16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3945 (Abstract ID)

Registration Code: S-N1462913704

APPLICATION OF ACTIVE BASE ISOLATION SYSTEM USING ABSOLUTE VIBRATION CONTROL TECHNOLOGY

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Abstract

Active base isolation system using absolute vibration control technology has been applied to a real full scale building. The building is Techno Station of Obayashi Corporation Technical Research Institute, the New Main Building of this facility. This has become the first active base isolation building all over the world.

The applied active base isolation system utilizes absolute vibration control theory. The absolute vibration control is active vibration control method for base isolated structures to stay in the absolute space and to have vibration free environment, by applying control forces through actuators during earthquakes. This control includes feedforward control, which applies counter force of the input ground motion, and feedback control, which adds absolute damping to the structural system. To confirm the performance of this absolute vibration control, shaking table tests were conducted for a 3 story small scaled building frame model. It was shown that by applying absolute vibration control, the acceleration of top of the model was reduced to about 1/10 of conventional passive base isolation buildings.

When applying absolute vibration control to a real full scale building, it is necessary to install fail safe mechanism in case that actuators are over loaded by input ground motion of more than expected level or unstable control condition. As fail safe mechanism for this absolute vibration control, the trigger system using friction dampers is installed between actuators and reaction foundation. Owing to this trigger system, active control force from hydraulic actuators is limited to the allowable design force.

The seismic performances of the active base isolation building are discussed through numerical simulation results. After completion of this building, observation data for several earthquakes are obtained by the monitoring system. These results are also introduced.

This active base isolation system can be applied not only to whole buildings, but also to some limited areas inside buildings. The prototype of the active base isolation floor has been developed and installed in the new multi-purpose open laboratory (OL2) of Obayashi Corporation Technical Research Institute. This active base isolation floor is expected to be applied to some very important rooms, which require high seismic performance, such as operation rooms in hospitals, server rooms in data centers, exhibition rooms in museums, and so on.

Keywords: base isolation, active control, absolute vibration control, hydraulic actuator, connecting spring

1. Introduction

One of the first base isolation office buildings in Japan is Obayashi Corporation Technical Research Institute High-Tech R&D Center which was built in 1986. This building is a 5-story RC building, which is base isolated with 14 laminated rubber bearings to have natural isolation period of 3 seconds. Steel bar dampers are also installed as energy dissipation devices of this base isolation system, which absorb seismic energy by yielding of steel when large deformation occurred at isolation layer.

Not much after the first base isolation building was built in Japan, the basic idea of active base isolation system using absolute vibration control technology was proposed and a series of studies are conducted in 1989-1991 including experimental verification with small scaled building frame model [1]. Even though the vibration control performance was confirmed through experiments, this system had not been applied to real full scale buildings at that time. One of the reasons was that isolators such as laminated rubber bearings were not enough flexible for the actuators to have reasonable force capacity and cost. Another reason was that the fail safe mechanism had not been established.

About Twenty years after that, fully active base isolation with fail safe mechanism has been developed and applied to the real full scale building, Techno Station of Obayashi Corporation Technical Research Institute, the New Main Building of this facility, which was built in September 2010. This building is the first active base isolation building all over the world. Since its completion, active control system has been activated for more than 140 earthquakes so far, and control performance was verified.

This active base isolation system can be applied not only to whole buildings, but also to some limited areas inside buildings, such as operation rooms in hospitals, server rooms in data centers, exhibition rooms in museums, and so on, which require high seismic performance.

In this paper, after explaining the theory of the absolute vibration control, the results of shaking table tests for a three story small scaled building frame model are shown. Then the application of this active base isolation system to a real full scale building is introduced. The seismic performances of the active base isolation building are discussed through numerical simulation results as well as earthquake observation records. Finally, prototype of active base isolation floor is introduced.

2. Outline of active base isolation system

2.1 Theory of absolute vibration control system

The absolute vibration control is active vibration control method for base isolated structures to stay in the absolute space and to have vibration free environment, by applying control forces through actuators during earthquakes. This control includes feedforward control, which applies counter force of the input ground motion, and feedback control, which adds absolute damping to the structural system. Here, the theory of absolute vibration control is shown for a multi degree of freedom system.

At first, the control force for feedforward control is considered. Usually, the equation of motion is defined using the displacement relative to ground as variable. In this relative coordinate, the equation of motion for a multi degree of freedom system with a control force shown in Fig.1 is written as follows.

