Experimental Study of Base Isolation System for Small Equipments and Its Evaluation

Katsumi Kurita*, Shigeru Aoki*, Yuji Nakanishi, Kazutoshi Tominaga**, Mitsuo Kanazawa*****

*(Department of Mechanical Engineering, Tokyo Metropolitan College of Industrial Technology, JAPAN)
** (Department of Production Systems Engineering, Tokyo Metropolitan College of Industrial Technology, JAPAN)
*** (Kanazawa Seisakusyo Co. Ltd., JAPAN)

ABSTRACT

A new device of reduction for seismic response using friction force was developed. In this paper, vibration analysis of a small base isolation system using the device was investigated by excitation experiment using artificial seismic waves. Peak acceleration amplitude on the base isolation system has decreased to 43 - 90% compared to input waves. And root mean square (RMS) amplitude has decreased to 76 - 94%. Although a spectral peak around 0.5 Hz that is equal to natural frequency of the system was identified when the input waves with low frequency band component were used, it was decreased using friction bearings that generate high friction force. Comparing the response waveforms of the excitation experiment and of the numerical analysis using a linear 2DOF model, it was good agreement. This system is useful for reduction of seismic response.

Keywords - Seismic Response, Friction Bearing, Ball, Marble Plate, Natural Frequency, Damping Ratio

I. INTRODUCTION

In order to protect building structures from seismic ground motion, structures are retrofitted by techniques of seismic isolation system [1-4] or vibration control system [5-6]. However, a technique of increasing structure stiffness for anti-earthquake reinforcement is generally used for retrofitting existing building structures. Therefore seismic response of structures does not decrease remarkably. Equipments set on building inside such as a computer server and an office automation equipment will overturn during a big earthquake, therefore they are higher than their width and depth. So small base isolation systems that can be installed inside building to decrease seismic response have been extensively developed [7]. For example, ball isolation type device [8], roller type using liner rail isolation device [9], friction pendulum isolation device with poly-curvature rail [10, 11] are used. The ball isolation type device shows good reduction of seismic response. However amplification by resonance is quite big, it is serious problem if an input wave is composed of broad band components that included natural frequency of this device. The isolation system with a friction damping is developed. Since the mechanism is complicated, it is not easy to install. So sliding type isolation device [12] is also used. Although the mechanism is very simple, it has no mechanism that generates restring force. Therefore it is impossible to return the original position after a big shaking.

We have developed a simple device using friction force to reduce seismic response [13]. The device consists of two plates having spherical concaves and an oval type metal (marble plate) or a spherical metal (steel ball).

In this study, vibration analysis of the small base isolation system that consisted of the device is investigated by excitation experiment using artificial seismic waves.

II. FRICTION BEARING

A friction bearing is shown in Fig. 1. It consists of two plates having spherical and the marble plate. Shape of the plate is square and length of 334 mm and thickness of edge is 62.4 mm. Radius of the concave is 500-600 mm. The marble plate slides between two plates and ground vibration is transmitted to the small base isolation system via the marble plate. It automatically returns to the original position by resilience of two concave plates. A 50mm steel ball is prepared instead of the marble plate. The restoring force in case of the steel ball is larger than the one in case of the marble plate. On the other hand, damping ratio in case of the steel ball is smaller.

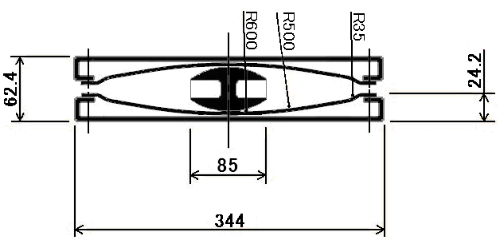

Figure 1 An example of friction bearing

The small base isolation system composed of friction bearings is shown in Fig. 2. This device is placed at each corner. The combination of friction bearings on this experiment is shown in Table 1. The same bearings are placed on the diagonal.

