# REAL-TIME HYBRID TEST SYSTEM USING SHAKING TABLE FOR PERFORMANCE EVALUATION OF ACTIVE MASS DAMPER

K. Fushihara[(1)], A. Yokoyama[(2)], Y.Mukai[(3)]

[(1)] *Graduate Student, Graduate School of Engineering, Kobe University, 198t040t@stu.kobe-u.ac.jp*
[(2)] *Graduate Student, Graduate School of Engineering, Kobe University, 191t058t@stu.kobe-u.ac.jp*
[(3)] *Associate Professor, Graduate School of Engineering, Kobe University, ymukai@port.kobe-u.ac.jp*

## Abstract

Recently, the demand for seismic reinforcement and renovation is increasing to improve the existing buildings, which are thought to be a lack of seismic resistance against future earthquakes. For seismic retrofitting, it is one of the useful methods to improve damping performance. A mass damper is introduced as one of the response control systems, which is sufficient to reduce the resonant vibration of structures. By adjusting its mechanical performance according to the target buildings, a mass damper can effectively work to absorb the vibration energy. An active mass damper (AMD) is introduced like a system that provides a force-generating mechanism such as a motor-drive to manipulate any motion of the additional mass. It is considered as a highly versatile system for response control; thus, the AMD system is thought to be available to use under various conditions. Accordingly, it is thought essential to operate the performance evaluation of the control device by the practical laboratory-test considering individual installation to the target building. From this viewpoint, a real-time hybrid (RTH) experiment system using a shaking table is developed in this study to estimate and verify the control performance of the practical AMD device.

The AMD is placed directly on the shaking table in this RTH experiment. The shaking table is controlled to reproduce the absolute floor displacement where the AMD is supposed to be placed on the target building. The target building is modeled numerically, and its behavior under the seismic-motion input is calculated by online simulation. The DSP controller of the RTH experiment system manipulates both the AMD and the shaking table every 2 ms. The accelerations and displacement of the moving mass, the acceleration of the shaking table, and the reacting force by the AMD's motion are directly measured and reflected the numerical integration in the DSP controller. Three-stories test-building model is supposed as the internal numerical model in this study. The total mass of the model is 1833 kg, and the natural periods of the model are 0.775 s, 0.309 s, and 0.195 s. The moving mass of the AMD is 52 kg, and the maximum stroke is 395 mm p-p. The velocity feedback method is examined as a control strategy.

Firstly, the reproducibility of the RTH experiment system is investigated by comparison of the shaking-table motions of the internal calculation in the DSP controller and the directly-measured data by sensors. Next, the control performance of the AMD is estimated, and the practical system-level difference is investigated through a comparison between the RTH experiment and the pure-simulation results. The influence of uncertainty factor, such as a friction of the bearing of the moving mass, can also be estimated by operating these RTH experiments.

*Keywords: Structural response control; Real-time hybrid test; Active mass damper; Performance evaluation*

## 1. Introduction

In general, anti-seismic performances of buildings are improved by reinforcing the stiffness and strength or increasing the damping and energy-absorption capacities. Various kinds of structural reinforcement techniques have already been proposed and introduced practically to the existing buildings. The most popularized way is an installation of inter-story dampers or an installation of additional braces to buildings. However, many inconveniences have existed to mount these devices on the existing buildings. Unlike the installation of the newly-constructing buildings, there are various restrictions related to the available space limitation. A mass damper system is another option of the response control, which is sufficient to reduce the resonant vibration of structures by adjusting its mechanical performance according to the target buildings. The mass damper system is regarded to provide the usability of installation in comparison to equipping the dampers or the braces to the inter-stories of buildings. Because the mass damper can directly place on the building's floor and has adjustability of its mechanical parameter following the building situation. The mass damper system consists of an additional moving mass, force-restoring mechanism, and energy-absorption mechanism. To use a mass damper system as a vibration control device, the natural period and damping ratio of the device is necessary to be adjusted according to the structural characteristics of the target buildings.

