REAL-TIME HYBRID TEST USING MULTI-ACTUATORS TO ESTIMATE RESPONSE CONTROL PERFORMANCE OF RC FRAME STRUCTURE

A. Yokoyama(1), K. Fushihara(2), Y. Mukai(3), T. Fujinaga(4), H. Fujitani(5)

(1) Graduate Student, Graduate School of Engineering, Kobe University, 191T058T@stu.kobe-u.ac.jp
(2) Graduate Student, Graduate School of Engineering, Kobe University, 198T040T@stu.kobe-u.ac.jp
(3) Associate Professor, Graduate School of Engineering, Kobe University, ymukai@port.kobe-u.ac.jp
(4) Associate Professor, Research Center for Urban Safety and Security, Kobe University, ftaka@kobe-u.ac.jp
(5) Professor, Graduate School of Engineering, Kobe University, fujitani@kobe-u.ac.jp

Abstract

In this study, an ordinary RC frame building is adopted as the target for seismic response control. An active mass damper (AMD) is used as the control device, and its performance is examined through a real-time hybrid (RTH) test. Most parts of the target RC building is provided as the analytical model for the online computer simulation. The only single column of the first story is prepared as the practical test specimen, and a high-speed hydraulic actuator loads it. The uncertainty of RC-column's behavior is focused on this test, and the practical behavior of this column can be directly reflected in the computer calculation on the response of the entire structural system. At the same time, the test device of the AMD to equip on the target building is also practically prepared. The floor response of the target building is directly generated by the shaking table. The AMD is placed on the shaking table, and then the AMD can be manipulated by online under synchronization with the RC building part model. Thus, our RTH experiment is categorized as a testing method that multi-actuators operate different motions for different test specimens at the same time.

In the operation of the RTH test, the earthquake input motion is applied for the building model in the DSP controller, and time-history response analysis is performed. At the same time, the actual displacement and restoring force of the RC-column specimen and the motion and reacting force of the AMD are directly measured and reflected in the online model simulation. Then, the DSP controller determines the next target motion of the internal building model and manipulates the deformation of the RC column driving by the high-speed actuator, and the absolute floor displacement at the AMD basement driving by shaking table. Since this RTH test system using multi-actuators which are placed at different laboratories, two DSP controllers (master and slave) are prepared, and the communication between these are performed via LAN cable. Control operation in the RTH test is executed every 0.002 s, but the signal time delay between two DSPs is less than this control time interval.

At first, the actuator's performance is evaluated, and the installation of the actuator time delay compensator is investigated. The hydraulic actuator has a time delay of about 0.046 s depending on its mechanical property. Both the PID controller and the time series compensator are applied in parallel to improve the actuator performance. It is confirmed that the compensator can reduce the time delay to less than a third of the initial value. Next, the reproducibility of this multi-actuators RTH test system is evaluated. The restoring force and deformation of the RC column, and the floor motion responses reproduced on the shaking table are evaluated. These test results are compared to the fully-numerical simulations. The control effect of the AMD to increase the damping effect for the target RC building model is also investigated in this RTH test.

Keywords: Active mass damper; Shaking table; Real-time hybrid test; Hydraulic actuator; RC frame building

1. Introduction

Structural reinforcement and renovation against strong earthquakes are highly demanded to improve the seismic performance of existing buildings. The building damage-risks by the earthquakes are concerned in the near future because of the lack of seismic-resistance capacity. A mass damper system is one of the response control methods which are popularized in the mechanical engineering field. Practical installations of this type of device to building structures can also be seen in many buildings. The mass damper provides the advantage of usability to place on the floor directly and to tune its mechanical parameter. Recently, utilization of a mass damper is focused not only on the anti-seismic design of the new construction but also on the seismic retrofit of the existing building or the vibration control of the temporal constructions.

It is given an essential role in the structural design to evaluate the performance of building structures against seismic excitations. In particular, numerical simulation for estimating the dynamic behavior of the building, it is necessary to identify all the structural elements accurately for response evaluation. The huge-scale shaking-table test using the entire-parts specimen of the building is an effective way to observe practical structural response, in a case where the properties of some structural parts cannot be clearly understood. However, from the reason of costs or test-system capacity, the entire building tests cannot be placed as the standard estimation way of the structural performance. The real-time hybrid (RTH) simulation/experiment method is considered as a useful way to respond to this requirement, in the practical meanings. Because most parts of the building structures can be numerically modeled, and only uncertain parts in the structural system can be focused experimentally.

In this study, we implemented a multi-actuators RTH experiment system, which can simultaneously evaluate the seismic performance of the target building and demonstrate the control effect of the damping device by using two actuators. Unlike the conventional RTH tests performed with a single actuator, the developing system can perform the partial deformation in the structural system by using the hydraulic actuator and the partial floor dynamic motions in the target by using the shaking-table.

2. Outline of the experimental system

2.1. Multi-actuators RTH experiment

An ordinary RC frame building is considered as the test target building to estimate its seismic performance. Moreover, an active mass damper (AMD) is the damping device to demonstrate the control forces. The RTH test is operated, while the actuator practically loads the single column specimen with an unidentified feature. At the same time, the shaking-table generates the dynamic floor response of the target building, as shown in Fig. 1. All the other parts of the target RC building excepting the single-column specimen are provided as the analytical model for online computer simulation in this RTH test.