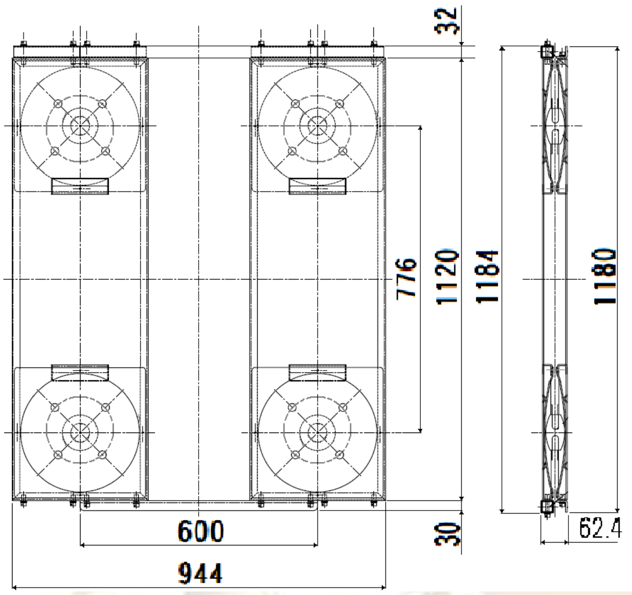

Figure 2 Size of the small base isolation system using the friction bearings (mm)

Table 1 Combination of the friction bearings for the small base isolation system

	Combination of the friction bearings
Case 1	4 Steel balls
Case 2	2 Steel balls and 2 Marble plates
Case 3	4 Marble plates

III. Excitation Experiment Using Artificial Seismic Waves

To know dynamic characteristics of the small base isolation system, the excitation experiment of this system is done using artificial seismic waves. Experimental setup is shown in Fig. 3. This system that installed a computer server rack is put on the shaking table. Size of this rack is 1850 mm height, 860 mm width, 1000 mm length. And its weight is 100 kg. Acceleration sensors (Kyowa AS-2GA) are installed on the shaking table, this system and the top of the computer server rack. Signal from acceleration sensors are recorded to a PC through an interface (Kyowa PCD-300A). Sampling rate is 0.01 sec/points.

Input waveforms as artificial seismic waves are shown in Fig. 4, and their Fourier spectra are shown in Fig. 5. Predominant frequency of the input waves is about 10Hz that is natural frequency of actual machine structures. The Fourier amplitude of the input wave 1 decreases at the frequency of lower than 1Hz. On the other hand, the amplitude of the input wave 2 and the input wave 3 decreases at the frequency of lower than 0.5Hz and lower than 0.4 Hz, respectively.

Figure 3 Experimental setup

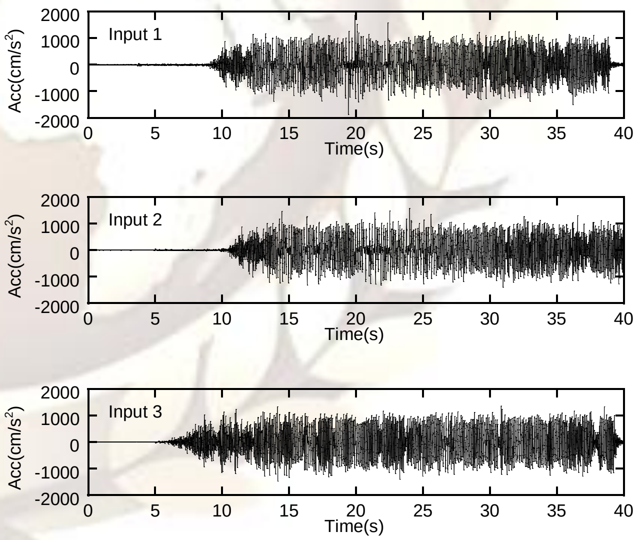

Figure 4 Artificial seismic waveforms as input waves

IV. Results

4.1 Acceleration response waveforms

Acceleration response waveforms on the small base isolation system are shown in Fig. 6 - Fig. 8. In case of the input wave 1, amplitude of the acceleration response waveform on the system using four sets of marble plate type friction bearing (case 3) is smallest. On the other hand, in case of

