REAL-TIME HYBRID LOADING TEST

The test structure to be considered in this study is a liquid storage tank with seismic isolation using laminated rubber bearings, and a viscous damper as the energy dissipation device, see Figl.1. In order to apply the real-time hybrid loading test, the structural system is divided into substructures. In this case, the liquid in the tank is regarded as the experimental substructure for the shake table test, the damper is the experimental substructure for the dynamic loading test, and the remaining structural elements are assumed to be the numerical substructure. Assuming that flexibility of the tank wall and supporting base of mass $m_{1,base}$ is to be negligible, and the behavior of the isolator to be linear elastic with the stiffness k and damping coefficient c, the numerical substructure can be modeled as a single DOF system, as shown in Fig.2.

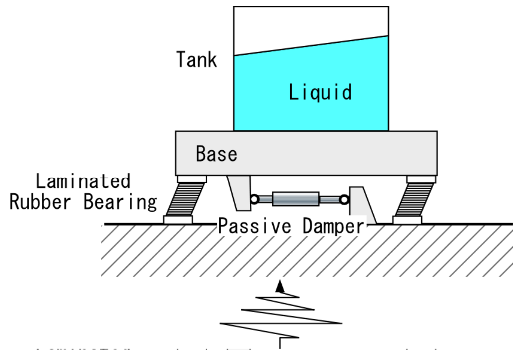

Figure 1 Liquid storage tank with seismic isolation system

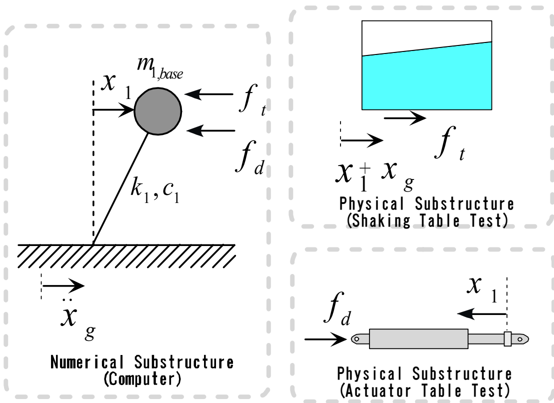

Figure 2 Substructure model

The equation of motion is expressed by

$$m_{1,base}\ddot{x}_1(i)+c_1\dot{x}_1(i)+k_1x_1(i)=-m_{1,base}\ddot{x}_g(i)+f_t(i)+f_d(i) \tag{2.1}$$

where i (i=1,2,…) denotes the time step, $f_t(i)$ is the base shear of the tank induced by the liquid content, $f_d(i)$ is the load of the damper, $\ddot{x}_g(i)$ is the ground acceleration. Using the numerical time integration of the equation of motion, the absolute displacements x_1+x_g and the relative displacements x_1 at the next time step are used as the control input signal for the shake table and the hydraulic actuator, respectively, to obtain the measured dynamic response of the test specimen at the time step. This process is repeated in real time for the designated duration of the response to simulate the dynamic behavior of the isolated liquid storage tank and the components.

3. TEST SYSTEM AND TEST SETUP

3.1. Test Specimens

An acrylic cylindrical tank of inner diameter 58.8cm and of height 50cm shown in Fig. 3 was used as the model of the liquid storage tank, and water with the depth of 20cm is used as the liquid content of the tank.

