Floating Type Isolation System Using Earthquake Early Warning

K. Minagawa
Saitama Institute of Technology, Saitama

S. Fujita
Tokyo Denki University, Tokyo

G. Tanaka
Oiles Corporation, Tochigi

H. Simosaka
Meiji University, Kanagawa

SUMMARY:
Long period seismic waves having predominant period of from a few seconds to a few ten seconds have recently been observed in various earthquakes. Therefore resonances of isolation structures are concerned, and research and development of an isolation system having very long natural period or no natural period is required. This study proposed a floating type seismic isolation system encompassing air bearings and Earthquake Early Warning (EEW) system. Such system exhibits adequate isolation performance. The air bearings are isolation device that may render infinite the superstructure natural period by floating them by using compressed air. EEW is a system that can expect earthquake intensity and arrival time before principal motion arrives, and the EEW is applied for a trigger of isolation in this system. This paper illustrates the proposed system and discusses the experimental results of a test carried out with the system.

Keywords: Seismic isolation, Long period seismic wave, Earthquake early warning

1. INTRODUCTION

In Japan, Applications of seismic isolation system into buildings, houses, equipment, art works and so on have been widely spread after the Great Hanshin-Awaji earthquake in 1995. Several thousand base isolated structures have already been built in Japan. In addition, effectiveness of seismic isolation system was confirmed in Great East Japan Earthquake in 2011 [Saito, 2011]. The basic principles of a seismic isolation system is to extend the natural period of a superstructure to approximately 3 seconds by inserting isolation bearings such as laminated rubber bearings between the superstructure and foundation. Through the application of the typical seismic isolation system, it is possible to reduce the response acceleration by 1/3 of the response acceleration of a non-isolated structure.

The Earthquake Early Warning (EEW) system [Japan Meteorological Agency] is also one of effective seismic resistant technologies. EEW system is a system that can expect earthquake intensity and arrival time as well as magnitude and earthquake focus before principal motion arrives. The warning is transmitted to residence via television, radio, cell phone and the Internet network.

Concern for long period seismic waves that have predominant period of more than a few seconds has been increasing. For example, in Great East Japan Earthquake in 2011, high-rise buildings located in Osaka (more than 700 km from earthquake focus) resonated by the long period seismic wave [Saito, 2011]. Base isolated structures also have risk of resonance with long period seismic waves. Additionally metropolises of Japan such as Tokyo, Osaka and Nagoya, are located on sedimentary layers, and it is expected that long period seismic waves are excited in large earthquakes.

This paper proposes a floating type seismic isolation system using EEW. This isolation system consists of air bearings as isolation device and EEW. The system isolates seismic ground motion and a superstructure by floating. EEW is applied for a trigger of floating. Thus the system is able to isolate long-period seismic waves, because the system possesses an infinite natural period. In this paper, an outline, basic properties and isolation performance of the floating type seismic isolation system are described.

2. FLOATING TYPE ISOLATION SYSTEM USING EARTHQUAKE EARLY WARNING

This isolation system is able to isolate superstructures from ground motion by floating them on a flat surface. The isolation system consists of isolation devices using air bearings and an isolation trigger using EEW.

The air bearings can float superstructures by compressed air. The air bearing can reduce contact friction between floor and the bearing by thin air film produced by compressed air. In this study, a diaphragm type air bearing is adopted as isolation device. Figure 1 shows the mechanics of the diaphragm type air bearing. The diaphragm type air bearing floats by blowing compressed air off from small holes in doughnut shape diaphragm made of rubber. The principle of operation is similar to air-cushion vehicle. This air bearing is generally used as heavy machinery moving equipment. The diaphragm type air bearing is available for rough surface such as concrete, because it is made of rubber and has sufficient floating height. The maximum capacity of an air bearing is 40000 kg, the diameter is 150 to 1400 mm, and friction coefficient is approximately 1/1000.

