A STUDY ON ACTIVE VIBRATION CONTROL SYSTEM USING AI TECHNOLOGY

S.Kitahara[(1)], M.Suzuki[(2)], Y.Sugimura[(3)] and K.Watanabe[(4)]

[(1)]*NTT FACILITIES, INC.,kitaha27@ntt-f.co.jp*
[(2)]*NTT FACILITIES, INC., suzuki29@ntt-f.co.jp*
[(3)]*NTT FACILITIES, INC., sugimu23@ntt-f.co.jp*
[(4)]*NTT FACILITIES, INC., watana5a@ntt-f.co.jp*

Abstract

・*Introduction*

In the 2011 off the Pacific coast of Tohoku earthquake which occurred in Japan, large sway continued for a long time in a high-rise building far from the epicenter due to a long-period ground motion, various damages have occurred such as damage to a ceiling and interior, failure of facilities and falling off a shelf. Such damage occurred not only in the Tokyo metropolitan area, but also in a high-rise building in Osaka city more than 700 km away from the epicenter, the top of the building swayed about 2.7m at maximum and so many people in the building felt uneasy. Even now, countermeasures against a long-period ground motion to existing a high-rise building have not progressed, and even in a huge earthquake along the Nankai Trough, which is predicted to occur with a high probability in the future, a long-period ground motion and damage to buildings is expected to occur.

・*Developments*

Based on these circumstances, the authors have been advancing research for a new active vibration control system for a high-rise building that exerts vibration suppression effects which cannot be achieved by conventional passive control technology. This system utilizes an AI technology for vibration control and realizing unprecedented high earthquake resistance and habitability against a long-period ground motion and aims at providing new value to a high-rise building. The newly developed active vibration control system controls the damper's damping force using an electric actuator connected in series with a viscous damper adopts the active control that gives necessary control power to a building by utilizing AI for the control, and the vibration of a building is controlled, therefore the sway is minimized as much as possible against earthquake vibration. Furthermore, the active vibration control system can exert a higher vibration suppression effect than passive control for large shakes caused by earthquakes, and small shakes such as wind and post-earthquake shakes, and these were confirmed by vibration experiment using testing device and simulation.

・*Remarks and Conclusion*

In the future, we are planning to further enhance the reliability of this active vibration control system and advance development as a useful technology for countermeasures against long-period ground motion in a high-rise building and improving the habitability against wind and earthquake.

Keywords: active vibration control, AI technology, long-period ground motion, vibration experiment, simulation

1. Introduction

In the 2011 Great East Japan Earthquake, large sway continued for a long time in a high-rise building far from the epicenter due to a long-period ground motion, various damages have occurred such as damage to a ceiling and interior, failure of facility and falling off a shelf. In high-rise buildings, not only in the Tokyo metropolitan area, but also in Osaka city more than 700 km from the epicenter, the top of the buildings swayed about 2.7m at maximum and so many people in the buildings felt uneasy.

Even now, countermeasures against a long-period ground motion to existing high-rise buildings have not progressed, and even in a huge earthquake along the Nankai Trough, which has a high probability of occurrence, a long-period ground motion is expected to occur.

The authors have been developing a new active vibration control system for high-rise buildings using an AI (Artificial Intelligence) technology for vibration control. [1][2]

1.1 Outline of the active vibration control system

The active vibration control system controls the damping force by using an electric actuator connected in series with viscous damper (Fig.1), vibration suppression can exert a higher effect than passive control by utilizing AI.

Specifically, the accelerometers installed on floors of a building measure the state of the building during earthquake, the AI determines the control force of the electric actuator based on the measured value, and the control force necessary for vibration control is given to the building as the damping force of the damper. By repeating these control operations, the response of a high-rise building during earthquake is suppressed autonomously.

1.2 System development that combines four technologies

The active vibration control system has been developed as a combination of the four technologies, "AI technology", "simulation technology", "robotics technology" and "shaking table test technology".

Control AI is created reproducing the real world in the virtual world authentically utilizes "AI technology" and "simulation technology", and we verify the effect of the active vibration control by faithfully reproducing the behavior of the vibration control system by test using a model specimen utilizes "robot technology" and "shaking table test technology".

