A STUDY ON IMPROVEMENT OF THREE-DIMENSIONAL SEISMIC ANALYSIS METHOD OF NUCLEAR BUILDING USING A LARGE-SCALE OBSERVATION SYSTEM (PART1: ANALYSIS OF ENTIRE RESPONSE OF THE REACTOR BUILDING BASED ON SEISMIC OBSEVATION RECORDS)

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ABSTRACT

Our research and development are aimed at improving the accuracy of the three-dimensional seismic analysis of nuclear buildings to better understand their three-dimensional seismic behaviour in response to enhanced impact assessment for external events such as earthquakes. In 2019, we began this research using actual seismic observation records in collaboration with the Nuclear Regulation Authority (NRA) and the Japan Atomic Energy Agency (JAEA). In this study, we constructed a large-scale observation system at the High Temperature Engineering Test Reactor (HTTR) of the JAEA that enabled simultaneous measurements at multiple positions during earthquakes or when using artificial waves. The accelerometers of the observation system were installed not only on/in the soil and on the floors, but also on the walls of the HTTR. In Part 1 of the series papers, we report the analysis results of the dominant frequency and vibration mode of the HTTR building using the seismic observation records obtained from this observation system.

INTRODUCTION

In Japan, the new regulatory requirements for commercial power reactors came into force on July 8, 2013. To perform a more accurate seismic evaluation against the requirements, it is necessary to evaluate the input seismic motion to the structures, systems, and components considering the local response of the reactor building. Therefore, in recent years, it is expected that three-dimensional finite element models that can evaluate the response of nuclear buildings, including the local responses of floors and walls will be applied more widely.

To validate the three-dimensional analysis method, it is important to confirm the consistency of the analytical results with the observation records. For this purpose, it is necessary to obtain seismic observation records from accelerometers installed in nuclear buildings and analyse the vibration characteristics. In a previous study, Shiomi et al. (2008) analysed seismic observation records from the Niigata Chuetsu-oki Earthquake in 2007 and examined the vibration characteristics of the Kashiwazaki-Kariwa Nuclear Power Plant. Also, Hijikata et al. (2010) conducted a simulation analysis of Unit 5 of the Kashiwazaki-Kariwa Nuclear Power Plant using the obtained observation records. In addition, many researchers conducted benchmark analyses comparing the results of seismic response analyses using a three-dimensional finite element model of the reactor building with seismic observation records at the Kashiwazaki-Kariwa Nuclear

Power Plant in the Kashiwazaki-Kariwa Research Initiative for Seismic Margin Assessment (KARISMA) reported (IAEA (2013)). However, there were few accelerometers installed at the plants. Therefore, it was difficult to grasp the detailed entire response of the reactor building from the seismic observation records.

In this study, a large-scale observation system was constructed for the HTTR building at the Oarai Research Institute of the JAEA, in which many accelerometers were installed to enable more detailed measurement of observation records. This system can observe both the earthquakes and artificial waves and work on the improvement of the three-dimensional seismic analysis method of buildings. We report on this research in a series of three papers, Part 1 to Part 3. To improve the three-dimensional seismic analysis method, it is important to understand the actual three-dimensional vibration behaviour of buildings. Therefore, analyses of vibration characteristics of the building using seismic observation records and artificial waves were performed for understanding the three-dimensional vibration behaviour of the building. The obtained knowledge through these analyses is shown in Parts 1 and 2, respectively. In addition, a three-dimensional finite element model was created for the HTTR building, and the vibration characteristics of the building were analysed. The analysis results using a three-dimensional finite element model were compared with the seismic observation results for validation of the three-dimensional seismic analysis method and the results are shown in Part 3.

In this paper, as Part 1 of the series papers, we describe an overview of the HTTR building and the large-scale observation system. Next, we calculate the Fourier amplitude ratios from the obtained seismic observation records and present the dominant frequencies of the HTTR building selected from the Fourier amplitude ratios. The results of the study using the 2020 earthquake observation records have been reported by Nishida et al. (2022 and 2023). In this paper, we added the results from analyses using the records from 2021 to 2022. Finally, we obtain the vibration modes for each of the dominant frequencies and discuss the vibration characteristics at each frequency.

OBSERVATION SYSTEM OVERVIEW

Outline of the HTTR Building

The HTTR building is a reinforced concrete structure (partly steel reinforced concrete or steel structure) with a steel-framed flat roof. The plan size of the building is 52.0 m (NS) x 50.0 m (EW), which is almost a square, and it has three basement floors and two floors above the ground. The foundation slab is a solid foundation with a thickness of 5.0 m. Figure 1 shows the overview of the HTTR building.

Location of Accelerometers

An overview diagram of the large-scale observation system installed in the HTTR building is shown in Figure 2 (Nishida et al. (2022)). Including mobile accelerometers, 21 accelerometers were added to the system to enable simultaneous observation at multiple locations. In addition, a vibration generator was installed to enable vibration measurements using artificial waves. The locations of the accelerometers are shown in Figures 3 and 4 (Nishida et al. (2023)). Four accelerometers per floor are installed along the east, west, south, and north exterior walls of the HTTR building on the third basement, first, second, third and rooftop floors. One accelerometer (UT05) is located on the first basement floor along the south exterior wall. Additionally, two accelerometers are installed inside the containment vessel (UT09 and UT10). The accelerometers E3 and E2 on the second and third floors on the east side and W2 on the third floor on the west side are installed for the purpose of measuring the local response of the wall.

