DYNAMIC BEHAVIOUR OF A MUSEUM BUILDING RETROFITTED USING BASE ISOLATION SYSTEM

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ABSTRACT :

The main building of the National Museum of Western Art (NMWA), Japan, is a historic building completed in 1959. To improve the seismic performance of the NMWA main building with preserving the artistic value, the base isolation system was adopted as a retrofitting method. The Building Research Institute (BRI) of Japan started strong motion observation targeted on the NMWA main building in 1999 in order to examine the performance of the base isolation system. The observation system has six tri-axial acceleration sensors in the building and on the ground. A number of valuable strong motion records have been accumulated since. Firstly, this paper introduces the strong motion observation system installed in the NMWA main building. Secondly, dynamic behaviour of the base isolated building is discussed by means of Fourier spectrum analyses for the strong motion record from an earthquake with the peak ground acceleration of about 0.1G. Finally, natural frequencies and damping ratios assuming a single-degree-of-freedom system are identified using 101 strong motion records. The dependence of natural frequencies upon displacements of the base isolation system can be clearly recognised through the analysis. Stable damping ratios that are independent of displacements of base isolation devices are also observed.

KEYWORDS: base isolation system, seismic retrofit, historic building, strong motion observation

1. INTRODUCTION

In Japan, base isolation technology has come into wide use since the Kobe Earthquake in 1995. As a method for seismic retrofitting of existing buildings, the base isolation system is often adopted as well. There is generally restriction on disposition of isolation devices in the seismic retrofitting, therefore it is important that performance of the base isolation system is being examined continuously.

The National Museum of Western Art (NMWA), Japan, is a museum that provides the public with opportunities to appreciate western art. The main building of the museum is a historically important building designed by the internationally renowned 20th century French architect Le Corbusier. To improve the seismic performance of the main building with preserving the artistic and historical value, the base isolation system was selected as a seismic retrofitting method. The retrofitting work was completed in 1998.

The Building Research Institute (BRI) of Japan has started strong motion observation targeted the NMWA main building in 1999, in order to examine the performance of the base isolation system. A number of valuable strong motion records have been accumulated since. Firstly, this paper introduces the strong motion observation system installed in the NMWA main building. Secondly, dynamic behaviour of the base isolated building is discussed by means of Fourier spectrum analyses for a strong motion record which has the largest peak ground acceleration of about 0.1G. Finally, first natural frequencies and damping ratios are identified for a lot of strong motion records by assuming a single-degree-of-freedom system. The features of identified natural frequencies and damping ratios are discussed with relations to maximum displacements of the system.

2. OUTLINE OF THE BUILDING

The National Museum of Western Art (NMWA) is a museum that provides the public with opportunities to appreciate western art, and is located in the Ueno Imperial Park, Tokyo, Japan. The main building of the museum is a historically important building designed by the internationally renowned 20th century French architect Le Corbusier (1887-1965). The building was completed in March 1959 as a symbol of the resumption of diplomatic ties between Japan and France after World War II. The main building is a reinforced concrete building with three floors above the ground and one floor below the ground. The site area is 1,587 square meters and the total floor area is 4,399 square meters.

To improve the seismic performance of the NMWA main building with preserving the artistic and historical value, the base isolation system was adopted as a seismic retrofitting method (Ooki, et al. 1998 and Hayashi et al. 1998). Forty-nine seismic isolators using high-damping rubber were installed between the basement floor of the existing superstructure and the newly constructed mat foundation. The retrofitting work was completed in 1998.

3. STRONG MOTION INSTRUMENTATION

The Building Research Institute (BRI) has installed strong motion instrument in the NMWA main building after the completion of the retrofitting work (Kashima el al. 2006). The recording system has six tri-axial acceleration sensors deploying in and around the building as shown in Figs. 1 and 2. Two sensors (BFW and BFE) are placed at the west and the east corners on the mat foundation. Other two sensors (1FW and 1FE) are fixed to the foundation of the superstructure (above the base isolation devices) at the corresponding corners. Another sensor (RF) is set up on a girder of the top floor and the last one (GL) is placed in the planting yard. Acceleration signals from all sensors are recorded on an IC memory card through the 24-bit digital processing system.

