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Paper No. 660. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DEVELOPMENT OF A REAL-TIME HYBRID EXPERIMENTAL SYSTEM WITH ACTUATOR DELAY COMPENSATION

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ABSTRACT

A real-time hybrid experimental method, in which output from an actuator-excited vibration experiment and response calculation are combined on-line and conducted simultaneously in real time, is being developed as a new seismic experimental method for structural systems. In real-time hybrid experiments, however, there is an inevitable actuator-response delay, which has an effect equivalent to negative damping. To solve this problem, a real-time hybrid experimental system including an actuator-delay compensation method was developed. This paper outlines the developed system and also shows some examples of seismic experiments which successfully demonstrate the advantages of the system.

KEYWORDS

Seismic Experiment; Seismic Response; Hybrid Experiment; Pseudo-Dynamic Experiment; Real Time; Hydraulic Actuator; Computer-Aided Test; Delay Compensation

INTRODUCTION

Evaluation of the seismic response of a structural system is usually conducted using a shaking table. However, shaking-table experiments for large-scale structures are sometimes difficult, due to table-capacity limitations. As a solution to this problem, Hakuno *et al.* (1969) proposed a seismic experimental method in which an actuator-excitation experiment on a part of a structural system are combined with vibration response calculations on a computer. This method has been developed and improved through various projects, which have been summarized by Iemura (1985), Takanashi *et al.* (1987) and Mahin *et al.* (1989). This method will be referred to here as a "hybrid experiment" because it is a *hybrid* of actuator-excitation experiments and computer simulation. Note that the method is also referred to in various other ways, such as *computer-actuator on-line experiment* or *pseudodynamic experiment.*

Usually, actuator excitation in hybrid experiments is conducted on an expanded time axis, so that the structural response can be observed easily. However, when the response depends heavily on velocity because of damping, the excitation should be conducted in real time; in other words, the actuator excitation and the computer simulation should be conducted on a common time axis. For this purpose, several systems have been developed (Hakuno, *et al.*, 1969; Nakashima, *et al.*, 1992; Nakagawa, *et al.*, 1994). Although these research efforts successfully showed the advantages of their various systems through the demonstration experiments, some limitations were found in application to experiments for wider variaties of structural systems. To achieve a more flexible and more practical experimental system, the authors developed a real-time hybrid experimental system using a hydraulic actuator having a large exciting force. Since the dynamic characteristics of hydraulic actuators inevitably include a response delay, which is equivalent to negative damping in a real-time hybrid experiment, a delay compensation method was developed and applied (Horiuchi, *et al.*, 1995). In this report, a short description of real-time hybrid experiments will be followed by an outline of the developed compensation method. Also, some examples for seismic experiments of actual systems will be shown.

OVERVIEW OF REAL-TIME HYBRID EXPERIMENTS

A conceptual view of a hybrid experiment is shown in Fig. 1. The original structure, of which the seismic response is of interest, is divided into two parts. One is actually modeled, and the model is excited with an actuator. The other is modeled numerically and inputted to a computer. In the computer, the vibration response of the numerical model is calculated based on the following equation of motion:

$$\boldsymbol{M}_c\ddot{\boldsymbol{x}} + \boldsymbol{C}_c\dot{\boldsymbol{x}} + \boldsymbol{K}_c\boldsymbol{x} = \boldsymbol{f} + \boldsymbol{q}, \tag{1}$$

where $\boldsymbol{M}_c$, $\boldsymbol{C}_c$ and $\boldsymbol{K}_c$ are the mass, damping and stiffness matrices, respectively, of the nimerical model, $\boldsymbol{x}$ is a relative displacement vector, $\boldsymbol{f}$ is an external force vector, $\boldsymbol{q}$ is a reaction force vector generated at the boundary of the actual and the numerical models, and the overdots represent differentiation with respect to time. The reaction force vector $\boldsymbol{q}$ is formally written using a displacement at the boundary x_b as follows;

$$\boldsymbol{q} = \boldsymbol{q}(x_b,\ \dot{x}_b,\ \ddot{x}_b,\ \cdots). \tag{2}$$