Seismic Observation Records Used for Analysis

In this study, eight records in which the maximum acceleration of UT07 on the first floor of the south side was large from 2021 to 2022 were selected and analysed. Table 1 shows the specifications of these earthquakes.

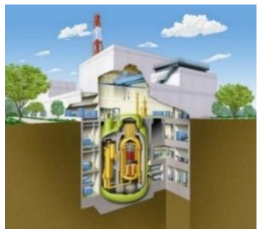


Figure 1. Overview of HTTR

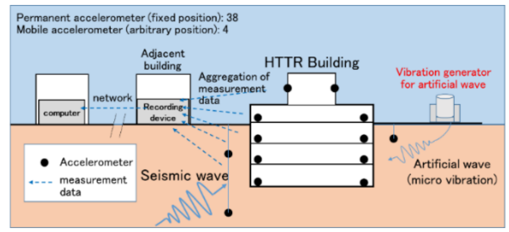


Figure 2. Overview of the large-scale observation system (Nishida et al. (2022))

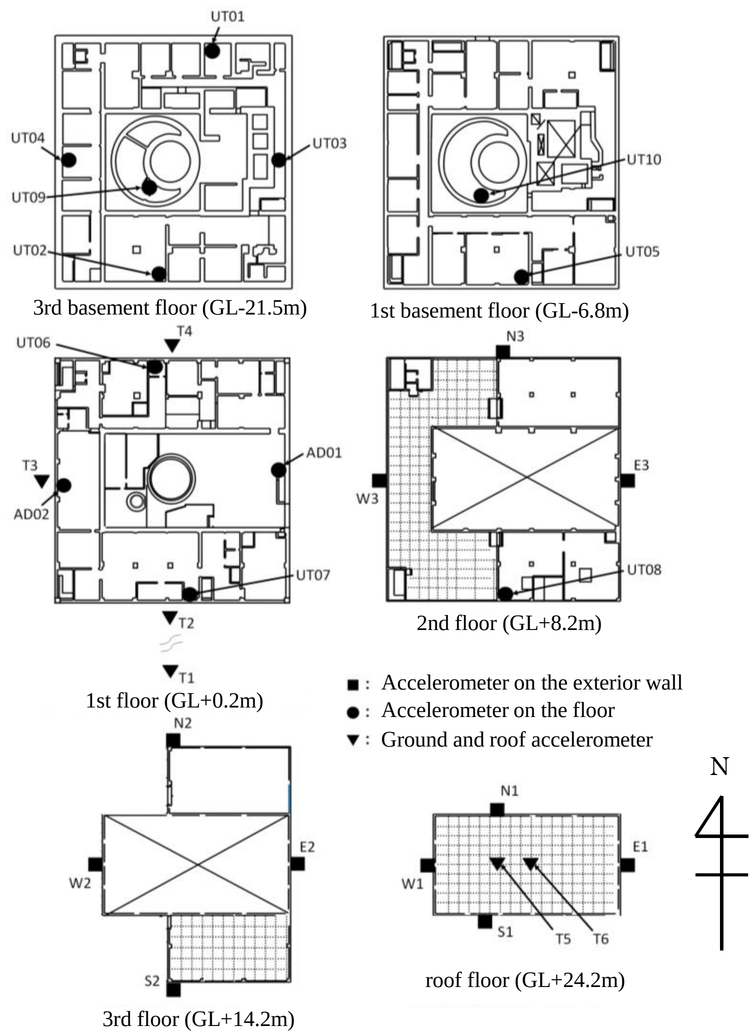


Figure 3. Locations of accelerometers (top view) (Nishida et al. (2023))

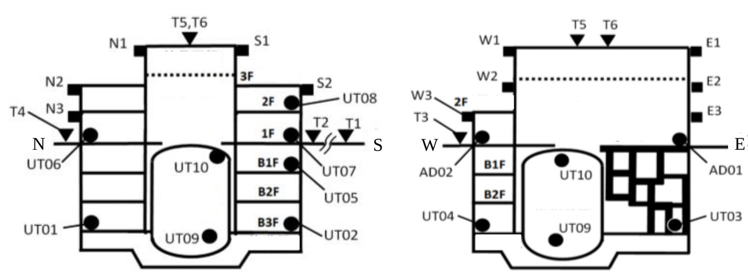


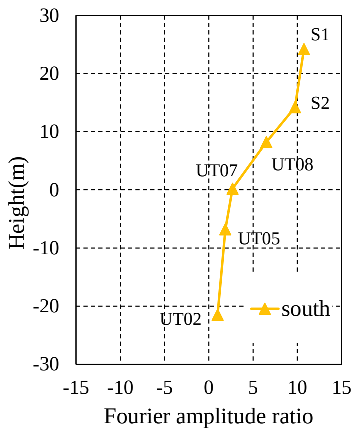
Figure 4. Locations of accelerometers (cross-section) (Nishida et al. (2023))

