Structural Health Monitoring of Steel Tower Structure Using Long-term Vibration Sensing with High-precision Accelerometers and MEMS Accelerometers

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Abstract - **Many steel tower structures built in Japan are aging and are increasingly at risk of collapse in the event of typhoons or major earthquakes. At the same time, it is difficult to proceed with rebuilding such aging structures with limited budgets and manpower, thus there is a need to monitor the health of the structures, and to equalize and facilitate the rebuilding work. For this purpose, it is necessary to make full use of sensing technology to diagnose deterioration in order to accurately assess the condition of steel tower structures. In this study, sensors were installed at multiple locations on an actual steel tower structure, and measurements were taken over a period of nine months. Data was measured and saved for five minutes, centered on the time when the maximum Root Mean Square (RMS) value of acceleration occurred each day. There have been no other studies in which measurements were taken and analyzed at the time when the maximum vibration occurred each day, with almost no missing data, over several months of constant measurement. This study aims to obtain knowledge that will be useful for monitoring the health of structures and for leveling and smoothing out reconstruction work in order to prevent loss of life due to the collapse of steel tower structures that have not yet been made apparent. In addition, although the use of high-precision accelerometers is preferable for data analysis, it is confirmed that the use of inexpensive MEMS accelerometers is sufficient in actual practice.**

Keywords-Vibration Sensing; Steel Tower Structure; Structural Health Monitoring; Micro Electro Mechanical Systems; Frequency Analysis

I. INTRODUCTION

In Japan, the civil infrastructure is aging, with approximately 60% of road bridges, river management facilities, such as sluice gates, and port quays, among them, being more than 50 years old after construction by 2033 [1]. This situation has been pointed out since the early 2000s, but it came to be highlighted as an important social issue after the 2013 Sasago Tunnel ceiling plate fall accident, in which nine people lost their lives when the vehicles they were traveling in became trapped under the fallen ceiling [2]. In a similar context, the maintenance and reconstruction of steel tower structures, which are ubiquitous throughout Japan for communication and power transmission, is one of the most pressing social issues that has yet to be acknowledged. Steel tower structures consist of a steel framework, and are used for power transmission towers, communication towers for mobile phone base stations, and transmission towers for broadcasting stations, as well as watchtowers for weather observations, lighthouses and firefighting. For power transmission alone, there are currently 240,000 towers supporting the electricity supply [3], and along with communication towers, they form the very infrastructure that underpins our social life. The rush to build transmission towers began in the 1970s, and although the average service life of these towers is estimated to be around 40 years, 120,000, or about half of the total, are overdue for renewal. For example, Typhoon No. 15, which hit the Japanese archipelago in September 2019, caused material damage, including the collapse of a transmission tower in Kimitsu, Chiba Prefecture, which was built in the 1970s, but fortunately no human casualties were reported [4]. For this reason, the importance of this social issue, as regards the maintenance and management of infrastructure as tunnels and bridges, has not yet been recognized. Clearly, many steel towers have reached the point where they need renewal, and the risk of collapse in the event of a typhoon or major earthquake is increasing. It is difficult, however, to renew of all of them at once with limited budgets and manpower, there is an urgent need to monitor their health and extend their service life, as well as to equalize and facilitate reconstruction work. It is therefore essential to accurately assess the condition of steel towers, and to diagnose deterioration using sensing and digital technology.

We have been researching and developing sensing systems that achieve highly accurate autonomous time synchronization for structural health monitoring and earthquake observation. In the light of the current situation, this study collected and analyzed measurement data over several months by installing sensors on a real steel tower in service to obtain knowledge useful for monitoring the health of towers and extending their service life, as well as for equalizing and facilitating reconstruction work, thereby to prevent loss of human life due to unforeseen tower collapse [1].