(a) Actuator and RC single column (b) Shaking table and AMD

Fig. 1 – Actuators for RTH test system and configuration equipping test specimens

Fig. 2 shows the conceptual diagram of the multi-actuators RTH test system in this study. An RC building model with an AMD installed on the top floor is assumed. The single-column placed at the first story is prepared as the practical test specimen, and a high-speed actuator loads it. The shaking-table reproduces the top floor's response of the target building for giving the AMD the floor motion behavior. First, the ground acceleration $\ddot{z}$ of seismic excitation is input to the numerical model, and the relative displacement response x calculated by computer is given to the column specimen by the hydraulic actuator. At the same time, the shaking-table reproduces the top floor's response acceleration $\ddot{y} = \ddot{x} + \ddot{z}$. Then, the restoring force of the column specimen f and the reaction force q of the AMD are measured and input to the numerical building model in the computer, and a response analysis considering the interaction forces are continued. By the response analysis, a control signal to the AMD and an output instruction to the shaking-table and the hydraulic actuator can be determined. These procedures are synchronized between the simulation part and the experimental part, and continuing step by step in real-time. This RTH test is also required to synchronize the two actuator's motion; these are the actuator and the shaking-table.

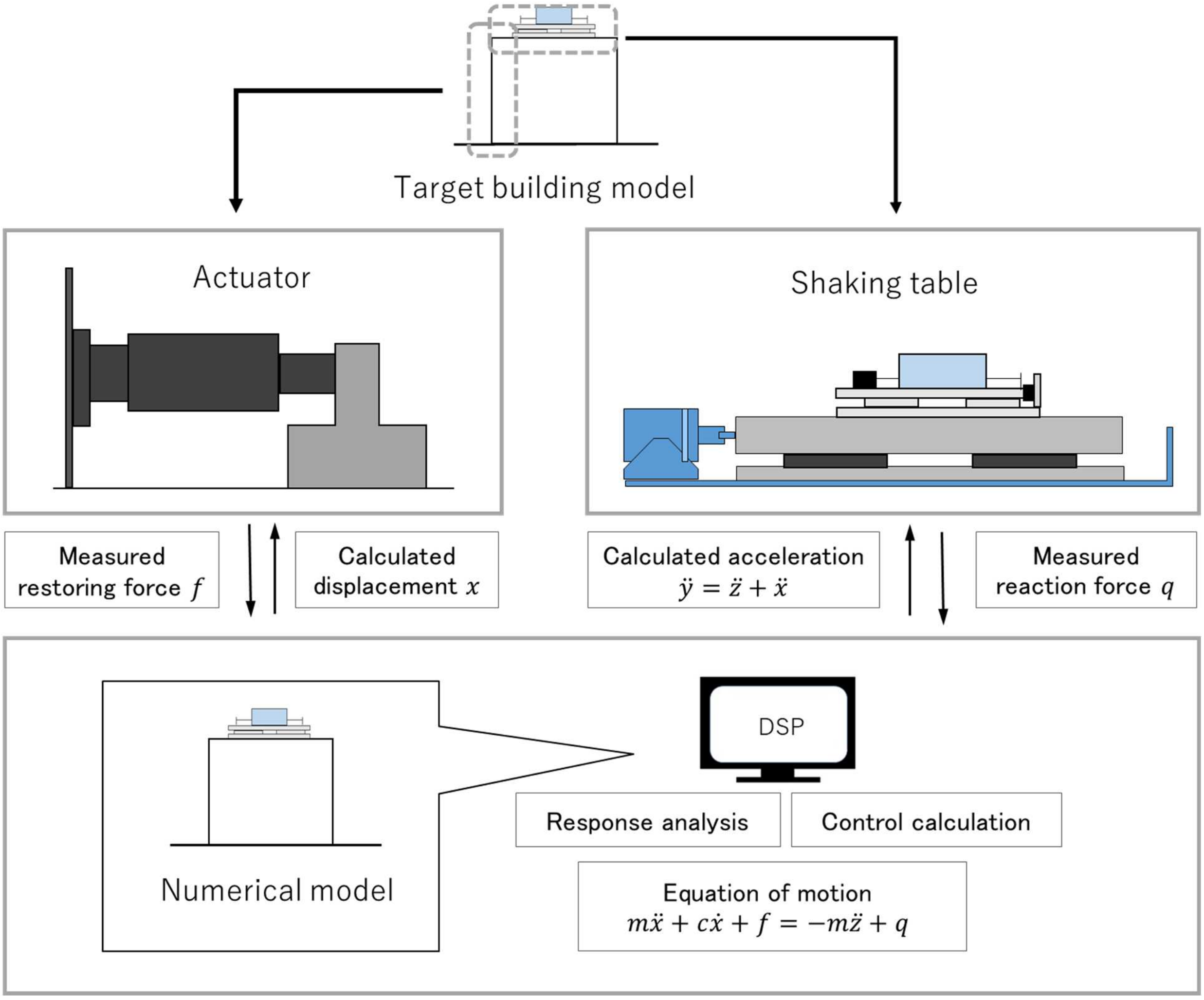


Fig. 2 – Conceptual diagram of the multi-actuators RTH test system

2.2. Outline of RC column specimen

Fig. 3 shows the RC column specimen used in the RTH test. The column specimen has a square cross-section of a width of 250 mm. A stub with a cross-section of 450 mm and a width of 350 mm is placed at the bottom of the specimen. The column height is 900 mm, and the loading point was set 750 mm from the top of the stub.