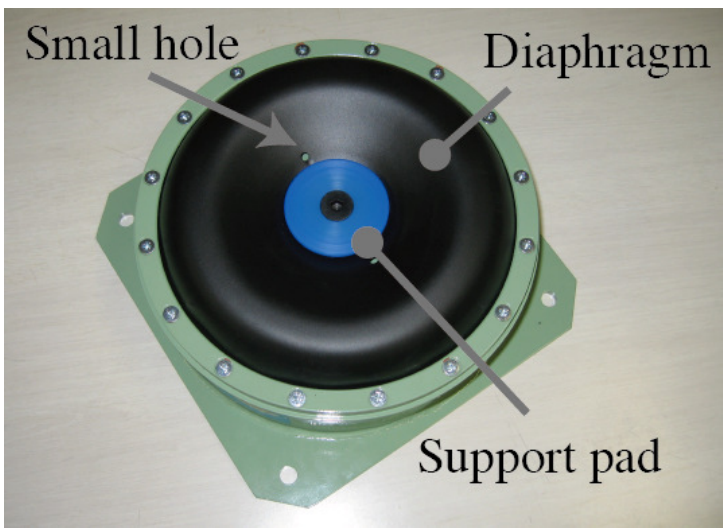

Figure 1. Air bearing

The isolation trigger using EEW controls supplement of compressed air. This trigger is able to avoid unnecessary floating of the isolation system. EEW system is a system that can expect earthquake intensity and arrival time as well as magnitude and earthquake focus before principal motion arrives.

The operation flow of EEW is as follows; at first, seismometers installed near an earthquake focus detect a primary wave, then this information is transmitted to the Japan Meteorological Agency (JMA). Next, earthquake intensity and estimated time of arrival at particular place are analyzed by using the information of the seismometers. Finally EEW is transmitted from JMA to residence via television, radio, cell phone and the Internet network.

Figure 2 shows a schematic of the isolation system. An air compressor provides compressed air to air bearings. An air tank accumulates compressed air. A PC analyzes information from EEW and determines activation of the system. P-wave sensor is seismograph, and it detects occurrence of earthquake as well as EEW. Thus this system operates properly even if EEW does not work well. An Uninterruptible Power Supply (UPS) system supplies electric power to the computer and the air compressor in case of blackout.

This system has adequate seismic performance, because the isolated structure floats and slides on a low friction flat surface generated by thin air film. Moreover the isolation device is powered by compressed air, so that the system possesses high safety. If the structure has not floated before principal motion arrives, support pads of air bearings isolate the structure from ground motion by sliding.

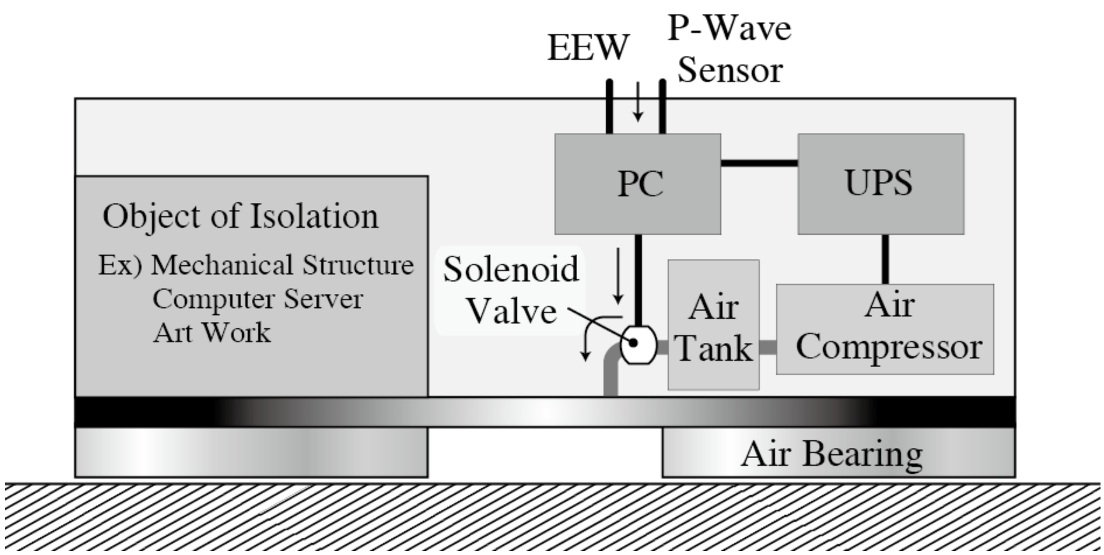

Figure 2. Schematic of the isolation system

3. SIMULATION ANALYSIS

Before investigation of isolation performance of the proposed system by experiments, simulation analysis was conducted. In this analysis, only horizontal motion was considered.