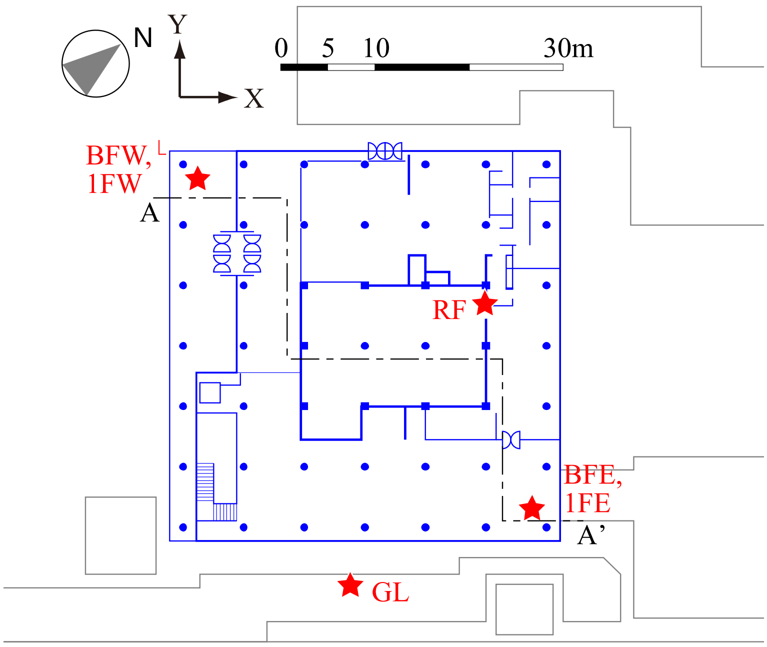


Figure 1 Sensor configuration in plan

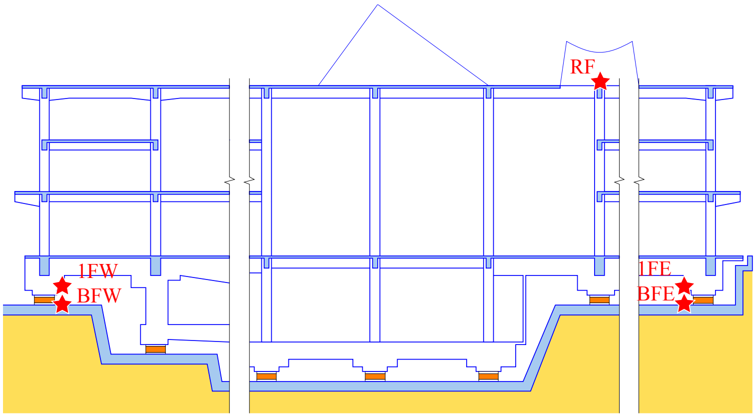


Figure 2 Sensor configuration in cross section (A-A')

4. STRONG MOTION RECORDS IN ANALYSIS

In this paper, 101 strong motion data recorded from 2000 to 2008 are treated. The epicentres of these earthquakes are plotted in Fig. 3. A circle indicates an epicentre and its size corresponds to the magnitude of an earthquake. The magnitudes were determined by the Japan Meteorological Agency (JMA) according to the JMA definition. The location of the NMWA station is also indicated by a solid star in Fig. 3. The magnitudes of the earthquakes range between 3.8 and 7.2, and epicentral distances vary from 13 km to 522 km. The peak ground accelerations (PGA) of those strong motion data are distributed between 0.052 m/s^2 and 0.942 m/s^2.

One strong motion data set which has the largest PGA of 0.942 m/s^2 is selected for the detailed analysis in the chapter 5. This strong motion data was recorded during an earthquake on February 16, 2005. The magnitude of the earthquake was 5.4 and the focal depth was 45 km. The epicentre of this earthquake was 37 km distant from the NMWA main building in the north direction as plotted by a solid circle in Fig. 3.