Table 1 shows the material properties of the rebar. The stiffness of the column is calculated by considering a static loading test results. Fig. 4 shows the relationship between the force and the drift angle of the column specimen. The maximum deformation is given to be 0.01 rad (δ =7.5mm); the loading history is cyclic, having the deformation steps by the increment of 1.5 mm from the original position (δ =1.5, 3.0. 4.5, 6.0, and 7.5mm). Each deformation step is repeated three times in the loading sequence. Table 2 shows the force vs. drift angle relationship of the RC column specimen.

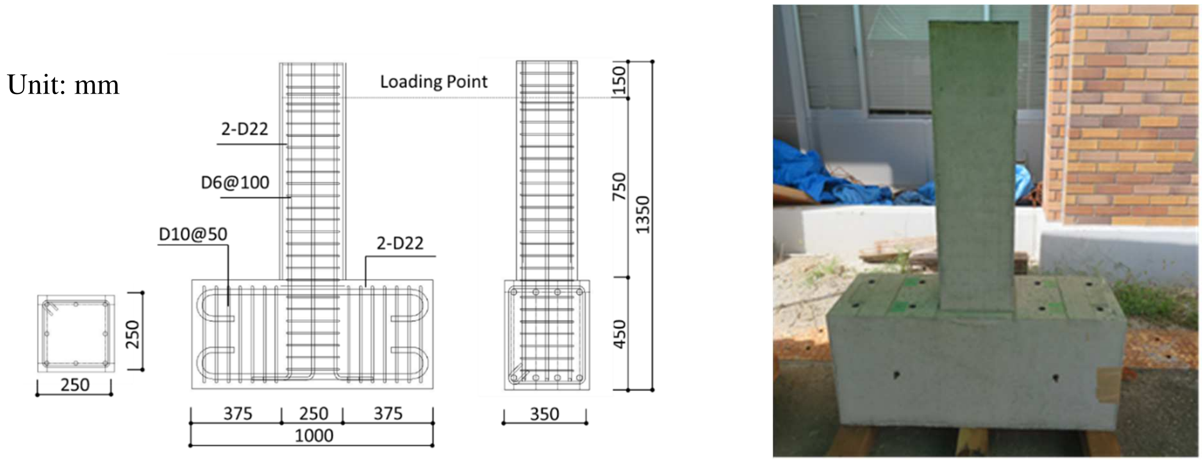


Fig. 3 – Configuration of the test specimen of RC column to set to the hydraulic actuator

Table 1 – Material properties of the rebars using in the RC column specimen

Rebar type	Yield stress (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
D6	334	509	31
D10	365	516	27
D22	381	566	20

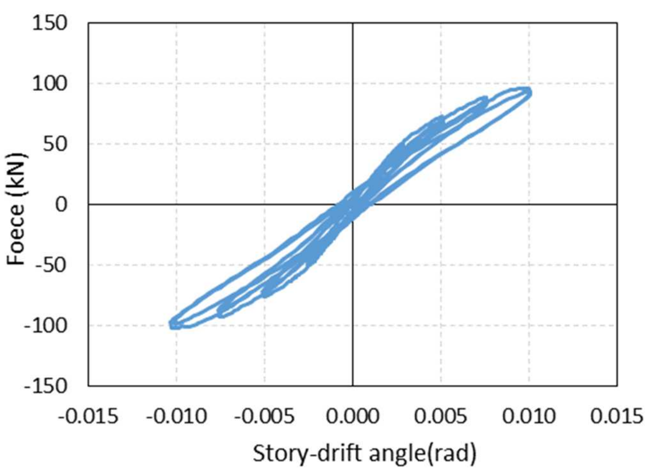


Fig. 4 – Force vs. drift angle relationship under static-loading test

Table 2 – The test condition of the RC specimen in the static loading.

Maximum deformation (rad)	axial force ratio	Concrete cylinder test results	
		Compressive strength (N/mm^2)	Tensile strength (N/mm^2)
0.01	0.2	36.5	2.98

2.3 Outline of assuming structural model and the correspondence with the column specimen

Fig. 5 shows the consideration of the entire structural model for the RTH test. The RC column specimen corresponds to the half part of the whole-span column; thus, its deformation δ is half of the whole-span column, then the stiffness of the whole-span column k' is adjusted to a half value as seen in Fig. 5 (d). The RTH test is operated by supposing the single-story building model, which contains the two practical parts; the RC column deformation and the top floor's motion. The hydraulic actuator and the shaking-table are synchronized by online, and the reproduced responses are measured. This test supposes a single-story building model for computer simulation; thus, the floor mass of the model is considered to be supported by four columns. The story stiffness is also considered to be four times the single column's stiffness. Every column contributes to having 1/4 weight of the entire floor mass M. The value of the weight of the target structural model is considered by giving the specified natural period; thus, this study supposed the initial structural parameters, as shown in Table 3. In the RTH test, the axial force of the RC column specimen is applied using the tension bars.