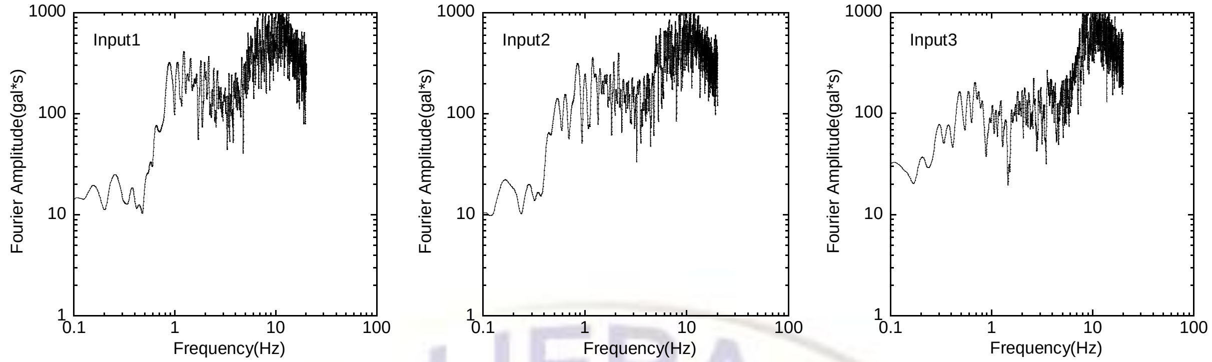

Figure 5 Fourier spectra of the input waves

the input wave 2 and the input wave 3, amplitude on the system using two sets of marble plate type and two sets of steel ball type friction bearing (case 2) is smallest. Although amplitude in case 1 is decreased until the time of 15 sec, large response amplitude with the frequency band around 0.5 Hz is identified.

4.2 Peak amplitude and root mean square amplitude of acceleration response waves

Peak amplitude and root mean square amplitude (RMS) of acceleration response waveforms are shown in Table 2 - Table 4 and Table 5 - Table 7, respectively. Peak amplitude of acceleration response waves on the small base isolation system decreases to 43 - 90 % compared to the input waves. Also RMS decreases to 76 - 94 %. However the best case of decreasing rate of peak amplitude is not always the best case of decreasing rate of RMS. This system has good ability to reduce seismic response in acceleration.

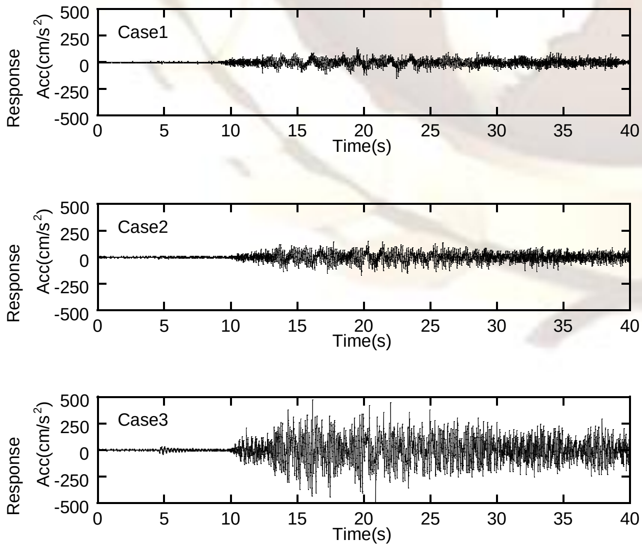

Figure 6 Acceleration response waveforms (Input wave 1)

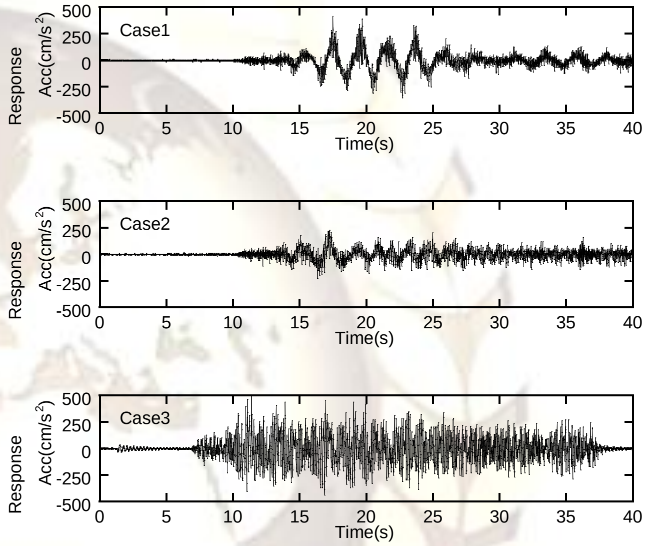

Figure 7 Acceleration response waveforms (Input wave 2)