1.3 Learning of control AI by building response simulator

There is no data accumulation from the past regarding active control to buildings subject to seismic ground motion, and machine learning based on mass data can’t be used to create control AI. We adopted "Deep Reinforcement Learning" which can acquire optimum active control rule through trial-and-error even if there is no accumulated data. The reason for adopting "Deep Reinforcement Learning" that combines "reinforcement learning" and "deep learning" is to express complex control rules that are difficult to predict and non-stationary by using a deep neural network.

1.4 Construction of real time control system

In the vibration control of building against seismic ground motion, it is important to give control force to the building in real time, and it is necessary for the electric actuator to execute the control obtained by the control AI without delay. In the verification test using the model specimen, the system was constructed that can execute control from sensing to nearly 0.1 seconds.

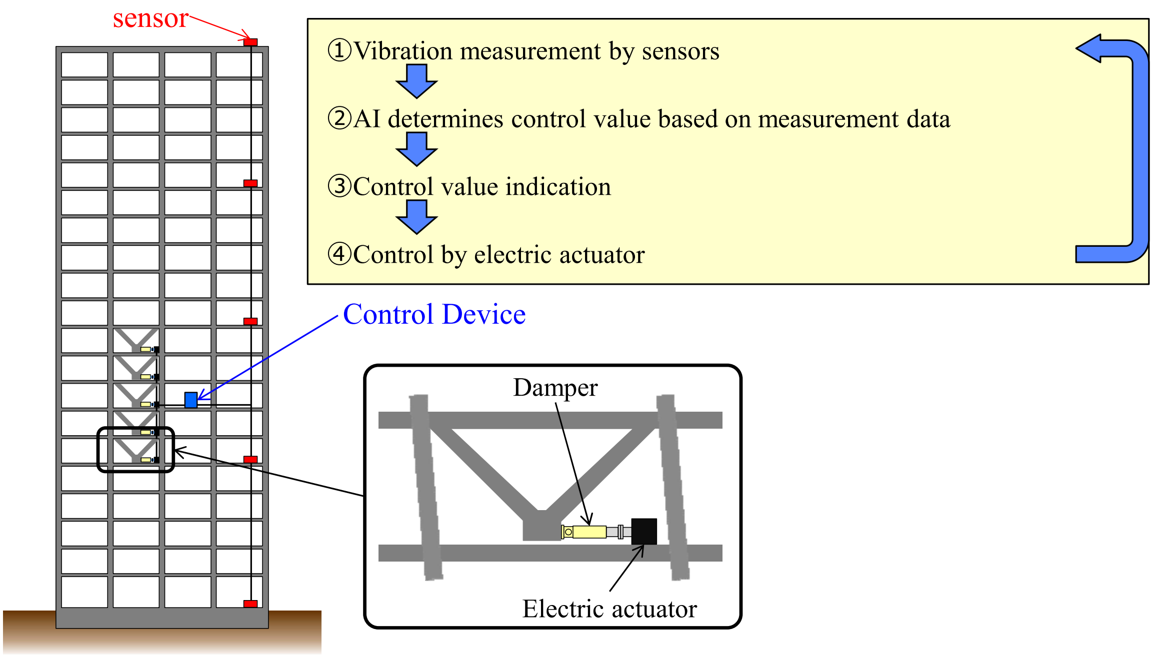

Fig. 1－The outline of the active vibration control system

2. Creation of control AI by Deep Reinforcement Learning

2.1 Application of reinforcement learning

In the reinforcement learning, instead of giving an output which is a correct answer to the input, good / bad of actions is given as an evaluation value of "reward" and the learning is performed based on this reward.

Fig. 2 shows the framework of the Deep Reinforcement Learning in this development. Learning of control AI is performed by using building response simulation considering the control force of the electric actuator and repeating the following steps.