Therefore, by repeating the following steps, the seismic response of the whole structure can be evaluated: (1) Measure the reaction force $\boldsymbol{q}$ from the actuator-excitation experiment; (2) calculate the vibration response of the numerical model using the measured reaction-force vector $\boldsymbol{q}$ and the predetermined external-force vector $\boldsymbol{f}$; (3) excite the actual model based on the calculated vibration response $\boldsymbol{x}$. This experimental method allows one to conduct seismic experiments economically by replacing a part of the structure with a numerical model. Also the method makes it possible to calculate seismic response for structures that include a part that is difficult to model numerically. From Eq. (2), it can be undersood that it is necessary to conduct the excitation experiment and the computer calculation on a common time axis, i.e. in real time, when the reaction force depends largely on displacement derivatives with respect to time.

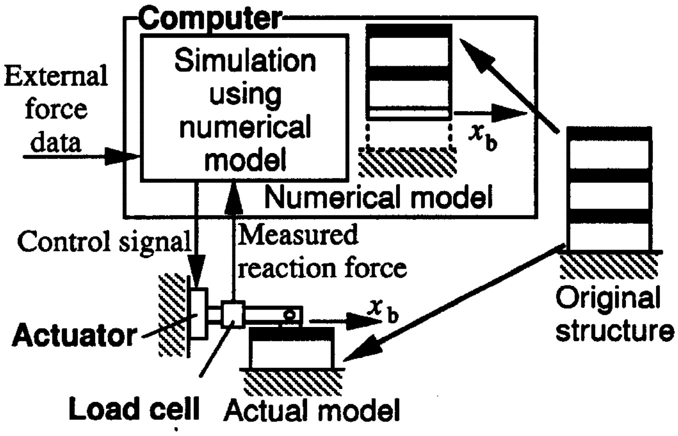


Figure 1: Conceptual view of hybrid experiment

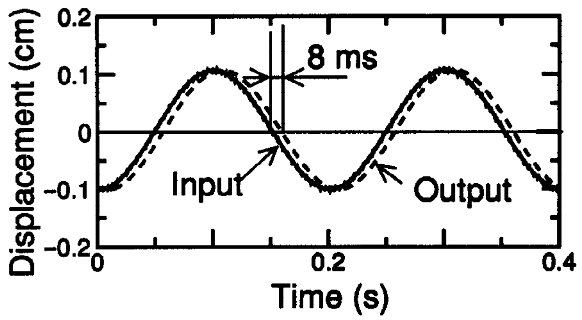


Figure 2: Time history of input and output signals for an actuator

ACTUATOR-DELAY COMPENSATION

Dynamic characteristics of hydraulic actuators

Since applying the hybrid experimental method to a large-scale structure requires a large actuator-excitation force, hydraulic actuators are preferable in such cases. However, the dynamic characteristics of hydraulic actuators include a small but inevitable response delay. A representative example of this delay characteristic is shown in Fig. 2, where the input signal and the resulting displacement are compared. This response delay is equivalent to negative damping in a real-time hybrid experiment for the following reasons: Consider an experiment for a single-degree-of-freedom (SDOF) system shown in Fig. 3, where a spring with a stiffness k is under excitation. Let ω_0 and δt be the natural circular frequency of the SDOF system and the response delay time of the actuator, respectively. The reaction force to be used for calculating q is proportional not to the calculated displacement of the mass x but to the actual excited displacement x''. Therefore, δE, the change in the total system energy per one period for free-vibration with the displacement amplitude A, becomes:

$$\delta E = \oint q\,dx = \int_0^T q\frac{dx}{dt}dt = \int_0^T (kx'')\frac{dx}{dt}dt = \int_0^T kA\sin(\omega_0 t - \omega_0 \delta t)\cdot A\omega\cos(\omega_0 t)dt = \frac{1}{2}kA^2\cdot 2\pi\omega_0\delta t, \quad (3)$$

where $T = 2\pi/\omega_0$. This energy change is the same as that caused by equivalent negative damping c_{eq}, where $c_{eq} = -k\delta t$. If the negative damping is larger than the inherent structural damping, the response will diverge and the experiment will thus become impossible. Therefore, this delay needs to be canceled.