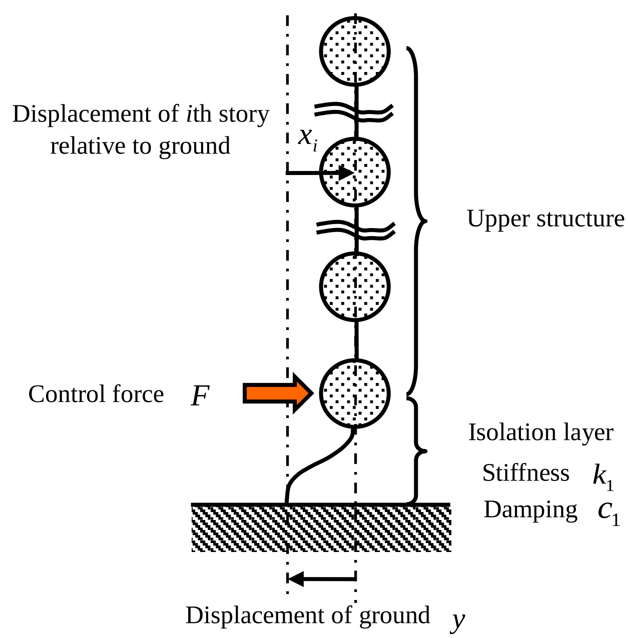


Fig. 1 – MDOF base isolation system

$$M\ddot{X} + C\dot{X} + KX = -M\begin{Bmatrix}1\\ \vdots\\ 1\end{Bmatrix}\ddot{y} \tag{1}$$

where $X = \begin{bmatrix}x_n & \cdots & x_1\end{bmatrix}^T$: displacement vector of each ith story relative to ground, M : mass matrices, C : damping matrices, K :stiffness matrices, $\ddot{y}$: acceleration of input ground motion.

Eq. (1) can be rewritten in the absolute coordinate as follows.

$$M\left(\ddot{X} + \begin{Bmatrix}1\\ \vdots\\ 1\end{Bmatrix}\ddot{y}\right) + C\left(\dot{X} + \begin{Bmatrix}1\\ \vdots\\ 1\end{Bmatrix}\dot{y}\right) + K\left(X + \begin{Bmatrix}1\\ \vdots\\ 1\end{Bmatrix}y\right) = \begin{Bmatrix}0\\ \vdots\\ 0\\ k_1\end{Bmatrix}y + \begin{Bmatrix}0\\ \vdots\\ 0\\ c_1\end{Bmatrix}\dot{y} \tag{2}$$

Where k_1 : stiffness of isolation layer, c_1 : damping of isolation layer, y : displacement of ground, $\dot{y}$: velocity of ground.

To obtain zero absolute displacement of the structure and to make the building stay in the absolute space, the feedforward control force F to cancel the input ground motion is needed only on the isolation layer as follows.

$$M\left(\ddot{X} + \begin{Bmatrix}1\\ \vdots\\ 1\end{Bmatrix}\ddot{y}\right) + C\left(\dot{X} + \begin{Bmatrix}1\\ \vdots\\ 1\end{Bmatrix}\dot{y}\right) + K\left(X + \begin{Bmatrix}1\\ \vdots\\ 1\end{Bmatrix}y\right) = \begin{Bmatrix}0\\ \vdots\\ 0\\ k_1\end{Bmatrix}y + \begin{Bmatrix}0\\ \vdots\\ 0\\ c_1\end{Bmatrix}\dot{y} + \begin{Bmatrix}0\\ \vdots\\ 0\\ F\end{Bmatrix} \tag{3}$$

$$F = -k_1 y - c_1\dot{y} \tag{4}$$

When the feedforward control force is applied to hold Eq. (4), the right hand side of Eq. (3) is to be zero, which means that the absolute displacement of the mass leads to zero for the mass to stay in the absolute space. However, in reality, the right hand side of Eq. (3) cannot be perfectly canceled only with feedforward control force, since there must exist some errors in the feedforward control force. That is, actuators have dynamics which mean that there are some errors between the commands to actuators and the responses of actuators in the frequency region higher than the natural frequency of the actuator. Also displacement and velocity obtained by sensors should include some noise. So, the feedback control is combined with the feedforward control to reduce the absolute response of the system. In this absolute control theory, the absolute velocity feedback is introduced as follows. This feedback control force is knows as skyhook damping.

$$F = -c_s\left(\dot{x}_1 + \dot{y}\right) \tag{5}$$

One of the special features of this absolute vibration control is that the connecting springs are installed between the actuators and the base isolated building. These connecting springs can prevent the high frequency vibration components from transferring from actuators to the building and avoid unstable control condition caused by control spill over. Also, installing of connecting springs make actuators be controlled with displacement not with load such as Eq. (4) and Eq. (5). With the stiffness of connecting spring k_s , the displacement of the actuator z to be controlled is obtained as follows.