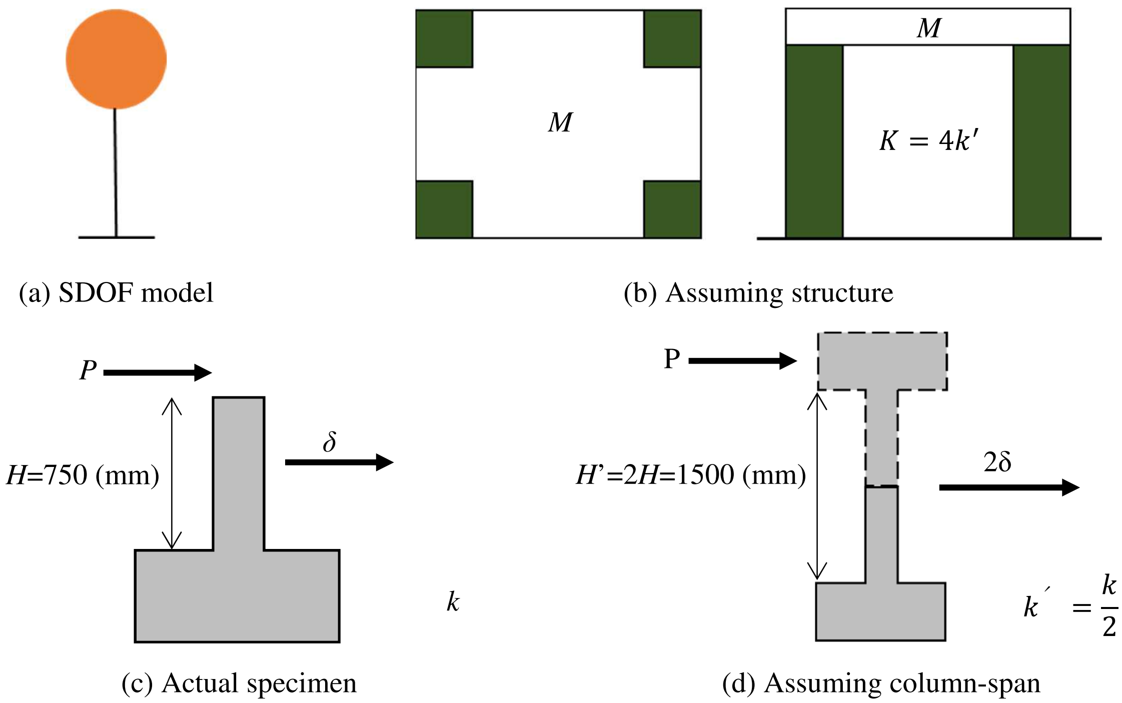


Fig.5 – Simulation model of the whole RC structure for the RTH test

Table 3 – Initial structural model's parameters

Natural period (s)	Mass (kg)	Stiffness (N/m)	Damping coefficient (Ns/m)
0.5	160,000	25,000,000 *	200,000

* These values are evaluated approximately using an elastic-stiffness from the gradient from the static loading test results.

3. Time delay compensation of driving the hydraulic actuator

3.1 Evaluation of time delay

It was confirmed that a time delay existed between the electric signal command and the reaction of the hydraulic actuator. In particular, as shown in Fig. 6, a time delay of about 0.05 s was observed on the reproduced displacement of the hydraulic actuator that depends on the hydraulic mechanism. The natural period of the target structural model in this test is supposed about 0.5 s. Thus, the time delay of the hydraulic actuator is thought to have significant influence to cause the RTH test performance to become unstable, because that the response delay must cause the online simulation to give the unexpectedly inaccurate results. Therefore, the immediate goal of this study is put on to compensate for the time delay of the hydraulic actuator

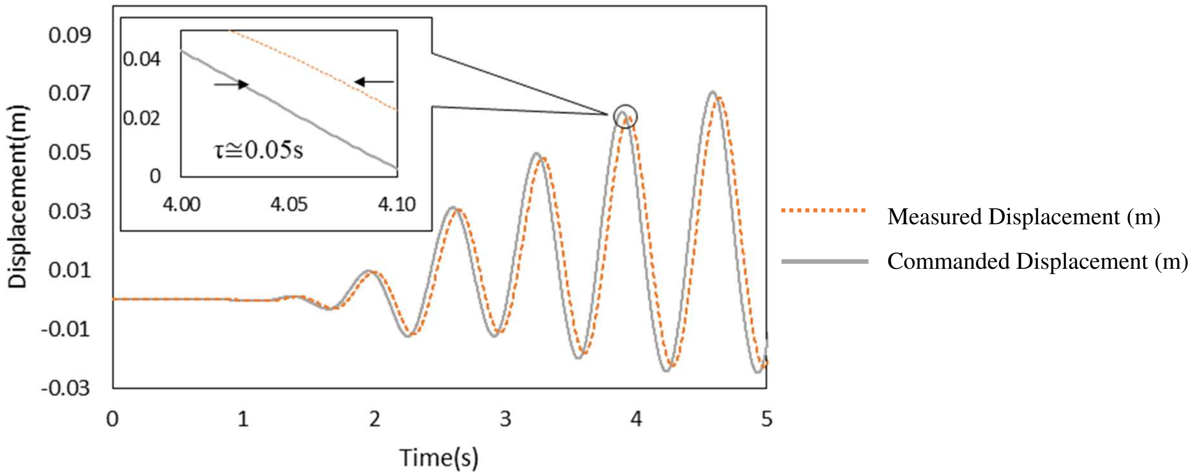


Fig.6 – Delay between command displacement and measured displacement of the hydraulic actuator