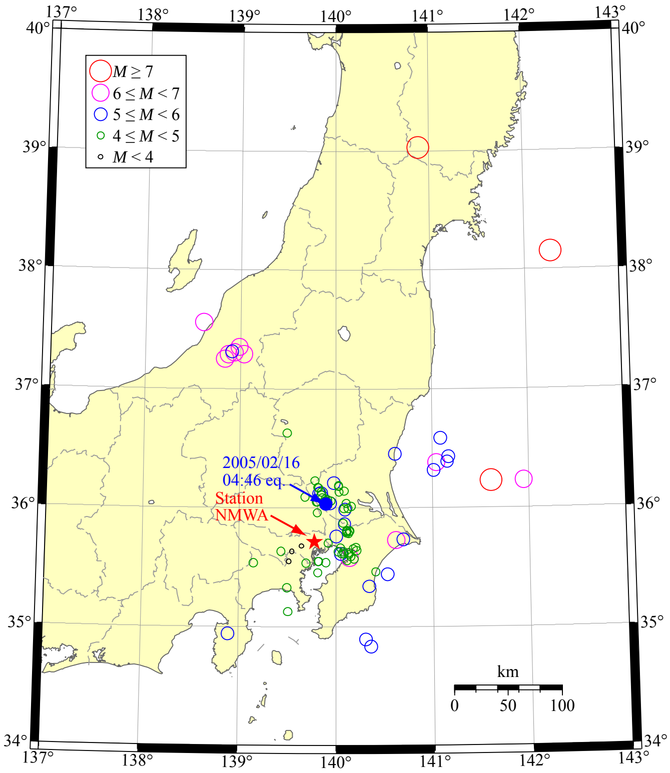


Figure 3 Location of the station NMWA and epicentres of analytical strong motion records

5. DYNAMIC CHARACTERISTICS OF THE BUILDING

Figure 4 shows acceleration waveform of each sensor in the X-direction for the earthquake of February 16, 2005. The top waveform is the acceleration on the ground (GL), the second one from the top is on the foundation mat (BF), and the third one and the bottom one are at the base and on the roof of the superstructure (1F and RF). Accelerations at BF and 1F are the mean values of the two sensors at the corresponding levels.

In comparison between the earthquake motion on the ground (GL) and the input motion at the foundation (BF), the peak acceleration decreases from 0.942 m/s^2 to 0.294 m/s^2. Remarkable reduction of high frequency components can be observed on the acceleration waveform at BF in Fig. 4. Looking at the difference between the accelerations at BF and at 1F, the peak value is reduced by 3/4 and additional low frequency components appear on the acceleration at 1F. Although the peak acceleration at RF is 1.5 times the value at 1F, the difference between both waveforms is small.

