Snow Load Effect to Vibration Characteristics of Japanese Traditional Wooden Main Temple Building and Three-Story Pagoda Based on Ambient Vibration and Earthquake Observation Records

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Abstract. Snow load effect to vibration characteristics of Japanese traditional wooden main temple building and three-story pagoda of "Jion-ji", Japan is studied using ambient vibration measurement and earthquake observation data. The 1st natural frequency of the main temple building ranged from 1.07 to 1.73 Hz in EW and 0.98 to 1.88 Hz in NS. The 1st natural frequency of the pagoda ranged from 1.23 to 1.66 Hz in EW and 1.20 to 1.49 Hz in NS. As a result, vibration characteristics of those heritage structures were affected by snow load distribution on the roof and amplitude of earthquake. In winter, thickly accumulated snow leads to the additional load, having caused the significant change of the vibration characteristics of the structure. The snow load on the natural frequency was as effective as small earthquakes. Large amplitude of strong earthquake is more effective to vibration characteristics of those buildings and decrease the natural frequency. From an earthquake engineering point of view, the equivalent mass of the structure with the snow load in winter was 1.9 times as heavy as that in summer, which indicated seismic safety of the structure would be affected by the snow load in snow area.

Keywords: Snow Load · Temple · Pagoda · Ambient Vibration · Earthquake Observation

1 Introduction

Multi-story pagoda is well known to be excellent earthquake resistance from the ancient period in Japan. Ohmori [1] studied the vibration characteristics of six five-story pagoda by ambient vibration and free vibration measurement. Sezawa and Kanai [2, 3] discussed the dissipation of the vibrational energy of five-story pagoda by numerical calculation. Yamabe and Kanai [4] pointed out that the principal axis of pagoda tends to have diagonal direction based on ambient vibration and free vibration measurement and earthquake

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observation. Hanazato et al. [5] developed the structural model of pagoda and discussed the structural safety in design. Ohba and Kinoshita [6] formulated the prediction relation of the 1^{st} and 2^{nd} natural frequency of pagoda to the height based on ambient vibration and free vibration measurement. Chiba et al. discussed the vibration characteristics of 1/5 scale model of pagoda by shaking table test [7]. Nakahara et al. [8] studied earthquake resistance and vibration characteristics of "Horyu-ji" temple in Japan by microtremor data and numerical analysis.

Thus, Vibration characteristics and earthquake resistance of pagoda have been studied by many researchers and basic characteristics are becoming clear. However, snow load effect to vibration characteristics of pagoda is not clearly understood in heavy snowfall area. Recently snowfall is locally getting heavier in short period that is alleged to global warming. Considering snow effect to structural design of building may become more important in the near future. Therefore, it is important to quantitatively investigate snow load effect to vibration characteristics of pagoda and other traditional wooden building. The author studied seasonal variation of vibration characteristics of multi-layered wooden building by ambient vibration measurement and earthquake observation, and pointed out that the effect of snow load is quantitatively same as small earthquake, but the effect of large earthquake tends to decrease the natural frequency of the building [9].

The authors conducted ambient vibration measurement and earthquake observation at the Japanese traditional wooden structures of the main temple building and the three-story pagoda, having discussed the effect of the snow load to the vibration characteristics of those structures. Both structures belong to the "Jion-ji" temple of Yamagata where is well known heavy snow region of the north Japan. Two types of measurement systems were installed for this study. One is the measurement of ambient vibration by utilizing velocity sensors, and the other is the long-term monitoring measurement system by MEMS accelerometers being measurable for wide range of amplitude from ambient vibration to strong motions due to earthquakes. We discuss the snow load and earthquake effect to vibration characteristics of the main temple building and the three-story pagoda of "Jion-ji" in the followings.

Investigation of vibration characteristics of pagoda and main temple building can be applied to structural design of mid-rise wooden buildings and wooden space structure. Providing basic information for structural design of modern wooden buildings and structures is expected.