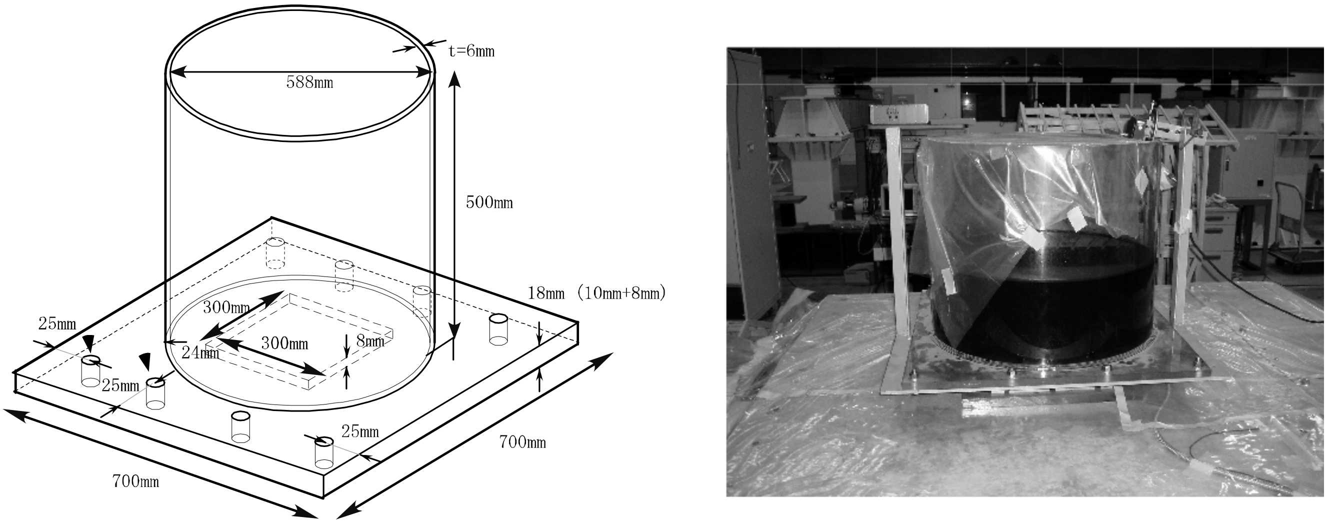

Figure 3 Liquid storage tank specimen

Results of sweep tests using unidirectional horizontal excitation is shown in Fig. 4. In the figure, the amplification factor is defined as the ratio of the base shear amplitude to the product of liquid content mass and the input acceleration amplitude. Theoretical sloshing periods at 0.857sec for the 1st mode and 0.48sec for the 2nd mode can be observed as the peaks of the dynamic amplification factor. The damping ratio of the 1st mode sloshing was found to be approximately 0.17% from a free vibration test.

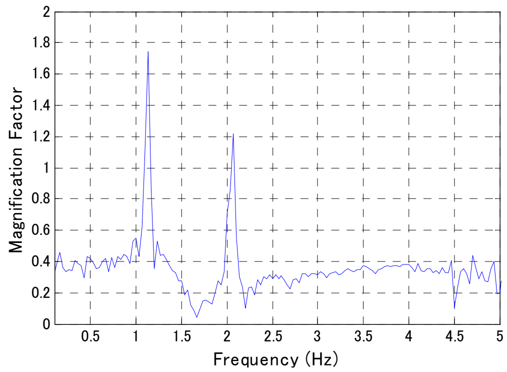

Figure 4 Frequency response of the liquid storage tank specimen

An oil damper of length 800mm and displacement stroke range of +/- 100mm was used as the energy dissipation device specimen. Result of a cyclic loading test using sinusoidal displacement input of amplitude 20mm and frequency 1.5Hz in Fig.5. Nonlinearity observed in the damping force – velocity relationship is a typical behavior of oil dampers, which indicates a notable difference from the characteristics of linear viscous model.