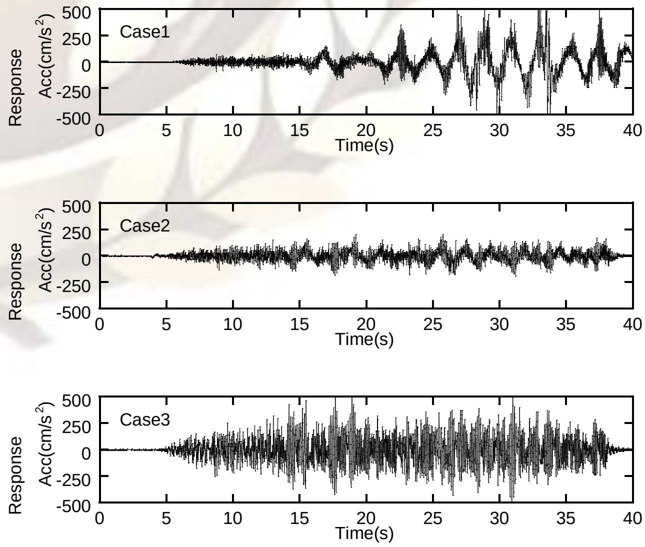

Figure 8 Acceleration response waveforms (Input wave 3)

Table 2 Peak amplitude of acceleration response wave (Input wave 1)

	Input(cm/s^2)	Res.(cm/s^2)
case1	1874	152
case2	1790	168
case3	1891	489

Table 3 Peak amplitude of acceleration response wave (Input wave 2)

	Input(cm/s^2)	Res.(cm/s^2)
case1	1562	413
case2	1807	228
case3	1655	506

Table 4 Peak amplitude of acceleration response wave (Input wave 3)

	Input(cm/s^2)	Res.(cm/s^2)
case1	1469	836
case2	1376	202
case3	1359	574

Table 5 Root mean square of acceleration response wave (Input wave 1)

	Input(cm/s^2)	Res.(cm/s^2)
case1	5.19	0.297
case2	5.08	0.401
case3	5.06	1.115

Table 6 Root mean square of acceleration response wave (Input wave 2)

	Input(cm/s^2)	Res.(cm/s^2)
case1	5.03	0.712
case2	5.01	0.493
case3	5.01	1.244

Table 7 Root mean square of acceleration response wave (Input wave 3)

	Input(cm/s^2)	Res.(cm/s^2)
case1	5.49	1.163
case2	5.47	0.520
case3	5.42	1.322

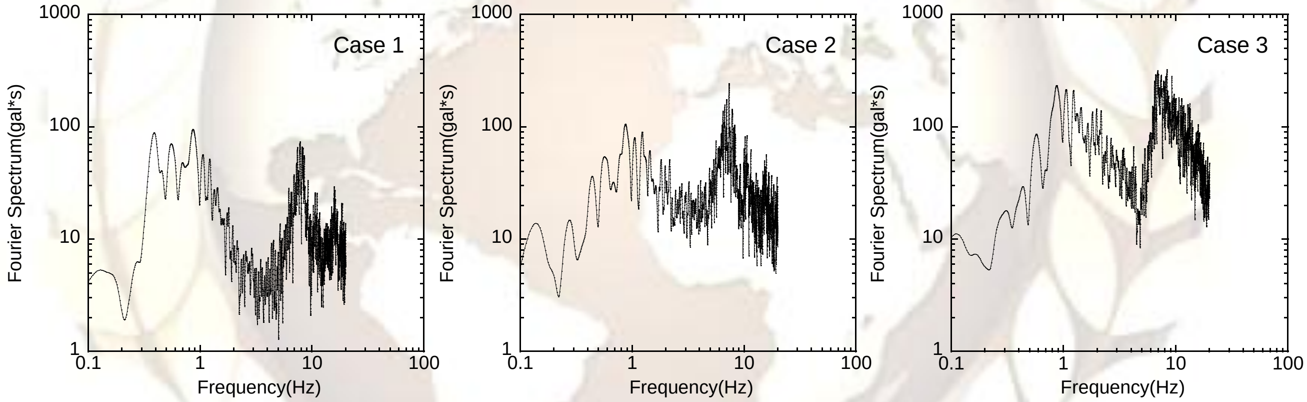

Figure 9 Fourier spectra of the acceleration response waves (Input wave 1)