Section II describes the state of the art of the research for structural health monitoring and sensor technologies. Section III describes the targeted steel tower structure and the installed sensing system, while Section IV presents the results of an analysis of the measured data. Section V gives a comparison of the measurement results obtained by high-precision accelerometers and MEMS accelerometers, and a discussion of their usefulness. From these results, Section VI presents the conclusions of the study and future tasks.

II. STATE OF THE ART

Many studies on the health monitoring of structures have been conducted since the early 2000s, and papers summarizing research trends at that time have been published [5]. Techniques and methodologies for monitoring of structures have been summarized, focusing on the modeling of structural behavior, data analysis methods and sensor technologies [6][7]. Many of the studies focus on social infrastructure structures, such as bridges and highways, where inspections are mandatory, and technologies, such as fiber-optic sensors, wireless sensor networks and image processing have been applied [8][9]. In recent years, machine learning has been utilized in this field, and efforts have been made to apply machine learning algorithms, acquire and process data, and improve prediction capabilities [10]. Moreover, real-time monitoring, data analysis and optimization of maintenance planning have been carried out with regard to structural health monitoring and management systems based on the Internet of Things (IoT) and cloud computing [11]. However, for steel tower structures, inspections are not mandatory and few studies have focused on maintenance management through structural health monitoring. In addition, because transmission towers are owned by electric power companies while communications towers are owned by telecommunications carriers, information on initiatives targeting them is not publicly available. In this study, sensors were installed at multiple locations on an actual steel tower structure, and measurements were taken over a period of nine months. Data was measured and saved for five minutes, centered on the time when the maximum RMS value of acceleration occurred each day. There have been no other studies in which measurements were taken and analyzed at the time when the maximum vibration occurred each day, with almost no missing data, over several months of constant measurement [6][7][8]. This study aims to obtain knowledge that will be useful for monitoring the health of structures and for leveling and smoothing out reconstruction work in order to prevent loss of life due to the collapse of steel tower structures that have not yet been made apparent.

III. STEEL TOWER STRUCTURE AND SENSING SYSTEM

For the many steel towers that require renewal, rather than just focusing on the number of years since construction, it is important to accurately assess their condition in order to monitor the health of individual towers, extend their service life, and equalize and facilitate reconstruction work. To perform such analyses, data must be acquired and collected from actual steel tower structures. Long-term measurements over a period of several months were therefore carried out on a steel tower constructed in Numazu, Shizuoka Prefecture, as shown in Figure 1. Also, it shows the arrangement and types of sensors used. The sensors were placed at the top, center and base of the steel tower in order to obtain data on the overall and local behavior of the tower, which is directly related to any damage it may have sustained.

Table I lists the installation location and the measurement data obtained. Accelerometers measure the acceleration at the top, center and base of the tower. In each part of the tower, both high-precision accelerometers and inexpensive MEMS accelerometers were installed. Table II lists the specifications of the two types of accelerometers. The high-precision accelerometer has a 3-axis crystal acceleration sensor with high accuracy and excellent stability, which is micro-fabricated from a highly accurate and stable crystal material. As shown in Table II, it has low noise and low power consumption and is capable of high-resolution vibration measurement. Compared to high-precision accelerometer, MEMS accelerometer has lower noise density performance, but it can be operated with low power consumption and can be procured at low cost. Although it is desirable to use high-precision accelerometers for any analysis, in view of the widespread use of measurement systems, it is important to determine the extent to which analysis is possible with MEMS accelerometers, which are not highly accurate but are very inexpensive.

The sampling frequency was 100 Hz, and data was measured and saved for 5 minutes around the time when the maximum RMS value of acceleration occurred on each day. Each sensor module had a built-in battery and wireless communication function that used the 2.4 GHz frequency band, and transmitted data wirelessly to a data logger for data recording, which was installed at the base shown in Figure 1. The batteries installed in each sensor module can power the system for approximately one year without needing to be replaced. Each sensor module stores data in its memory and transmits the data wirelessly to the logger. The logger was installed in a small temporary structure adjacent to the base of the tower structure and provided with Internet access, allowing data to be collected remotely.

