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BASE ISOLATION SYSTEM FOR ELECTRIC RACK IN NUCLEAR POWER PLANT AGAINST EARTHQUAKE AND FLYING OBJECT INPACT USING AIR FLOATING TECHNIQUE

Osamu FURUYA[1], Sun Gook CHO[2], Hiroshi KURABAYASHI[3] and Kunio SAMPEI[4]

[1] Professor, Tokyo Denki University, Saitama, JAPAN (osamu.furuya@mail.dendai.ac.jp)
[2] CEO, Innose Tech Co., LTD., Incheon, KOREA
[3] CEO, Vibro-System, Tokyo, JAPAN
[4] Managing Director, Sansei AIR Danshin System Co., LTD., Tokyo, JAPAN

ABSTRACT

Securement of Seismic performance is one of the very important safety management for nuclear power plant (NPP). After Fukushima accident, the structural design standards have been revised to ensure more seismic safety. Moreover, several techniques for seismic safety of the structure are proposed including rubber or sliding bearings for base isolation to aggressively reduce the seismic responses of structure, system and component. Base isolation system has a function to remove vibration in higher frequency range such as a low pass filter. On the other hand, the impact caused by airplane crash to the NPP structure brings also a significant problem to keep the functions of various equipment in the facility. However, former and later input wave level are fairly different in viewpoint of maximum acceleration and displacement. Therefore, since it is extremely difficult to reduce the response of both input vibration ranges by using one device or mechanism, an isolation system that blocks the energy transmission of the response vibration will become a good solution. The study has been investigating a combined isolation system using air floating technique to control the vibration response of important rack type structure in NPP against earthquake and missile impact. This paper introduces the systematic concept and the fundamental performance of the proposed air floating system.

INTRODUCTION

The rational methods based on the latest technical knowledge must always be adopt to a seismic safety in the structure, system and component for the highly safety securing in nuclear power facilities during earthquake. After Fukushima accident, the regulation for safety management in various countries is enhanced for nuclear security. In a such situation, the application of base-isolation system which has been confirmed an achievement for upgrading a seismic safety improvement during earthquake is regarded as an important technique. The base-isolation system largely reduces energy transmission to the objective structure from the base during earthquake. In addition, the responses in target structure also reduces by removing a vibration in high frequency range during earthquake such as a low-path filter. However, there are still some problems in the point of view for the application to nuclear power facilities. As a base-isolation device, some emergency center reconsiders to adopt a structural design using base-isolation system, and changes to seismic resistant design because that the uncertainty of base isolation layer in a design extension condition.

Detailed evaluation about an effect to the equipment and piping of high frequency wave is an important task since the example of examination for a response of building and translation to floor by air plane crash or missile impact. Moreover, evaluation of structural responses using base isolation system due to airplane crash has not been fully investigated until now. It is difficult to reduce the dynamic responses of the structure in wide frequency range from seismic wave to air plane or missile impact and in wide acceleration level at the same isolation device. Therefore, this study has been developed the air floating technique to cut off the energy transmission to the equipment from the floor vibration. This paper introduces a basic performance of the isolation system by analytical and experimental approach.

AIR-FLOATING TECHNIQUE

The technique of air floating system has applied to an air bearing [1] and a flow dynamic conveyer to convey coal, gypsum, ash in iron places [2]. The air floating system for a base-isolation has been already applied to some structures. The base isolation system for light wait mechanical structure such as a server rack using an emergency earthquake prediction warning [3][4][5][6] and the floating system for a detached house was developed to lift up in seismic event over a setting acceleration [7]. However, the base isolation system using air floating technique has not been investigated to cut off an energy translation in a structure. Especially, the theoretical and engineering special knowledge for a steady state limitation of air floating height has not been obtained. In particular, the elucidation of mechanism for the vibrating phenomenon which is produced from air pressure and the rigidity of seal part of the air floating layer is necessary to secure a stable air layer to support a target structure. Moreover, countermeasure of rocking motion activated by the relations between the vertical base isolation and the low pressure in air floating layer are important. Furthermore, the establishment of the semi-active control technique to control a floating time concerning earthquake input is a scientific examination matter.

Figure 1 shows the basic concept of air-floating base isolation system. The proposed system in this study is the system construction that the pressurized air in the accumulator tank is exhausted to the base isolation layer when an accelerometer senses optional acceleration level. The base isolation layer is arranged from a spring element to adjust a natural period and damping element.