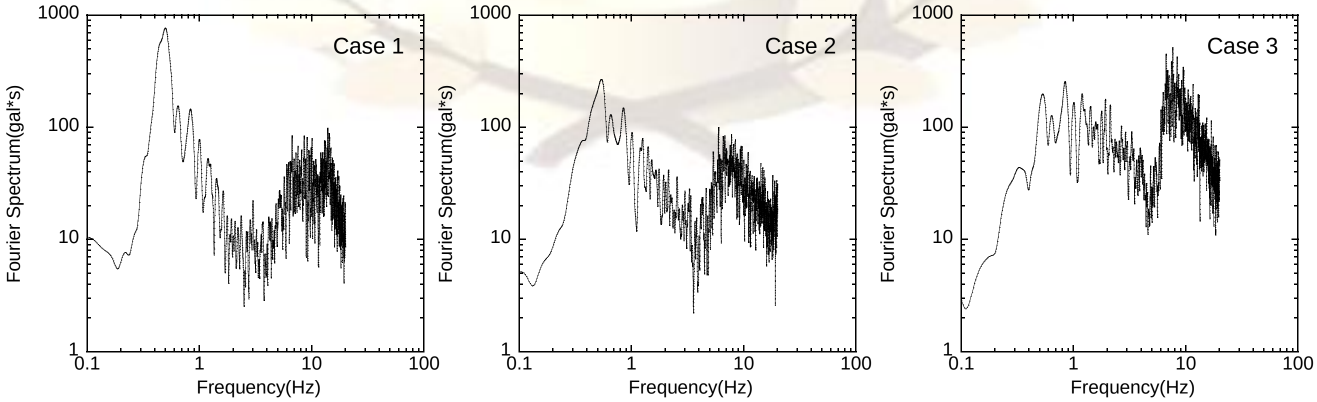

Figure 10 Fourier spectra of the acceleration response waves (Input wave 2)

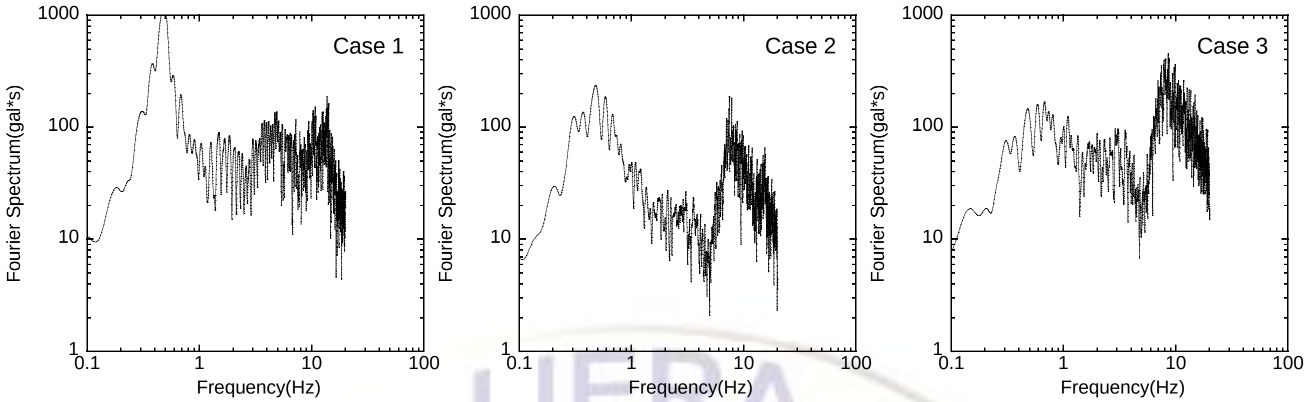

Figure 11 Fourier spectra of the acceleration response waves (Input wave 3)