3.2 Identification of the time-delay model

In compensating for the time delay of the hydraulic actuator, it is necessary to identify the time delay model firstly. As the authorized method, a step response method is used. In which, a control target is regarded to have a first-order delay system and a time lag system. As seen in Fig. 7, a step-function input is applied to the actuator, and the step response is measured. Here, the gray line indicates the commanded displacement, and the orange line indicates the measured response displacement. A gradient at the inflection point while growing the step response is depicted with a black line, and the time at which the tangent intersects the time axis is determined as a time lag *L* (s). Then, the progress time interval by which the tangent intersects the line in the steady-state of the step response after the time lag *L* is determined as a time constant *T* (s). Table 4 shows these parameters calculated from this test in order to identify the time delay model. When the gain of the steady-state is *K*, the controlled object can be described by the transfer function in Eq. (1).

$$\mathrm{G(s)} = \frac{K}{Ts+1}e^{-Ls} \tag{1}$$

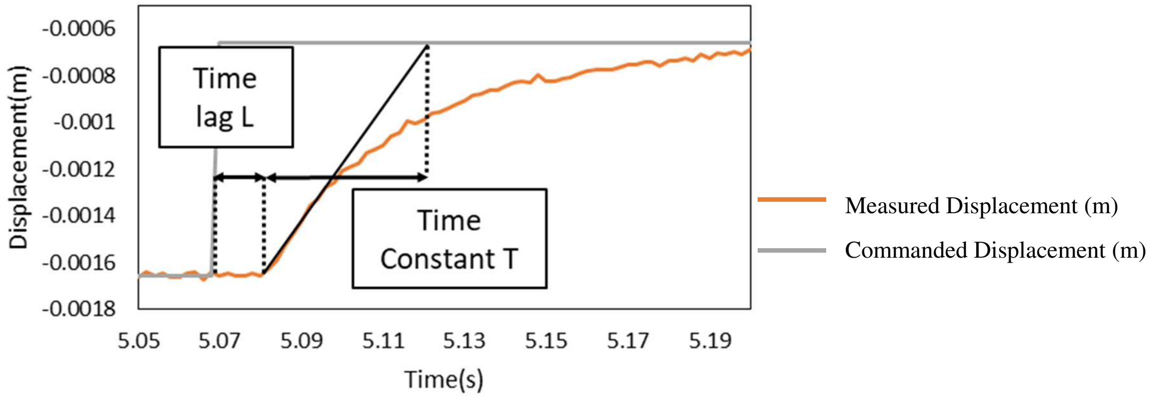


Fig. 7 – Identification of the time delay by step response method

Table 4 – Parameters calculated by the step response method

Time lag L (s)	Time constant T (s)
0.014	0.030

3.3 Actuator delay compensation using PID control and time series compensator

PID control combines the three operations of proportional operation, integration operation, and differential operation on the deviation signal e (t) between the output y (t) measured from the control target and the target value r (t) to be followed. This way is a control method for determining the input u (t) for compensating the control target output. The relationship among the output value y (t), the target value r (t), and the deviation signal e (t) is shown in Eq. (2). By applying the PID control method, it is possible to make a slow rise in the time constant to increase sharply. The compensating input based on PID control can be expressed by Eq. (3). Eq. (4) expresses the Laplace transform of Eq. (3), and describes the transfer characteristic between input and output in the s-region. The block diagram of the PID controller is depicted in Fig. 8. Table 5 shows the proportional constant P, integration constant I, and differential constant D used in this RTH test to compensate for the hydraulic actuator motion.

$$e(t) = r(t) - y(t) \tag{2}$$

$$u(t) = Pe(t) + I\int_0^t e(t)d\tau + D\frac{de(t)}{dt} \tag{3}$$

$$U(s) = \left(\mathrm{P} + \mathrm{I}\frac{1}{s} + Ds\right)E(s) \tag{4}$$

Table 5 – Parameters used in PID control

Proportional constant P	Integration constant I	Differential constant D
1.93	0.047	0