A tuned mass damper (TMD) is the standard-type control device, and the parameter tuning method to design a TMD system has also been theoretically introduced. A TMD is sufficient to reduce the resonant vibration of the target buildings as far as the device is tuned to the optimal condition. However, once the parameter of the TMD happens to deviate from the optimal value, the response control effects will be suddenly decreased. An active mass damper (AMD) system can improve this problem, which provides a force-generating mechanism such as a motor-drive to manipulate any motion of the additional mass; thus, the AMD is considered to have a high versatility for response control. The AMD also has the advantage of reducing a volume of the additional mass to give an equivalent performance using the TMD and to be adjustable to the control parameters for a change of the system characteristics of the target structures.

Such a feature of AMD is thought to be useful to install various kinds of buildings, and the authors aim to develop a general-purpose AMD device that can be installed in buildings with various conditions. It is thought essential to operate a performance evaluation of the control system of the AMD under the practical device level according to individual installation to the target building in order to use the AMD system under various conditions. From these viewpoints, a real-time hybrid (RTH) experiment system using a shaking table is developed in this study to estimate and verify the control performance of the practical AMD device. The installation of the AMD can enough to be placed directly on the shaking table in this RTH experiment.

## 2. Configuration of the AMD device and overview of RTH experiment system

### 2.1 Configuration of the RTHS system

In this study, an RTH experiment is performed considering the situation that an AMD device is installed on the top floor of a three-story building model. Since the RTH test is an experimental method for combining the experiment and the analysis in real-time operation only using a partial test specimen, it is possible to limit the objects to be tested on the actual machine. In this study, a three-story building equipped with an AMD device on the top floor is assumed as the entire test target. The RTH system is composed of a simulation model for the three-story building part and a practical specimen for the AMD device, which is available to place on the shaking table.

To perform the RTH experiment procedures, firstly, the seismic wave input is given to the internal simulation model of the building part in the simulator. At the same time, the actual control force from the AMD device is measured and applied to the third floor of the building model. The response analysis of the building model is sequentially performed to calculate the building model motion by real-time. The shaking table reproduces the absolute displacement of the third floor of the building model calculated by the simulator. The operation of the RTH experiment continues the loop of every unit-process step by step until the seismic wave input. This unit operation is made every 2 ms. The outline of the RTH test is depicted in Fig. 1, and structural parameters of the assumed building model in the DSP controller are shown in Table 1.



 

Table 1 - Specification of three-mass model building model

| Floor/Story/Mode | Mass (kg) | Stiffness (kN/m) | Damping (N s/m) | Natural period (s) |
|---|---|---|---|---|
| 3rd | 611 | 138 | 467 | 0.195 |
| 2nd | 611 | 221 | 465 | 0.309 |
| 1st | 611 | 213 | 456 | 0.775 |