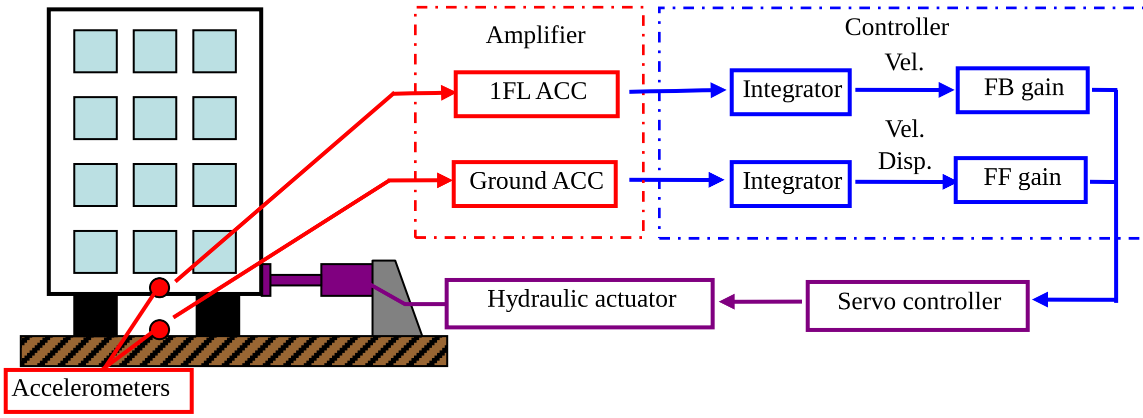


Fig. 2 – Block diagram of control system

$$F = k_s(z - x) \tag{6}$$

$$z = -\left(\frac{k_1 + k_s}{k_s} y + \frac{c_1}{k_s}\dot{y}\right) - \frac{c_s}{k_s}(\dot{x}_1 + \dot{y}) \tag{7}$$

2.2 Control system

The block diagram of the active control system is shown in Fig. 2. The system consists of accelerometers which are installed on the ground and the structure, amplifiers, a controller which includes AD/DA converters and signal processors, and hydraulic actuators.

To realize absolute vibration control described in previous section, it is necessary to obtain absolute displacement and velocity of the ground and absolute velocity of the structure. However, it is impossible to measure absolute displacement of the ground directly. So, in this system, velocity and displacement of the ground are obtained using acceleration of the ground which is integrated in the digital controller. Velocity of the structure is obtained through acceleration of the structure as well.

These velocity and displacement of the ground and velocity of the structure are multiplied by feedforward gain (FF gain) and feedback gain (FB gain), respectively, and added to have command input to the servo controller of the actuators.

2.3 Experimental verification

To confirm the performance of this absolute vibration control, shaking table tests were conducted for a three story small scaled building frame model. The schematic and the photos of the experimental setup are shown in Fig. 3 and Fig. 4. Each floor of this model has mass of 2,650kg, giving total mass of 10,600kg including base isolation floor. The model is supported by four laminated rubber bearings to have isolation natural period of 1.6 seconds.

As for active control devices, a hydraulic actuator with capacity of 24kN is installed. The actuator is connected to the building model using laminated rubber bearings as connecting springs.

The results of the shaking table tests for the scaled Kokuji-ha wave, which is the design input ground motion generated according to the design spectrum of the Building Standard Law of Japan, are shown in Fig. 5. This input wave is scaled in magnitude to have maximum acceleration of 100 cm/sec^2, and also scaled by a factor of 1/3 in time. The results for active base isolation with absolute vibration control are compared with conventional passive base isolation.