Table 1: The target seismic observation records

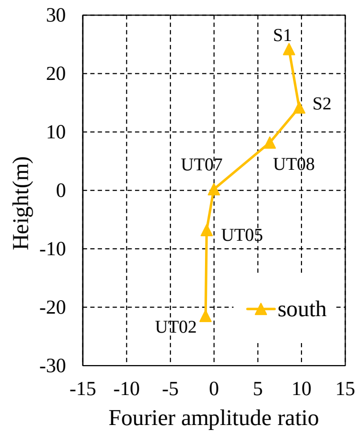
Observation records information		Focal depth (km)	Magnitude	Max acceleration (UT07) (Gal)		
Date	Epicenter			NS	EW	UD
March 20, 2021	Offshore Miyagi Prefecture	59	6.9	17.0	13.2	8.9
May 1, 2021	Offshore Miyagi Prefecture	51	6.8	8.9	6.4	6.5
November 1, 2021	Northern Ibaraki Prefecture	57	5.3	37.3	27.7	15.1
December 2, 2021	Southern Ibaraki Prefecture	65	5.1	5.0	5.0	5.5
March 16, 2022	Offshore Fukushima Prefecture	57	7.4	59.4	43.2	45.3
April 2, 2022	Northern Ibaraki Prefecture	56	4.4	13.4	5.4	8.1
May 29, 2022	Offshore Ibaraki Prefecture	44	5.3	40.5	24.5	14.6
November 9, 2022	Southern Ibaraki Prefecture	48	4.9	15.3	10.0	5.4

Analysis method

First, we calculated the ratio of the Fourier amplitude of the building's upper part to that of the building's foundation from seismic observation records and analysed the vibration modes for the dominant frequencies obtained. Vibration modes are determined by considering both amplitude and phase. When only the amplitude is obtained from the Fourier amplitude ratio, the resulting vibration mode is depicted in Figure 5(a), which may not be suitable for studying the shape of building deformations. Therefore, the phase difference is considered, revealing second- and third-order mode shapes at high frequencies, as illustrated in Figure 5(b). In this study, Figure 5(b) displays the vibration modes at the dominant frequencies.



(a) Consider only amplitude ratio



(b) Consider amplitude ratio and phase difference

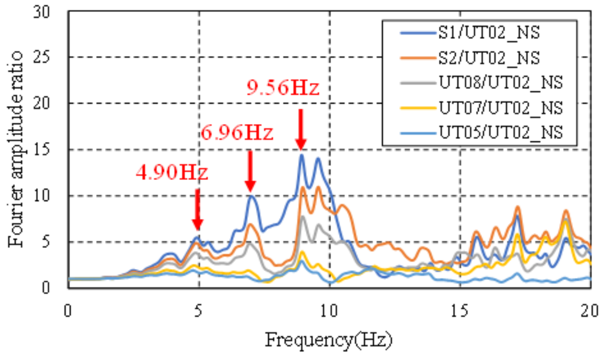
Figure 5. Difference in mode diagram (March 16, 2022, NS direction, Around 9 Hz)

ANALYSIS RESULTS

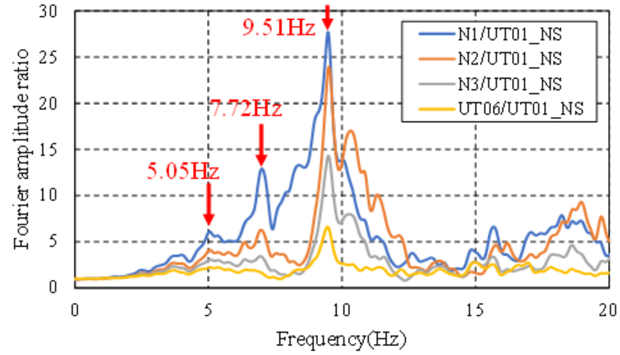
Determination of Dominant Frequency

We calculated Fourier amplitude ratios for the third basement floor for each of the east, west, south, and north exterior walls. In this paper, we present the results obtained from two earthquakes (March 20, 2021 and March 16, 2022) with large magnitudes.

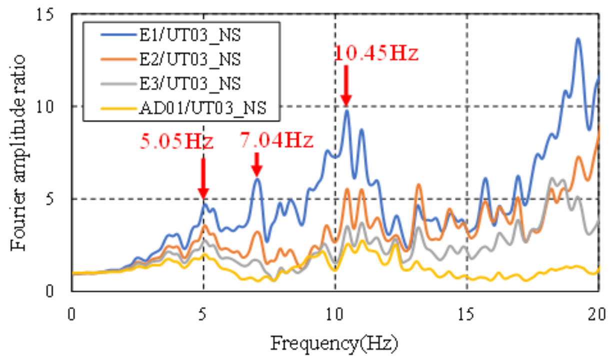
Figures 6-9 show the Fourier amplitude ratios obtained from the observation records mentioned above. They are smoothed with a Parzen Window (bandwidth = 0.4 Hz). The north and south walls are out-of-plane in the NS direction and in-plane in the EW direction. The east and west walls are in-plane for the NS direction and out-of-plane for the EW direction. In this study, we conducted an analysis using records from accelerometers installed to measure the entire response of the HTTR building.