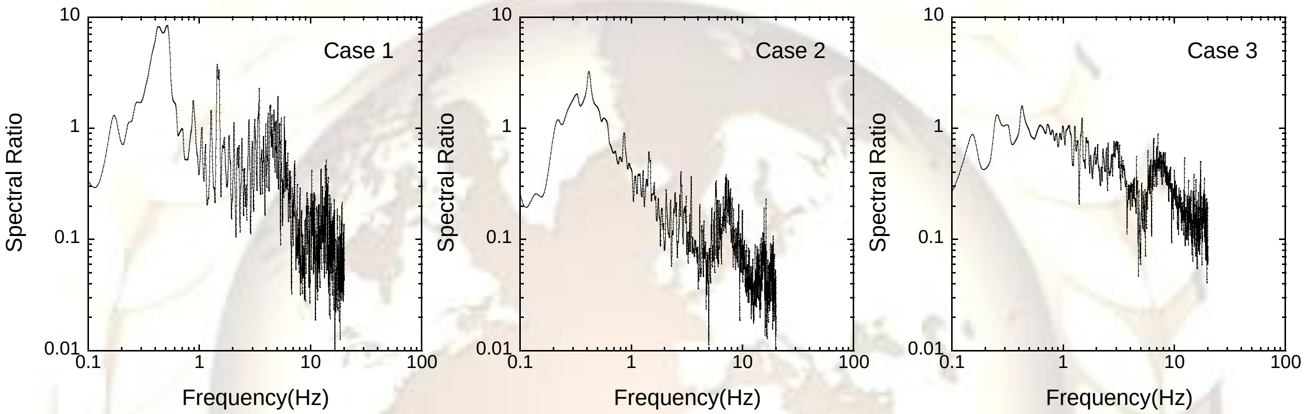

Figure 12 Spectral ratios dividing the input wave spectrum by the response acceleration spectrum (Input wave 3)

4.3 Fourier spectra of acceleration response waves

Fourier spectra of acceleration response waves recorded on the small base isolation system are shown in Fig. 9 - Fig. 11. In case of the input wave 1, although the shape of Fourier spectrum between in case 2 and in case 3 is almost same, the level of Fourier amplitude in case 3 is higher than the one in case 2. In case 1 of the input wave 2 and the input wave 3, a peak of Fourier spectrum around the frequency of 0.5 Hz can be identified. This frequency band is equivalent to natural frequency of the small base isolation system, it is generated by resonance. On the other hand, in case 3 of the input wave 2 and input wave 3, the peak of spectrum amplitude by resonance is restrained. However the decreasing rate at the high frequency band gets worse.

4.4 Spectral ratios

Spectral ratios that divided the input wave spectrum by the response acceleration spectrum on the small base isolation system in the input wave 3 are shown in Fig. 12. A peak is identified at the frequency of 0.5 Hz in case 1. Increasing the marble plate type friction bearing on this system, value of the peak is decreased. Some sharp pulses in acceleration response waveform from 25 to 35 s shown in Fig. 8 are identified in case 1. Since motion of the small base isolation system by resonance has exceeded a clearance of displacement, the sever rack on this system lost a balance and rocking motion was generated. So the reduction rate at the frequency from 1 Hz to 5 Hz is not so good. In case 3, value of the peak by resonance is restrained using the marble plate bearing that may generate high friction force. However, the decreasing rate at the high frequency band is getting worse.

V. ESTIMATION OF NATURAL FREQUENCY AND DAMPING RATIO OF THIS SYSTEM

Fitting a theoretical transfer function for the spectral ratio by a forwarding model, natural frequency and damping ratio that are very important factor to control this system are evaluated. A model of liner 2DOF system shown in Fig. 13 is used for the theoretical transfer function. The equation of motion is as followings,

$$m_1\ddot{x}_1 + c_1(\dot{x}_1 - \dot{y}) + c_2(\dot{x}_1 - \dot{x}_2) + k_1(x_1 - y) + k_2(x_1 - x_2) = 0 \quad (1)$$

$$m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) = 0 \quad (2)$$

where m is mass, $x, \dot{x}, \ddot{x}$ are displacement, velocity and acceleration, and $y, \dot{y}$ are displacement and velocity of an input motion, k is spring constant, and c is damping coefficient. And the transfer functions calculated the Laplace transform of the equation (1) and (2) are as followings,

$$\left|\frac{X_1(i\omega)}{Y(i\omega)}\right| = \left|\frac{A}{B+C}\right| \quad (3)$$

$$\left|\frac{X_2(i\omega)}{Y(i\omega)}\right| = \left|\frac{D}{B+C}\right| \quad (4)$$

where

$$A = (\omega_1^{\ 2} + 2\zeta_1\omega_1 s)(\omega_2^{\ 2} + 2\zeta_2\omega_2 s + s^2)$$
$$B = \{(\omega_1^{\ 2} + s^2)(\omega_2^{\ 2} + s^2) + \gamma\omega_2^{\ 2} s^2\} + 2\zeta_2\omega_2 s\left\{\omega_1^{\ 2} + s^2(1+\gamma)\right\}$$
$$C = 2\zeta_1\omega_1 s(\omega_2^{\ 2} + 2\zeta_2\omega_2 s + s^2)$$
$$D = (\omega_1^{\ 2} + 2\zeta_1\omega_1 s)(\omega_2^{\ 2} + 2\zeta_2\omega_2 s)$$