3.1. Equation of Motion

The analytical model is rigid body on flat friction surface having friction coefficient μ. Deformation of the superstructure is ignored because motion of isolation layer is more dominant than superstructure. The condition of motion is classified into two phases. The first phase is the no sliding phase. When frictional force exceeds inertia force, superstructure does not slide. The second phase is the sliding phase. When inertia force exceeds friction force, the superstructure slides. Equation of motion of each condition is as follows;

Phase 1: No sliding phase

$$\ddot{x} = 0, \quad \dot{x} = 0, \quad x = const \tag{1}$$

Phase 2: Sliding phase

$$\begin{aligned} m\ddot{x} + \mu mg \cdot \mathrm{sgn}(\dot{x}) &= -m\ddot{z}_H \\ \ddot{x} + \mu g \cdot \mathrm{sgn}(\dot{x}) &= -\ddot{z}_H \end{aligned} \tag{2}$$

Switching condition of phase 1 to 2

$$|m\ddot{z}_H| > \mu mg \tag{3}$$

Switching condition of phase 2 to 1

$$\dot{x} = 0 \quad \text{and} \quad |m(\ddot{x} + \ddot{z}_H)| \le \mu mg \tag{4}$$

Where, m is mass of superstructure, μ is friction coefficient of air film, $\ddot{z}_H$ is horizontal seismic input acceleration and g is the gravity acceleration.

3.2. Analytical Results

Seismic response analysis was carried out. Friction coefficient of air bearing of 0.001 was used. Input waves were the JMA Kobe NS wave (1995) at original level (8.18 m/s^2) and the JMA Tomakomai NS wave (2003) at original level (0.23 m/s^2). The JMA Kobe NS wave was observed near the earthquake focus, so it has predominant period of less than 1 second. The JMA Tomakomai NS wave contains the long period component of approximately 10 second.

Figure 3 shows time histories of isolation system with air bearing. As shown in Fig. 3, response acceleration of the isolation system is small, so that this system has adequate performance of isolation. Response acceleration does not exceed 0.0098m/s^2. This is because inertia force operated to the isolation system does not exceed frictional force when rigid body slides on flat surface. However response displacement is relatively large. Additionally residual displacement remains after seismic input stopped because no restoring force is contained in this system.

As a result, adequate isolation performance is confirmed from this analysis. The performance of acceleration reduction was much superior to conventional isolation system, however large response displacement was a problem.