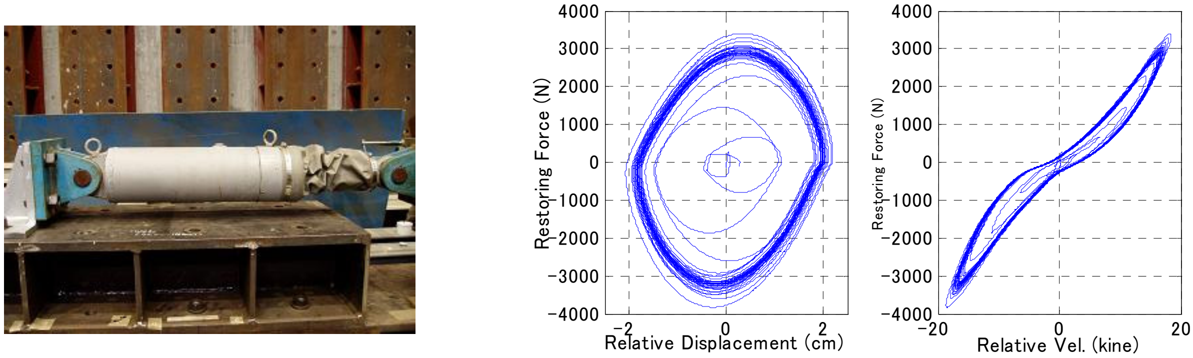

Figure 5 Oil damper specimen and response to cyclic loading

3.2. Test Equipments

A servo-controlled electro-hydraulic shake table and a servo-controlled electro-hydraulic dynamic actuator are used for the loading of the liquid-storage tank and the oil damper, respectively. Specifications for the shake table and the actuator are shown in Tables 1 and 2.

Table 1 Specifications of the Shake Table

Table size	1.5 m × 1.5 m
Maximum mass capacity	2 ton
Maximum excitation force	3 tonf
Stroke	±100mm (uniaxial)
Frequency of operation	0.5～30 Hz

Table 2 Specifications of the Actuator

Maximum load	± 50 kN
Stroke	± 50mm
Maximum velocity	25 kine

3.3. Test Control System

Numerical calculation of model response, and control signal generation are performed by a DSP system board based on the TMS320C6701GJC floating-point DSP chip. The external I/O interface consists of two 4-channel 16-bit AD converter modules and a 4-channel 16-bit DA converter module. The conversion time of the AD and DA converters is 10ms in the simultaneous conversion mode. The DSP board and I/O interface modules are installed on the PCI bus of a PC. The schematics of the developed test system including the control system are shown in Fig. 6.