① The agent observes the response of the building at time t_i as state s_i.
② The agent determines and execute the axis velocity of the actuator as the action a_i based on the state s_i.
③ The building model receives the control force by the actuator and transits to the new state $s_{(i+1)}$.
④ The agent acquires the reward $r_{(i+1)}$ corresponding to the state $s_{(i+1)}$ after the transition.
⑤ Learn based on reward $r_{(i+1)}$ acquired by the agent (then update control AI).
→ Return to ①

The objective of reinforcement learning is to acquire a strategy for selecting actions from the state so that the control AI maximizes the cumulative reward that can be acquired over the future. In this paper, Q learning as a representative learning method is adopted to maximize cumulative reward over the future. [2]

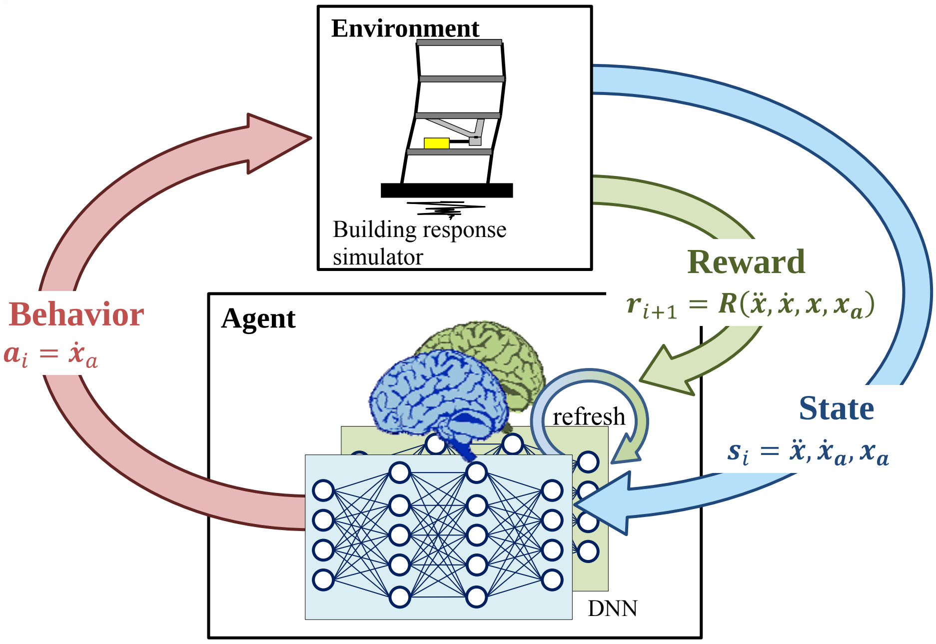

Fig. 2－Deep Reinforcement Learning by using building response simulator

2.2 Input waves for learning

In preparing the control AI for active vibration control, it is important what kind of input seismic waves are selected. Although it is possible to use a strong motion records observed in the past, the learning is done for many strong motion records in order to prevent over learning which exerts its control effect only for a specific earthquake and the time required for the learning calculation becomes longer accordingly. In this development, an artificial wave (referred to as "learning wave") was created in which natural period of the target building was easily excited, with the intention of learning effective control on the building response using as few input wave as possible.

An example of the input learning wave used for learning is shown in Fig. 3

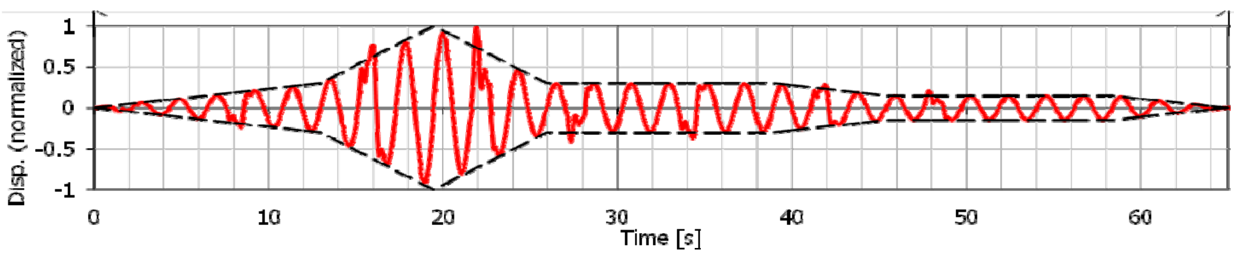

Fig. 3－An example of learning wave

3. Study on long-period ground motion by using model specimens

3.1 Outline of model specimens

The effectiveness of the active vibration control system as a countermeasure against a long-period ground motion was verified by a verification test by using model specimens capable of reproducing the characteristics of a high-rise building. For the verification test, the 3D shaking table test system "DUAL FORCE" owned by our company was used. (Fig. 4) [1]