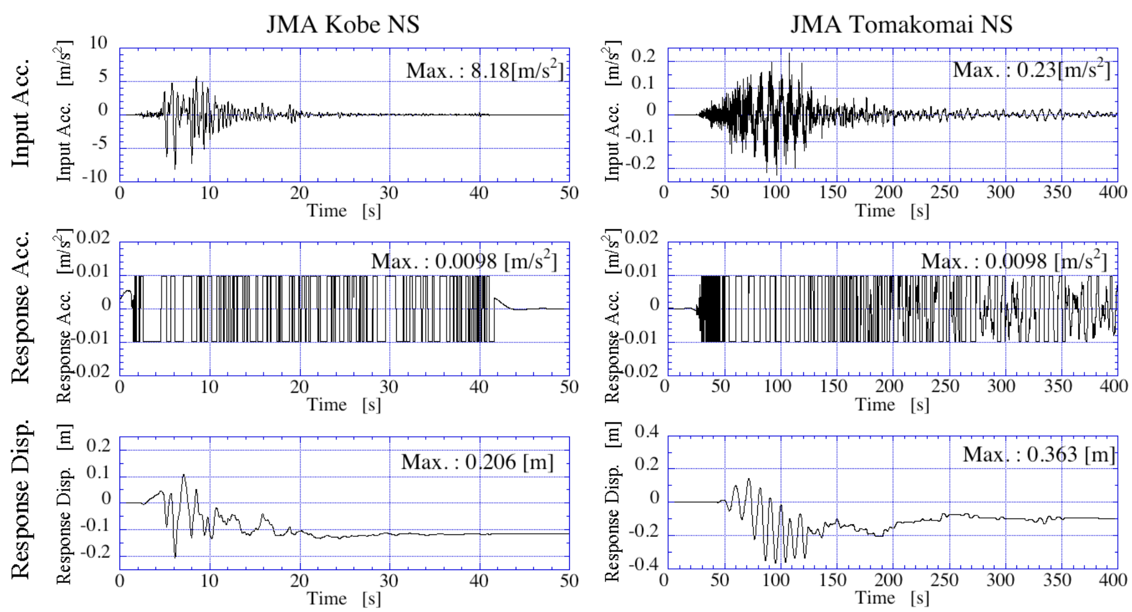

Figure 3. Analytical Results

4. EXPERIMENT

In order to investigate basic performance of the proposed system, experiments were conducted. In the experiments, friction coefficient of air bearings, vertical properties, and isolation performance were investigated.

4.1. Experimental Isolation System

An experimental isolation system was made in order to investigate the behavior and isolation performance of the proposed system. Figure 6 shows a composition of the experimental isolation system. These components are based on concept of the floating type isolation system shown in Fig. 2. First, compressed air is generated by an air compressor, and is accumulated in an air tank. Next, supplying compressed air is controlled by solenoid valve, and opening and closing the solenoid valve is controlled by a signal from an EEW receiving PC. After that, compressed air flows into a mist separator, an air dryer and a regulator in order to regulate air condition. Then a manifold separates compressed air into each air bearing, and a speed controller adjusts air pressure and flow rate of each air bearing. Finally compressed air flows into air bearings through small air tanks. These small air tanks remove variation of air pressure just before air bearings.

A frame made of carbon steel is an isolation target. The manifold, the speed controller, the small air tanks and air bearings were set on the isolation frame. Figure 5 shows dimension of the isolation frame. The frame has width of 0.750 m on a side, height of 0.261 m, and weighs 636 kg. Four air bearings that have capacity of 235 kg and diameter of 0.150 m are installed under each corner of the frame.

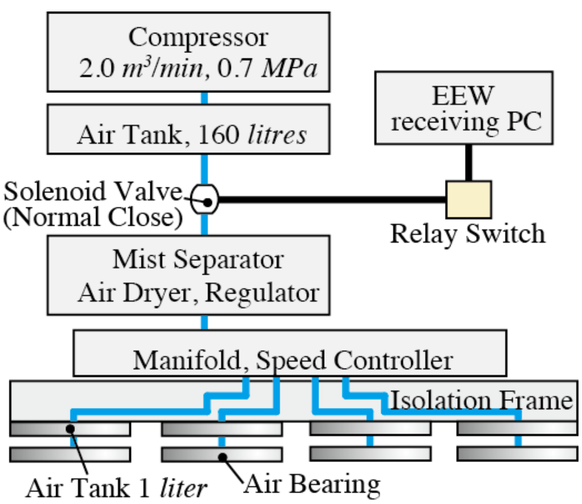

Figure 4. Composition of experimental model

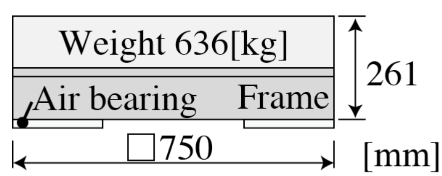

Figure 5. Dimension of isolation frame

4.2. Basic properties

Friction coefficient, vertical natural frequency and vertical damping ratio of the isolation frame are investigated in this section.

Floating height of the isolation frame is so low and velocity of the compressed air between air bearings and ground is so fast that the system has frictional resistance in horizontal direction. Therefore the friction coefficient between air bearings and a steel table was investigated. The friction coefficient was measured by a spring scale. The isolation frame was pulled by the spring scale, then horizontal force for starting to move was measured. The measured horizontal force F_H was 3.04 N.

In this test, a different weight from Fig. 5 was used and the weight m was 664 kg. Therefore the friction coefficient μ is calculated as follows:

$$\mu = \frac{F_H}{mg} = \frac{3.04}{664 \times 9.81} = 4.67 \times 10^{-4} \quad (5)$$

As a result, it was confirmed that the system has very small friction coefficient and there is few influence of friction resistance on the system.