The method of compasating for actuator delay

The proposed compensation method predicts the displacement of the actuator at the time after the

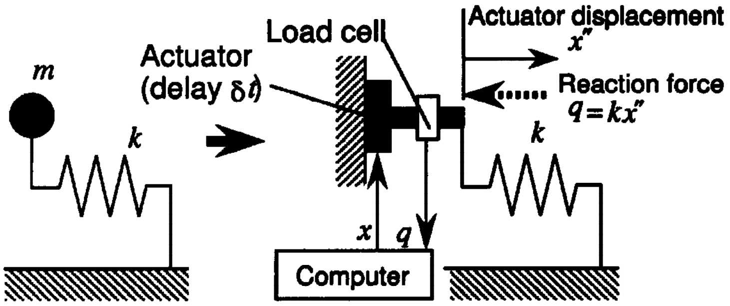
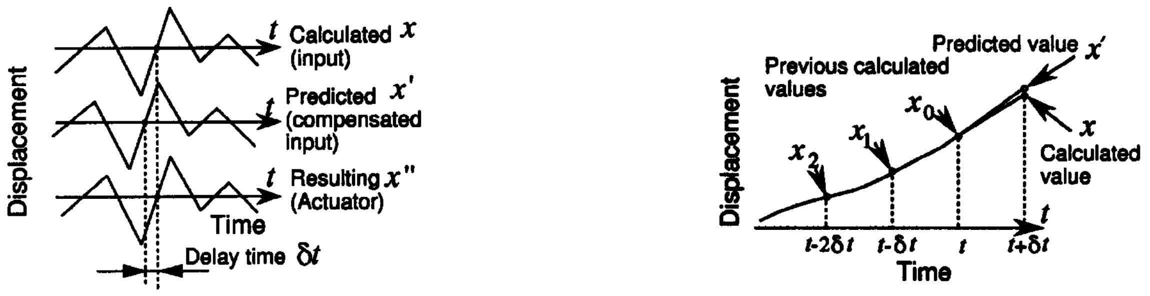


Figure 3: Real-time hybrid experiment for a single-degree-of-freedom system



(a) Displacement prediction for delay compensation

(b) Calculation of predicted value x'

Figure 4: Schematic of the prediction method

Table 1: Constants in the equation for prediction

Order n	a_0	a_1	a_2	a_3	a_4
0	1	–	–	–	–
1	2	−1	–	–	–
2	3	−3	1	–	–
3	4	−6	4	−1	–
4	5	−10	10	−5	1

actuator delay δt (Horiuchi, *et al.*, 1995). A schematic of this process is shown in Fig. 4(a), where x, x' and x'' are the displacements *calculated* (by the computer), *predicted* (by the prediction subsystem) and *resulting* (by the actuator), respectively. By inputting the predicted value x' as a control signal to the actuator, the resulting displacement x'' becomes almost identical to the calculated one (x), because the input signal occurs after the delay period. Since the prediction-calculation time needs to be small in order to accomplish real-time experiments, the following simple equation is used, by which the predicted value x' is extrapolated using an nth-order polynomial function based on the present and n previous calculated values, as shown in Fig. 4(b).