The model specimen is a 4-layer model with a primary natural period of about 2 seconds, assumed to be a 20-story high-rise building. The primary natural period and the damping factor of the model specimens obtained by free vibration without a damper are respectively 2.1 seconds and 3% in both X and Y directions.

In the shaking table test, a sine wave having the same period as the primary natural period of the model specimens is set as an input wave in order to confirm the vibration suppression effect under an earthquake environment where a building resonates in addition to the seismic ground motion having the long-period components.

3.2 Study results

Fig. 5 shows an example of test results by seismic motion having the long-period components. Through shaking table tests, it was confirmed that active control using control AI is effective for response control of buildings, and it is possible to suppress the response of buildings compared to conventional passive control.

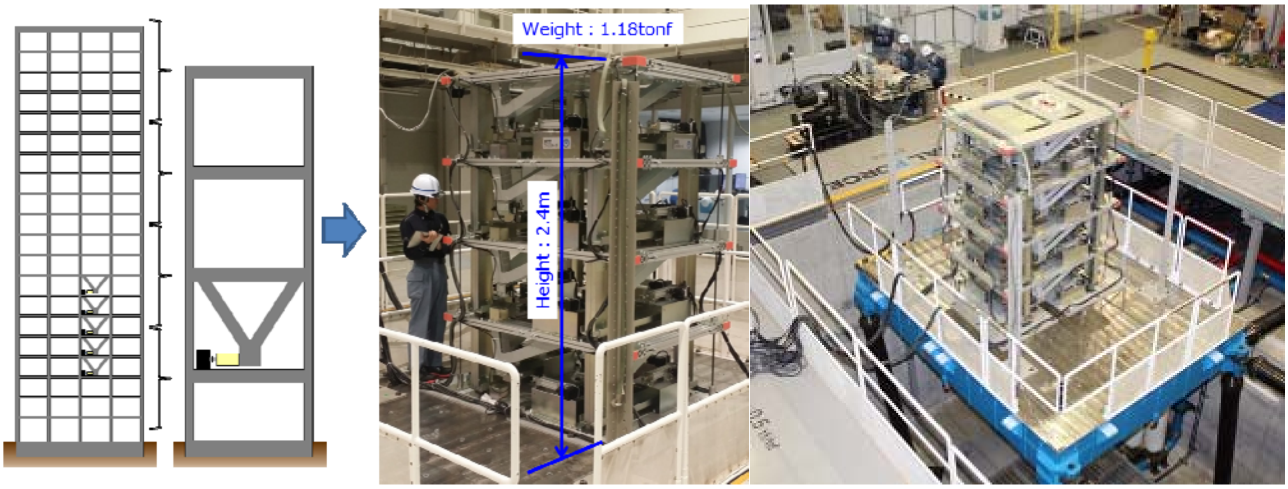

Fig. 4－Model specimen and the 3D shaking table test system "DUAL FORCE"