Next, vertical natural frequency and vertical damping ratio were investigated. This is because floating air bearings work as air springs for vertical direction. Both properties are investigated from transfer function. The transfer function was obtained by exciting a portable shaker on the top of the isolation frame. Weight of a fixing part of the shaker is 46.8 kg, and weight of a shaking part of the shaker is 20.0 kg. Response acceleration of the isolation frame and the shaking part are measured.

Figure 6 shows a frequency response of the transfer function. From Fig. 6, the frequency response has a peak at 6.05 Hz, and its gain is 15.66 dB. Therefore the vertical natural frequency is 6.05 Hz, and damping ratio is 9.58 %. Although the isolation frame has the natural frequency around vertical predominant frequency of some earthquake wave, it has adequate damping performance. Therefore it is expected that this damping performance prevents a resonance during an earthquake.

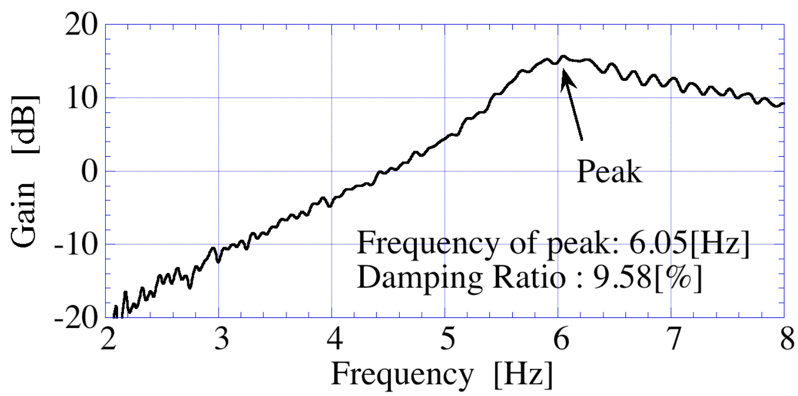

Figure 6. Frequency response of transfer function

4.3. Vibration Experiment

In order to investigate isolation performance, three-dimensional vibration experiment was conducted. First, experiment for investigation regarding an influence of vertical motion on horizontal motion was carried out. Then, three-dimensional vibration test for investigation of actual isolation performance using a computer server rack is carried out.

A three-dimensional electromagnetic shaking table that has width of 2 m on a side is utilized for these experiments. JMA Kobe waves are used as input wave, although the amplitude is adjusted according to performance of the shaking table.

4.3.1. Influence of vertical motion on horizontal motion

Two-dimensional (i.e. one horizontal and one vertical) vibration test was carried out in order to investigate influence of vertical motion on horizontal motion.

Figure 7 shows comparison of response between one-dimensional (1D) input (NS direction) and two-dimensional (2D) input (NS and UD direction). Green dotted lines show results of 1D input, and blue solid lines show results of 2D input.

First, we pay attention to results of NS direction. From Fig. 7, it is confirmed that waveform of response acceleration of 1D input is almost straight, so this system has adequate performance of isolation against horizontal input. Floating height is constant as well. Therefore the experimental model is very stable against only horizontal input. On the other hand, response of 2D input is larger than 1D input. However the maximum horizontal response acceleration is 12.8 % of the maximum horizontal input acceleration. Therefore it is expected that the isolation system retains good isolation performance even actual seismic events.

Then, we pay attention to results of UD direction. It is confirmed that vertical response acceleration of 2D input is equivalent to vertical input acceleration, although the experimental model has the natural frequency around predominant frequency of input wave. This is because the experimental model has adequate vertical damping performance. Although floating height varies according to input wave, the variation range is small, that is 3 mm peak to peak. Therefore there are few risks of vertical collision between the experimental model and the shaking table.