2 Outline of the Investigated Buildings: Main Temple Building and Three-Story Pagoda

The temple of "Jion-ji" exists in Yamagata of northern east of Japan. The temple is the religious complex consisting of three temples and 17 monk's residences. The main temple building was constructed in 1618 and designated as the national important cultural property in 1950. According to the investigation report of "Jion-ji" temple, the height of the main temple building is 15.06 m and eave height is 5.34 m. It is one-story wooden structure with seven spans in girder direction (EW) and five spans in the direction perpendicular to the girder (NS). The rood structure is gabled type called "Irimoya-dukuri" with the thatched roof.

The original three-story pagoda was burn down in 1823 and rebuilt in 1830. The three-story pagoda was registered tangible cultural property of Yamagata Prefecture in1955. The total height including the top called “Sorin” made of metal is 23.92 m, and the height of the tower is 14.61 m. It is a traditional Japanese-style pagoda with copper plate tiled roofing.

Photos in Fig. 1 are the main temple building and the three-story pagoda in summer and winter, respectively. In winter season of 2020–2021 and 2021–2022, snow was thickly accumulated on the roof of the main temple building. However, the three-story pagoda stands without snow on its roof because snow on the copper plate tiled roof tends to slide down without accumulation.

Fig. 1. Photo of the main temple building and the three-story pagoda (left: 26 May of 2022, right: 22 Dec. of 2020 with snow)

3 Ambient Vibration Measurement and Earthquake Observation of the Main Temple Building

Two types of measurement systems were installed for this study. One is the measurement of ambient vibration by utilizing velocity-meters, and the other is the long-term monitoring measurement system by MEMS accelerometers being measurable for wide range of amplitude from ambient vibration to strong motions due to earthquakes. In the followings, vibration characteristics of the main temple building, and the three-story pagoda are studied based on the results of the ambient vibration measurement and earthquake observation.

In case of the main temple building, sensors were placed on the girders and on the foundation to understand the basic vibration characteristics of the building. Sensor location is illustrated in Fig. 2. Blue squares of #1 to #9 are the positions of the velocity-meters and orange stars are the positions of the MEMS accelerometers of com5, com6, com7 and com10.

The ambient vibration measurement lasts 10 min. The window is applied to all the duration and divided into the 40.96 s small data. Shifting by the half of the window width, and applying FFT to the 40.96 s small data, and average characteristics of the 10 min data of each velocity-meter are obtained.

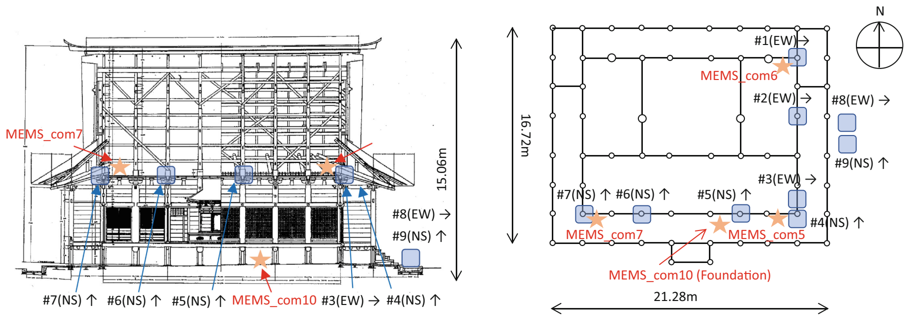

Fig. 2. Section [10] and schematic plan of the main temple building with sensor location

Ambient vibration measurements were carried out several times both in summer and winter after 2019 to discuss the snow load effect on the natural frequency of 1st mode. Amplitude ratios of #3/#8 in EW direction and #4/#9 in NS direction are shown in Fig. 3 on behalf of all the velocity-meters. The 1st natural frequency is estimated 1.61 Hz in EW and 1.86 Hz in NS at the corner of the building on 2019/09/08. All the natural frequencies of the 1st mode of the main temple building estimated by amplitude ratios of #1 to #7 compared to #8 and #9 are summarized in Table 1.