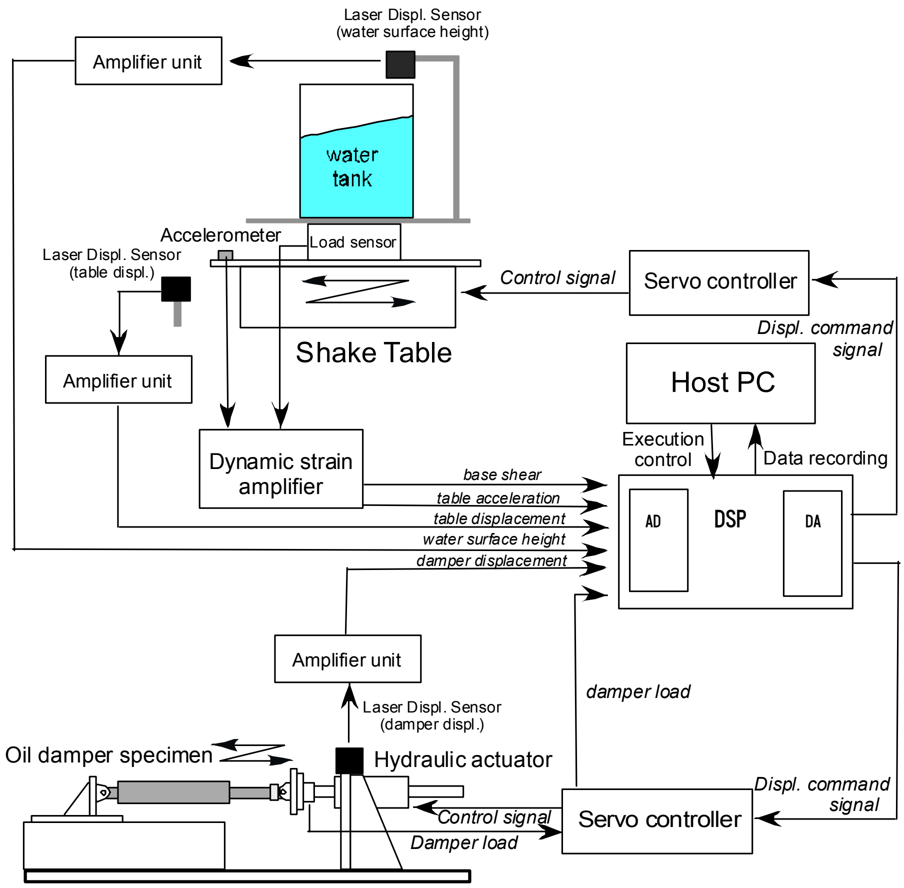

Figure 6 Schematics of test system and test setup

4. STABILITY ANALYSIS OF REAL-TIME HYBRID LOADING TEST SYSTEM

The response time delay is an inherent problem associated with loading equipments that involve the hydraulic system dynamics. This time delay problem appearing in the shake table and the actuator is one of the issues to be considered in the discussion on the feasibility of the real-time hybrid loading test, and this problem has to be overcome toward the end of the actual implementation of the test method. In the situation of the testing described above, interaction among the test equipments, controllers and test specimens can be viewed as a single and complicated dynamic system, which includes several feedback actions. Response time delay in the system elements, which is not assumed in the original formulation of the test method, affects the result of the test as negative damping is introduced into the system. This effect can cause not only inaccuracy in the test result, but also instability or divergence of the system, rendering the test system totally unreliable in some cases.

In this study, the stability limit in equipment time delay is determined by deriving the transfer function with respect to the input-output relationship in the real-time hybrid loading test system, for the evaluation of the reliability and feasibility of the test system and of the implementation of the test method. The dynamic property of the structural system to be considered can be approximately modeled by a linear 2-DOF system shown in Fig.7, assuming that the classical Housner model represents the principal mode of sloshing of the liquid content in the liquid storage tank, and the behavior of the oil tank is represented by a linear spring-dashpot model. In Fig.7, the mass of the part of liquid content is divided into $m_{1,liq}$ and m_2 in accordance with the formulation of Housner model.

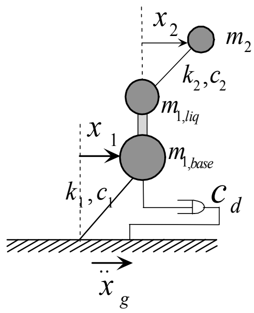

Figure 7 Linearized model of isolated tank system

The system block diagram of the dynamic system that represents the real-time hybrid loading test is determined considering the input-output relationships of the test equipments and test control system including the phase delay, as shown in Fig. 8 where $G_c(s)$ is the transfer function of the numerical substructure (external load input and absolute acceleration response), $G_t(s)$ is the transfer function of the part of liquid content corresponding to the mass m_2 (absolute acceleration input and the absolute acceleration response), $G_d(s)$ is the transfer function of the damper (relative displacement input and the damping force output), $G_{shk}(s)$ and $G_{act}(s)$ are the time delay transfer functions that represent the dynamics of shake table and the actuator, respectively.

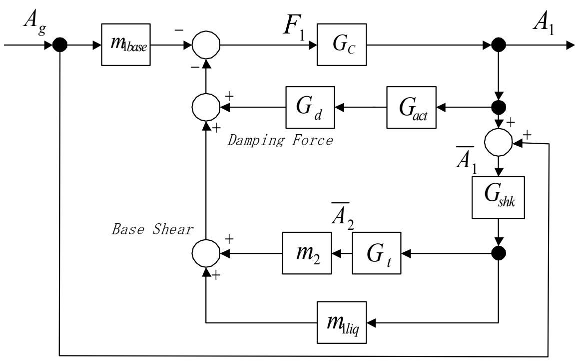

Figure 8 Block diagram of the hybrid loading test process with a linear structure model