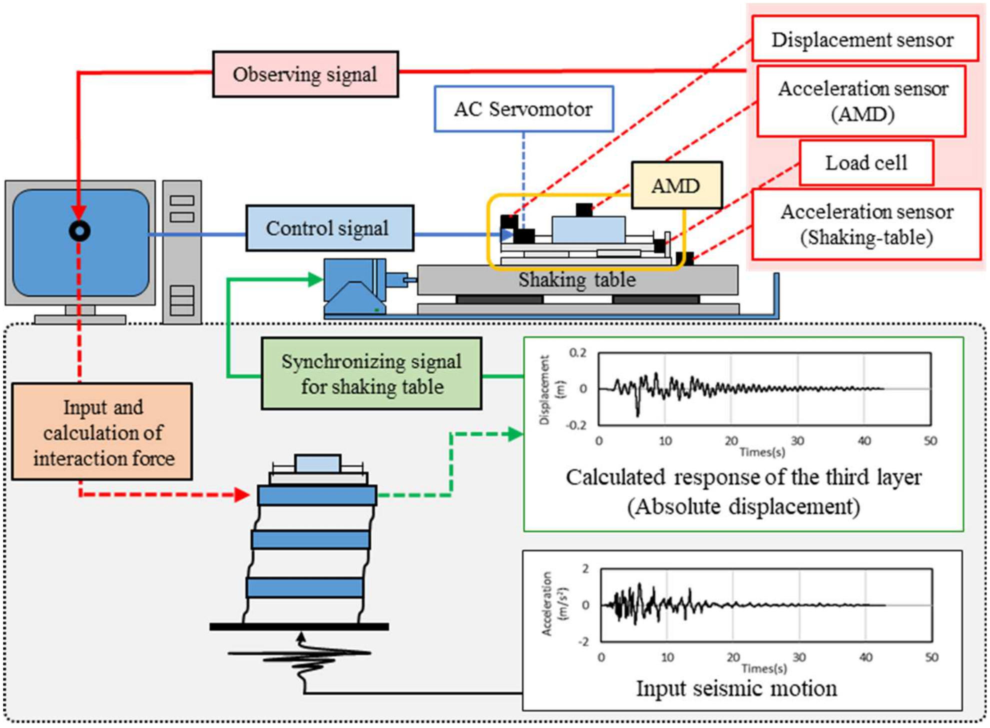


Fig. 1 - Conceptual flow diagram and principal components for the RTH test system

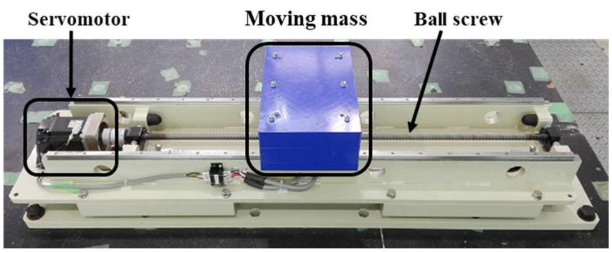


Fig. 2 - Overview of the AMD device

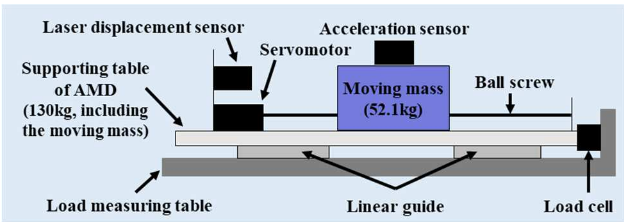


Fig. 3 - Schematic diagram of the AMD device

## 2.2 Configuration of AMD devices

Fig. 2 is an overview of the AMD device used in this study and Fig. 3 is a schematic diagram of the AMD device. This device drives the additional mass in the horizontal direction by rotating a ball screw under the control of an AC servo motor. The control method of the motor is a torque control. Specifications of the AMD device are shown in Table 2. As shown in Fig. 2 and Fig. 3, the AMD device has a load measuring table, and the reaction force of the AMD can be directly measured by a load cell.



 

## 2.3 Control low of the AMD

### 2.3.1 Velocity feedback control

In this experiment, the feedback force proportional to the relative velocity between the third floor of the assumed building model and the basement was input to the third floor of the assumed building model. As shown in Fig. 4, while any stiffness and damping element between the AMD device and the third floor of the building are not considered, bearings that drive and support AMD generate frictional resistance cannot be ignored. The difference between the driving force of the AC servo motor, which is given by the control voltage signal, and the frictional force existing on the linear guide is considered as the inertial force of the AMD. Accordingly, the control force input to the third floor of the target building can be regarded as equal to the inertia force of the AMD.

Equations of motion, control force vector, and feedback force are represented by Eq. (1) to Eq. (3). Since the difference between the feedback force and the frictional force is considered as the inertial force of AMD, the absolute acceleration $z$ of AMD can be expressed by Eq. (4).