ω is angular frequency, i is imaginary unit, ω_0 is natural angular frequency, ζ is damping ratio, γ is mass ratio. The mass of computer server m_1 and the upper plate mass of the base isolation system m_2 were 100 kg and 35 kg, respectively, the mass ratio was 2.85.

An example of comparison between the spectral ratio and the fitting of the transfer function is shown in Fig. 14. And evaluated the parameters are shown in Table 8. The shape of the theoretical transfer function indicates two resonance peaks and an anti-resonance valley. If the valley of the spectral ratio at the frequency of 5Hz is considered to be an anti-resonance point, although locations of peaks are a little bit different, it is possible to explain the shape of the spectral ratio.

VI. Numerical Analysis

6.1 Analytical model

The base isolation system is approximately modeled by a linear 2DOF model in Fig. 13. And natural frequency and damping ratio for this analysis are used the values shown in Table 8 evaluated in chapter 5. The calculation is done in frequency domain using equation (3).

6.2 Comparison acceleration response waveforms between by the excitation experiment and by the numerical analysis

Comparison acceleration response waveforms between by the excitation experiment and by the numerical analysis are shown in Fig. 15. And peak acceleration amplitude and RMS are shown in Table 9 and Table 10.

In excitation experiment of case 1, since motion of the small base isolation system by resonance has exceeded clearance of the friction bearing, the sever rack on this system lost a balance and rocking motion was generated. Therefore some

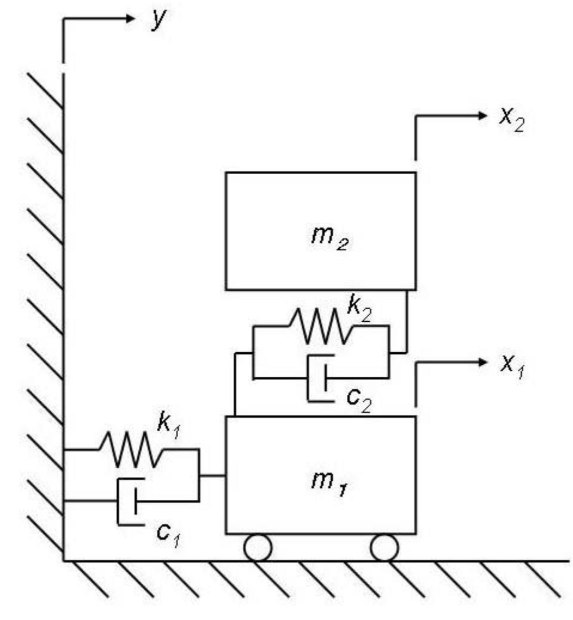

Figure 13 2DOF model for calculating a theoretical transfer function

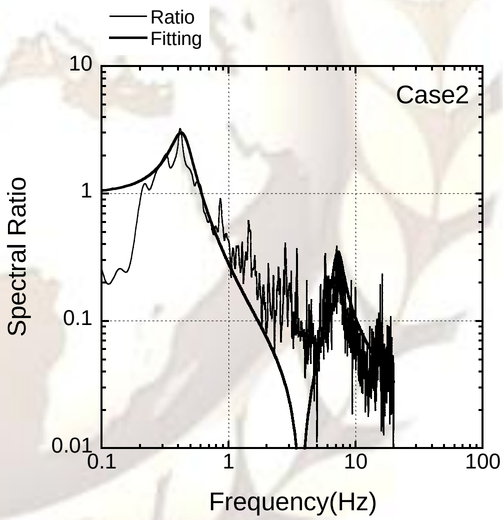

Figure 14 Comparison between the spectral ratio and the theoretical transfer function using 2DOF

Table 8 Natural frequency and damping ratio (input wave 3)

	Natural frequency f_o (Hz)		Damping ratio ζ	
	Base	Server	Base	Server
Case 1	0.90	2.42	0.14	0.002
Case 2	0.85	3.70	0.35	0.03
Case 3	0.81	3.72	1.50	0.03

sharp pulses on the response waveform were identified. However the response waveform shapes between them are almost same except the part of some sharp pulses. In case 2 and case 3, although the different of peak acceleration amplitude and RMS between by the excitation experiment and by the numerical analysis is less than 35 %, the response waveforms on the numerical analysis by the linear 2DOF approximately explain the response waveforms.