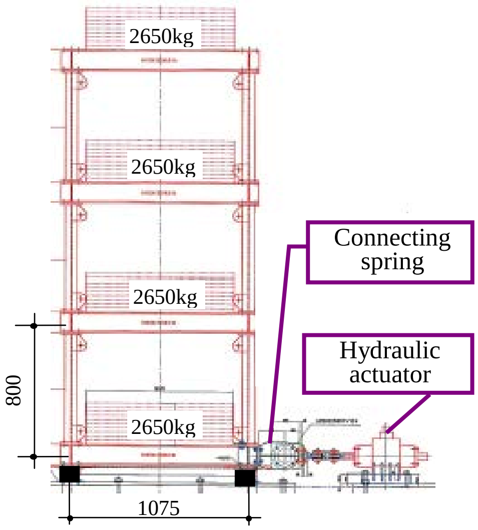
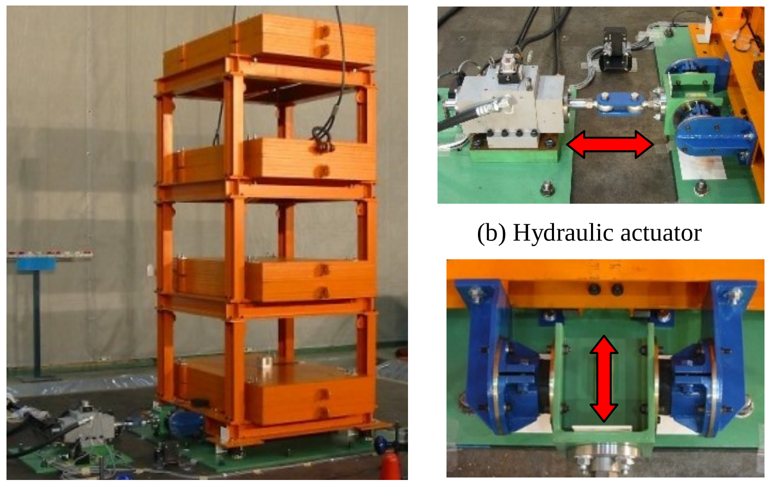


Fig. 3 – Schematic of test structure

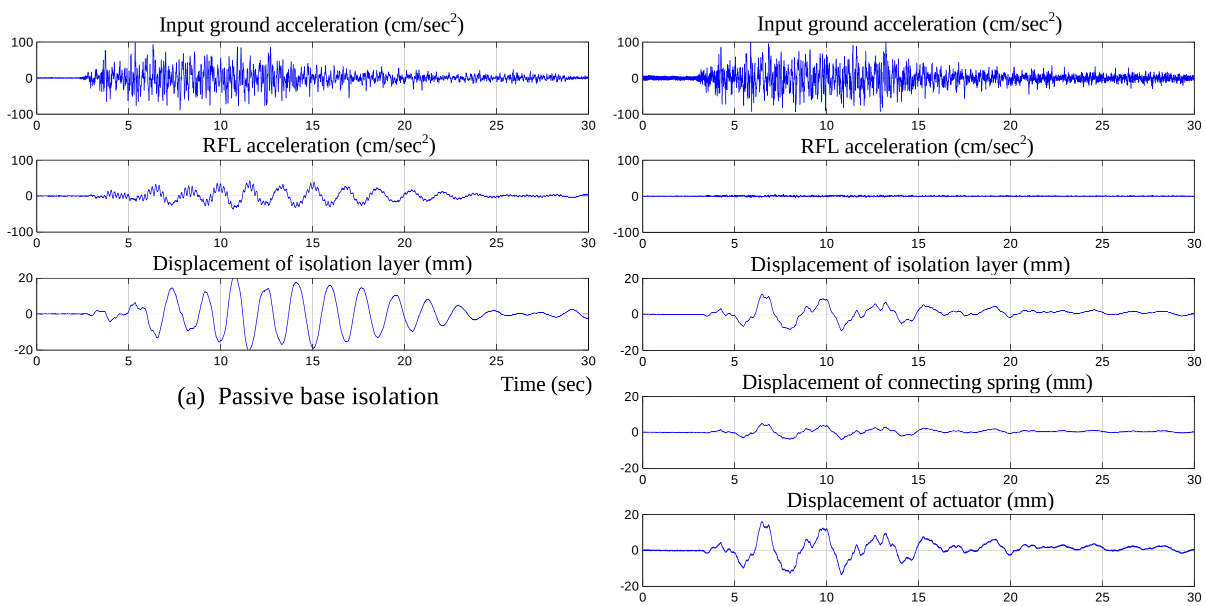


(b) Hydraulic actuator

(a) Test structure

(c) Connecting spring

Fig. 4 – Photos of test structure



(a) Passive base isolation

(b) Active base isolation

Fig. 5 – Results of shaking table tests

It is shown that by applying absolute vibration control, the acceleration of top of the model was reduced to about 1/10 of conventional passive base isolation buildings.

3. Application to real full scale building

3.1 Outline of applied building

The building, to which the active base isolation system is applied, is Obayashi Corporation Technical Research Institute New Main Building "Techno Station", which was constructed in a suburb of Tokyo, in September, 2010 [2]. A photo of Techno Station is shown in Fig. 6.