TABLE I. INSTALLATION LOCATIONS AND MEASUREMENT DATA OF SENSOR

Sensor	Installation Location	Measurement Data
Accelerometer	Tower top, center, base	Acceleration in two horizontal directions and vertical direction

TABLE II. SPECIFICATIONS OF HIGH-PRECISION AND MEMS ACCELEROMETER

	High-precision Accelerometer	MEMS Accelerometer
Model	EPSON M-A351AS	Analog Devices ADXL355
Direction	3 axes (2 horizontal, 1 vertical)	3 axes (2 horizontal, 1 vertical)
Range	±5G	±2G
Noise Density	0.5 μG/√Hz	22.5 μG/√Hz
Operating Temperature	-20 ℃ to +85 ℃	-40 ℃ to +125 ℃
Power Consumption	20mA	200μA
Interface	SPI	SPI/I^2C

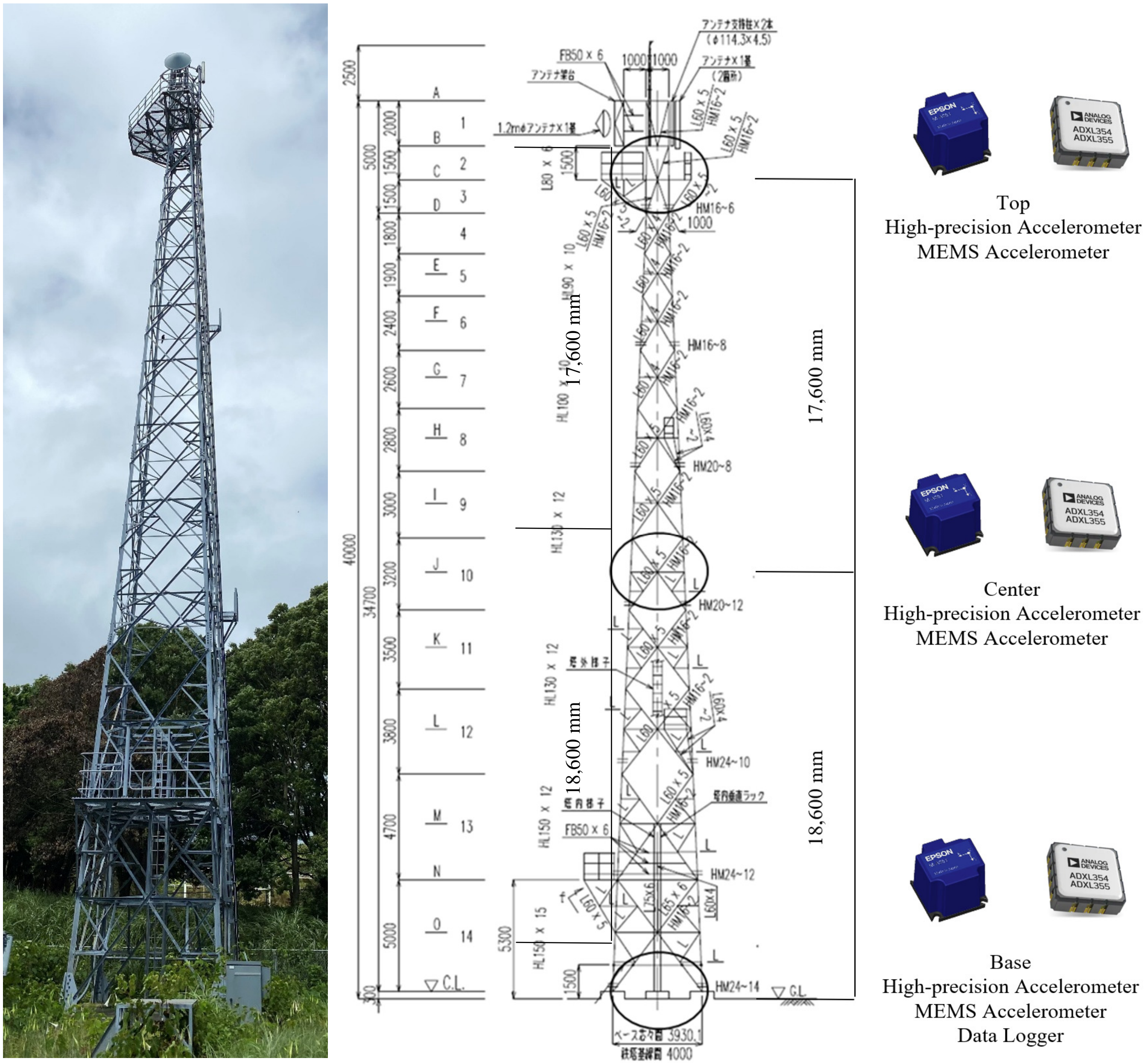


Figure 1. Steel tower structure and sensor location.

IV. DATA ANALYSIS

The accelerometers measured the acceleration at the top, center and base to capture the main vibration modes of the steel tower, and to check for excessive vibration and deformation in each part and between parts. In this study, measurements were taken over a nine-month period from February to October 2023. Data was measured and stored for five minutes, centered on the time when the maximum RMS value of daily acceleration occurred. There have been no other research studies in which measurements were taken almost without missing data at the time when the maximum vibration occurred each day on an actual tower structure, and the results of frequency analysis over several months were presented [4][5][6]. The results below show the long-term changes in the dynamic characteristics of the tower structure.

Figure 2 shows the maximum values measured by high-precision accelerometers during the measurement period.

Figure 3 shows the Fourier spectra of the measured data at the top of the tower obtained by a high-precision accelerometer during the measurement period. In Figures 3(a) to (c), the diagrams on the left show the 3D Fourier spectrum with the date and frequency during the nine-month measurement period on the horizontal axis and amplitude plotted on the vertical axis; the diagrams on the right show this spectrum viewed from directly above, with the date and frequency on the axis and the amplitude in color. The white areas in the right diagrams are areas of missing data. The diagrams on the left give an overview of which frequencies were predominant with respect to acceleration at the top of the tower during the nine-month period, and whether these frequencies changed or not. From the