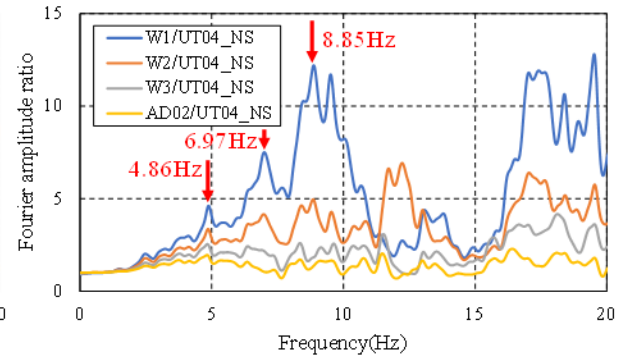
(a) South wall (out-of-plane)



(b) North wall (out-of-plane)

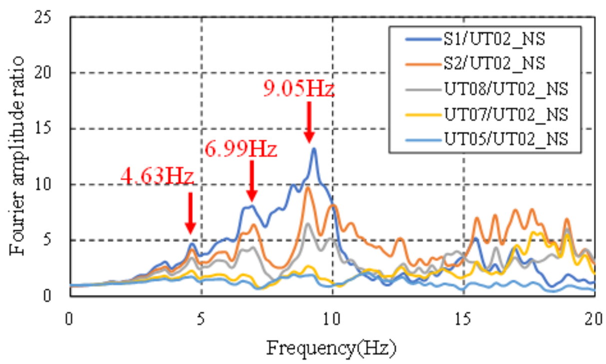


(c) East wall (in-plane)

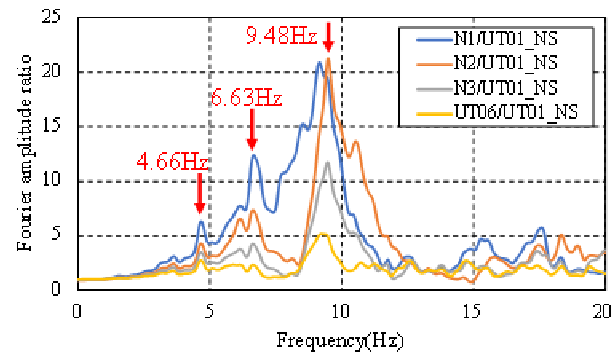


(d) West wall (in-plane)

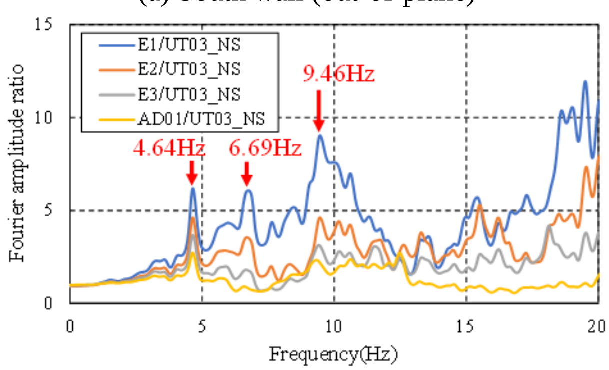
Figure 6. Fourier amplitude ratio (March 20, 2021, NS direction)



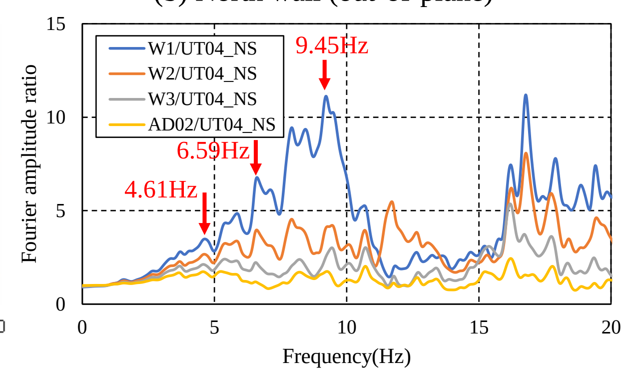
(a) South wall (out-of-plane)



(b) North wall (out-of-plane)

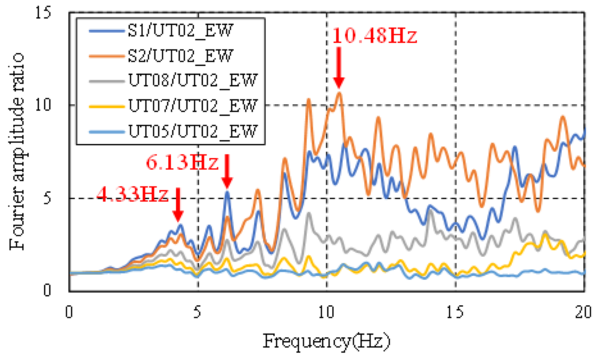


(c) East wall (in-plane)

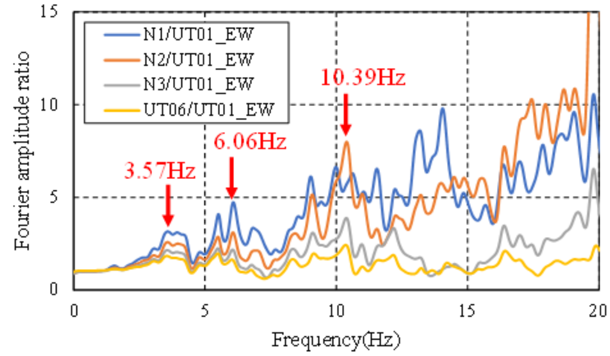


(d) West wall (in-plane)