Fig. 6 – Photo of active base isolated building

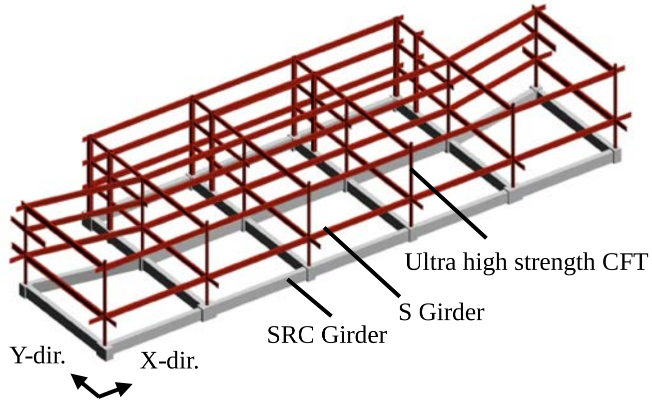


Fig. 7 – Structural framing of upper structure

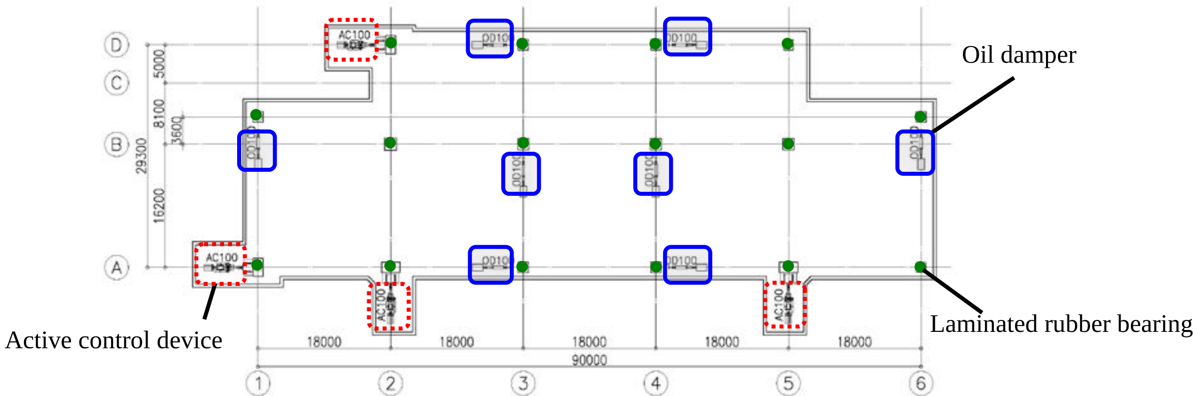


Fig. 8 – Layout of devices on isolation layer

The building is a three story steel building with height of 16m and plan size of 97m x 34m. The building is supported by 16 laminated rubber bearings and 8 oil dampers, four in each horizontal direction, are used as passive base isolation system. Natural period of 5.2s and damping factor of 20% are obtained with these devices. Four hydraulic actuators, two in each horizontal direction, are installed in pit area around the building. The structural framing of upper structure and the layout of devices on the isolation layer are shown in Fig. 7 and Fig. 8, respectively.

3.2 Configuration of active control system

The active control system consists of hydraulic actuators, connecting springs, and trigger system. The schematic of the active control system is shown in Fig. 9.

Hydraulic actuators are controlled with servomechanism and could produce any force commanded by the controller. The maximum control force of the hydraulic actuator is 1,100kN, and its maximum stroke is 200mm. The photo of the actuator is shown in Fig. 10.

When applying absolute vibration control to a real full scale building, it is necessary to install fail safe mechanism in case that actuators are over loaded by input ground motion of more than expected level or unstable control condition. As fail safe mechanism for this absolute vibration control, the trigger system using friction dampers is installed between actuators and reaction foundations. Owing to this trigger system, active control force from hydraulic actuators is limited to the allowable design force.

In this building, the capacity of the trigger system is designed to be 1,000kN. When the control force by an actuator goes beyond this load capacity, the trigger system slides and the building behaves as passive base isolation with friction dampers. The earthquake level where the trigger system works is set to be about 200 cm/sec^2. The photo of the trigger system is shown in Fig. 11.