Table 2 - Specifications of the AMD device

| | |
|---|---|
| Moving mass | 52.1kg |
| The total mass of AMD | 130kg |
| Control method | Torque control |
| Stroke length | ±408 mm（to the stopper） |
| Limit sensor position | Electrically shut off the motor at ±395 mm |
| Drive mechanism | AC servomotor and ball screw (lead pitch 30mm) |
| Maximum torque | 1.5 kN ※1 |
| Maximum velocity | 1.5 m/s ※1 |
| Driving force of AMD | 260 N/V ※2 |

※1 Conversion value for 30mm ball screw lead.

※2 Calculated from the sine-wave excitation test.

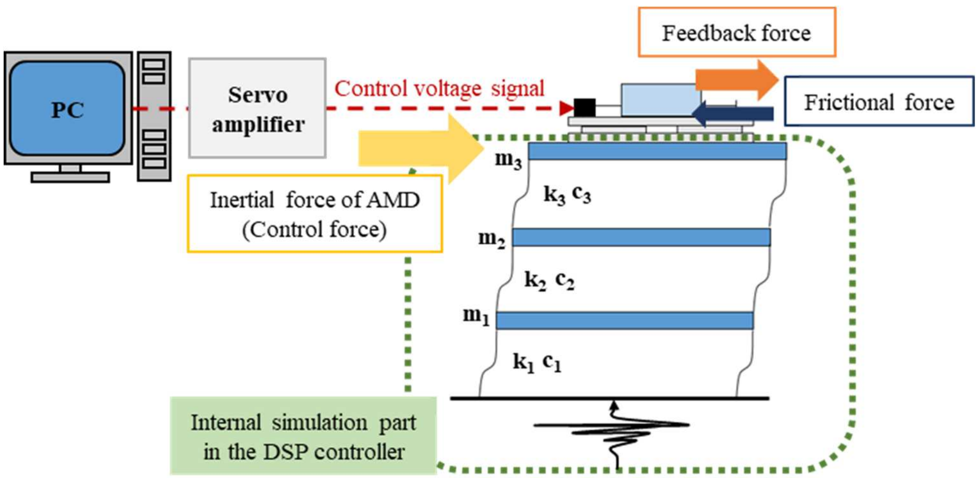


Fig. 4 - Overview of feedback control using AMD



 

$$\boldsymbol{M\ddot{x}} + \boldsymbol{C\dot{x}} + \boldsymbol{Kx} = -\boldsymbol{M}\ddot{y}\boldsymbol{d} + \boldsymbol{f} \tag{1}$$

[ $\boldsymbol{M}$ : Mass matrix, $\boldsymbol{K}$ : Stiffness matrix, $\boldsymbol{C}$ : Damping matrix
$\boldsymbol{x}$ : Displacement vector relative to basement, $\boldsymbol{f}$ : Control force vector
$\ddot{y}$ : Input scceleration to the basement, $\boldsymbol{d} = \{1\ 1\ 1\}^T$ : Position vector of the seismic force ]

$$\boldsymbol{f} = \{0\ 0\ F_3\}^T \tag{2}$$

$$F_3 = G_3 \times \dot{x}_3 \tag{3}$$

[ $F_3$ : Feedback force, $G_3$ : Feedback gain, $\dot{x}_3$ : Relative velocity of the third floor ]

$$z = (F_3 - f_a) / m_a \tag{4}$$

[ $z$ : Absolute acceleration of AMD, $m_a$ : Mass of AMD, $f_a$ : Frictional force ]

### 2.4 Seismic wave input

The maximum acceleration values of the original waves used in this study and the input magnification factors for the RTH experiment are shown in Table 4.

Table 4 - Input seismic wave

| Input seismic wave | Maximum acceleration | Input magnification |
|---|---|---|
| BCJ-L1 | 2.07 (m/s$^2$) | 30% |
| El Centro (1940) NS | 3.42 (m/s$^2$) | 30% |
| Hachinohe (1968) NS | 2.30 (m/s$^2$) | 50% |
| JR Takatori (1995) NS | 6.08 (m/s$^2$) | 15 % |
| JMA Kobe (1995) NS | 8.18 (m/s$^2$) | 15% |

## 3. Numerical simulations

### 3.1 Analysis model

In this experiment, the control force calculation is not considering the influence of friction caused at the bearing supporting of the AMD; thus, the DSP controller is analyzing a mass model such as shown in Fig. 5. In the numerical simulations of the following section, the effect of the frictional force is not considered.