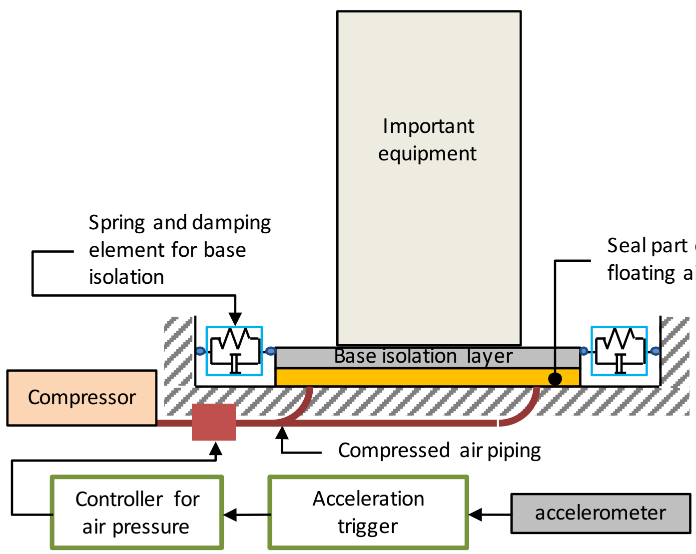


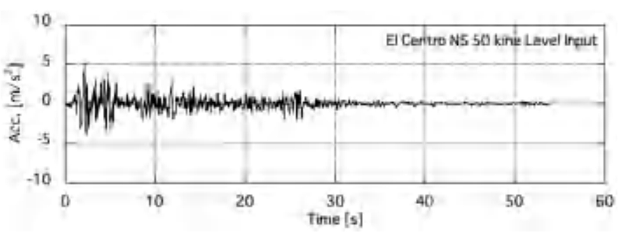
Figure 1. Basic concept for air-floating base isolation system

FUNDAMENTAL PERFORMANCE ANALYSIS IN HORIZONTAL DIRECTION

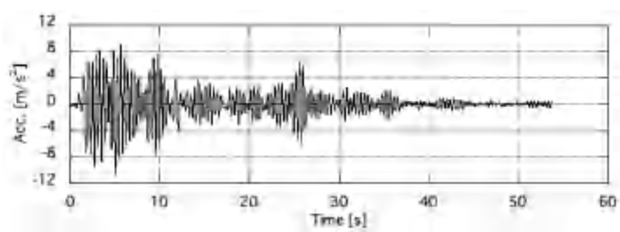
At first the time response analysis using friction coefficient as an analytical parameter is carried out to confirm a base isolation performance in horizontal direction at air floating condition. In this analysis, the response wave obtained by time response analysis for nuclear building is used for an input wave to the equipment that is a target mechanical structure for air floating. The analytical results can compare the response in sliding bearing as one of representative base isolation system for equipment by using friction coefficient as an analytical parameter. Besides, the reason to assume a friction coefficient as a parameter is to join some kind of mechanical parts including the spring element to base isolation layer from the viewpoint of adjustment in the air floating in a failsafe and a natural period adjustment.

Figure 2 shows the analytical result with El Centro NS 50kine level input. In the figures, (a) is the acceleration of input seismic wave, (b) is the response acceleration in building, (c) is the response acceleration in equipment and (d) is the response displacement in equipment. The mass of a nuclear building and an equipment are set to 100,000ton and 10ton. The friction coefficients are 0.05, 0.01, 0.005 and 0.001 as an analytical parameter. Since the friction coefficient of the general mechanical structure becomes around 0.005, the friction coefficient of air floating base isolation system is assumed around 0.001.

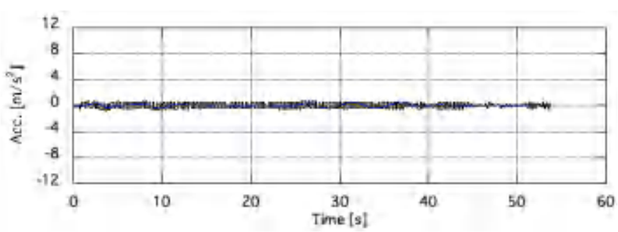
Although the maximum response acceleration of nuclear building becomes two times, the response acceleration of the equipment decreases in less than 1/10 in all friction coefficients using the time response analysis. The maximum response displacement is around from 170mm to 330mm.