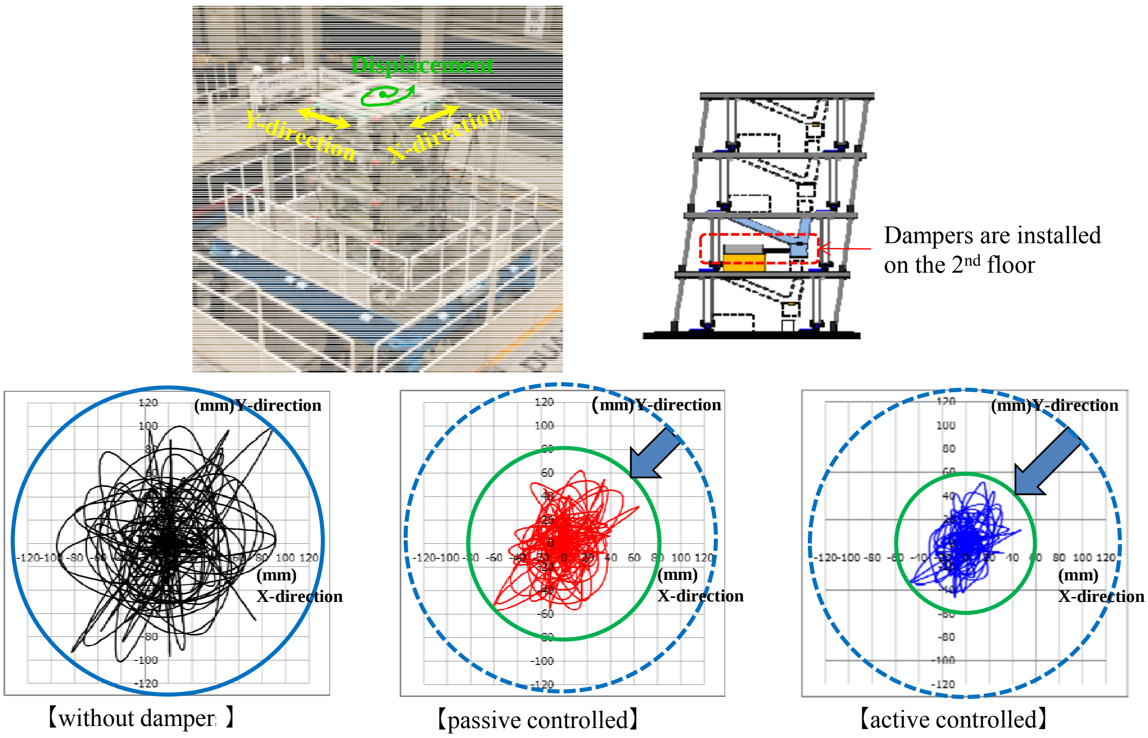

Fig. 5－Test results of shaking table test on a long-period ground motion

4. Study on habitability using simulation

4.1 Outline of analysis model

The effectiveness of the active vibration control system for habitability was verified by simulation under small amplitude such as wind or post-earthquake shake. [3]

The analysis model is a 36-mass-point equivalent shear type model that aggregates the mass of each floor. Fig. 6 shows the multi-mass system model and the eigenvalue analysis results. A linear viscous damper was modeled for the vibration suppression system, and the damping force was set to 2000 kN when the damper axis velocity (actuator shaft speed + inter-layer speed) was 5 cm/s. As shown in Fig. 6, the floors on which the active vibration control element is modeled are four cases: 9, 18, 27, and 34 floors.

The control AI is created by deep reinforcement learning, and the input wave for learning are shown in Table 1.