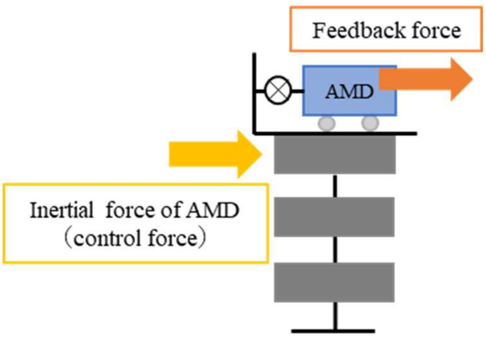


Fig.5 - Analysis model configuration

### 3.2 Determination of feedback gain

In order to determine the value of the feedback gain $G_3$ used in the RTH experiment, a preliminary analysis was performed changing $G_3$ as a parameter, and the control effects were compared at the time of JR Takatori 15% input. As shown in Fig. 6, the value of $G_3$ (on the horizontal axis in Fig. 6) was considered from 0 to 3000 (Ns/m), and the RMS value of the relative displacement, the relative velocity, and the absolute acceleration of each floor (these are indicated in the vertical axis) are evaluated.



 

As seen in Fig. 6, it can be seen that the gradient of the RMS value becomes slow decrement when $G_3$ exceeds about 1000. In the following RTH experiment, the control operation of the AMD is performed under two kinds of feedback gains of $G_3$ = 1000 and 2000 (Ns/m).

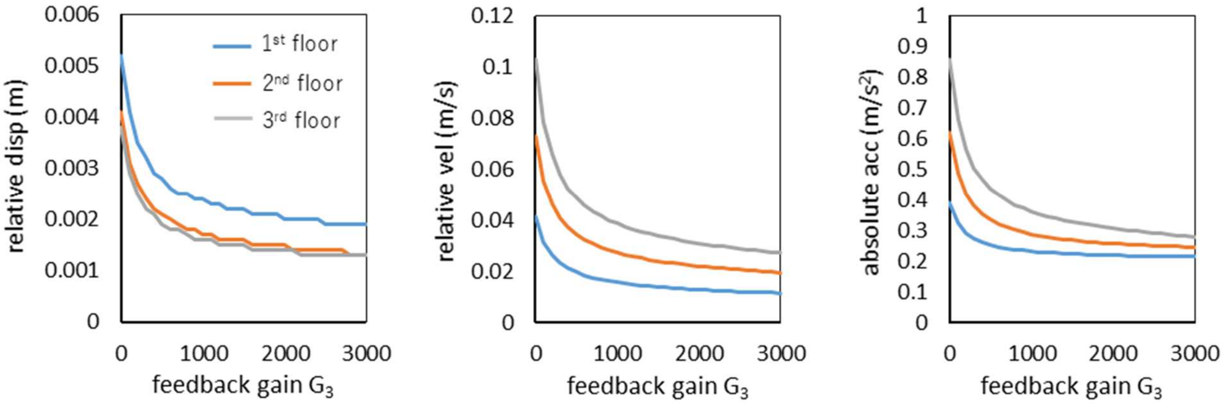

Fig. 6 - RMS value's variation of the relative displacement, relative velocity, and absolute acceleration of each floor depending on the feedback gain $G_3$.

## 4. Verification of RTS experiment results

Using the analysis model shown in Fig. 5, numerical analyses were performed without considering friction, and the results were compared with experimental results. Fig. 7 shows the time history waveforms of the third floor's absolute displacement and acceleration, the third floor's relative displacement, and the control force when the operation of the controller with the velocity feedback gain $G_3$ = 0 (non-control) and 1000 (Ns/m). These are the cases of 30% input of the BCJ-L1 wave. The control force in the experiment is obtained by multiplying the AMD acceleration by the AMD mass. The third floor's absolute displacement and acceleration are the practical motions reproduced by the shaking-table that are directly manipulated by the DSP controller's command. By evaluating these results, the accurate motion of the internal simulation results can be practically given on the shaking-table. Moreover, by observing the third floor's relative displacement and the control force of the AMD, there is a good agreement of the simulation and the RTH results for both cases during control and during non-control.