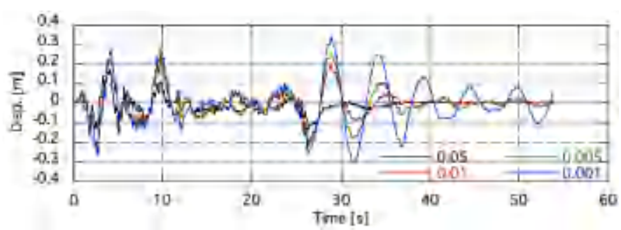
(a) Input Seismic Wave



(b) Response acc. in building



(c) Response acc. in equipment



(d) Response disp. In equipment

Figure 2. Time history input and responses for fundamental performance of base-isolation system

BASIC PERFRMANCE OF BASE ISOLATION SYSTEM IN SHAKING TABLE TEST

Basic base isolation performance is examined bout analysed horizontal effect using simple air floating base isolation system in shaking table test. The test apparatus has the base isolation system constructed by two air floating unit and two guide rails to prevent from yawing and rocking in base isolation layer as shown in Fig.3. The air floating unit is used a bellows type air spring, and buoys at optional acceleration level by compressed air pressure. The base isolation layer is design for the compactification of the system by using the elasto-plastic damper of 1.2second first stiffness, 17mm yield displacement and 200mm maximum displacement in center of base isolation layer and also spring element to control 4second natural period. Besides, the target performances are to be less than 200gal in maximum response acceleration and 180mm in maximum response displacement at 50kine level seismic wave input.

Figure 4 shows the one of experimental result in shaking tale test using El Centro NS. The black line indicates the acceleration in shaking table, and also the red line shows the acceleration in base isolation system. Base isolation effect is satisfied the target performance as shown in the figure. Figure 5 shows the analytical model for shaking table test specimen. The analytical model is constructed from mass, spring element, damping element, elasto-plastic restoring force and friction force with the similar as shaking table test. Figure 6 shows the comparison with the analytical and experimental results. It was confirmed that the analytical model can express the horizontal experimental results including air floating system.