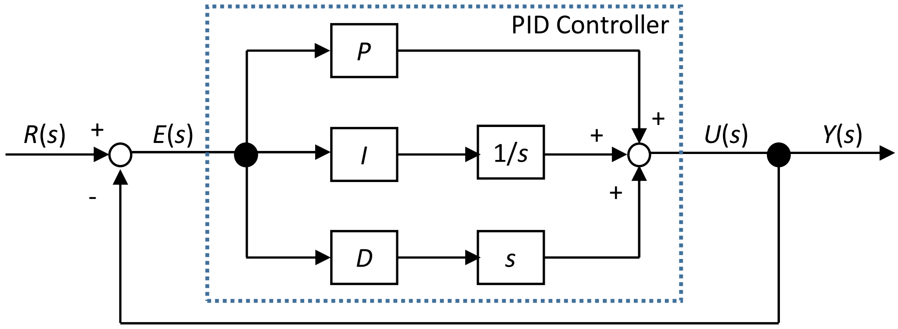


Fig. 8 – Block diagram of PID control

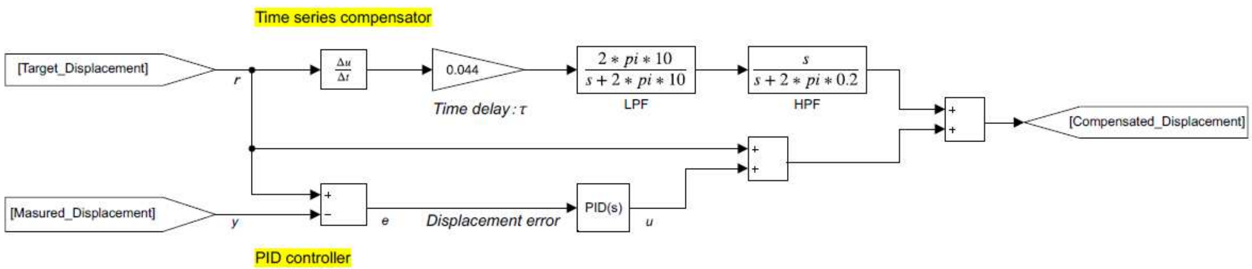


Fig.9 – Simulink block diagram of the actuator delay compensator

PID controller is installed for the error correction between the target signal and the measured signal of the hydraulic actuator displacement. To improve the actuator delay more effectively, the time series compensator is also introduced to the control operation of the hydraulic actuator. By evaluating the value of the time delay τ , the target input for the feedforward compensation related to the referential value after the time interval τ is considered. At the time t, the target displacement after the time interval τ can be expressed $r(t+\tau)$. Using the Tayler series, this expression can be expanded to the power series of τ.

$$r(t+\tau) = r(t) + \dot{r}(t)\tau + \frac{1}{2!}\ddot{r}(t)\tau^2 + \cdots \tag{5}$$

In this study, approximately considering until the first-order term in the Tayler series, the following time series compensator is installed to drive the hydraulic actuator in parallel with the PID controller. The Matlab/Simulink block diagram of the actuator delay compensator part is shown in Fig. 9.

$$r(t+\tau) \cong r(t) + \dot{r}(t)\tau \tag{6}$$

3.4 Compensating result of the hydraulic actuator motion using PID control

In Fig. 10, the commanded value, the compensated measured value, and the measured value without compensation are compared when a sine wave is used as an input. It can be confirmed that the delay time, which was about 0.044 s without compensation, was reduced to about 0.012 s with compensation. Fig. 11 shows the commanded displacement and the measured displacement of the actuator using PID control when a random wave is applied. In this case, the time difference between the commanded displacement and the measured displacement is as small as about 0.016 s, and the effectiveness of the PID control can be confirmed.