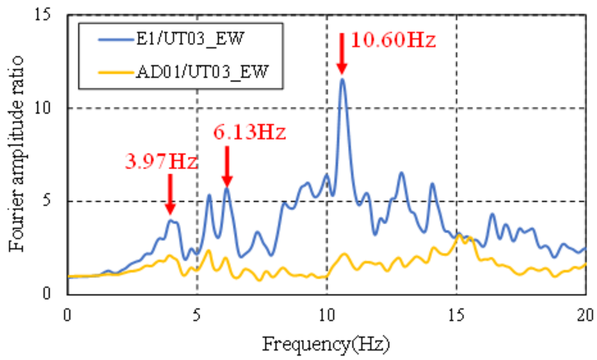
Figure 7. Fourier amplitude ratio (March 16, 2022, NS direction)



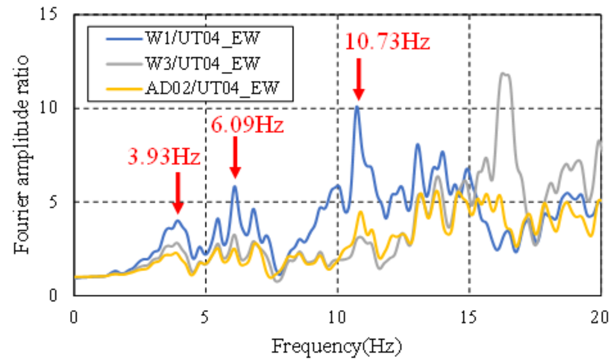
(a) South wall (in-plane)



(b) North wall (in-plane)

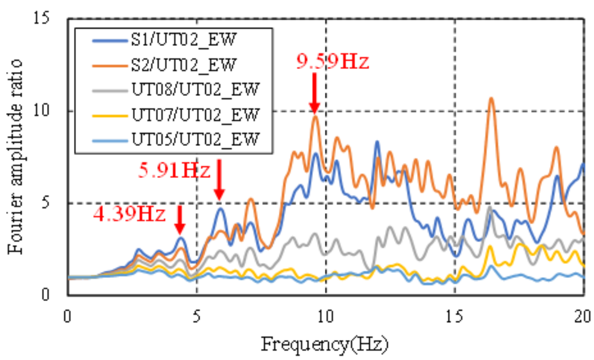


(c) East wall (out-of-plane)

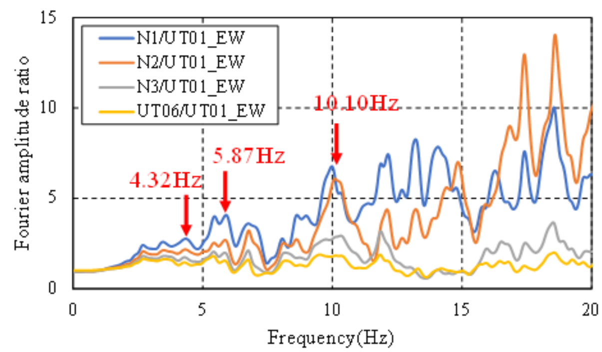


(d) West wall (out-of-plane)

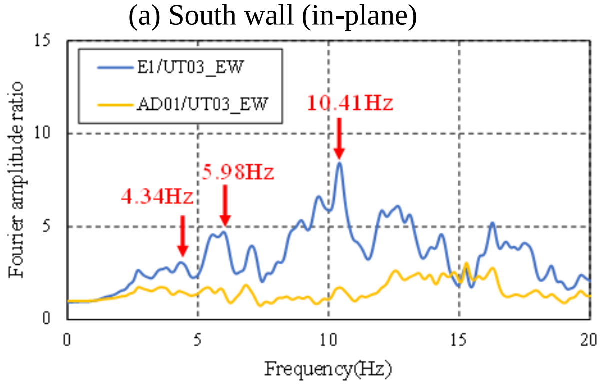
Figure 8. Fourier amplitude ratio (March 20, 2021, EW direction)



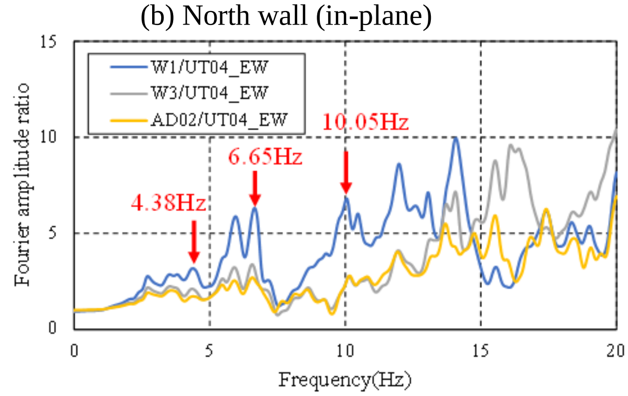
(a) South wall (in-plane)



(b) North wall (in-plane)



(c) East wall (out-of-plane)



(d) West wall (out-of-plane)

Figure 9. Fourier amplitude ratio (March 16, 2022, EW direction)

From Figures 6 and 7, three relatively clear peaks are observed in the Fourier amplitude ratio in the NS direction. Although the values are slightly different for east, west, south, and north, the frequencies around 4 Hz, 7 Hz, and 9 Hz were selected as the dominant frequencies. Table 2 lists the selected dominant frequencies in the NS direction.