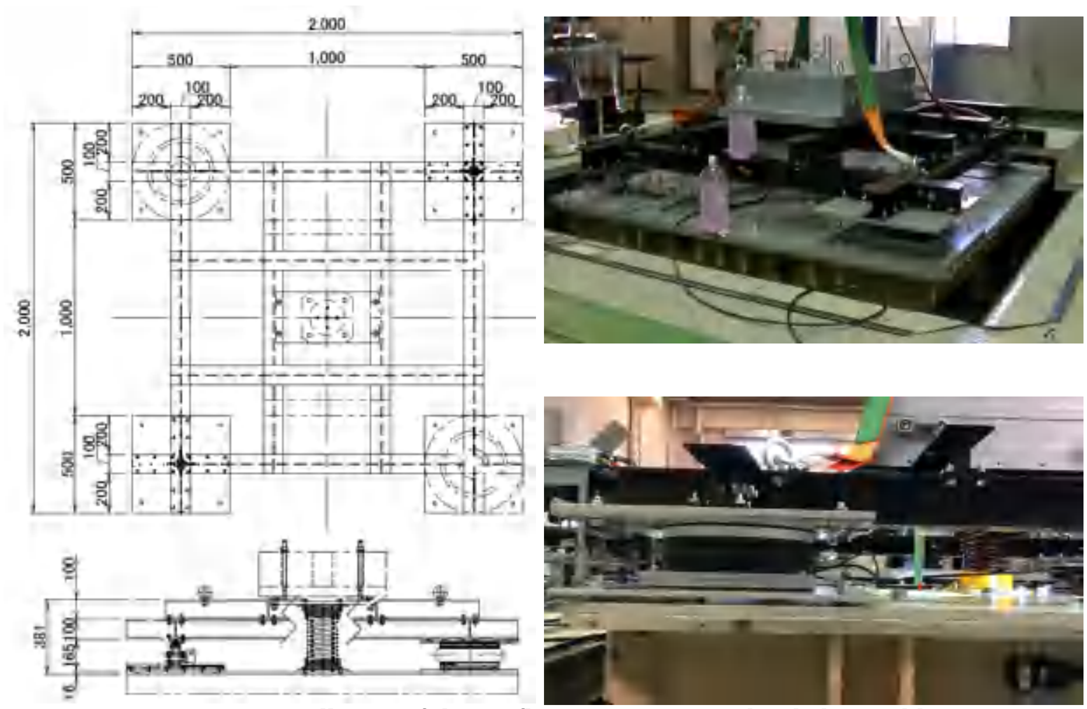


Figure 3. Installation of the air floating system on the shaking table

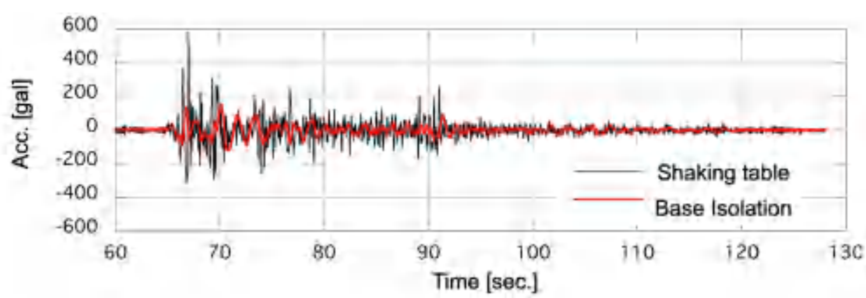
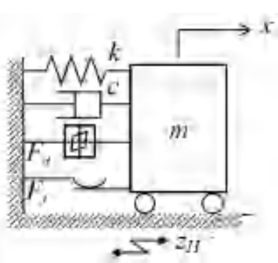


Figure 4. One of horizontal base isolation effect (El Centro NS 50kine level input)



m	Mass
c	Spring element
F_d	Damping element
F_f	Elasto-plastic force
x	Relative disp. From base
z_H	Input acceleration

Figure 5. Analytical model of the air floating system in horizontal direction

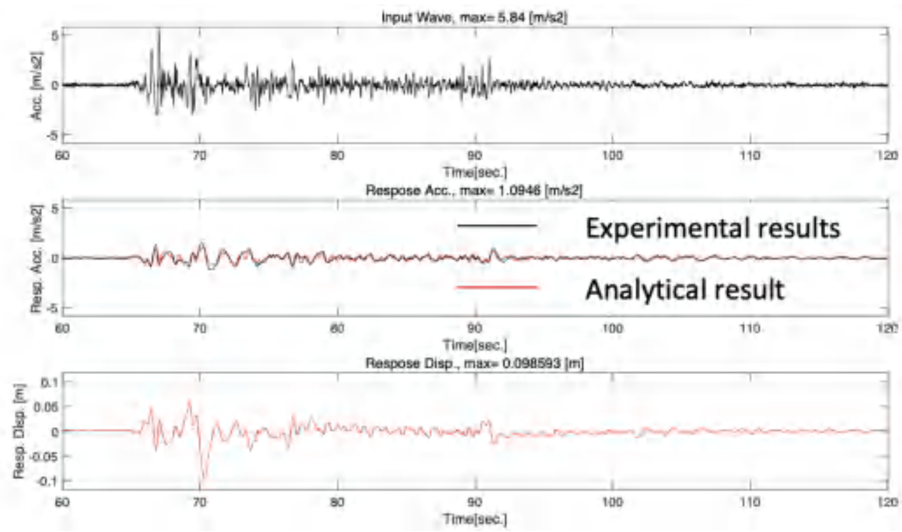


Figure 6. Comparison of analytical results with the experimental results

BASIC CHARACTERISTIC IN HORIZONTAL AND VERTICAL DIRECTION

In generally, there is a problem of rocking motion in vertical isolation system such as air floating system because of resonance frequency. Time response analysis is carried out to obtain the relation between the suitable design specification of air floating layer and the prevention of rocking motion by using natural period of base isolation in horizontal direction, natural frequency of base isolation in vertical direction and eccentricity and aspect ratio of the equipment as analytical parameters. The analytical model shown in Fig.7 is considered to evaluate a basic characteristic of rocking motion, and is constructed from a ridged body mass, a spring element and a damping element in horizontal and vertical direction. Besides, since the actual spring element at air floating works uniformly on the face of base isolation layer, the springs in vertical and horizontal direction are simply assumed as a spring element of both ends of base isolation shown in the figure.