Referring to the block diagram, the transfer function of the test system treating the ground acceleration as the input and the relative acceleration response of the numerical substructure as the output can be derived as the following expression:

$$G_{sys} = \frac{G_c\{G_{shk}(m_2G_t + m_{1,liq}) + m_{1,base}\}}{-1 - G_c\{G_dG_{act} + G_{shk}(m_2G_t + m_{1,liq})\}} \tag{4.1}$$

The stability of the system can be determined by examining if all the poles of the transfer function locate in the stability region (the left half complex plane of *s*). As a representative example, Fig. 9 shows one of the results of the stability analysis of the test system expressed as the 'stable region' of combinations of the delay time of the actuator (represented by the horizontal axis) and that of the shake table (the vertical axis), for the case of $m_{1,base}$= 478.5kg, natural period and damping ratio of the isolated tank are specified as T_1=1.25sec and h_1=0.1, respectively. This results indicates that the delay time of the shake table is more influential and sensitive to the stability of the real-time hybrid loading test system than the delay time of the actuator for the case of assumed parameters. For example, compared with the observation that critical delay time of actuator affecting the stability is of the order of 0.1sec, the delay time of the shake table of only 0.01sec can induce instability, and that minimum requirements for the shake table delay time and the actuator delay time for stability is less than, say, 0.04 sec and 0.25 sec, respectively. Therefore, delay compensation for the shake table is particularly important for the successful development of the test system.

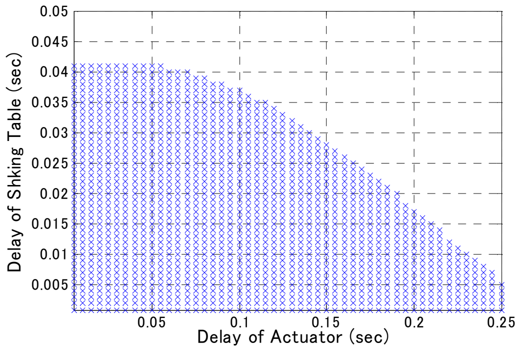

Figure 9 Stable region of the system in terms of delay times

5. IMPLEMENTATION OF REAL-TIME HYBRID LOADING TEST ALGORITHM

The real-time hybrid loading test algorithm was implemented to the test control system described in section 3.3. As the numerical time integration scheme, the operator splitting method was used, with the integration time interval of 1ms. The frequency-phase response plots for the shake table and the actuator is shown in Fig.10, which indicates typical feature of the time delay response. In the developed system, a digital filter of the form of a cascade of a 3rd-order FIR filter for compensation of response dynamics of the hydraulic system and a 3rd-order IIR filter for the noise reduction is employed for the delay time compensation of the shake table and the actuator. The frequency-phase response plots for the case with the delay time compensation by the application of the digital filter to the command signals for the shake table and the actuator are also shown in Fig.11.