Figures 8 and 9 show that the Fourier amplitude ratio in the EW direction has some minor peaks compared to the NS direction, but the overall trend is the same as in the NS direction, with amplitude ratio peaks around 4 Hz, 6 Hz, and 10 Hz. Table 3 lists the selected dominant frequencies in the EW direction.

From the above, it was found that the overall tendency of the Fourier amplitude ratio was different between the NS direction and the EW direction, and the dominant frequency also had slightly different values depending on each exterior wall. It seems that the vibration of each exterior wall influences the vibration of the other exterior walls. It is necessary to discuss causes of complicated phenomena of the building vibration.

Table 2: Dominant frequencies (NS direction)

	Dominant frequency (Hz)		
	Around 4Hz	Around 7Hz	Around 9Hz
South	4.90	6.96	9.56
North	5.05	6.96	9.51
East	5.05	7.04	10.45
West	4.86	6.97	8.85

(a) Earthquake on March 20, 2021

	Dominant frequency (Hz)		
	Around 4Hz	Around 7Hz	Around 9Hz
South	4.63	6.99	9.05
North	4.66	6.63	9.48
East	4.64	6.69	9.46
West	4.61	6.59	9.45

(b) Earthquake on March 16, 2022

Table 3: Dominant frequencies (EW direction)

	Dominant frequency (Hz)		
	Around 4Hz	Around 6Hz	Around 10Hz
South	4.33	6.13	10.48
North	3.57	6.06	10.39
East	3.97	6.13	10.60
West	3.93	6.09	10.73

(a) Earthquake on March 20, 2021

	Dominant frequency (Hz)		
	Around 4Hz	Around 6Hz	Around 10Hz
South	4.39	5.91	9.59
North	4.32	5.87	10.10
East	4.34	5.98	10.41
West	4.38	6.65	10.05

(b) Earthquake on March 16, 2022

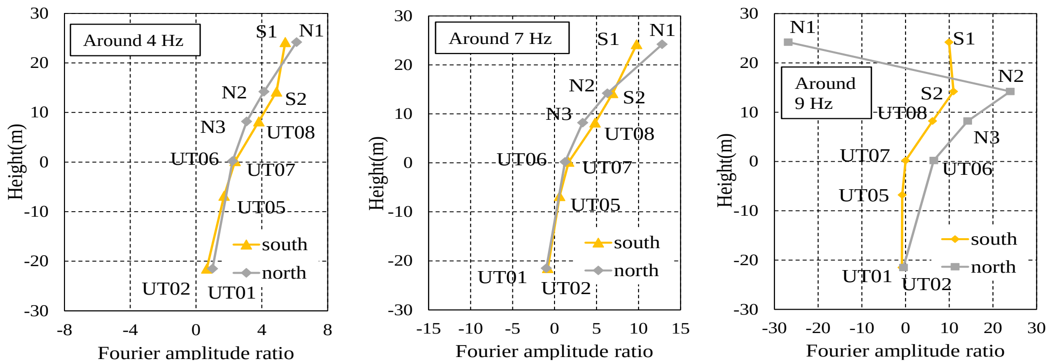
Vibration Mode

We obtained the vibration modes at the dominant frequencies in Tables 2 and 3. Vibration mode diagrams for the March 20, 2021 and March 16, 2022 earthquake records are shown in Figures 10-13. When the dominant frequencies were approximately equal, the vibration modes were almost similar regardless of the seismic observation records.

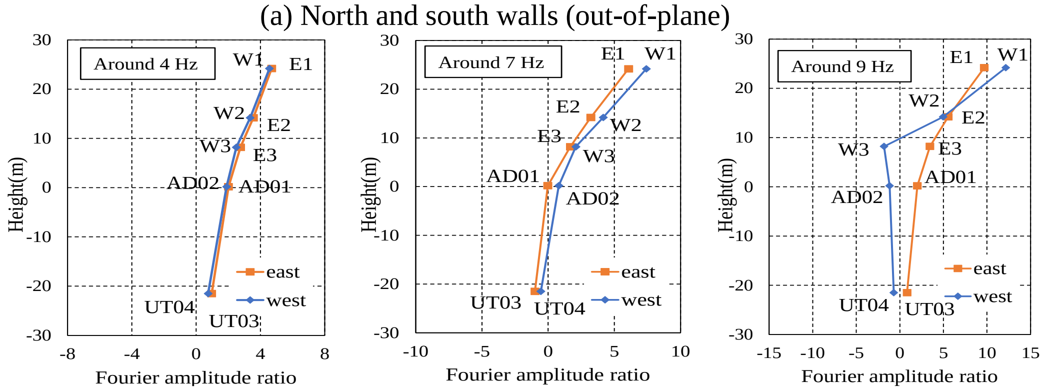
At frequencies around 4 Hz, deformation is almost uniform from the third basement floor to the rooftop floor. This is because the HTTR building is vibrating due to rocking, which is a rigid body rotation of the foundation of the building, around 4 Hz.

At frequencies around 6-7 Hz, the deformation of the ground floor is large than that of the basement floor. The amplitude ratio is larger on the rooftop floor, and all floors vibrate in the same direction. These characteristics suggest that the superstructure of the HTTR building is vibrating in first-order mode at around 6-7 Hz.