$$x' = \sum_{i=0}^{n} a_i x_i, \tag{4}$$

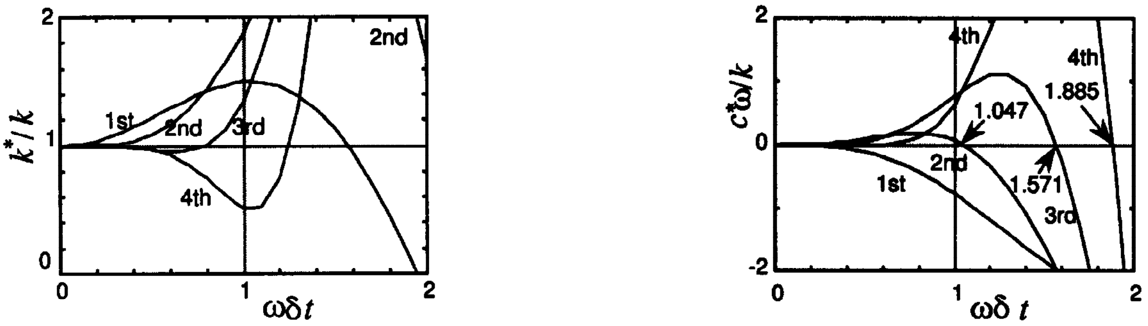
where n is the order of prediction, x_0 is the present calculated displacement, x_i is the calculated displacement $\delta t \times i$ units of time ago, and a_i are the constants shown in Table 1. By introducing the prediction subsystem on the SDOF experiment shown in Fig. 3, the predicted value x' becomes the control signal to the actuator, instead of the calculated value x. When the calculated vibration response is a sinusoidal wave with a circular frequency of ω, the reaction force q used in the calculation becomes

$$q = k_n^* x + c_n^* \dot{x}, \tag{5}$$

where k_n^* and c_n^* are the apparent stiffness and damping, respectively, for the nth-order prediction, in which

$$k_n^*/k = \sum_{i=0}^{n} a_i \cos(i+1)\omega\delta t, \qquad c_n^*\omega/k = -\sum_{i=0}^{n} a_i \sin(i+1)\omega\delta t. \tag{6}$$

The apparent stiffness k_n^* and damping c_n^* can be expressed as functions of $\omega\delta t$ as shown in Figs. 5 (a) and (b). Observe that k_n^*/k is almost equal to one and $c_n^*\omega/k$ is almost equal to zero when $\omega\delta t$ is small, although the prediction causes small variations both in stiffness and damping. It should be noted, however, that the damping becomes negative, and thus the calculation diverges, when a natural frequency of the structure considered is larger than a critical value that depends on the prediction depth n and the delay time δt. This is the limitation of this method. In the experiments discussed below, the third-order prediction was used because it requires only a small calculation load and gives a large critical value $\omega\delta t$ of 1.571 for stable calculation.



(a) Apparent stiffness

(b) Apparent damping

Figure 5: Variation of apparent additional stiffness and damping for $\omega\delta t$

Evaluation of the developed system

A real-time hybrid experimental system including the compensation subsystem was investigated using the test set-up shown in Fig. 6(a), where the actuator excited no real structural system and the reaction force to be measured was instead calculated by multiplying the measured resulting displacement and a stiffness constant. In this way, the influence of structural characteristics could be neglected, allowing the experimenters to focus on the influence of actuator control on the system's performance. The structural model under consideration is the 4-degree-of-freedom model shown in Fig. 6(b). Using white noise as the ground acceleration, the response curve as shown in Fig. 7(a) was obtained. Although the compensation affected high-order modes, the lower modes, which are important for seismic response, could be evaluated precisely. In addition, the result comparisons for a ten-period harmonic-wave excitation were made. The maximum displacement and an example time history are shown in Figs. 7 (b) and (c). Since the experimental and the analytical results are very close, it can be concluded that a system using the proposed compensation can perform seismic experiments for structures with high precision.