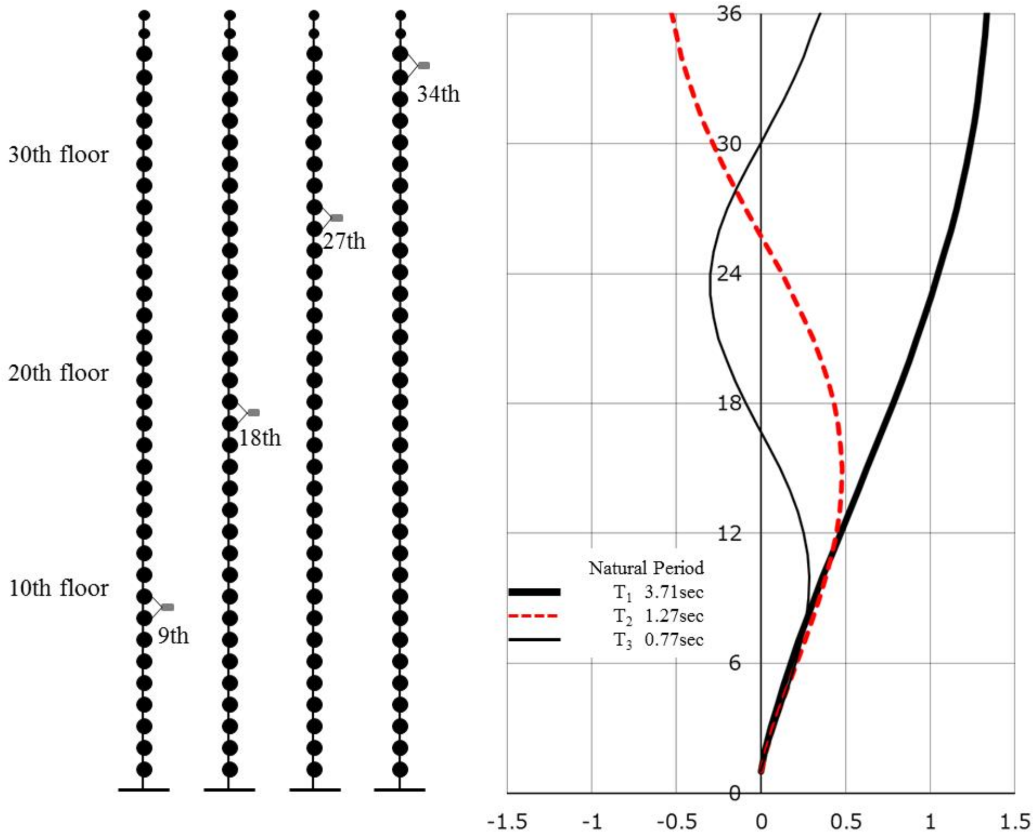

Fig. 6－Floors where active vibration control element is modeled and natural period of analysis model

Table 1－Learning wave used for simulation

Wave	Maximum acceleration	Maximum velocity	Maximum displacement
DL0.5-1	3.77 cm/s^2	0.50 cm/s	0.13 cm

4.2 Study results

The maximum relative displacement of active vibration control model is lower than without a damper in all cases. (Fig. 7) Especially the relative displacement at 33th mass point is greatly reduced when an active vibration control system is installed on the 9th floor. (Fig. 8)

On the other hand, the maximum absolute acceleration of active vibration control model partly exceeded the values of without a damper, especially on the peripheral floors where active vibration control element is modeled. However, the maximum acceleration is instantaneous and the waves include relatively high-frequent vibrations and deviate from the primary period of the building. Therefore, the absolute acceleration have little affect on habitability.