At frequencies around 9-10 Hz, the trends differed between the out-of-plane and in-plane directions. In the NS direction, the third floor and the rooftop floor vibrated in a reversed-phase in the north and south walls, which are in the out-of-plane direction. However, the east and west walls, which are in-plane direction, no phase difference was observed as for the north and south walls. For the west walls, the in-plane deformation above the second floor was significant. This is presumably because the west walls have less stiffness than the west walls above the second floor. In the EW direction, the north and south walls are in-plane direction, but the features of the mode diagram were common to the NS direction. For the east and

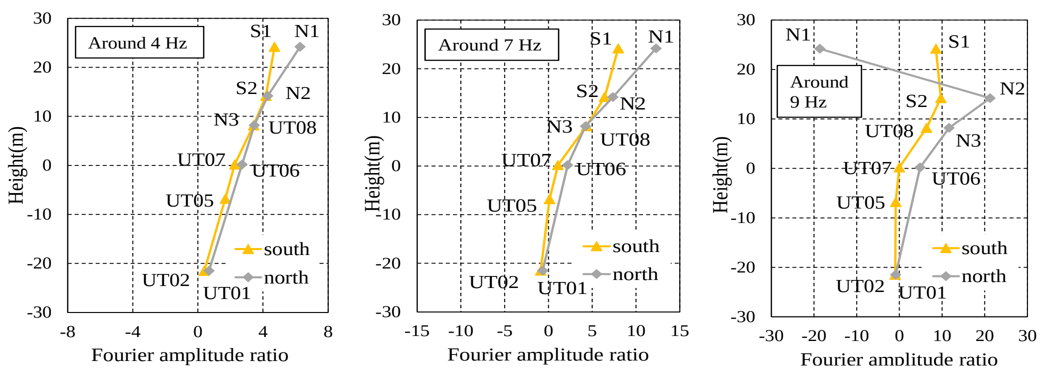


(a) North and south walls (out-of-plane)

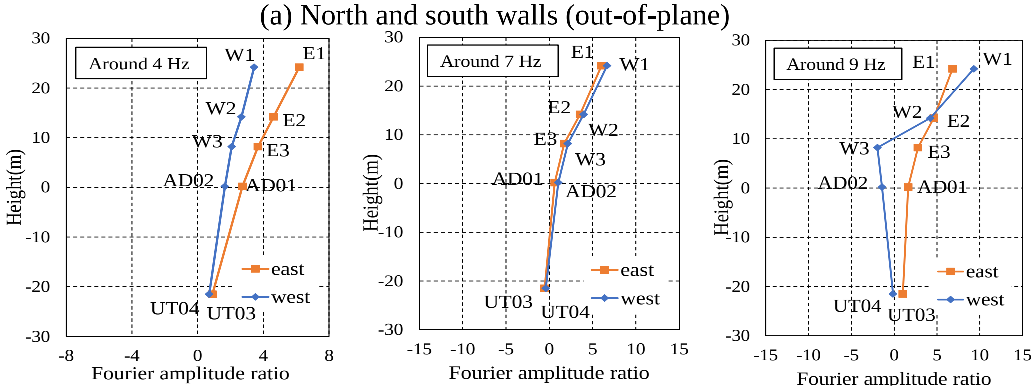


(b) East and west walls (in-plane)

Figure 10. Mode diagram (March 20, 2021, NS direction)

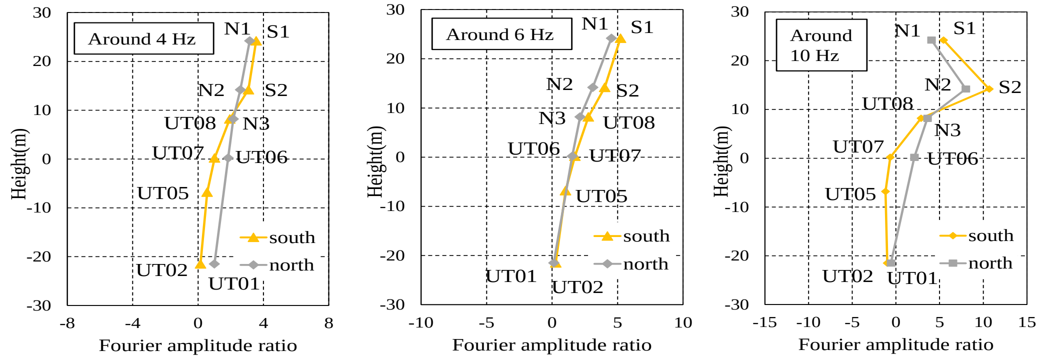


(a) North and south walls (out-of-plane)

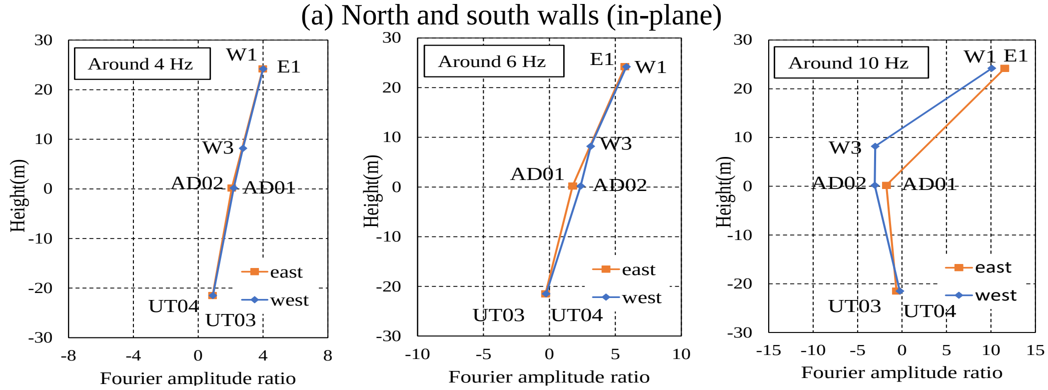


(b) East and west walls (in-plane)