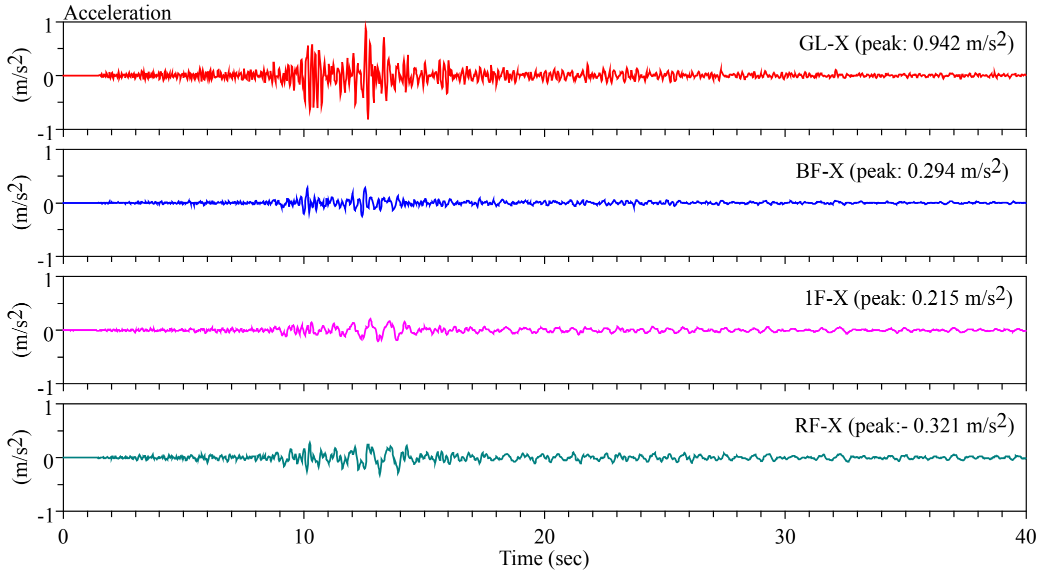


Figure 4 Acceleration records in X-direction in the earthquake on February 16, 2005

Figure 5 shows Fourier spectral ratios of accelerations at some pairs of places for the earthquake of February 16, 2005. In each graph, Fourier spectral ratios in three directions, X, Y and Z, are illustrated. Before calculating a spectral ratio, Fourier spectra are smoothed using the Parzen window with the width of 0.2 Hz.

Figure 5 (a) represents spectral ratios between accelerations at BF and at GL, indicating the input loss due to the soil-structure interaction. The spectral ratios in the horizontal directions (X and Y) are nearly 1.0 in the frequency range lower than 2 Hz, and falls to less than 0.5 in the frequency range higher than 4 Hz.

Figure 5 (b) indicates spectral ratios of accelerations at 1F to ones at BF and represents the characteristics of the seismic isolation devices that are installed in between. Low peaks can be found at frequencies between 1 Hz and 2 Hz on the spectral ratios in the horizontal directions. The horizontal spectral ratios show wavy shape having deep dips in the high frequency range. By contrast, the spectral ratio in the vertical direction is flat and its value is 1 in the frequency range lower than 8 Hz.

Figure 5 (c) shows spectral ratios between accelerations at RF and at 1F, indicating the response characteristics of the superstructure. The peaks corresponding to the first natural frequencies in the both horizontal directions appear at frequencies between 3 Hz and 4 Hz.

Figure 5 (d) indicates spectral ratios between accelerations at RF and at GL that represents overall characteristics of the building system including the soil-structure interaction and the base isolation system. Low peaks can be observed at frequencies of 1.16 Hz and 1.54 Hz in X- and Y-directions, respectively. These are the first natural frequencies of the overall systems in corresponding directions. In the frequency range higher than 4 Hz, spectral ratios in the horizontal directions are reduced by a half or less. This is caused by the input loss due to the kinematic soil-structure interaction and the embedment as shown in Fig. 5 (a). Looking at the spectral ratio in the vertical (Z) direction, there is no fluctuation in the frequency range lower than 4 Hz.