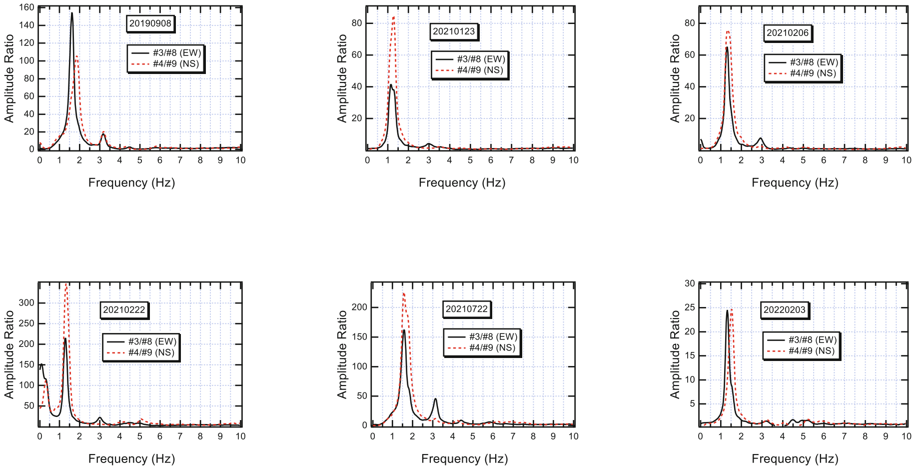

Fig. 3. Amplitude ratio of the main temple building by velocity-meters

Table 1. The 1st natural frequency of the main temple building (unit: Hz)

	#1(EW)	#2(EW)	#3(EW)	#4(NS)	#5(NS)	#6(NS)	#7(NS)
2019/9/8	1.88	1.61	1.61	1.86	1.78	1.76	1.78
2021/1/23 (snow)	1.29	1.29	1.15	1.27	1.27	1.27	1.27
2021/2/6 (snow)	1.49	1.44	1.32	1.32	1.42	1.42	1.42
2021/2/22 (snow)	1.44	1.29	1.29	1.32	1.39	1.39	1.39
2021/7/22	1.81	1.64	1.59	1.56	1.73	1.73	1.73
2022/2/3 (snow)	1.54	1.54	1.32	1.54	1.51	1.46	1.46

Seasonal variation of the 1st natural frequency of the main temple building by velocity-meters is shown in Fig. 4. The 1st natural frequency tends to be slightly higher at the corner of #1 in EW and #4 in NS than other positions. Based on the results of #2 and #3 in EW and #5, #6 and #7 in NS, the 1st natural frequency tends to be higher in NS than in EW. It can be considered because there are more structural walls installed in NS than in EW. Results from the measurements in winter (2021/1/23, 2021/2/06, 2022/2/22, 2022/2/3) show the 1st natural frequency becomes lower than in summer. The variation was caused by snow load thickly accumulated on the thatched roof of which thickness was estimated about 1m at deepest. Damping factors of the main temple building estimated by free vibration test on 2019/09/08 were also about 1.9% in EW and 2.3% in NS.

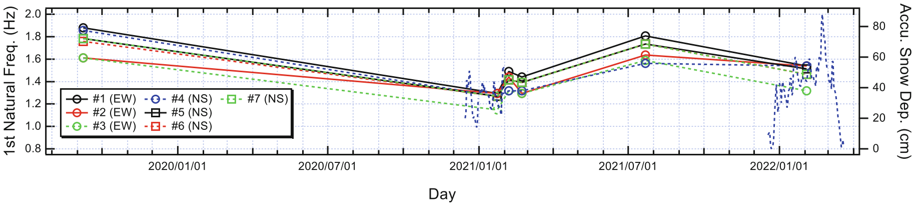

Fig. 4. Seasonal variation of the 1st natural frequency of the main temple building by velocity-meters

MEMS accelerometer can record vibration data from low amplitude as 0.1gal to large amplitude as strong earthquake in tri-axis. Ambient vibration measurement started on 2019/09/08 and currently continues at the time of Feb. 2023. Four sets of sensors were placed into the main temple building of com5, com6, com7, and com10 (on the foundation) shown in Fig. 2. Amplitude ratios of com5 to com10 estimated by MEMS accelerometers are shown in Fig. 5. Ambient vibration data recorded by MEMS accelerometers are not good enough S/N ratio in resting state for the signal analysis to obtain vibration characteristics of the building. Some effort was necessary to find appropriate data having good S/N ratio. However, amplitude ratio can be derived from the recorded data including small earthquake, and ambient vibration with large amplitude generated by human activity.