## 5. Consideration of control effect based on the velocity feedback low

The control effect is compared in three cases that are $G_3$ = 0, 1000, 2000 (Ns/m). Fig. 8 shows a time history waveform of the absolute acceleration, relative velocity, relative displacement, and control force of the third floor of the assumed building model when 15% of JR Takatori wave is input. Table 5 shows the RMS values of the absolute acceleration, relative velocity, and relative displacement of the third floor, and the response reduction rate calculated by Eq. (5). Table 6 shows the maximum values of the relative displacement, relative speed, absolute acceleration of the third floor, control force, and the AMD displacement.

$$\text{Response reduction rate (\%)} = \left(1 - \frac{RMS_c}{RMS_n}\right) \times 100 \quad (5)$$

In which, $RMS_c$ : RMS value of control response, $RMS_n$ : RMS value of non-control response.



 

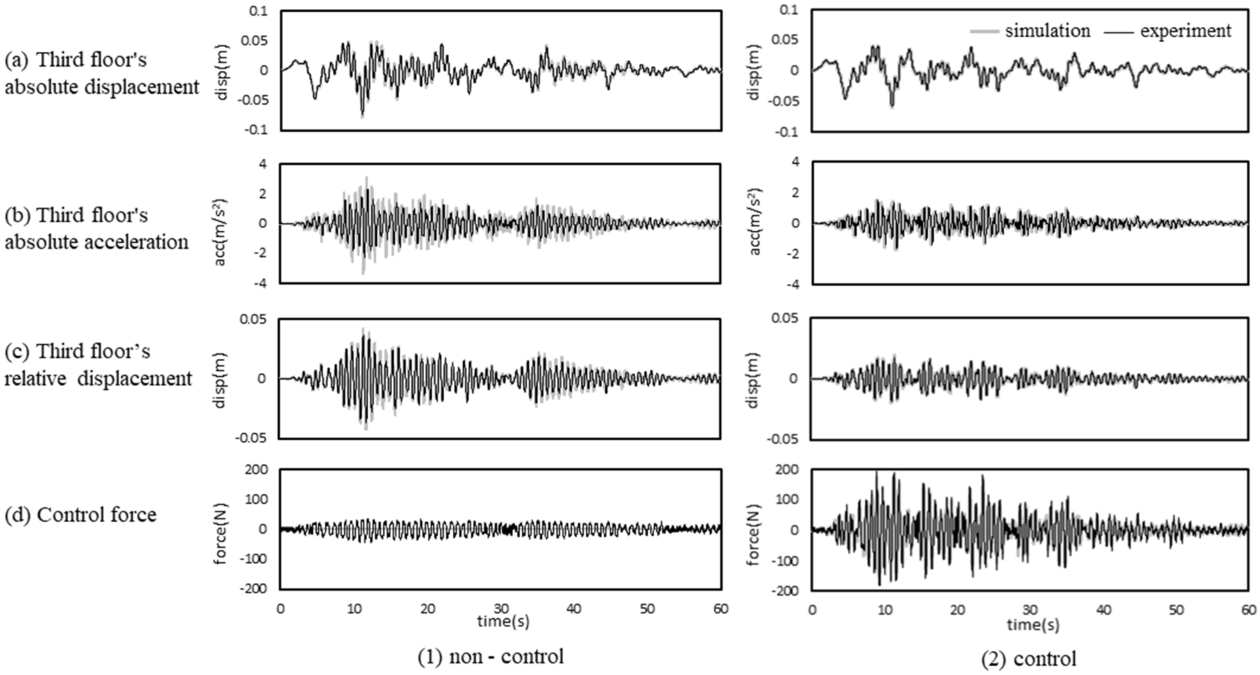


Fig. 7 - The time history waveforms (BCJ-L1 30%)