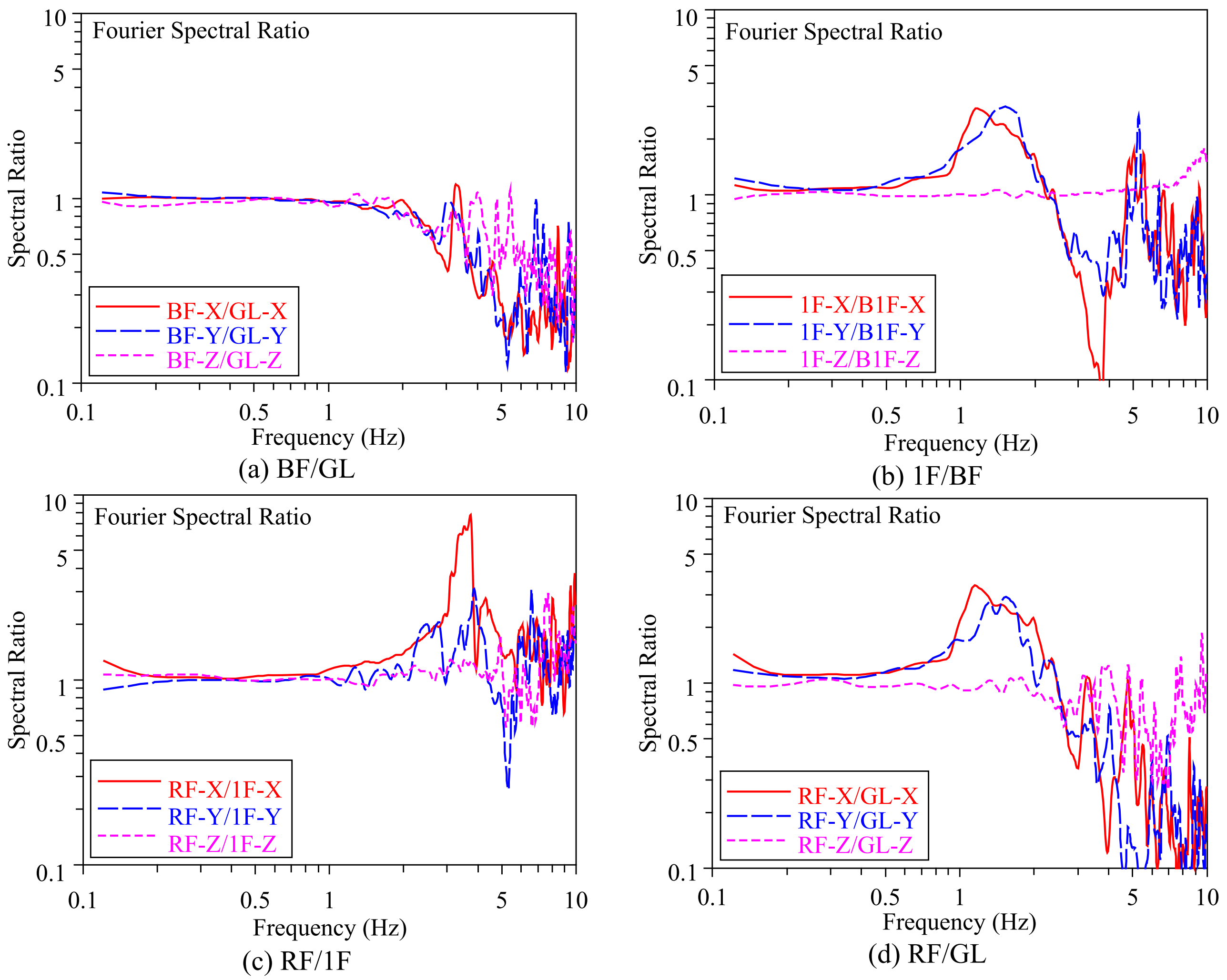
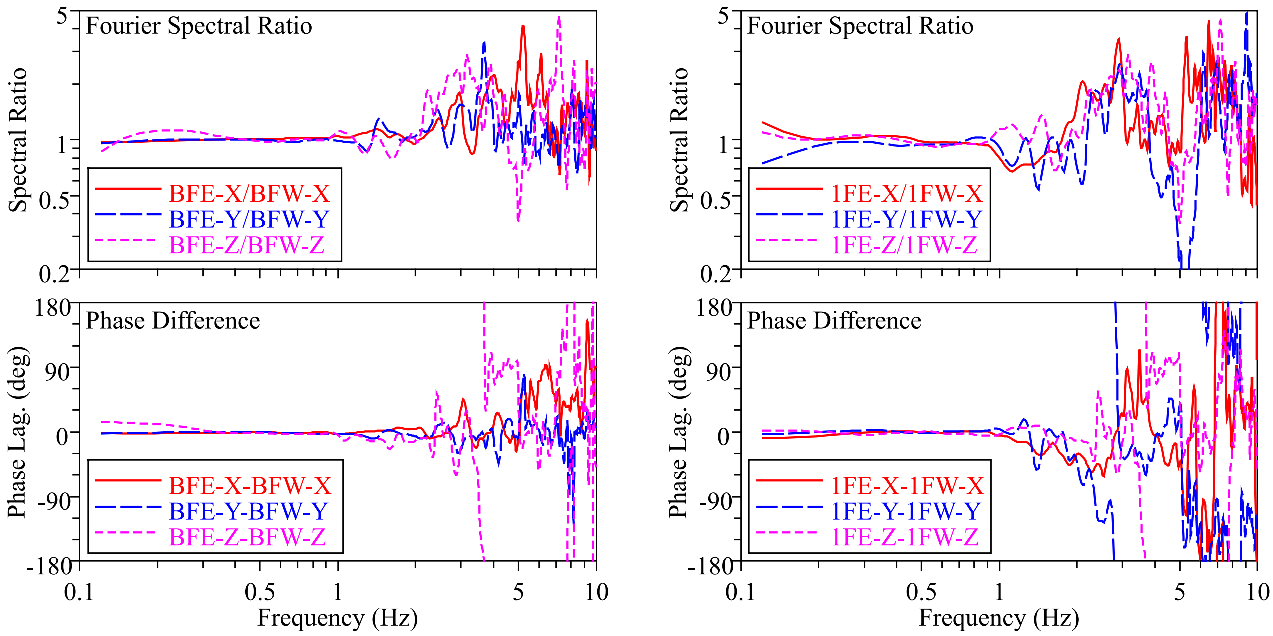