Figure 11. Mode diagram (March 16, 2022, NS direction)

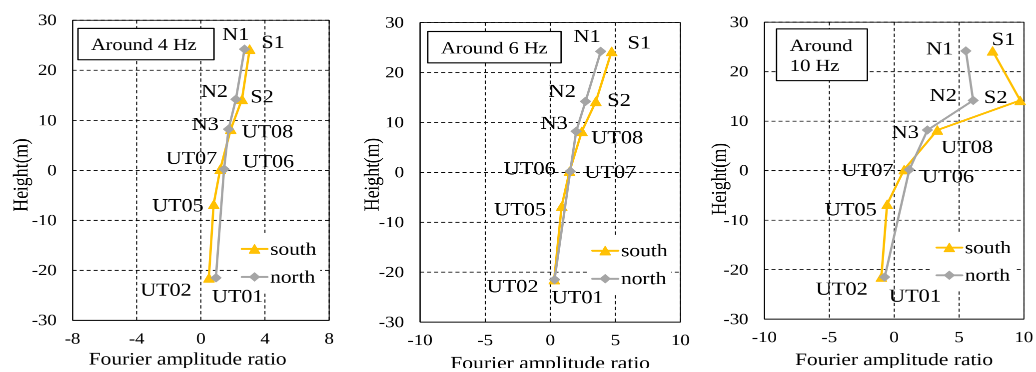


(a) North and south walls (in-plane)

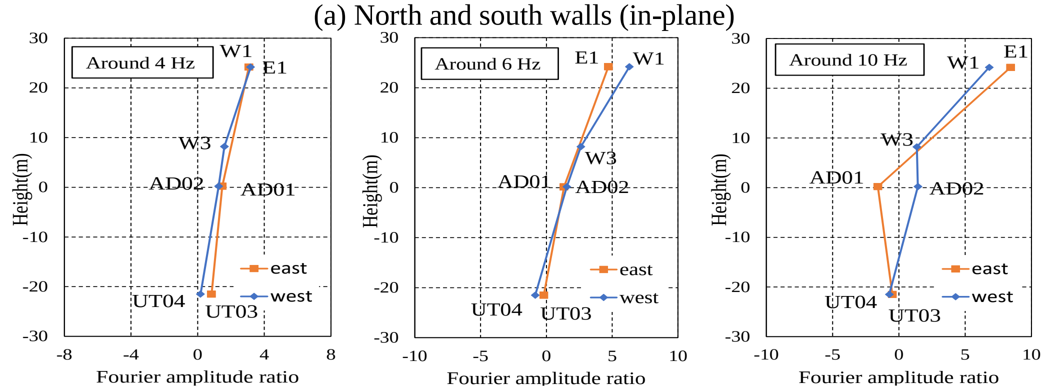


(b) East and west walls (out-of-plane)

Figure 12. Mode diagram (March 20, 2021, EW direction)



(a) North and south walls (in-plane)



(b) East and west walls (out-of-plane)

Figure 13. Mode diagram (March 16, 2022, EW direction)

west walls, which are in the out-of-plane direction, the overall trends were rocking at around 4 Hz, first-order building deformation mode at around 6-7 Hz, and second-order building deformation mode around 9-10 Hz.

CONCLUSION

In order to clarify the detailed vibration characteristics of the HTTR building, the dominant frequencies were selected by the transfer function based on the seismic observation records. In addition, vibration modes were obtained for each dominant frequency, and vibration characteristics at each frequency were analysed. The results are summarized as follows.

1) The dominant frequencies were determined based on the Fourier amplitude ratios for the third basement floor. For all exterior walls, the amplitude ratio peaked at around 4 Hz, 7 Hz, and 9 Hz in the NS direction and at around 4 Hz, 6Hz, and 10 Hz in the EW direction.
   The overall tendency of the Fourier amplitude ratio is different between the NS direction and the EW direction. In the NS direction, the peaks are relatively clear, whereas in the EW direction, many small amplitude ratio peaks can be seen.
2) Vibrations due to rocking at around 4 Hz and first-order building deformation mode at around 6-7 Hz were considered to have occurred. Vibration modes at these frequencies did not differ depending on the out-of-plane or in-plane direction for the two earthquakes used in this study. On the other hand, vibration modes were different in out-of-plane and in-plane directions at around 9-10 Hz.

In this study, the frequencies at which the Fourier amplitude ratio peaks in the NS and EW directions were determined as the dominant frequency, and the vibration modes of the HTTR building at those frequencies were obtained. On the other hand, it has not been able to investigate the cause of the slight difference in the dominant frequencies for each exterior wall. Furthermore, it remains a challenge to clarify the deformation of the exterior walls in the north, south, east, and west at the same time. Further studies are required to understand the three-dimensional vibration characteristics of nuclear buildings.

ACKNOWLEDGMENTS

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