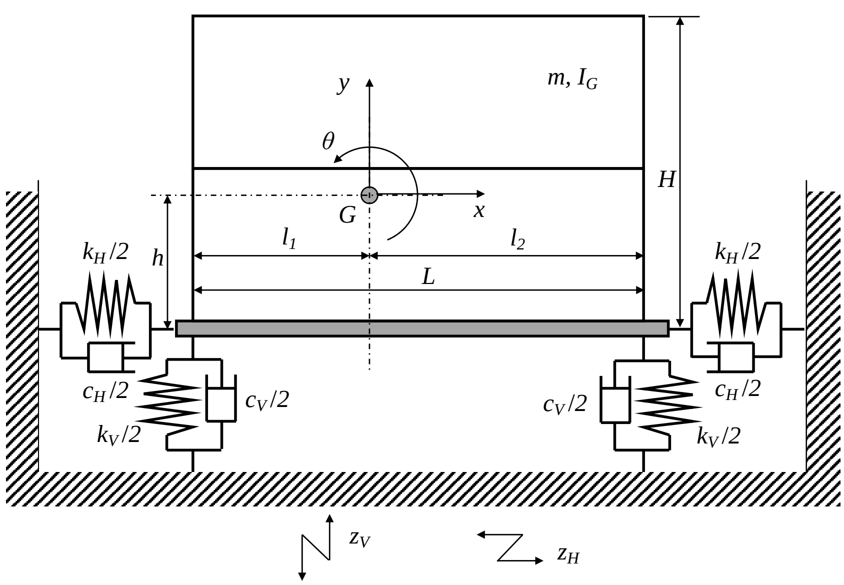


Figure 7. Analytical model for rocking movement in air floating system

The equation of motion for the analytical model is as shown in bellow,

$$m\ddot{x} + c_H\dot{x} + k_H x + c_H h\dot{\theta} + k_H h\theta = -m\ddot{z}_H \tag{1}$$

$$m\ddot{y} + c_V\dot{y} + k_V y + \frac{c_V}{2}(l_2 - l_1)\dot{\theta} + \frac{k_V}{2}(l_2 - l_1)\theta = -m\ddot{z}_V \tag{2}$$

$$\begin{aligned} I_G\ddot{\theta} + \left(\frac{c_V}{2}{l_1}^2 + \frac{c_V}{2}{l_2}^2 + c_H h^2\right)\dot{\theta} + \left(\frac{k_V}{2}{l_1}^2 + \frac{k_V}{2}{l_2}^2 + k_H h^2\right)\theta \\ + c_H h\dot{x} + k_H h x + \frac{c_V}{2}(l_2 - l_1)\dot{y} + \frac{k_V}{2}(l_2 - l_1)y = 0 \end{aligned} \tag{3}$$

The obtained equations of motions are transformed,

$$\ddot{x} = -\frac{c_H}{m}\dot{x} - \frac{k_H}{m}x - \frac{c_H h}{m}\dot{\theta} - \frac{k_H h}{m}\theta - \ddot{z}_H \tag{4}$$

$$\ddot{y} = -\frac{c_V}{m}\dot{y} - \frac{k_V}{m}y - \frac{c_V}{2m}(l_2 - l_1)\dot{\theta} - \frac{k_V}{2m}(l_2 - l_1)\theta - \ddot{z}_V \tag{5}$$

$$\begin{aligned} \ddot{\theta} = -\frac{1}{I_G}\left(\frac{c_V}{2}{l_1}^2 + \frac{c_V}{2}{l_2}^2 + c_H h^2\right)\dot{\theta} - \frac{1}{I_G}\left(\frac{k_V}{2}{l_1}^2 + \frac{k_V}{2}{l_2}^2 + k_H h^2\right)\theta \\ -\frac{c_H h}{I_G}\dot{x} + \frac{k_H h}{I_G}x - \frac{c_V}{2I_G}(l_2 - l_1)\dot{y} - \frac{k_V}{2I_G}(l_2 - l_1)y \end{aligned} \tag{6}$$

Above equations are transformed by matrix,

$$\dot{X} = AX + B\ddot{z}_H \tag{7}$$

In here, the parameters of equation are constructed as following.

$$X = \left[x\ y\ \theta\ \dot{x}\ \dot{y}\ \dot{\theta}\right]^T \tag{8}$$

Moreover, the construction matrix is as bellow.