Figure 5 Fourier spectral ratios of RF/1F, 1F/BF, RF/1F and RF/GL for the earthquake on Feb. 16, 2005

To examine torsional movement of the structure, acceleration records in two corners at BF and at 1F are compared. Fourier spectral ratios and phase differences between accelerations at BFW and BFE are shown in Fig. 6 (a). A solid line, a dashed line and a dotted line indicate values in the X-, Y- and Z-directions, respectively. In the lower frequency range up to 2 Hz, the spectral ratios are nearly 1.0 and no differences are recognized in phase in every direction. Although some differences in spectral ratios appear in the frequency range higher than 3 Hz, it can be pointed out that torsional movement is little in the input motion.

Fourier spectral ratios and phase differences between acceleration records at 1FW and at 1FE are shown in Fig. 6 (b). Reversals of the phase appear at the frequency of 3 Hz and the spectral ratios rise at the same frequency. It can be interpreted that torsional motion predominates at the frequency of 3 Hz.



(a) BFE/BFW (b) 1FE/1FW

Figure 6 Fourier spectral ratios and phase differences of BFE/BFW and 1FE/1FW for the earthquake on Feb. 16, 2005

6. GENERAL FEATURE OF BASE ISOLATION SYSTEM

In order to discuss general features of dynamic characteristics of the base isolation system, the fundamental natural frequency f and damping ratio h of the overall system for each earthquake record are identified. For the system identification, two independent single-degree-of-freedom systems are assumed, one each for the X-direction and the Y-direction as shown in Fig.7. Acceleration records at GL and RF are used as the input and the response (output) of the system.

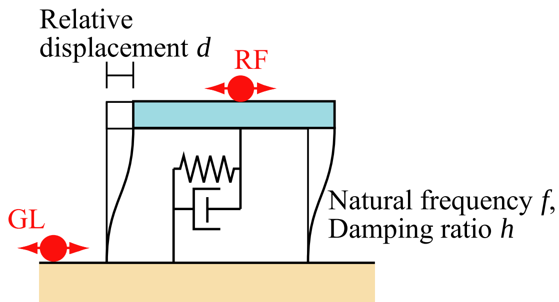


Figure 7 SDOF model

The identification is made by searching the best fitted f and h using the steepest descent algorithm (e.g. Michalewicz and Fogel 1999). The fitness is represented by the function $F(f,h)$ defined in Eqn. 6.1.

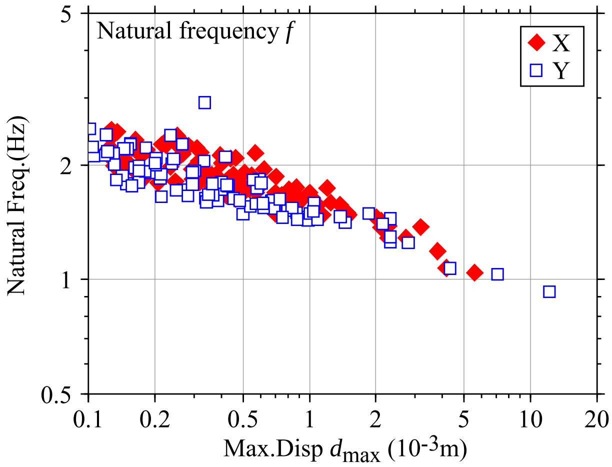
$$F(f,h) = \int_{T_F} (d_S(t) - d_O(t))^2 \, dt \qquad (6.1)$$