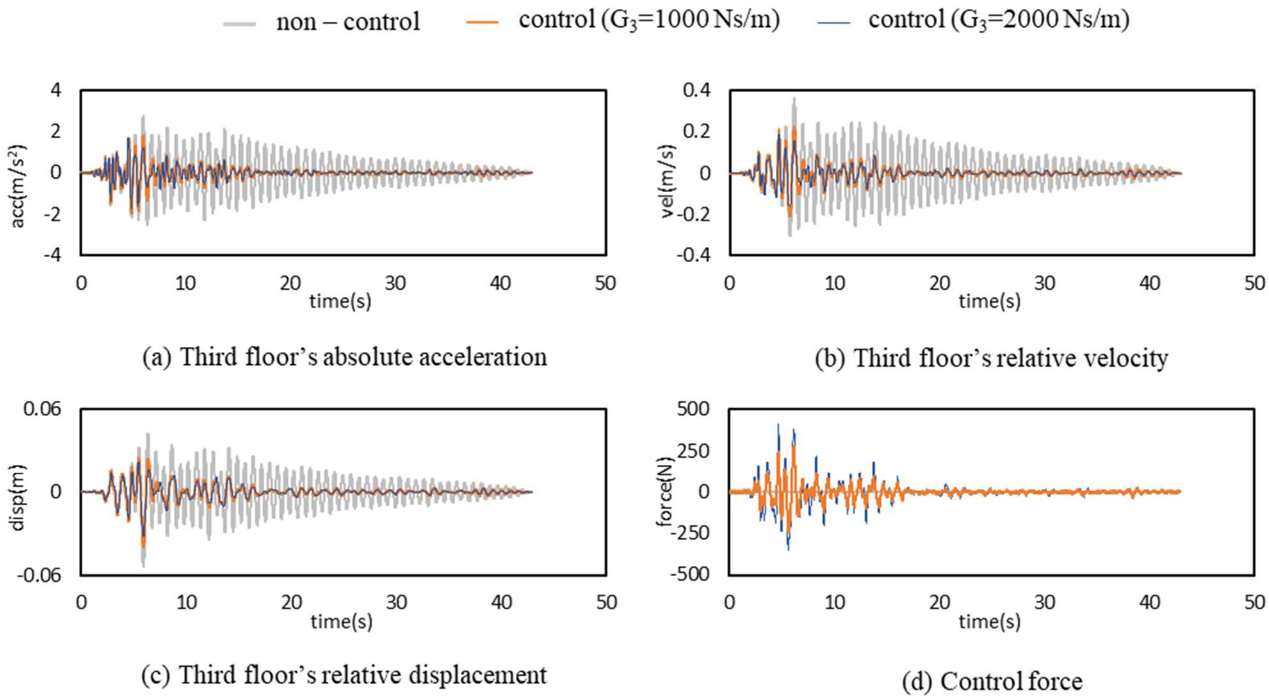


Fig. 8 - The time history waveforms (JR Takatori NS : 15%)

## 6. Conclusion

In this study, the RTH experimental system to reproduce the top floor motion of the assumed building model on the shaking table is proposed and developed. The performance of the AMD device practically evaluated on the shaking-table. While the frictional force generated at the bearing of the moving maas of the AMD could not be accurately estimated, the RTH experiment is considered to have an advantage to availability to operate the entire performance evaluation without the modeling of this uncertain part of the AMD. The velocity feedback control using the AMD is tested, and the control performance influenced by the uncertain frictional force is observed through the RTH experiment.

As the performance test of the RTH system, it was confirmed that good reproducibility could be performed on the shaking table by comparing the DSP controlling signal and the measured response. The control performance of the velocity feedback control was also evaluated in the RTH tests. While ignoring the practical friction-force effect in the control operation, the deterioration of the control effects was not so sensitively caused in the various kinds of seismic wave input. It was confirmed that the control effect of the AMD was observed using this RTH test system.