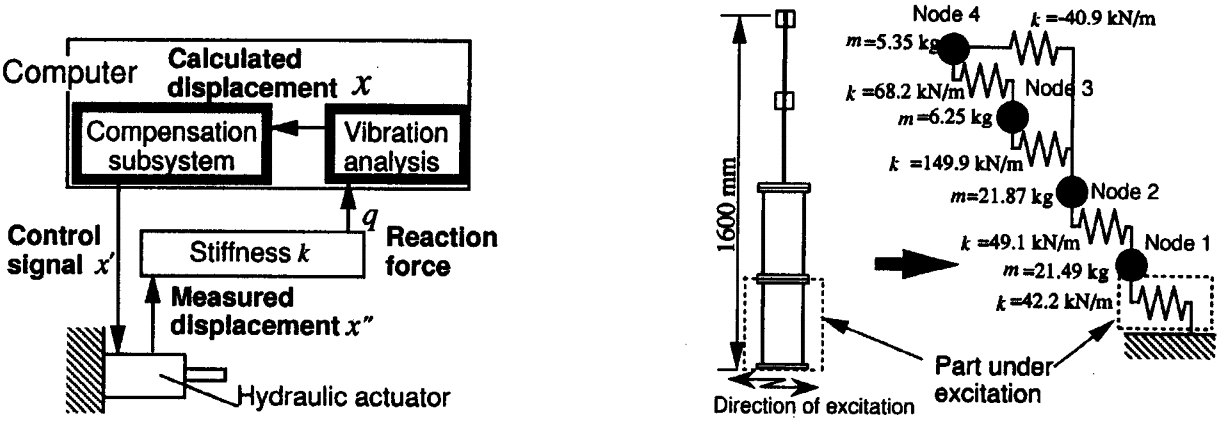
EXAMPLES OF SEISMIC EXPERIMENTS

FRP column of Thyrister valve

A thyristor valve is an electrical power system in which thyristor modules are supported by metal frames and fiber-reinforced-plastic (FRP) columns, as shown in Fig. 8(a). It is difficult to conduct its seismic experiments using shaking tables because of its large scale and heavy weight. Therefore, the seismic response of a part of an FRP column (Fig. 8(a)) was evaluated (Inoue *et al*, to be published) by means of the real-time hybrid experimental system described above. The experimental system used here is summarized in Table 2(a). A Digital Signal Processor (DSP) was used as a computer because the number of degrees of freedom is small in this numerical model. It should be noted that a computer with more computation power would be necessary if a complex numerical model were required. The response was evaluated for three-period harmonic wave excitations at the first natural frequency of the system. The maximum reaction force obtained for various excitation amplitudes is shown in Fig. 8(b). The reaction force showed nonlinearity caused by damage when the excitation became much larger than the design level (0.3 m/s^2). It was found, however, that the FRP columns were damaged only at their end-flanges and failure of the entire structure was not observed even under strong excitation conditions.

Energy absorber for piping systems

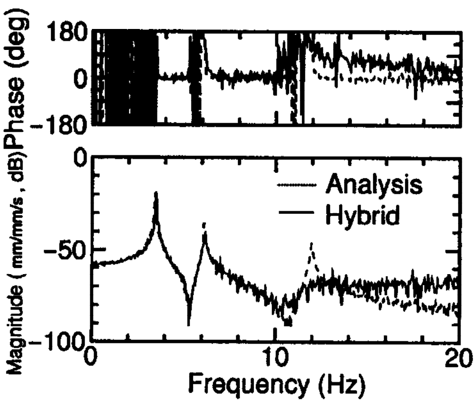
An energy absorber (EAB) is a type of support for piping systems (Fig. 9(a)) which can dissipate vibration energy in the piping system by hysteretic deformation of steel plates contained in it. A series of shaking-table experiments using the simple piping system shown in Fig. 9(a) had been conducted to