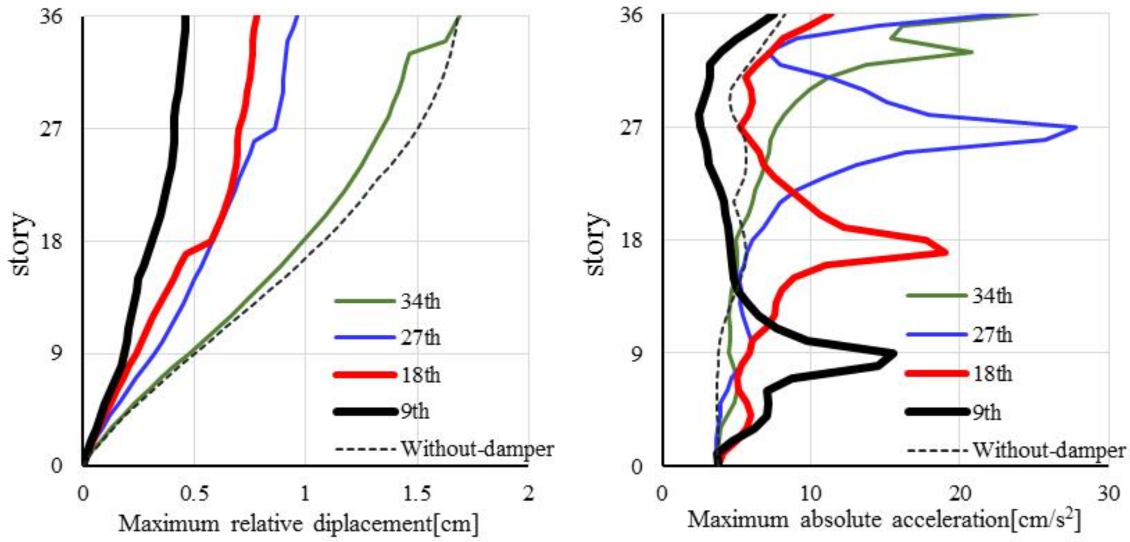

Fig. 7－Maximum relative displacement and absolute acceleration

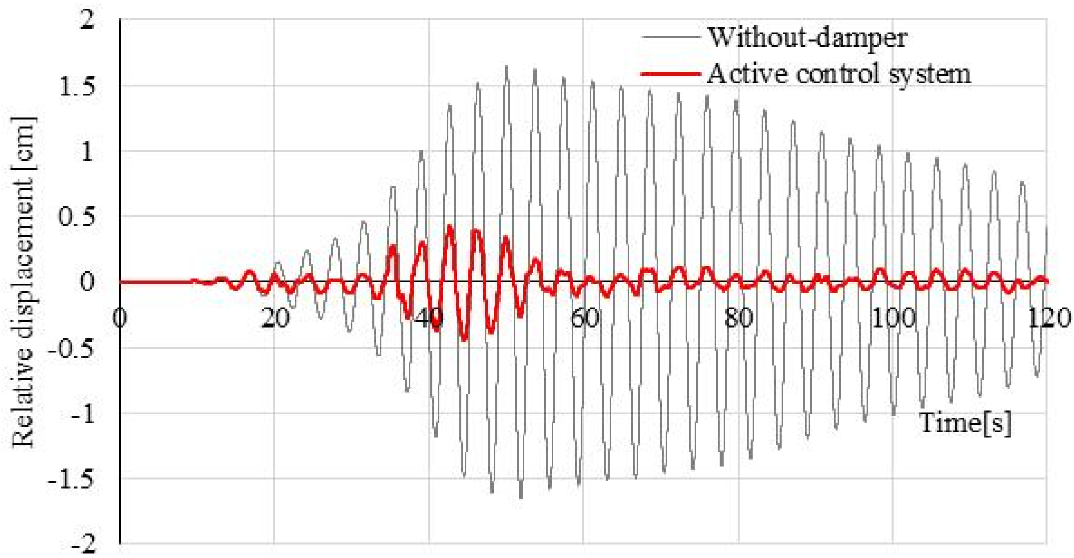

Fig. 8－Time history of relative displacement at 33th mass point
(Floor on which the active vibration control element is modeled: 9th floor)

5. Conclusion

This paper verified the vibration suppression effect of the active vibration control system using AI technology which controls the damping force by using the electric actuator connected in series with the damper.

・Shaking table tests confirmed that a high vibration suppression effect for long-period ground motions can be exhibited.

・Simulation confirmed that a high vibration suppression effect for small amplitude such as wind or post-earthquake shake can be exhibited.

In the future, we are planning to further enhance the reliability of this active vibration control system and advance development as a useful technology for countermeasures against long-period ground motion in a high-rise building and improving the habitability by small amplitude such as wind or post-earthquake shake.

References

[1] Mikio Suzuki, Masateru Hayashi, Daisuke Chiba and Keisuke Watanabe (2018): Development of Active Response Control System Using AI (Part1~Part5). Summaries of technical papers of annual meeting, Architectural Institute of Japan (in Japanese)

[2] Keisuke Watanabe, Mikio Suzuki, Masateru Hayashi and Yoshifumi Sugimura (2019): Development of active response control system using artificial intelligence. Structural Engineers World Congress 2019, Istanbul, Turkey

[3] Mikio Suzuki, Masateru Hayashi, Yoshifumi Sugimura and Keisuke Watanabe (2019): A Study on Application of Active Response Control System Using AI for Upgrading Habitability (Part1~Part3). Summaries of technical papers of annual meeting, Architectural Institute of Japan (in Japanese)