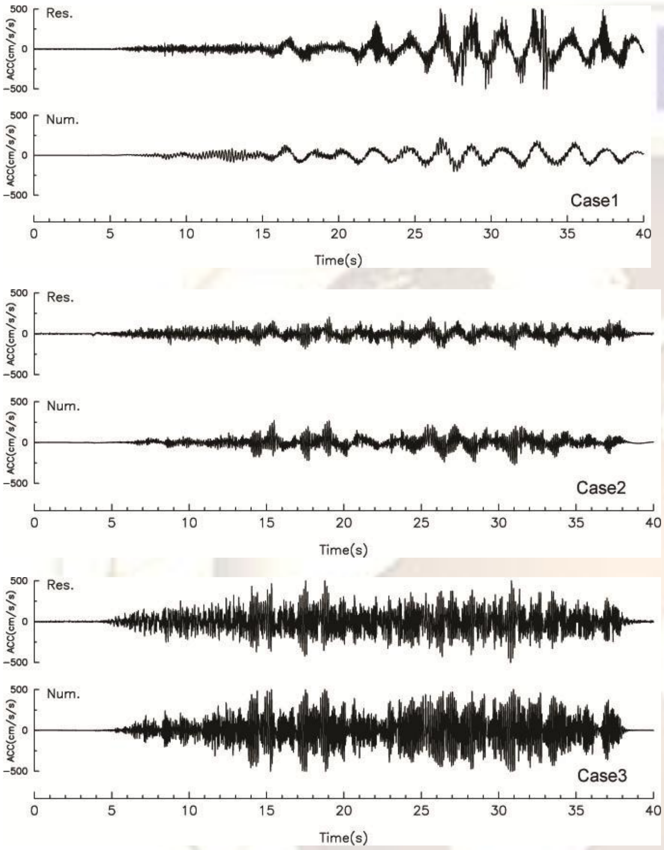

Figure 15 Comparison between response waveform and numerical analysis

Table 9 Comparison of peak amplitude of acceleration response wave (input wave 3)

	Peak amplitude of acceleration response wave	
	Experiment (cm/s^2)	Numerical (cm/s^2)
Case 1	836	221
Case 2	203	271
Case 3	574	521

Table 10 Comparison of RMS (input wave 3)

	RMS of acceleration response wave	
	Experiment (cm/s^2)	Numerical (cm/s^2)
Case 1	90.2	46.3
Case 2	40.4	50.4
Case 3	102.6	137.6

VII. CONCLUSION

We developed the new device that sandwiched the marble plate or the steel ball between two plates of spherical concave, and built the small base isolation system composed of this device. And vibration analysis of this system was investigated by excitation experiment using artificial seismic waves.

In excitation experiment using artificial seismic waves, peak acceleration amplitude on this system has decreased to 43 - 90 % compared to the input waves. Also RMS amplitude decreased to 76 - 94 %.

The spectral peak around the frequency of 0.5 Hz on the Fourier spectrum was identified when the input waves with low frequency band component were used, the peak on the spectral ratio in case using four sets of the steel ball type friction bearing was identified. Since this frequency band was equivalent to natural frequency of this system, it was generated by resonance. It was decreased using the friction bearings that generated high friction force. However the decreasing rate at the high frequency band gets worse.

Fitting the theoretical transfer function for the spectral ratio by a forwarding model, natural frequency was evaluated to f_0=0.81 – 0.90 Hz. And damping ratio in case of four sets of the steel ball type friction bearing (low friction) and in case of four sets of the marble plate type friction bearing (high friction) were 0.14 and 1.50, respectively.

Comparing the acceleration response waveforms between by excitation experiment and by numerical analysis, it is good agreement.

This system is effective for reduction of seismic response.

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