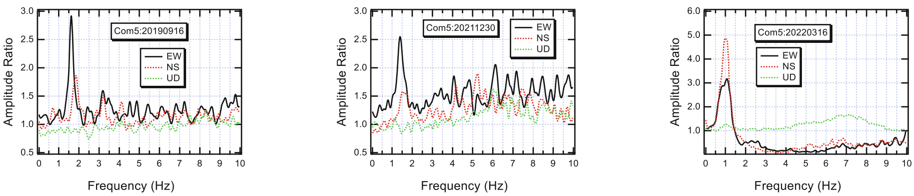

Fig. 5. Amplitude ratio of the main temple building by MEMS accelerometers (com5/com10)

In Fig. 5, amplitude ratios of 2019/09/16 and 2011/12/30 are estimated by the data including large amplitude ambient vibration generated by human walking. Case of 2019/09/16 is without snow on the roof, and case of 2021/12/30 is thickly accumulated snow on the roof. Amplitude ratio of 2022/03/16 is including earthquake that is the largest (max. acc. is 135gal in NS) during the observation period. It can be found that the 1st natural frequency in large earthquake (2022/03/16) is lowest during the observation period. The 1st natural frequency with snow on the roof is lower than without snow. Variation of the natural frequency depends on the amplitude of vibration and weight of the roof.

Analyzing other data and obtaining amplitude ratio of different observation period, seasonal variation of the 1st natural frequency of the main temple building by MEMS accelerometers (com5/com10) is shown in Fig. 6. Blue dotted line is the accumulated snow depth observed in Yamagata city about 20 km south from the site of “Jion-ji”. As suggesting from the results of Fig. 5, the 1st natural frequency tends to be lower in earthquake. When snow is on the roof, the natural frequency is also shifting to lower range of frequency but stay in the middle of earthquake and ambient vibration without snow. The highest of the 1st natural frequency is 1.73 Hz in EW and 1.88 Hz in NS, and the lowest is 1.07 Hz in EW and 0.98 Hz in NS. The ratio of the highest to the lowest is 1.62 in EW and 1.92 in NS. Difference in EW and NS can be considered because snow on the roof may not have been uniformly distributed, and the directivity of earthquake.

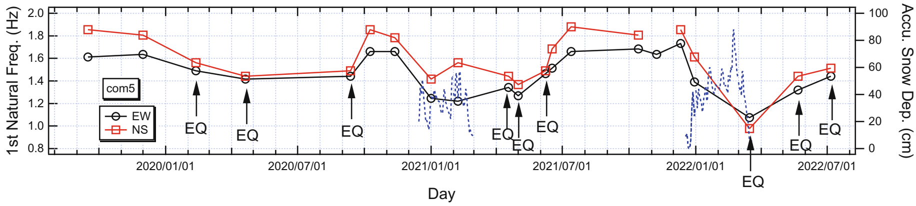

Fig. 6. Seasonal variation of the 1st natural frequency of the main temple building by MEMS accelerometers (com5/com10)

Displacement time history of com 5 and com10 and displacement orbit in EW and NS plane are shown in Fig. 7. Displacement is derived by applying numerical integration twice to the recorded acceleration data. To avoid long period component, band pass filter of 1 to 2 Hz including the 1st natural frequency is applied. Comparing displacements of com5 to com10, the roof of the main temple building behaves in phase with the foundation in almost all the duration, especially before the large amplitude. However, after large amplitude, displacement of the roof tends to be out of phase with the foundation. Displacement orbit also indicates interesting result. While displacement orbit of the foundation (com10) shapes almost the round, the roof (com5) looks like moving in the shape of ellipse with gradient axis. It can be said because snow on the roof may not have been uniformly distributed, as well as the 1st natural frequency variation.