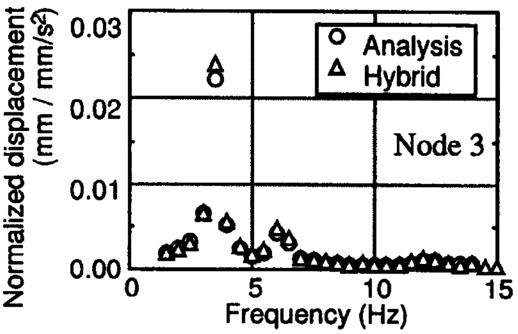
(a) Experimental set-ups

(b) Structural model under experiment

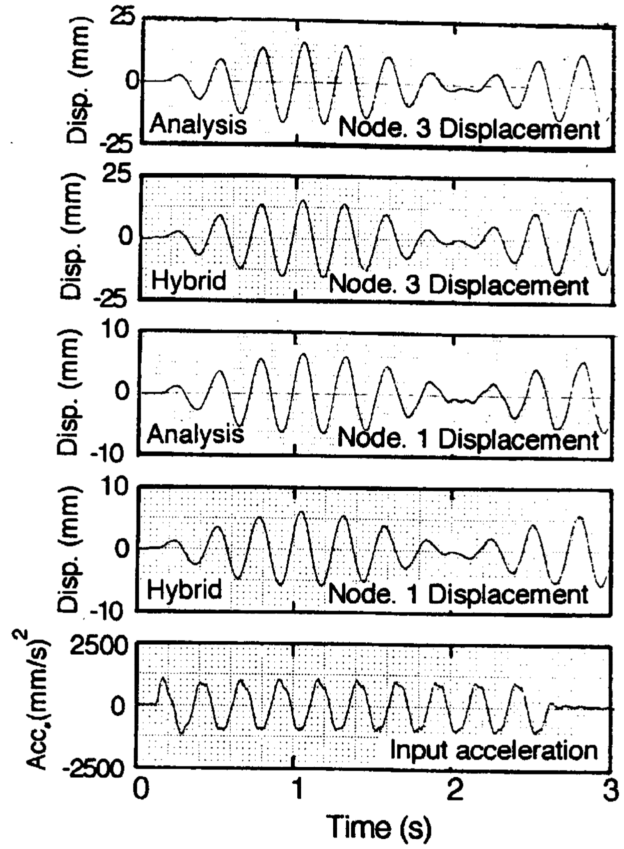
Figure 6: Conceptual view of testing experiment



(a) Response curve of the structural model



(b) Maximum displacement caused by 10-period harmonic excitation



(c) Displacement time histories

Figure 7: Results of verification experiments

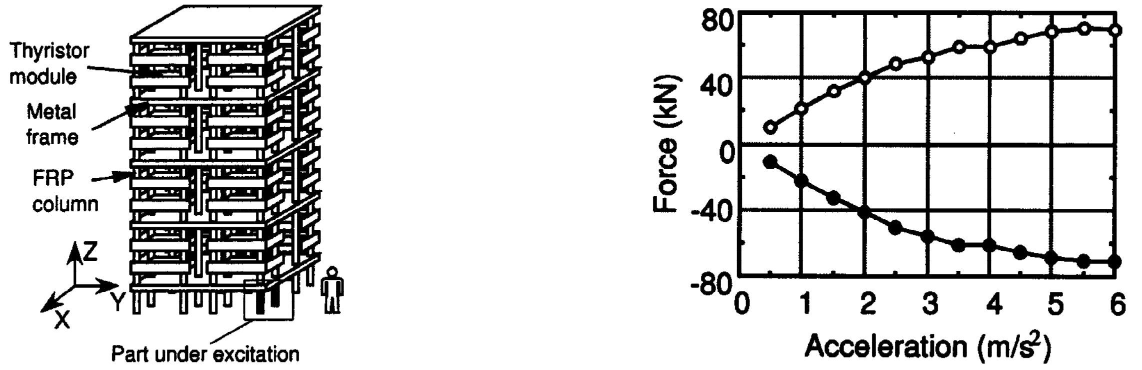
Table 2: Specification of the hybrid experimental system

(a) FRP-column experiment

Actuator	
Exciting force	Max 98 kN (10 t)
Stroke	Max ± 75 mm
Dynamic range	30 Hz (90° Phase)
Computer	
DSP	TMS320C30
Time integral method	Central difference