diagrams on the right, the predominant frequencies and their changes can be clearly observed. Since this is the acceleration at the top of the tower, the first-order natural frequencies in the horizontal directions of the targeted steel tower can be obtained. From Figure 3(a), in the x-direction, the horizontal natural frequency can be observed at 1.66 Hz, and from (b), in the y-direction, at 1.59 Hz. Also, no change was observed during the nine months when the measurements were conducted. From (c), the natural frequency in the vertical direction (z-direction) can be observed at 42.5 Hz. Natural frequency is the inherent resonant frequency of a structure. It varies depending on the shape, restraint position, and Young's modulus and density of the material. At this frequency, once an external force is applied, the structure resonates and continues to vibrate on its own without the application of an external force. Natural frequency is determined by the mass and stiffness of the structure, so if the structure is damaged, its stiffness decreases and the natural frequency decreases.

Figure 4 shows the Fourier spectra of the measured data obtained at the center of the tower by the high-precision accelerometer during the measurement period. Since it is the acceleration at the center, the second-order natural frequencies in the horizontal direction of the targeted steel tower can be obtained. From Figures 4(a) and (b), the dominant frequency is around 6.5 Hz in both the x- and y-directions, but there is no clear peak. It can also be seen that there was no change during the nine months in which the measurements were conducted.

The day when the maximum acceleration occurred is indicated by ▼ in Figure 2. Figure 5 shows the time history waveforms of the data measured at the top of the tower by the high-precision accelerometer at this time. From Figure 5, it can be seen that at the top of the tower, accelerations of similar magnitude occur in the x and y-directions, which are horizontal directions, while almost no acceleration occurs in the z-direction, which is the vertical direction. As indicated in (2) above, the natural frequency in the x-direction can be observed at 1.66 Hz, and from (b), the horizontal natural frequency in the y-direction, at 1.59 Hz. In general, there is little structural difference between steel towers in the x- and y-directions, thus the natural frequencies are also close.