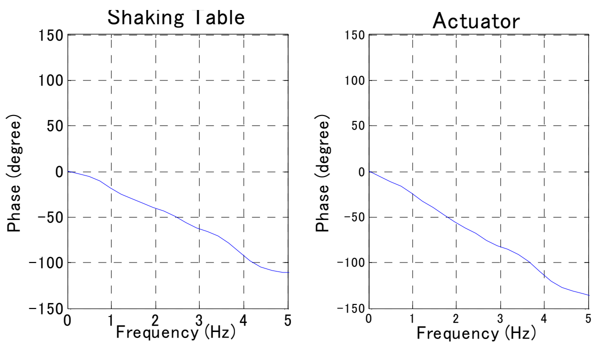

Figure 10 Frequency-phase delay characteristics of the loading equipments

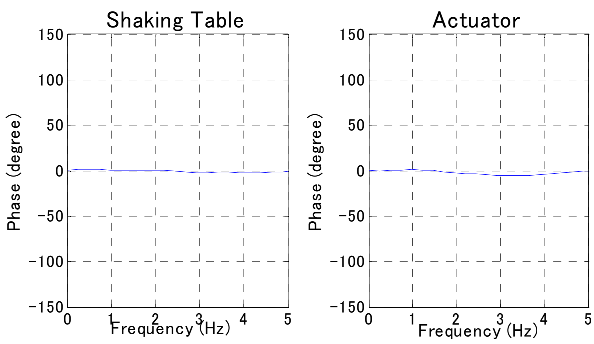

Figure 11 Frequency-phase delay characteristics of the loading equipments with the application of delay compensation

6. VERIFICATION TEST

A series of real-time hybrid loading tests were conducted using the developed test system. Figure 12 shows the test result for the case of $m_{1,base}$=478.5kg, T_1=1.25sec, h_1 =10%, and the ground acceleration input is the El Centro record NS component with the compressed time axis by a scale factor of 1/4. This is a case such that the behavior of the liquid content can sufficiently be represented by the linear approximation due to the fact that the motion of the liquid content is dominated by the 1st mode sloshing as the natural period of the isolated tank system is relatively long. The test result shows a good agreement with the time histories obtained by the numerical simulation using the linearized model, indicating that the reliability of the real-time hybrid loading test for this case.

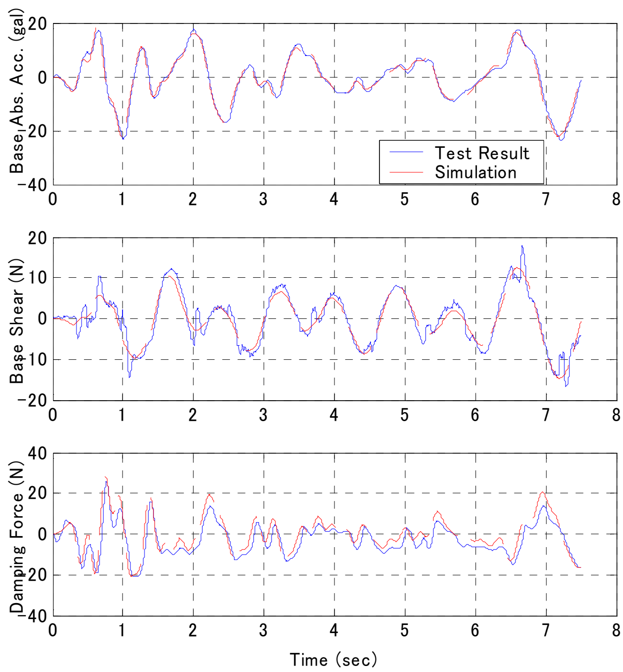

Figure 12 Test result: m_{1base}=478.5kg, T_1=1.25sec (long period and linear liquid behavior)

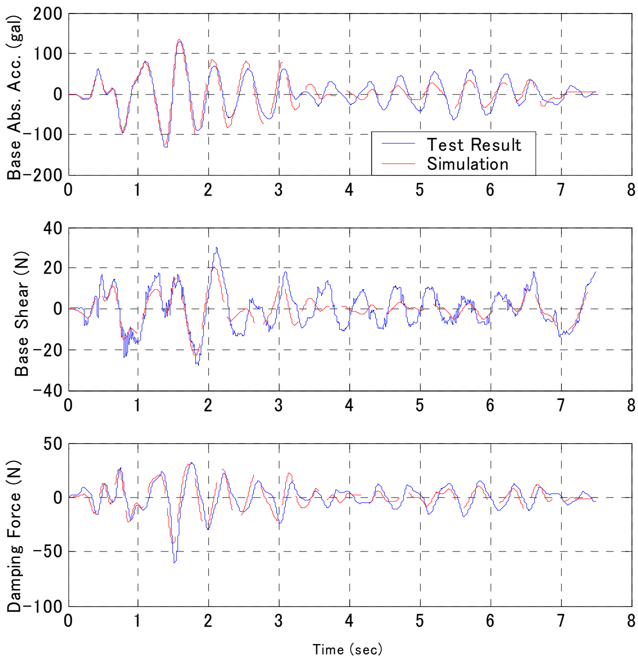

Figure 13 Test result: m_{1bas}e=179kg, T_1=0.5sec (short period and nonlinear liquid behavior)