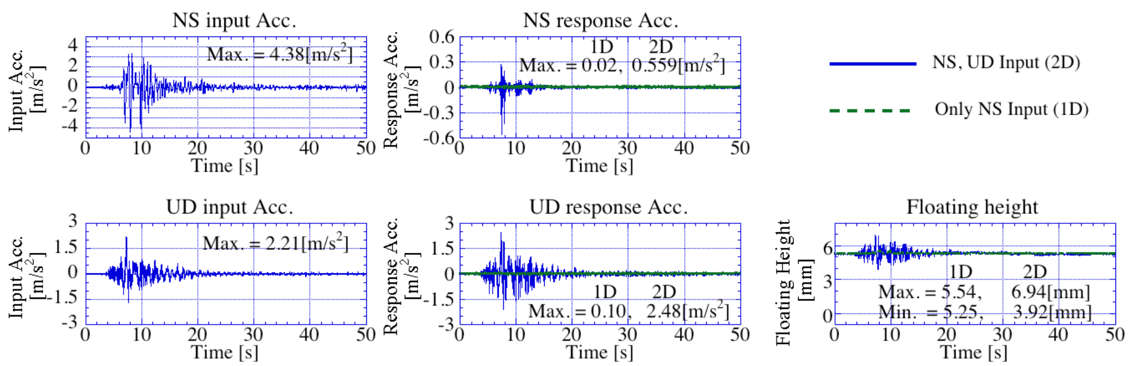

Figure 7. Comparison between one-dimensional input and two-dimensional input

4.3.2. Investigation into isolation performance

Isolation performance of the proposed system is investigated by three-dimensional vibration test. A computer server rack is applied as an isolation target, and it is placed on the isolation frame or the shaking table without fixing. The computer server rack has width of 0.565 m, depth of 0.675 m, height of 1.750 m, weight of 102 kg. Accelerations of top of the computer server rack are measured by accelerometers.

Figures 8 and 9 show time histories without and with isolation system, respectively. From Fig. 8, it is confirmed that responses of the computer server rack without isolation system resonate, and their amplification ratios to inputs were 142% for NS direction, 145% for EW direction, 369% for UD direction. On the other hand, isolation system suppresses horizontal response acceleration compared with input, and their amplification ratios were 22% for NS direction, 38% for EW direction, 200% for UD direction. Although response of UD direction of the isolation system is larger than input, the response is small than it without isolation system.

As a result, good isolation performance was confirmed.