Figures 6 and 7 show the time history waveforms and Fourier spectra of the measured data in each direction by the high-precision accelerometers on the day when the maximum acceleration of the measurement period occurred. In both the x-direction shown in Figure 6 and the y-direction shown in Figure 7, the base of tower does not vibrate, and the acceleration increases towards the center and the top of the tower, indicating the first-order mode vibrations are dominant, while the higher-order mode vibrations are small. Therefore, the first-order natural frequencies in two horizontal directions are appropriate as a risk indicator for detecting deterioration and damage to steel towers. If there is a change in the risk index, specifically if a trend toward a decrease in the natural frequency is observed, it can be assumed that the stiffness of the structure has decreased, which will lead to an increased priority for detailed inspections and planned reconstruction work.

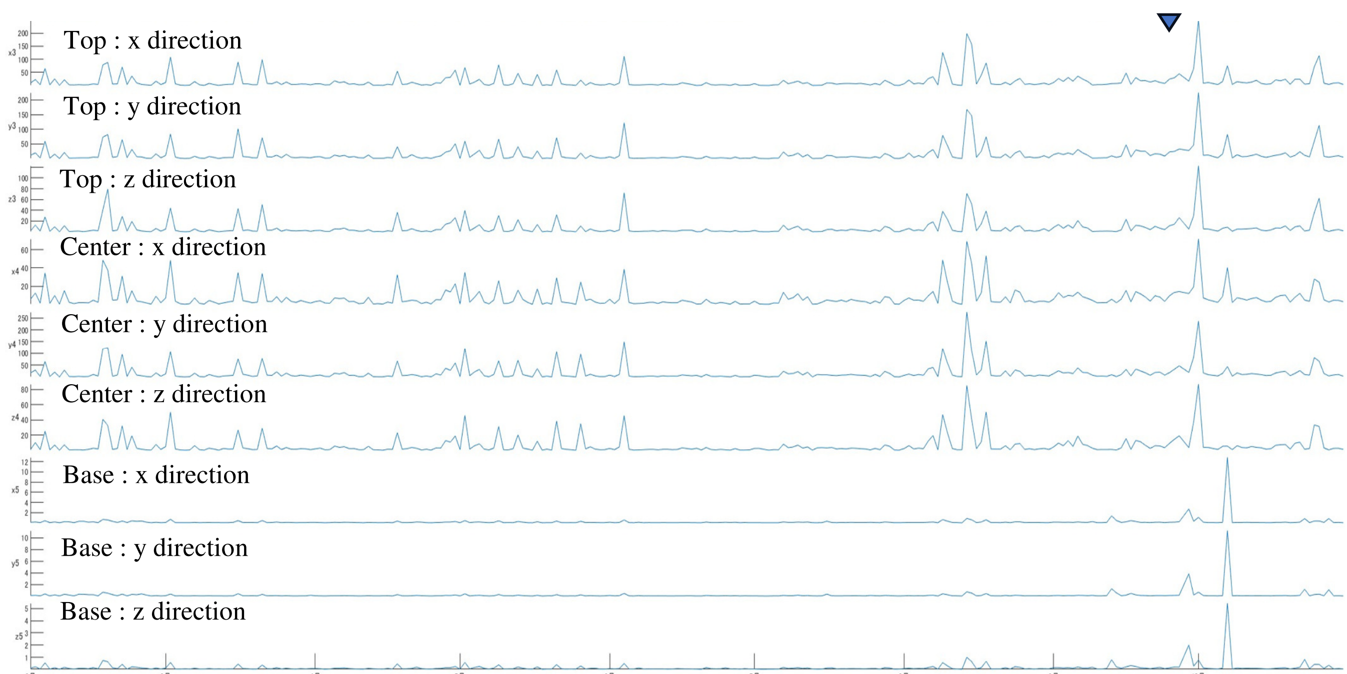
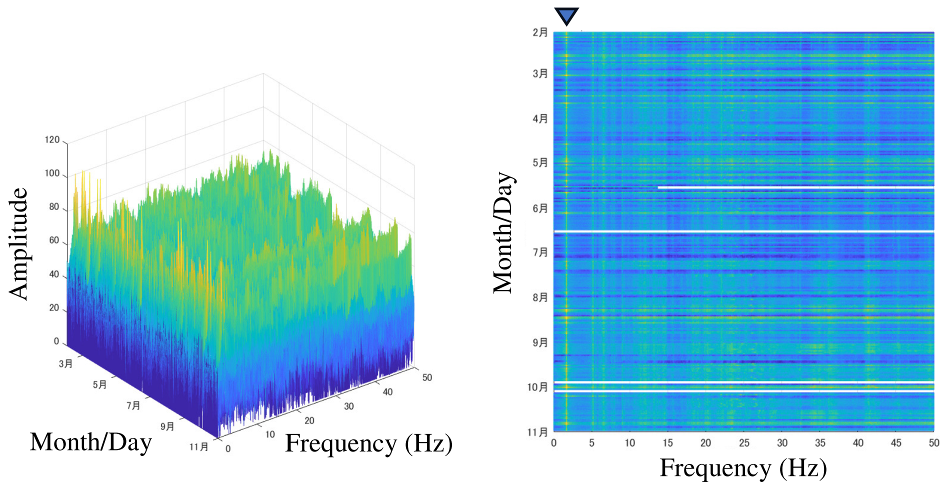
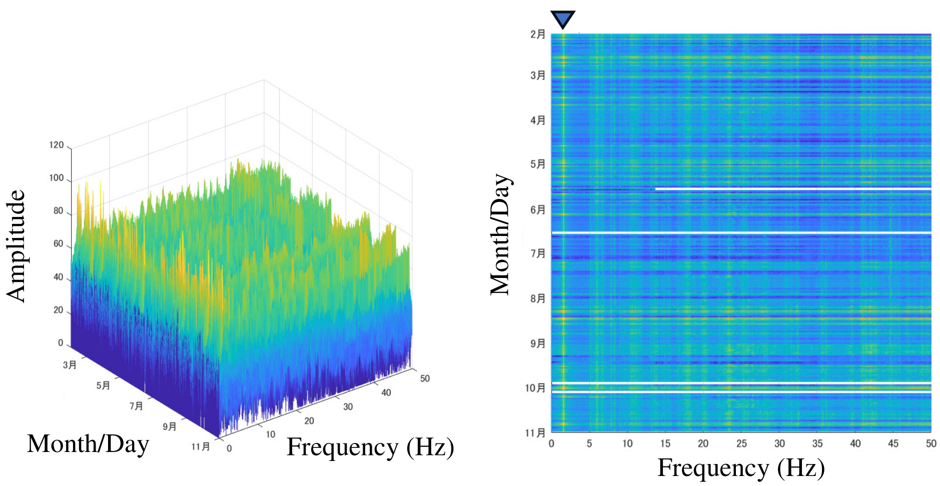