where $d_S(t)$ is the simulated relative displacement for certain f and h, and $d_O(t)$ is the observed relative displacement. T_F is the time span to be fitted and is normally set to 20 seconds by taking the respective 10 seconds on both sides of the peak time of $d_O(t)$. $d_O(t)$ was calculated from the absolute displacements of the two sensors (RF and GL in Fig. 7), which are calculated by integrating the accelerations using the Fast Fourier

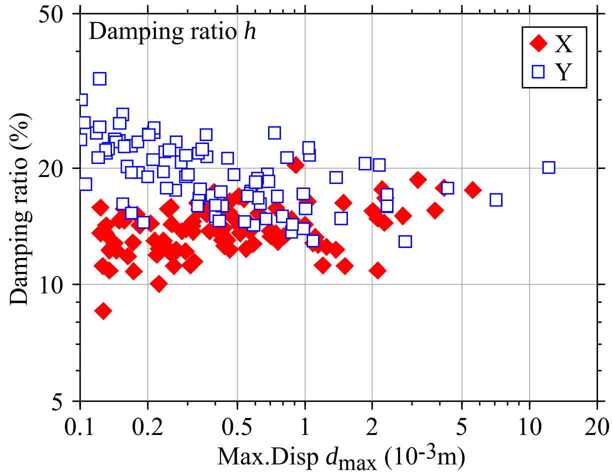
Transformation (FFT) technique.

The relation between fundamental natural frequencies f and maximum relative displacements d_{max} identified from the 101 strong motion records is shown in Fig. 8 (a). Solid diamonds and hollow squares indicate the values in the X- and Y-directions, respectively. The dependence of the natural frequency on the amplitude of the relative displacement clearly appears on the graph. The natural frequencies are decreasing with the increase of the maximum relative displacement, and fall to 1 Hz in d_{max} of 10 mm. Differences between the values in the X- and the Y-directions are little.

The relation between identified damping ratios h and d_{max} is shown in Fig. 8 (b). In contrast to the natural frequencies, the amplitude-dependence on the damping ratios is small. It can be pointed out that the base isolation system shows large damping effect even in the small displacement range. It can be attributed to the property of the high-damping rubber bearings. In addition, certain differences of damping ratios between in the X- and the Y-directions appear in the small displacement range. Further discussion is necessary on this.



(a) Natural frequencies



(b) Damping ratios

Figure 8 Identified natural frequencies and damping ratios

7. CONCLUSIONS

Building Research Institute is conducting the strong motion observation targeted on a historic museum building that has been retrofitted using a base isolation system. The observation system has six tri-axial acceleration sensors in and around the building. A number of strong motion records have been accumulated since the retrofitting work was completed in 1999.

According to the Fourier spectrum analysis using a strong motion record having the largest PGA of 0.942 m/s^2, the first natural frequencies of the overall systems in the X- and Y-directions were found at 1.16 Hz and 1.54 Hz, respectively. In addition, the reduction in seismic input motion appeared in the frequency range higher than 4 Hz. It resulted from the effect of the base isolation system and the influence of the soil-structure interaction. Looking at the Fourier spectral ratios between two records in the opposite corners at the basement of the superstructure, torsional movement was found at the frequency around 3 Hz.

Dynamic characteristics of the base isolated building were discussed through the system identification for 101 strong motion records. The dependence of the natural frequency upon the amplitude of the relative displacement was clearly observed. The natural frequencies in the X- and Y-directions ranged around 2 Hz for the records with relative displacements less than 0.5 mm, and fell to 1 Hz for the records with ones around 10 mm.

According to our study in this paper, it can be pointed out the base isolation system has been performing as well as expected in the structural design. It is hoped that the outcome of our study be of some contribution to ensure the seismic safety of the building.

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