$$A = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \tag{9}$$

$$A_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{10}$$

$$A_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{11}$$

$$A_3 = \begin{bmatrix} -\frac{k_H}{m} & 0 & -\frac{k_H h}{m} \\ 0 & -\frac{k_V}{m} & -\frac{k_V}{2m}(l_2 - l_1) \\ \frac{k_H h}{I_G} & -\frac{k_V}{2I_G}(l_2 - l_1) & -\frac{1}{I_G}\left\{\frac{k_V}{2}\left({l_1}^2 + {l_2}^2\right) + k_H h^2\right\} \end{bmatrix} \tag{12}$$

$$A_4 = \begin{bmatrix} -\frac{c_H}{m} & 0 & -\frac{c_H h}{m} \\ 0 & -\frac{c_V}{m} & -\frac{c_V}{2m}(l_2 - l_1) \\ -\frac{c_H h}{I_G} & -\frac{c_V}{2I_G}(l_2 - l_1) & -\frac{1}{I_G}\left\{\frac{c_V}{2}\left({l_1}^2 + {l_2}^2\right) + c_H h^2\right\} \end{bmatrix} \tag{13}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix}^T \tag{14}$$

In here,

m: mass of target equipment and upper plate of base isolation
I_G: moment of inertia around the center of gravity
c_H: damping coefficient of air floating layer in horizontal direction
c_V: damping coefficient of air floating layer in vertical direction
k_H: stiffness of air floating layer in horizontal direction
k_V: spring constant of air floating layer in vertical direction
x: relative displacement of the center of gravity to the ground in horizontal direction
y: relative displacement of the center of gravity to the ground in vertical direction
θ: rotation angle at the center of gravity of the target structure
z_H: horizontal ground displacement
z_V: vertical ground displacement
l: target structure width
l_1: horizontal distance from the left end to the center of gravity
l_2: horizontal distance from the right end to the center of gravity
H: height to the top of the target structure
h: height to center of gravity position

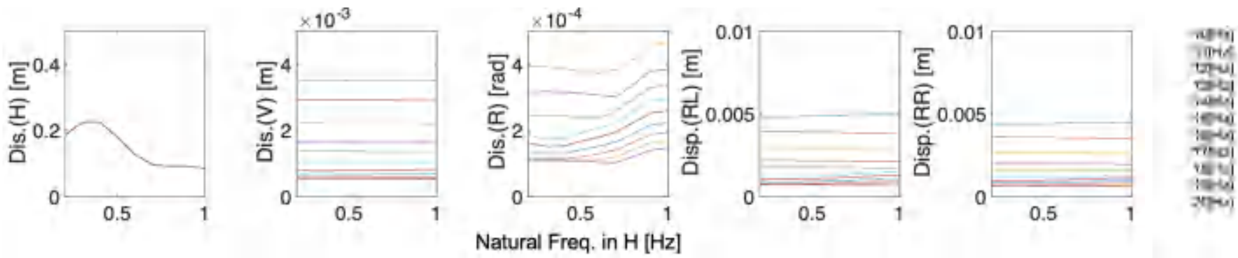
In the analysis, the analytical parameters are considered to evaluate rocking motion as shown in Table 1. The parameters are a horizontal natural period in base isolation, vertical natural frequency in base isolation, eccentricity, aspect ratio as an element affecting the rocking behavior. Input wave is El Centro NS 50kine as horizontal component and 25kine as vertical component.

Table 1: Analytical parameters

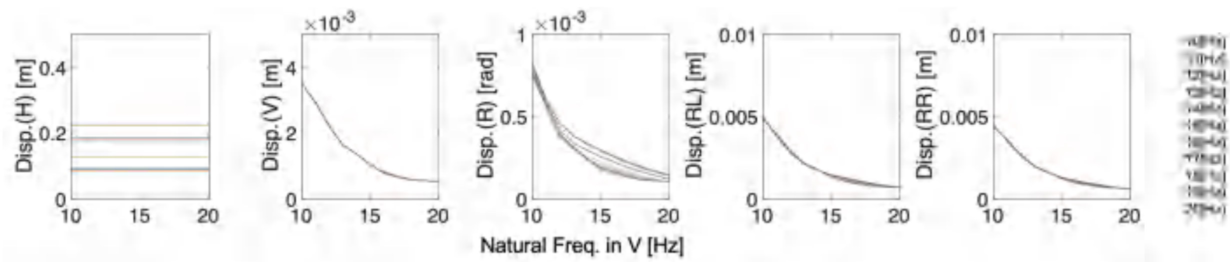
Item	Specification
Mass	10ton
Horizontal natural period	1s～5s
Vertical natural frequency	10Hz～20Hz
Horizontal damping ratio	0.2
Vertical damping ratio	0.1
Eccentricity（＝Eccentric distance／Wide of Base isolation layer）	0.1～0.5
Aspect ratio（＝Height／Wide）	0.5～1.5