Figure 13 shows the test result for the case of $m_{1,base}$=179kg, T_1=0.5sec, using the same ground acceleration input as in the previous case. The dynamic response of the liquid content exhibits short period motion and evident nonlinear behavior appears especially as a considerable deviation in the base shear and acceleration time histories from the numerical simulation using the linearized model. It should also be noted that the influence of the behavior of the experimental substructure to the total system is greater than in the previous case , since the assumed mass of the base part was set to be smaller. Considering that the test system and test results were found to be sufficiently reliable within the frequency range of 0.1-5Hz, the result shown in Fig. 13 strongly suggests that the behavior of the isolated tank model in this case reflects the nonlinearity of the test specimens.

7. CONCLUSIONS

The real-time hybrid loading test method developed in this study consists of the shaking table test, a real-time loading test using a dynamic actuator for the specimens that are parts of the structural system to be considered, and numerical computation for the other part of the structure. The coupled time delay effect of the shake table and the hydraulic actuator is analyzed using the transfer function approach and numerical stability analysis, and required time-delay characteristics of the test equipments are discussed based on the calculated stability region in terms of the combination of the time-delay parameters for the different test equipments.

In order to demonstrate the feasibility of the test method, a series of hybrid simulation tests of a cylindrical liquid storage tank with seismic isolators and a seismic damper are conducted. Two independent test equipments to perform the dynamic excitation test of a scaled tank model by a shake table, and real-time loading test of a seismic damper specimen using a dynamic actuator are treated as the experimental simulation elements, and combined in the framework of real-time hybrid simulation together with numerical simulation of the other parts of the structural system including the seismic isolators. Implementation of the test method includes the dynamic compensation of the delay effects of the loading equipments using digital filters.

Reliability of the test system is examined by the comparison of the verification test in a linear range with reference theoretical prediction. In the hybrid simulation tests for strong seismic inputs in which nonlinear breaking water surface is observed in the tank, the developed system is shown to be capable of producing test results including the effect of nonlinearity of the specimen. The method developed in this study is a promising and useful approach for the verification of the dynamic behavior of various types of structural system, if successfully applied to test equipments with greater loading capacity.

REFERENCES

Igarashi, A., Iemura, H. and Suwa, T. (2000). Development of substructured shake table test method, *Proc. 12th World Conference on Earthquake Engineering*, Paper No.1775.

Darby, P., Williams, M. S. and Blakeborough, A. (2002). Stability and delay compensation for real-time substructure testing, *J. Engineering Mechanics*, ASCE.

Igarashi, A., Iemura, H. and Tanaka, H. (2003). Development of substructure hybrid shake table test system and application to verification tests of vibration control devices, *J. Structural Eng.*, JSCE, **49A,** 281-288.

Shrimali, M. K. and Jangid, R. S. (2002). A comparative study of performance of various isolation systems for liquid storage tanks, *Intl. J. Structural Stability and Dynamics*, **2:4**.

Spencer, W. Jr., Finholt, T. A., Foster, I., Kesselman, C., Beldica, C., Futrelle, J., Gullapalli, S., Hubbard, P. , Liming, L., Marcusiu, D., Pearlman, L., Severance, C.and Yang, G.Q. (2004). NEESGRID: A Distributed Collaboratory for Advanced Earthquake Engineering Experiment and Simulation, *Proc. 13th World Conference on Earthquake Engineering*, Paper No.1674.