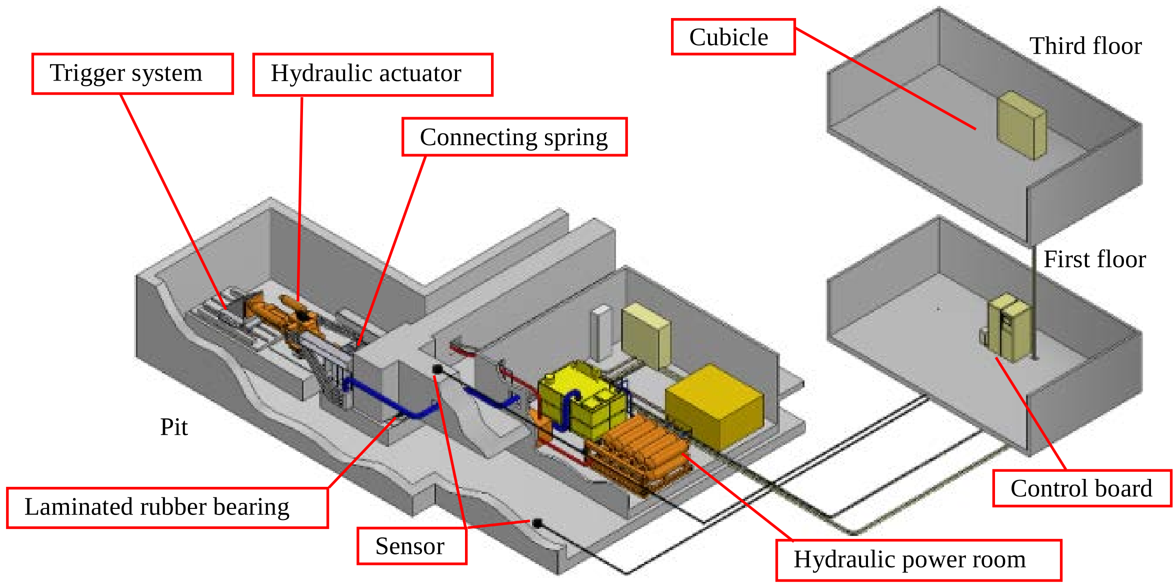


Fig. 9 – Configuration of active control system

Fig. 10 – Photo of hydraulic actuator

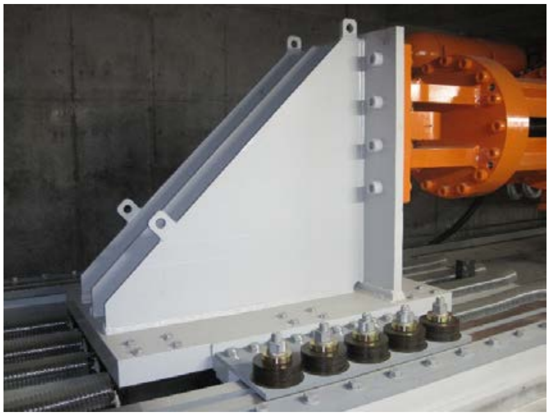


Fig. 11 – Photo of trigger system

3.3 Results of numerical simulation

Numerical simulation was conducted to examine the control performance of the installed active base isolation system. Two cases, the cases with and without the active control system, are compared. The input ground motion is the Kokuji-ha wave described in section 2.3.

The relationship between the maximum acceleration of input ground motion and that of building response is shown in Fig.12. It is shown that when the input ground acceleration is below 200 cm/sec^2, which is the designed input acceleration level for active control, acceleration response is perfectly reduced with active control. Even when the input acceleration is over designed acceleration level, the acceleration response is still better than that of conventional passive base isolation systems.

The maximum acceleration and the maximum displacement of each floor due to level 1 earthquake, which is frequent earthquake with return period of around 50 years, are shown in Fig. 13. Not much difference between with and without active control system is shown for the maximum displacement of base isolation. However, the acceleration response is reduced to 1/10 by active control system.

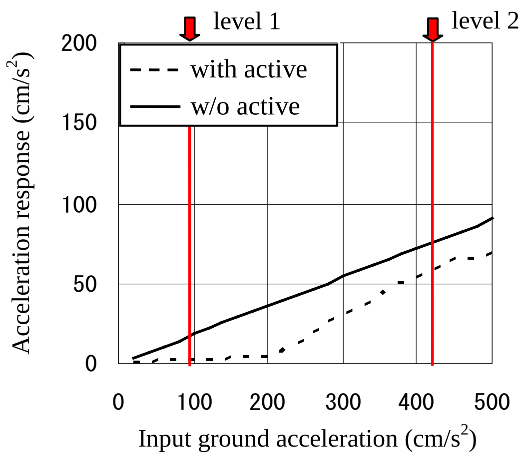


Fig. – 12 Acceleration responses due to input level (X-dir.)

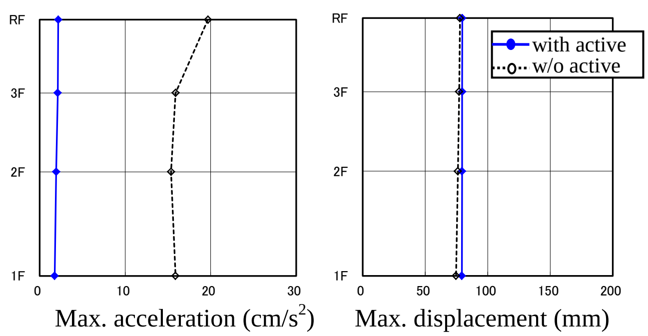


Fig. – 13 Maximum responses for level 1 input ground motion (X-dir.)