In order to investigate the influence of horizontal natural period and vertical natural frequency on rocking vibration, analytical specifications are analyzed with width 3 m, height 1.8 m (aspect ratio 0.6) and eccentricity 0.1. Besides, it is assumed that the height of the center of gravity is given at 40% of the total height. An example of the analytical result is shown in Fig.4. The figure (a) shows the relationship between the horizontal natural period and the response; from the figure on the left, the horizontal maximum response displacement, the vertical maximum response displacement of the left end of the base isolation layer, the vertical maximum response displacement of the right end of the base isolation layer. The figure (b) shows the relationship between the vertical natural frequency and the response; from the figure on the left, the horizontal maximum response displacement, the vertical maximum response displacement of the left end of the base isolation layer, the vertical maximum response displacement of the right end of the base isolation layer.

As the results, the natural frequency in the horizontal direction has a low contribution of rocking. On the other hand, when the natural frequency in the vertical direction decreases, it is confirmed that the rocking vibration is excited. However, the maximum vertical displacement of the end of the base isolation layer is 5 mm or less, and the rotation angle is considered to be a negligible range of about 1/10 degree. From the results, it is considered that the rocking behavior of the base isolation layer in the case of using the air floating technique can ignore the influence by setting the vertical natural frequency over 10 Hz, and also a stable base isolation effect can be expected.



(a) Response in horizontal base isolation



(b) Response in vertical base isolation

Figure 8. Response tendency due to variation of natural period in horizontal and vertical base isolation （El Centro NS 50kine level+UD 25kine level）

BASIC PERFORMANCE BY SHAKING TABLE TEST USING PRACTUCAL USED TYPE BASE ISOLATION SYSTEM

Based on the previous investigation, the practical used type base isolation system is designed and manufactured and examine a basic performance from shaking table test. Figure 9 shows the test specimen. The test specimen has a maximum mounting weight of 400 kg, a maximum displacement of 100 mm, a natural period of 3.5 seconds, an external size of 1800 × 1000 × 175 H, and a maximum floating height of 27 mm. Air floating elements are installed at the four corners of the base isolation layer. The base isolation period is adjusted by 12 spring elements. Figure 10 shows the flow chart to the floating and the test specimen. As shown in the figure, compressed air is sent to the air floating element with an acceleration input of 5 [gal] or more, and the target object floats up to 27 mm at maximum.

Figure 11 shows the measurement for El Centro NS 940 gal input as an example of test results. The results are input acceleration from the upper row in the left column, Input acceleration from the upper row in the left row, horizontal acceleration at the seismic isolation target structure (left end), vertical acceleration on the seismic isolation target structure (left end), horizontal displacement at seismic isolation target structure, horizontal acceleration at the seismic isolation target structure (right end) from the upper right column, vertical acceleration at the seismic isolation target structure (right end), vertical displacement of seismic isolation target structure.

As the results show, it was confirmed that the maximum response acceleration was reduced to about 1/10, moreover that the rocking vibration at the end of the device was almost negligible. Furthermore, as the vertical floating height in the lower right, compressed air is sent to the floating unit and is lifted to the maximum height in a few seconds when an acceleration exceeding 5 gal is detected. Then the stable floating height is kept.