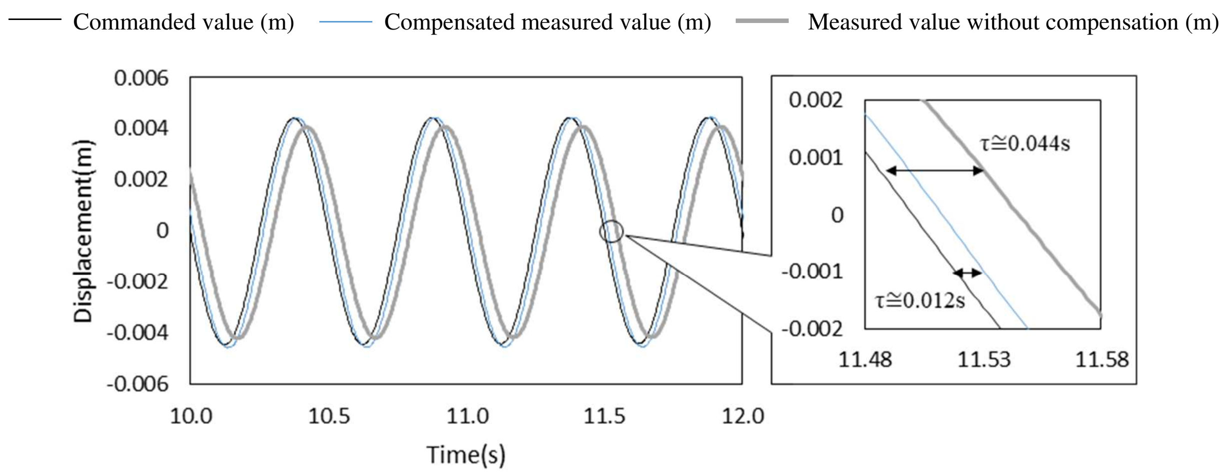


Fig. 10 Compensating result of the hydraulic actuator motion using PID control

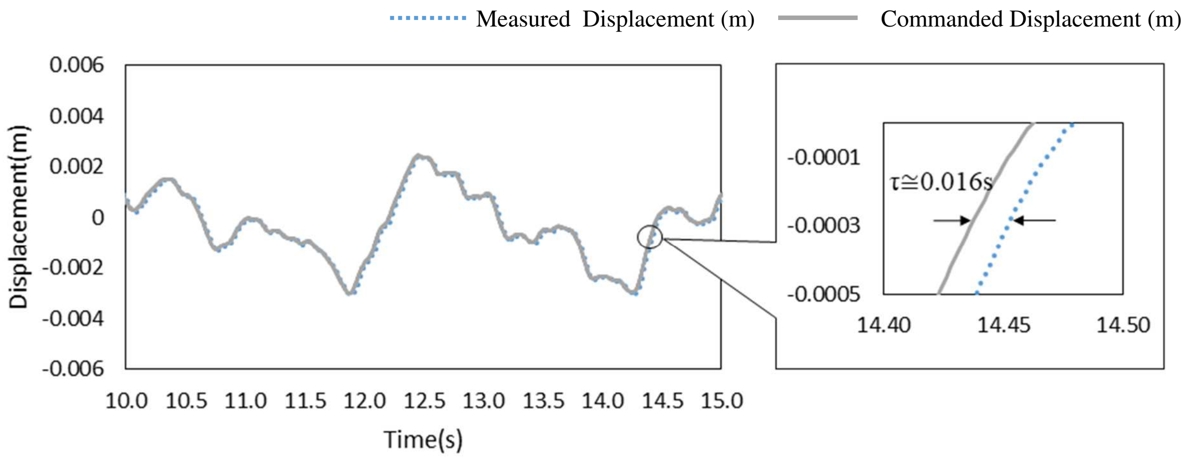
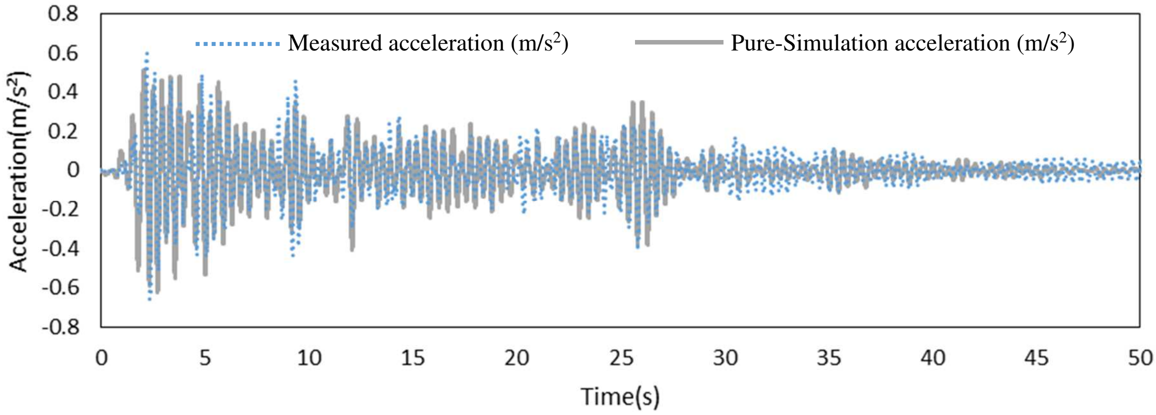


Fig. 11 Compensating result of the hydraulic actuator motion using PID control

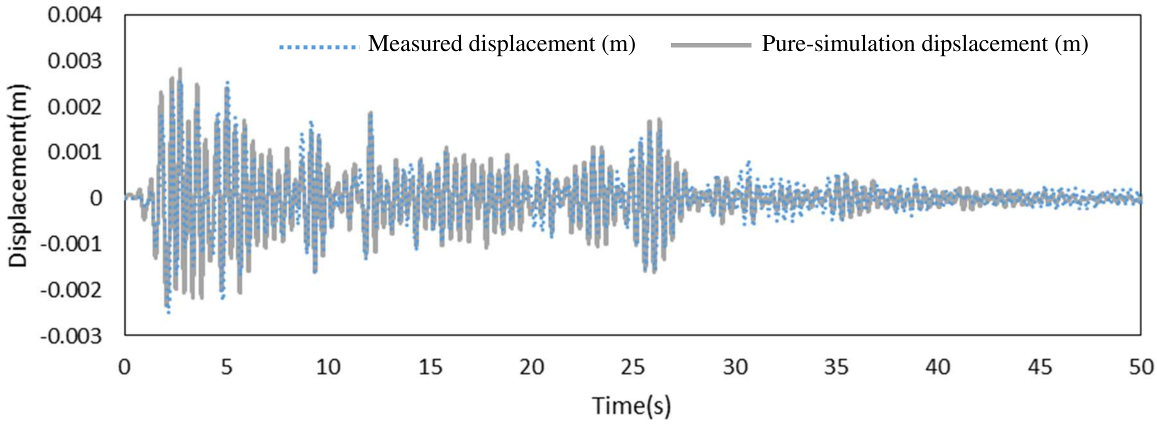
4. Comparison of RTH test results and numerical analysis

In the previous section, compensating for the time delay of the hydraulic actuator is investigated. In this section, improving the accuracy of the RTH test system is observed. Fig. 12 shows the comparison between the measured response in the RTH test and the pure-simulation results. As seen in these figures, it is found that RTH test results have good agreements with the pure-simulation results on both of the shaking-table motion to reproduce the floor acceleration and the hydraulic actuator motion to reproduce the story displacement.

Fig. 13 shows the comparison of the response under control and without control using the velocity feedback control using the AMD. Control force is given to be equivalent feedback gain G=120,000 (Ns/m), which is corresponding to the damping factor of about 3% on the target building model. As seen in Fig. 13, It can be observed the control performance that the AMD can effectively reduce the inter-story displacement and the floor acceleration.