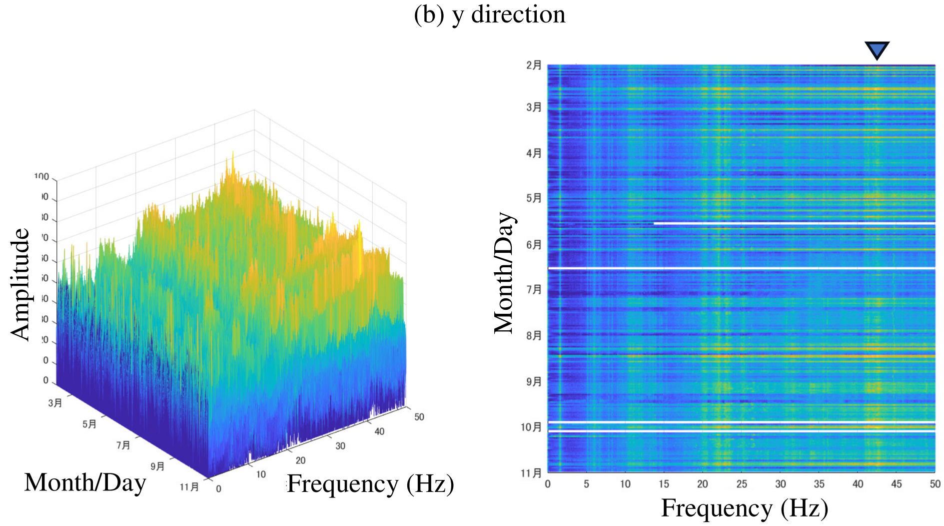
Figure 2. Maximum values measured by high-precision accelerometers during the measurement period.



(a) x direction

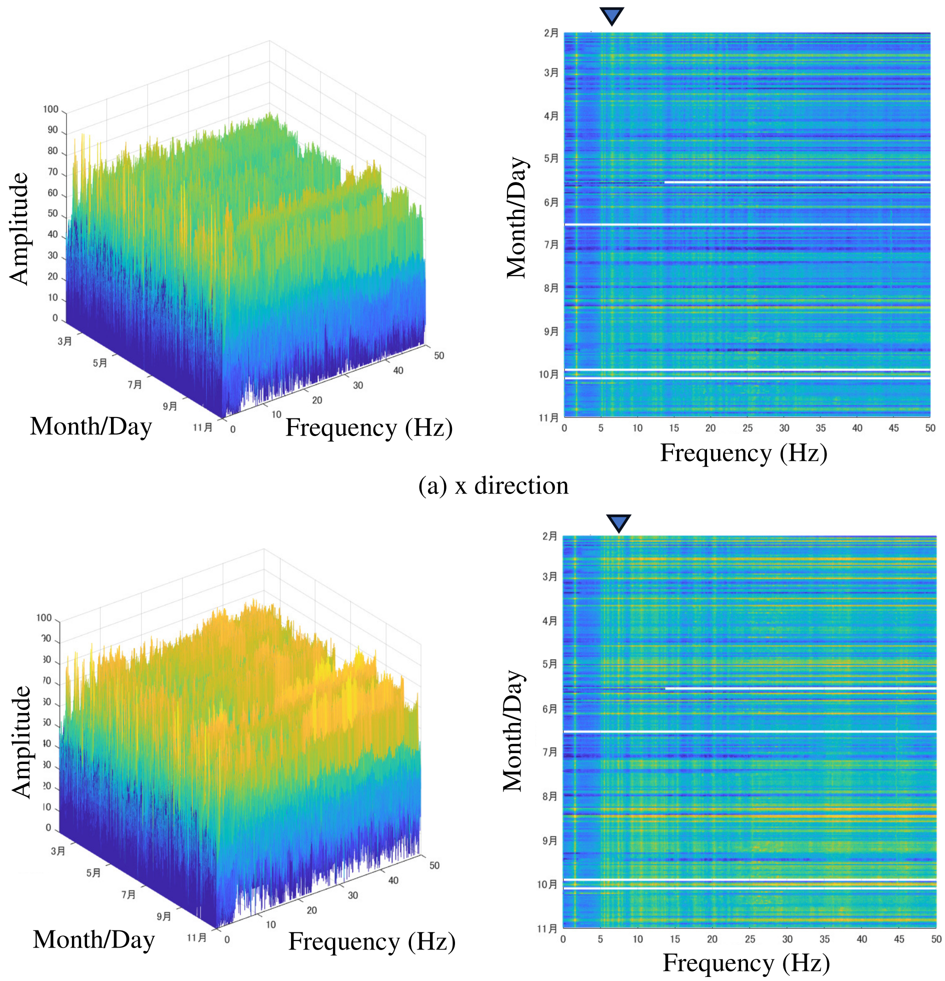


(b) y direction



(c) z direction

Figure 3. Fourier spectra of measured data at the top of the tower obtained by high-precision accelerometer during the measurement period.