(b) 4-story-building experiment

Actuator	
Exciting force	Max 500 kN (51 t)
Stroke	Max ± 300 mm
Dynamic range	10 Hz (90° Phase)
Computer	
SRC	(Umekita *et al.*, 1995)
Time integral method	Central difference



(a) Schematic view of a thyrister valve (b) Maximum reaction force of structural model

Figure 8: Outline of FRP-column experiment

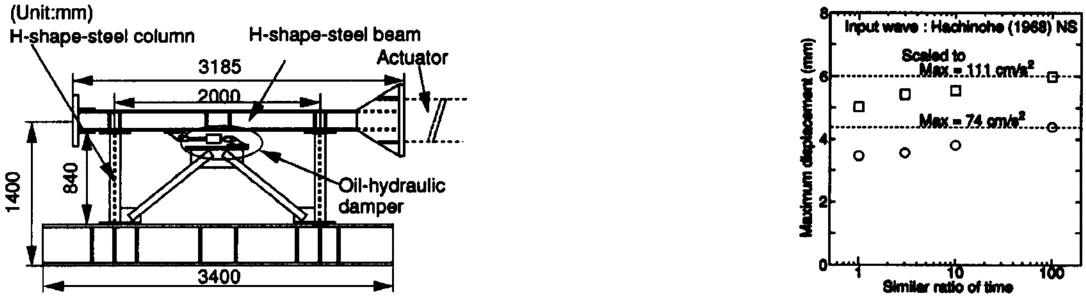
(a) Experimental set-up (b) Maximum response at the EAB position

Figure 9: Outline of EAB experiment

show the EAB performance (Namita *et al.*, 1995). The authors conducted real-time hybrid experiments for the same structure to verify the present experimental method, in which the EAB was actually modeled and the motion of the pipe was simulated by an actuator. In addition, the response under a large excitation, which was impossible with the shaking table, was also evaluated. The system used here is as shown in Table 2(a). The maximum displacement responses at the EAB are compared for the two methods in Fig. 9(b). Since the results are almost identical, it can be concluded that the structural response can be obtained precisely using the system developed.

4-story steel building

The structure under experiment (Fig. 10) was a model of the first story of a steel building. The upper stories were numerically modeled and the seismic response of a 4-story building was evaluated using a real-time hybrid experiment. The purpose was to evaluate the performance of an oil-hydraulic seismic damper. Also, the necessity for real-time experimentation was investigated by conducting the experiment with various similarity ratios for the time axis. The system used is summarized in Table 2(b). An actuator with a larger exciting force was employed, since the structure under experiment was large and rigid. Also, the Super Real-time Controller (SRC, Umekita *et al.*, 1995) served as the computer. The SRC can perform large matrix calculations with a small time step as well as communicate with other devices through A/D and D/A converters. The maximum displacement for various ratios of time similarity are shown in Fig. 10(b). Note that the results with similarity ratio of one were obtained from real-time experiment, and others came from *pseudodynamic* experiment. As observed in the figure, the pseudodynamic experiments show larger displacement than the real-time one, because the damping force could not be precisely evaluated. Therefore, it can be concluded that the precise evaluation of seismic response *requires* real-time experimentation.



(a) Schematic view of the first-story model (b) Maximum displacement at the first story

Figure 10: Outline of 4-story-steel-building experiment

CONCLUSIONS

Since the actuator response delay is equivalent to negative damping in real-time hybrid experiments, a method to cancel the delay out was proposed, in order to produce a practical real-time hybrid experimental system. The capability of the developed experimental system for seismic experiments was successfully demonstrated in a structural vibration test. In addition, three examples using the developed system for seismic experiments for actual structures were presented, in which useful information on the tested structures was obtained.

ACKNOWLEDGMENT

The third experimental example is part of a joint experimental research project of Obayashi Corporation and Hitachi, Ltd. The useful discussions held during the research with Dr. M. Seki, Messrs. H. Katsumata, Y. Shinabe and T. Sano of Obayashi Corporation are gratefully appreciated.

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