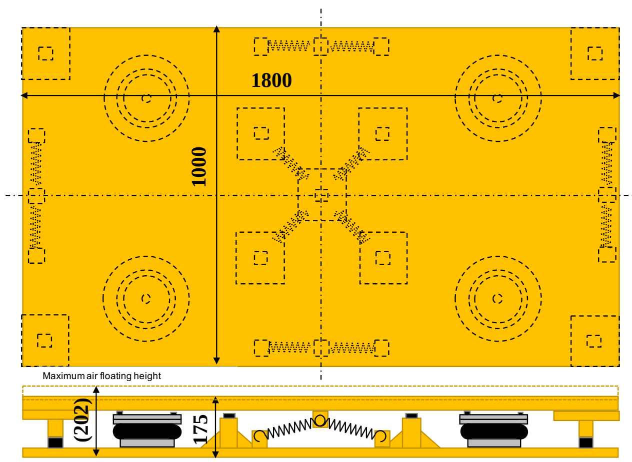


Figure 9. Actual experimental apparatus for shaking table test

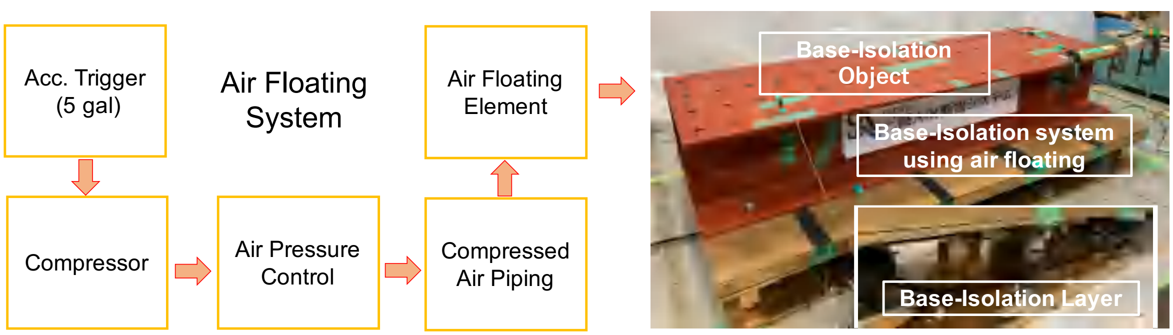


Figure 10. System condition of experimental apparatus for shaking table test

CONCLUSION

This paper describes the basic performance of the floating typed base isolation system using air springs identified by analytical and experimental studies. As a result, the same acceleration response reduction effect as the conventional base isolation system was confirmed. Specifically, the response acceleration was reduced by up to 1/10, and it was confirmed from the vertical acceleration that the problem of rocking motion at the moment of floating was small. As a result, the base isolation system by air floating can be considered to be a stroke-free and isolation natural period-free. Therefore, the air-floating base isolation system can be adopted for a wide range of vibration area from airplane impact to seismic input level. The authors are actively promoting research and development.

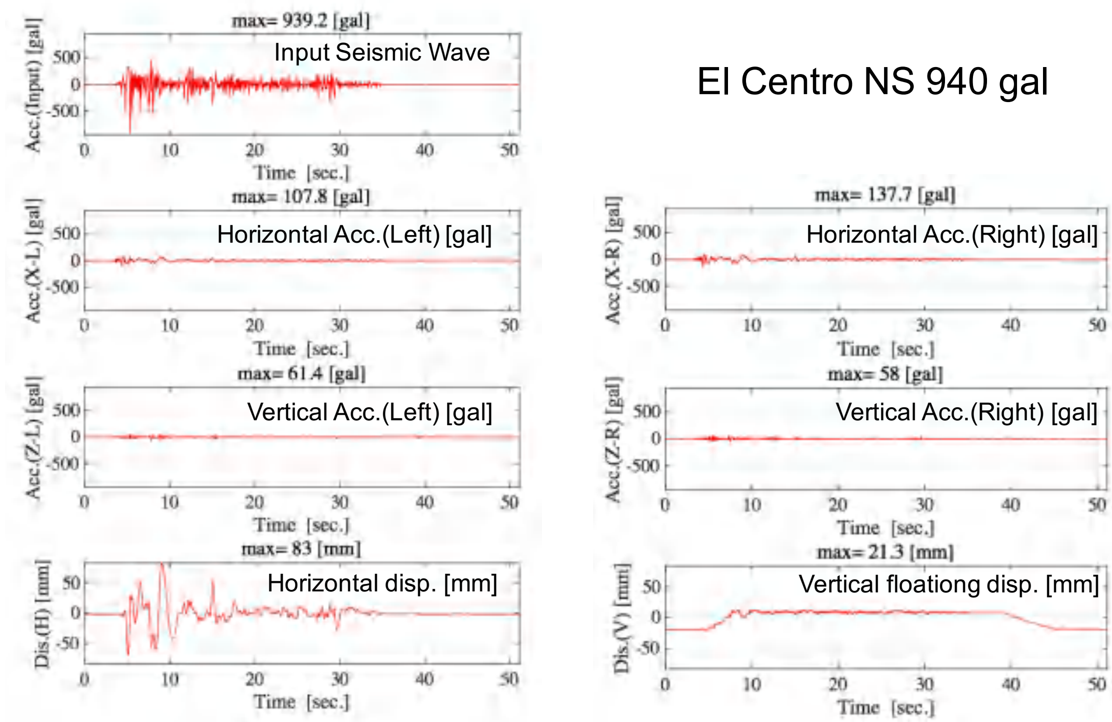


Figure 11. Experimental results from shaking table test (El Centro NS 940 gal input)

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