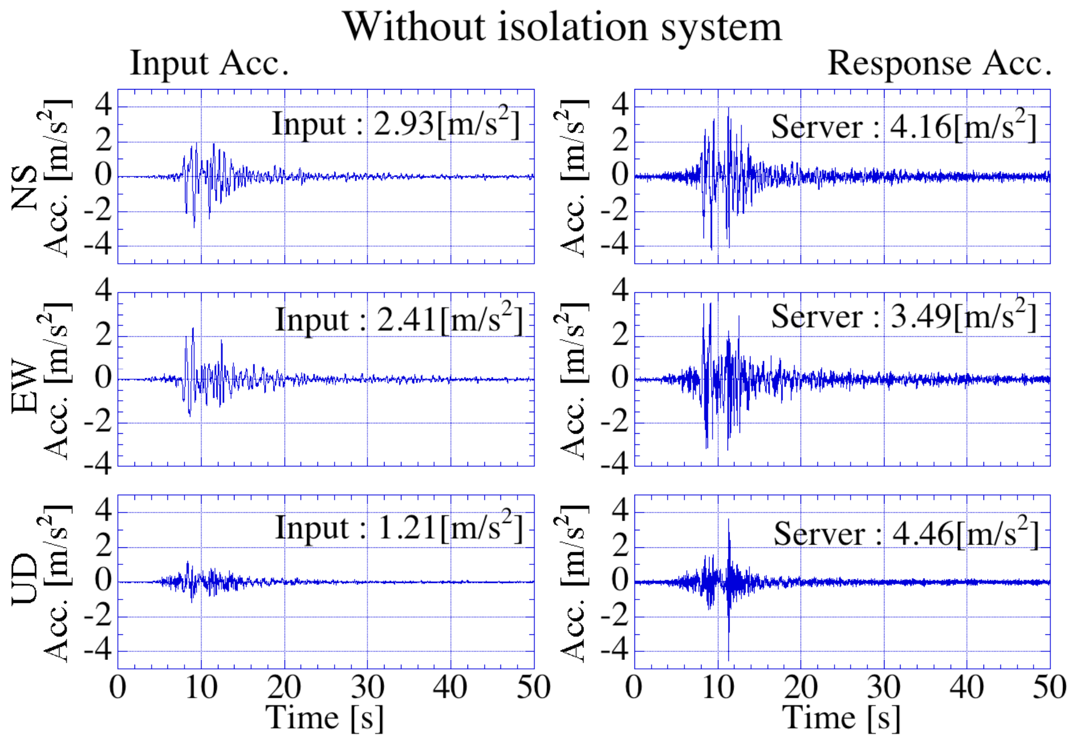

Figure 8. Time histories without isolation system

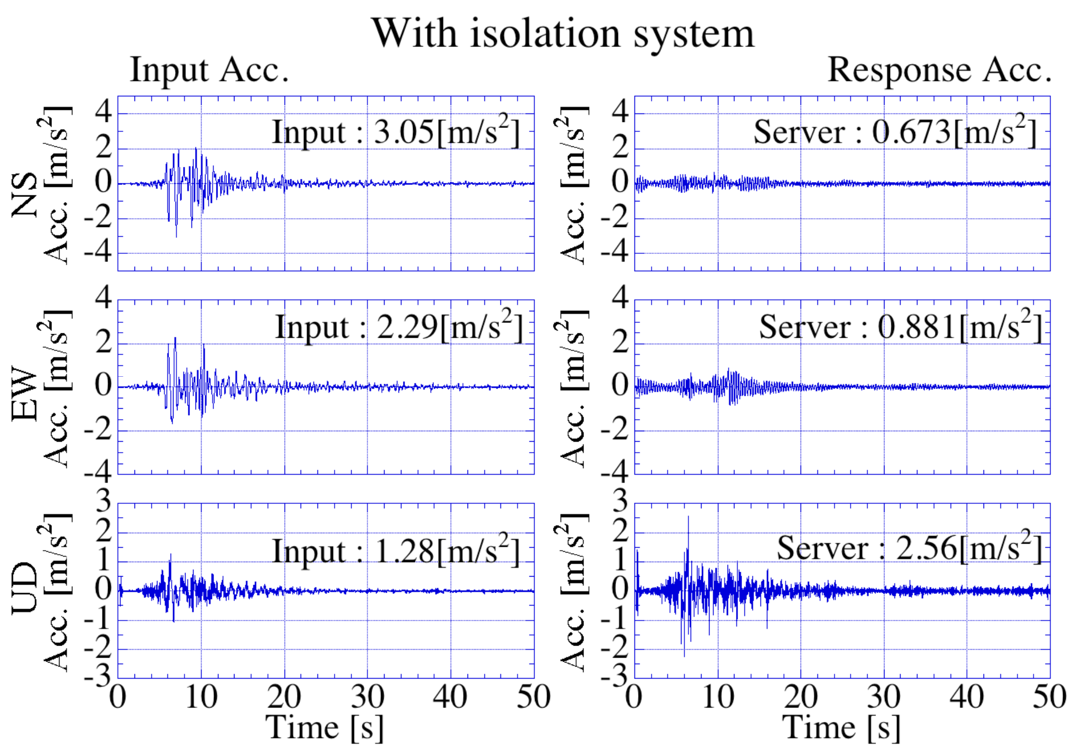

Figure 9. Time histories with isolation system

5. CONCLUSION

In this paper, floating type isolation system was proposed, and basic properties and isolation performance were investigated by analysis and experiment.

It was confirmed from simulation analysis and three-dimensional vibration tests that the floating type isolation system has adequate seismic isolation performance.

Although the isolation system has equivalent vertical natural frequency to predominant frequency of some seismic wave, the vertical response of the superstructure is well suppressed because the isolation system has adequate vertical damping performance as well.

In order to improve the performance of the isolation system, provision against vertical response is required. Suppression of response displacement is also required.

ACKNOWLEDGEMENT
This study was supported by Grant-in-Aid for Scientific Research (C) #19560241, Japan Society for the Promotion of Science. The authors would like to express their appreciations to Mr. S. Shioda and Mr. K. Hosono of Graduate School of Tokyo Denki University for their devoted assistance.

REFERENCES

Saito, T. (2011). "Behavior of high-rise buildings and seismic isolated buildings in the great east Japan earthquake, *Bulletin of Japan Association for Earthquake Engineering,* **15**, 65-68, [in Japanese].

Japan Meteorological Agency, Earthquake Early Warnings, http://www.jma.go.jp/jma/en/Activities /eew.html.