(a) Absolute accelerations of the 1st floor (reproduced by the shaking-table)



(b) Inter-story displacement of 1st story (reproduced by the hydraulic actuator)

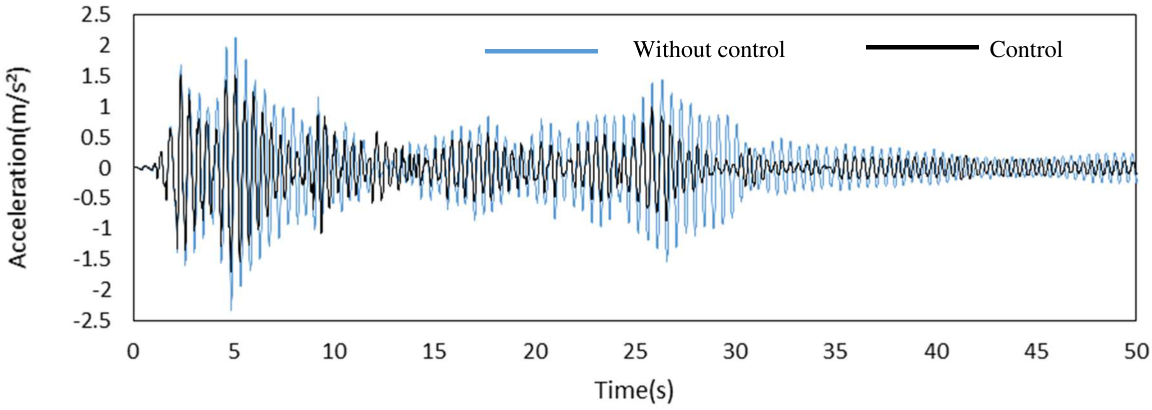
Fig. 12 – Measured response in the RTH test vs. pure-simulation results (El Centro 10%)

5. Conclusion

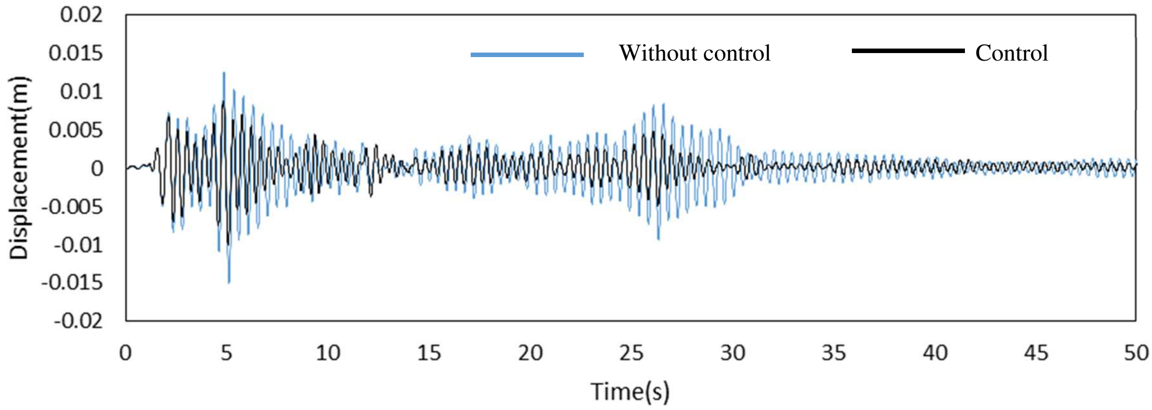
In this study, the multi-actuators RTH test, that is used the high-speed hydraulic actuator to deform the RC test specimen and the shaking-table to reproduce the floor acceleration response, is conducted. As concluding remarks, findings are summarized as follows;

(1) Due to the time delay between the control signal and the actuator motion, the system performance of the RTH test becomes inaccurate and instability. The PID controller and the time series compensator is installed to improve the system performance depending on the 1st order time-delay system of the hydraulic actuator. As aa result, the time delay can be adequately compensated.

(2) The RTH test performed by that hydraulic actuator and the shaking-table is synchronized by online. Comparing the reproduced response between the RTH test and the pure-simulation, these results show good agreements, and the accurate reproducibility of this multi-actuators RTH test system could be confirmed.



(a) Absolute accelerations of the 1st floor (reproduced by the shaking-table)



(b) Inter-story displacement of 1st story (reproduced by the hydraulic actuator)

Fig. 13 – Comparison of responses between with/without control in the RTH test (El Centro 20%)

Acknowledgments

The part of this study was supported by JSPS KAKENHI Grant Number 18H01587 and JSPS grant No. R2904 in the program for Fostering Globally Talented Researchers.

References

[1] Velagic J (2008): Design of Smith-like Predictive Controller with Communication with Communication Delay Adaptation, *International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering*, 2(11), pp.2447-2481.

[2] Horiuchi T, Inoue M, Konno T, and Namita Y. (1999): Real-time hybrid experimental system with actuator delay compensation and its application to a piping system with energy absorber, *Earthquake Engineering and Structural Dynamics*, 28, pp.1121–1141.

[3] Chae Y, Kazemibidokhti K, Ricles J M (2013): Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation, *Earthquake Engineering and Structural Dynamics*, 42, pp. 1697-1715.