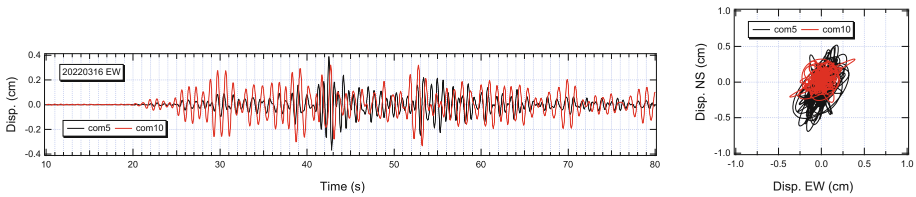

Fig. 7. Displacement time history of com 5 and com10 and displacement orbit in EW and NS plane.

4 Ambient Vibration Measurement and Earthquake Observation of the Three-Story Pagod

Ambient vibration measurement was conducted on 2019/09/08 for the three-story pagoda by velocity-meters. Four sets of velocity-meters were installed into the pagoda. As well as the main temple building, MEMS accelerometers were installed into the pagoda for the long-term monitoring. Three sets of sensors were installed at the top, the middle layer, and entrance of the three-story pagoda. Sensor location is shown in Fig. 8 with the façade and schematic plan of the pagoda. According to the amplitude ratio of RF/1F measured on 2019/09/08, the 1st natural frequency of the three-story pagoda was estimated 1.45 Hz in EW and 1.36 Hz in NS. Clear small peaks indicating torsional motion at around 2.0 Hz, and the second mode at around 3.5 Hz are found in both directions.

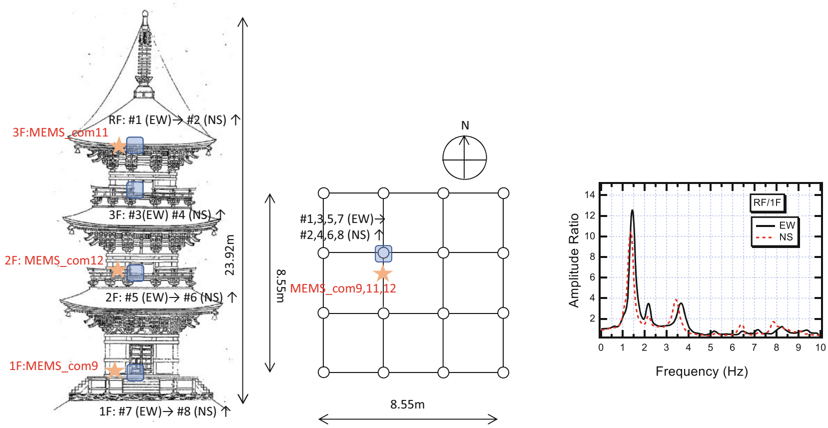

Fig. 8. Façade [10] and schematic plan of the three-story pagoda with sensor location (left and center); Amplitude ratio estimated on 2019/09/08 (right)

Amplitude ratios of 3F/1F of the three-story pagoda estimated by MEMS accelerometers are shown in Fig. 9. Ambient vibration measurement started on 2019/09/08 at the same time as the main temple building. Three sets of sensors were placed into the pagoda of com9, com11, and com12 shown in Fig. 8. Amplitude ratios of com11 (3F) to com9 (1F) estimated by one-hour records of MEMS accelerometers are shown in Fig. 9. As well as the main temple building, ambient vibration data recorded by MEMS accelerometers are not so good S/N ratio that data including earthquake and large amplitude of ambient vibration are adopted for the analysis. In Fig. 9, amplitude ratios of 3F/1F of 2020/01/03 include small earthquake without snow even in winter season. Amplitude ratio of 2021/02/13 are affected by large amplitude of earthquake (max. acc. is 49gal in EW). Amplitude ratio of 2021/02/19 are ambient vibration in snow season. It is clearly understood that the 1st natural frequency under the earthquake of 2021/02/13 is 1.36 Hz in EW and 1.33 Hz in NS that is the lowest. On the other hand, the 1st natural frequency under the small earthquake of 2020/01/03 is 1.51 Hz in EW and 1.42 Hz in NS that is almost the same as that of ambient vibration with snow of 2021/02/19. Amplitude at the 1st natural frequency becomes larger under earthquake than ambient vibration. Moreover, Peak shape at the 1st natural frequency of amplitude ratio of 2021/02/13 is spread wider than small earthquake of 2020/01/03. That indicates that the pagoda has potential of a high damping factor and much energy consumption under large earthquake.