Table 5 - RTH test results (RMS values and the response reduction rate, at 3rd floor)

| Seismic wave | $G_3$ (Ns/m) | Relative displacement (m) | Relative velocity (m/s) | Absolute acceleration (m/s$^2$) |
|---|---|---|---|---|
| BCJ-L1 | 0 | 0.0102 | 0.0835 | 0.733 |
| | 1000 | 0.00515 (*49.6%) | 0.0424 (*49.2%) | 0.413 (*43.7%) |
| | 2000 | 0.00377 (*63.1%) | 0.0315 (*62.4%) | 0.331 (*54.9%) |
| Elcentro (1940) NS | 0 | 0.0117 | 0.0949 | 0.793 |
| | 1000 | 0.00512 (*56.2%) | 0.0413 (*56.5%) | 0.373 (*52.9%) |
| | 2000 | 0.00389 (*66.7%) | 0.0318 (*66.5%) | 0.304 (*61.7%) |
| Hachinohe (1968) NS | 0 | 0.0133 | 0.106 | 0.889 |
| | 1000 | 0.0059 (*55.8%) | 0.0447 (*57.9%) | 0.414 (*53.4%) |
| | 2000 | 0.0047 (*64.3%) | 0.0356 (*66.5%) | 0.347 (*60.9%) |
| JR Takatori (1995) NS | 0 | 0.0128 | 0.101 | 0.831 |
| | 1000 | 0.00561 (*56.3%) | 0.0380 (*62.5%) | 0.323 (*61.2%) |
| | 2000 | 0.00490 (*61.8%) | 0.0314 (*69.0%) | 0.271 (*67.4%) |
| JMA Kobe (1995) NS | 0 | 0.0126 | 0.103 | 0.881 |
| | 1000 | 0.00785 (*37.5%) | 0.0649 (*37.0%) | 0.585 (*33.6%) |
| | 2000 | 0.00587 (*53.3%) | 0.0491 (*52.3%) | 0.464 (*47.3%) |

* response reduction rate

Table 6 – RTH test results (Maximum values, at 3rd floor)

| Seismic wave | $G_3$ (Ns/m) | Relative displacement (m) | Relative velocity (m/s) | Absolute acceleration (m/s$^2$) | Control force (N) | AMD displacement (m) |
|---|---|---|---|---|---|---|
| BCJ-L1 | 0 | 0.0429 | 0.353 | 3.26 | 0 | 0.125 |
| | 1000 | 0.0180 | 0.167 | 2.00 | 195 | 0.260 |
| | 2000 | 0.0157 | 0.133 | 1.59 | 303 | 0.288 |
| Elcentro (1940) NS | 0 | 0.0386 | 0.300 | 2.82 | 0 | 0.124 |
| | 1000 | 0.0284 | 0.231 | 2.01 | 253 | 0.203 |
| | 2000 | 0.0217 | 0.207 | 1.63 | 379 | 0.318 |
| Hachinohe (1968) NS | 0 | 0.0415 | 0.421 | 3.74 | 0 | 0.0969 |
| | 1000 | 0.0343 | 0.336 | 3.00 | 387 | 0.209 |
| | 2000 | 0.0292 | 0.273 | 2.50 | 602 | 0.284 |
| JR Takatori (1995) NS | 0 | 0.0541 | 0.362 | 2.74 | 0 | 0.0928 |
| | 1000 | 0.0400 | 0.225 | 1.81 | 278 | 0.156 |
| | 2000 | 0.0321 | 0.186 | 1.66 | 409 | 0..181 |
| JMA Kobe (1995) NS | 0 | 0.0678 | 0.561 | 4.94 | 0 | 0.0252 |
| | 1000 | 0.0452 | 0.419 | 3.36 | 491 | 0.0582 |
| | 2000 | 0.0321 | 0.328 | 2.80 | 737 | 0.105 |



 

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