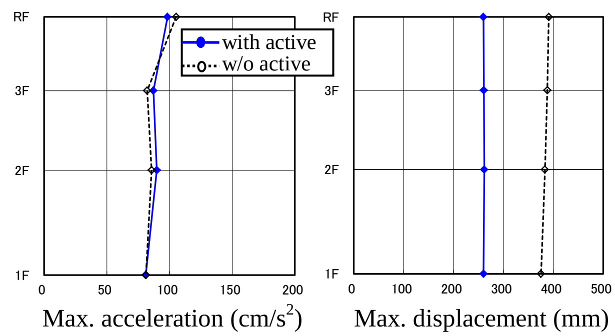


Fig. – 14 Maximum responses for level 2 input ground motion (X-dir.)

The maximum acceleration and the maximum displacement of each floor due to level 2 earthquake, which is design earthquake with return period of around 500 years, are shown in Fig. 14. For this input earthquake level, the trigger system works and the active control force is not fully applied the structure. However the maximum responses are still reduced by active control.

3.4 Earthquake observation records

During the Great East Japan Earthquake on March 11th, 2011, since the input ground motion displacement was larger than the maximum stroke of the hydraulic actuator, the fail safe system inside the active controller was activated and the building behaved as passive base isolation building.

After that, the fail safe system inside the active controller has been made adjustment. The active control system has been activated for more than 140 earthquakes so far, and the control performance was verified. One of the largest earthquake records observed is shown in Fig. 15. The input acceleration at basement was reduced to 1/4 at 1FL of the building.

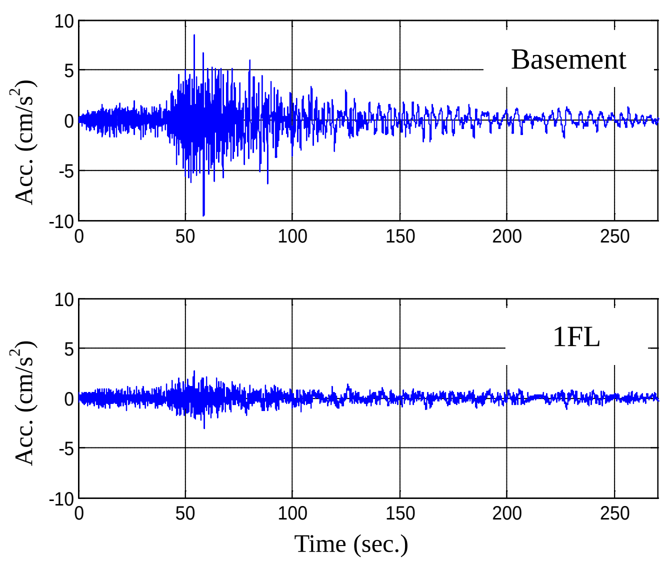


Fig. 15 – Earthquake observation record (Sanrikuoki Earthquake on December 7th, 2012)

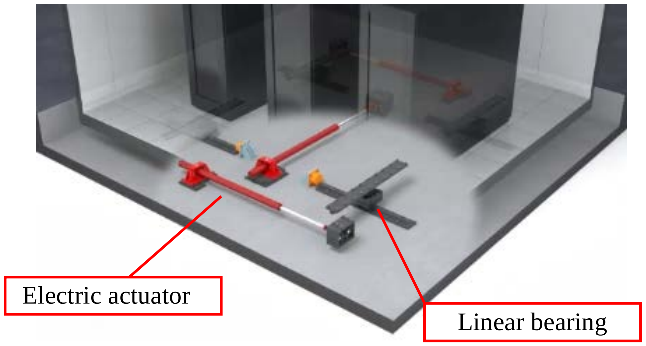


Fig. 16 – Image of active base isolation floor

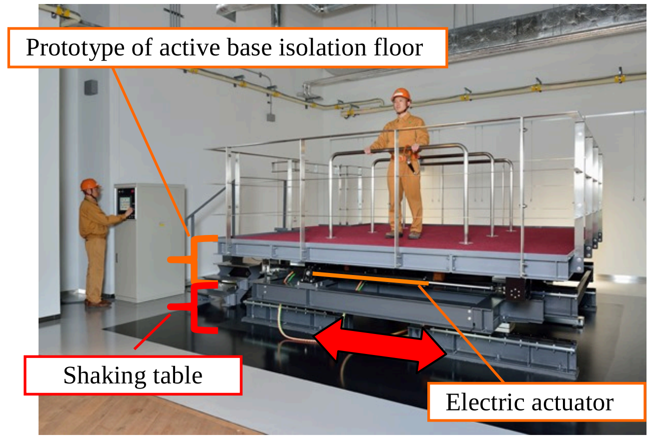


Fig. 17 – Photo of prototype of active base isolation floor equipped with shaking table