Figure 10 shows seasonal variation of the 1st natural frequency of the three-story pagoda by MEMS accelerometer (com11/com9). Likewise in Fig. 5, blue dotted line

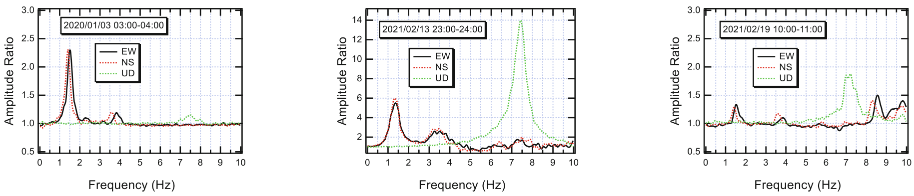

Fig. 9. Amplitude ratio of 3F/1F of pagoda by MEMS accelerometers

is the accumulated snow depth observed in Yamagata city. Although decrease of the 1st natural frequency can be seen in the pagoda, the effect of earthquake and snow is relatively small compares to the main temple building. The highest of the 1st natural frequency is 1.66 Hz in EW and 1.49 Hz in NS, and the lowest is 1.23 Hz in EW and 1.20 Hz in NS. The ratios of the highest to the lowest are 1.35 in EW and 1.24 in NS that are smaller than the main temple building. Snow was rarely accumulated on the roof of the pagoda because of the copper plate tiled roofing, so difference in EW and NS can be considered because of the amplitude of earthquake. Damping factors measured in summer were 3.2% in EW and 3.1% in NS for the pagoda based on the results of free vibration measurement.

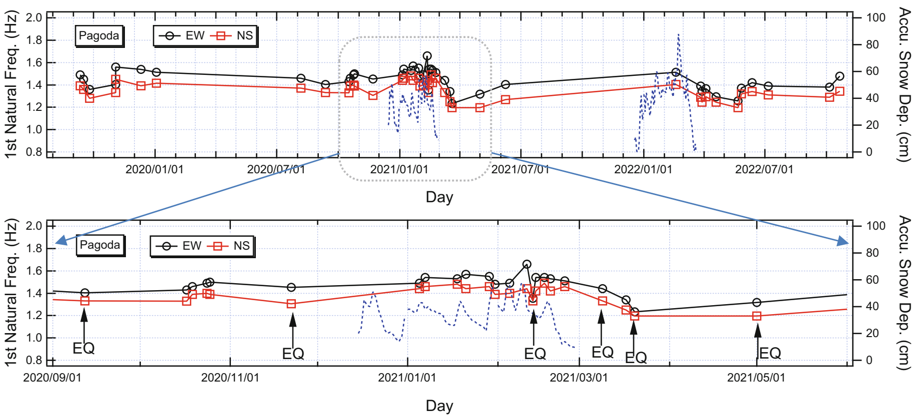

Fig. 10. Seasonal variation of the 1st natural frequency of the three-story pagoda by MEMS accelerometer (com11/com9)

Displacement time history in EW and displacement orbit in EW and NS plane of com 9 (1F), com12 (2F) and com11 (3F) are shown in Fig. 11. As well as the main temple building, displacement is derived by applying numerical integration twice to the recorded acceleration data. To avoid long period component, band pass filter of 1 to 2 Hz including the 1st natural frequency is applied.