4. Application to base isolation floor

This active base isolation system can be applied not only to whole buildings, but also to some limited areas inside buildings, such as operation rooms in hospitals, server rooms in data centers, exhibition rooms in museums, and so on, which require high seismic performance. The application image of the active base isolation floor is shown in Fig. 16. When applying an active control system to a base isolation floor, it is required that the system including actuators must be compact. So, electric actuators driven by AC servo motors are selected. These actuators are installed within the raised base isolation floor, which depth can be less than 0.4m.

The prototype of the active base isolation floor, shown in Fig. 17, has been developed and installed in the new multi-purpose open laboratory (OL2) of Obayashi Corporation Technical Research Institute. The floor size of the prototype is 3.6m x 3.6m. The depth of the raised base isolation floor is around 0.4m. The floor is supported by four cross linear bearings. Three electric actuators driven by AC servo motors are installed within the raised floor, two for one horizontal direction, and one for the other horizontal direction. The maximum control force and stroke of the actuator is 1kN and 500mm, respectively. This active control system works even for level 2 earthquake, which is design earthquake with return period of around 500 years.

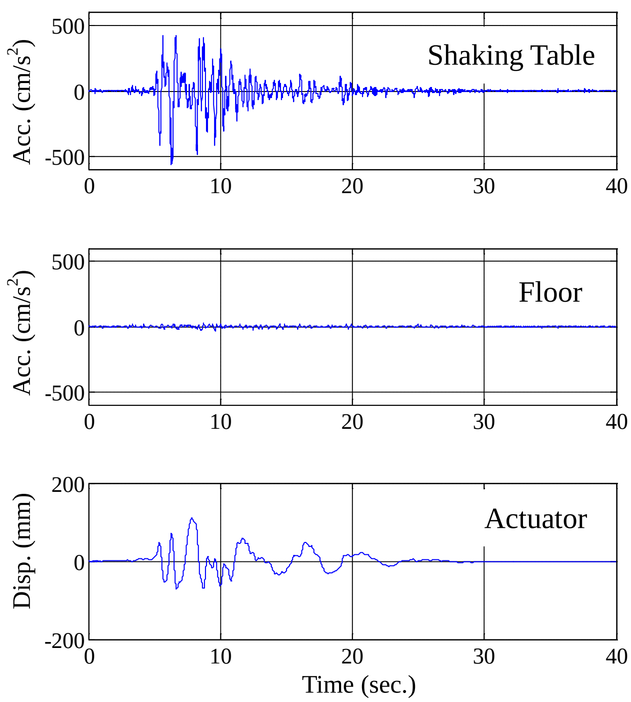


Fig. 18 – Performance of active base isolation floor (70% of JMA Kobe Earthquake)

This prototype model also equipped with shaking table below its isolation layer. The vibration control performance can be confirmed using this shaking table. The example of the confirmed performance is shown in Fig. 18. As shown in this figure, the input ground notion produced by the shaking table is reduce to around 1/20 on the active base isolation floor for 70% of JMA Kobe Earthquake.

5. Conclusion

Active base isolation system using absolute vibration control technology, which can realize vibration free environment during earthquakes, has been developed and installed on a real full scale building, Techno Station of Obayashi Corporation Technical Research Institute.

With this system, the optimum control force, which is calculated based on the absolute vibration control theory, is applied to the base isolated building, and the building responses are reduced to around 1/10 compared to that of conventional passive base isolated building. The performance has been confirmed by experiment using scaled model structure.

For Techno Station, four 1,100kN hydraulic actuators, two for each horizontal direction, are installed and the active control perfectly suppress the building response up to the input ground acceleration of around 200cm/s^2. Even for the input ground motion above this level, where trigger system works and active control force is not fully applied to the building, the building response is better than the conventional passive base isolated building, which is confirmed by numerical simulation. Since the completion of the building, the active control system has been activated for more than 140 earthquakes so far, and the control performance was verified by the earthquake observation records.

This active base isolation system can be applied not only to whole buildings, but also to some limited areas inside buildings. The prototype of the active base isolation floor has been developed and installed on the new multi-purpose open laboratory (OL2) of Obayashi Corporation Technical Research Institute. This active base isolation floor is expected to be applied to some very important rooms, which require high seismic performance, such as operation rooms in hospitals, server rooms in data centers, exhibition rooms in museums, and so on.

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