Comparing displacements of 1F to 3F, all the floors behave in phase in almost all the duration, especially 2F and 3F. However, displacement of 1F tends to be out of phase with 2F and 3F after large amplitude. Displacement orbit shows the behavior of the pagoda is complicated as sometimes like an ellipse flat in EW and sometimes with gradient axis in NW-SE direction.

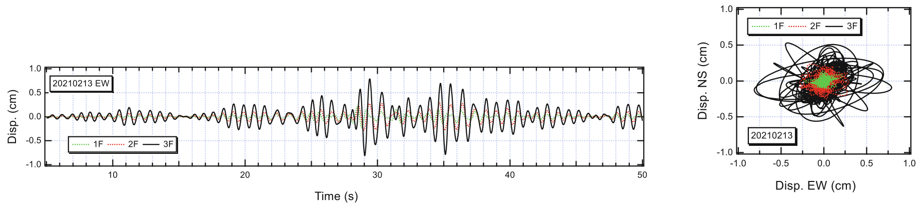

Fig. 11. Displacement wave forms and particle orbit in EW and NS

5 Conclusions

Vibration characteristics of the main temple building and the three-story pagoda in heavy snowfall area in the northern Japan were investigated using ambient vibration measurement and earthquake observation. The effects of snow on the roof and earthquake were discussed. Findings in this study are described below.

1) The 1^{st} natural frequency of the main temple building is estimated 1.61 Hz in EW and 1.86 Hz in NS at the corner of the building by velocity-meters on 2019/09/08 and tends to be higher in NS than in EW. It can be considered because there are more structural walls installed in NS than in EW. Results from the measurements in winter indicate that the 1^{st} natural frequency becomes lower than in summer. The variation was caused by snow load thickly accumulated on the thatched roof.
2) According to the results of MEMS accelerometers of the main temple building, the highest of the 1^{st} natural frequency is 1.73 Hz in EW and 1.88 Hz in NS, and the lowest is 1.07 Hz in EW and 0.98 Hz in NS. Variation in the 1^{st} natural frequency can be considered because of snow on the roof and large amplitude of earthquake.
3) The roof of the main temple building behaves in phase with the foundation, especially before the large amplitude coming. However, after large amplitude, displacement of the roof tends to be out of phase with the foundation. While displacement orbit of the foundation shapes almost the round, the roof behaves in the shape of ellipse with gradient axis.
4) Based on the results of the amplitude ratios of RF/1F of the pagoda measured on 2019/09/08, the 1^{st} natural frequency of the three-story pagoda was estimated 1.45 Hz in EW and 1.36 Hz in NS. Clear small peaks indicating torsional motion at around 2.0 Hz, and the second mode at around 3.5 Hz are found in both directions.
5) Although decrease of the 1^{st} natural frequency can be seen in the three-story pagoda, the effect of earthquake and snow is relatively small compared to the main temple building. The highest of the 1^{st} natural frequency is 1.66 Hz in EW and 1.49 Hz in NS, and the lowest is 1.23 Hz in EW and 1.20 Hz in NS. Variation seen in the pagoda is smaller than the main temple building. Snow was rarely accumulated on the roof of the pagoda because of the copper plate tiled roofing that is effective to decrease the snow load effect.

6) All the floors of the pagoda behave in phase in almost all the duration, especially 2F and 3F. However, displacement of 1F tends to be out of phase with 2F and 3F after large amplitude coming. Displacement orbit shows the behavior of the pagoda is so complicated that sometimes as an ellipse flat in EW and sometimes with gradient axis in NW-SE direction.

As a whole, the snow load effect to vibration characteristics of the main temple building and the three-story pagoda of "Jion-ji" temple is quantitatively same as the case of small earthquake. In case of large earthquake of which maximum acceleration is over 100gal, the effect is larger than snow load. However, if strong earthquake hits the buildings with snow on the roof in winter, damage will be more sever than in other season without snow. The results indicate good agreement with the case of multi-layered wooden building of the author's previous study.

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