(a) x direction

(b) y direction

Figure 4. Fourier spectra of measured data at the top of the tower obtained by high-precision accelerometer during the measurement period.

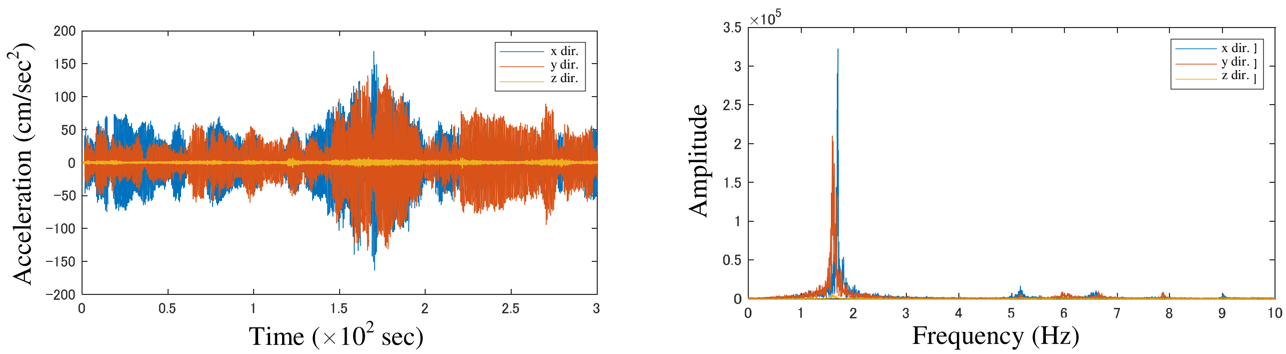


Figure 5. Fourier spectra of measured data at the top of the tower obtained by high-precision accelerometer during the measurement period.

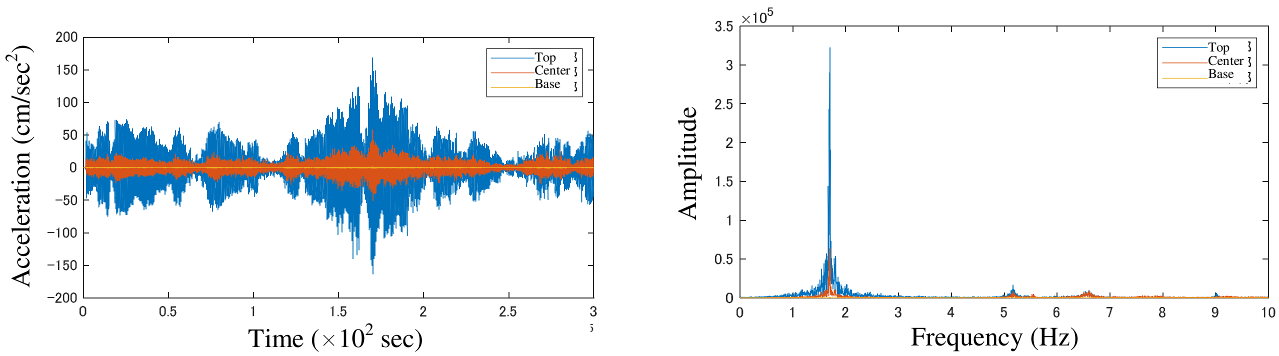


Figure 6. Fourier spectra of measured data obtained by high-precision accelerometer during the measurement period (x direction).

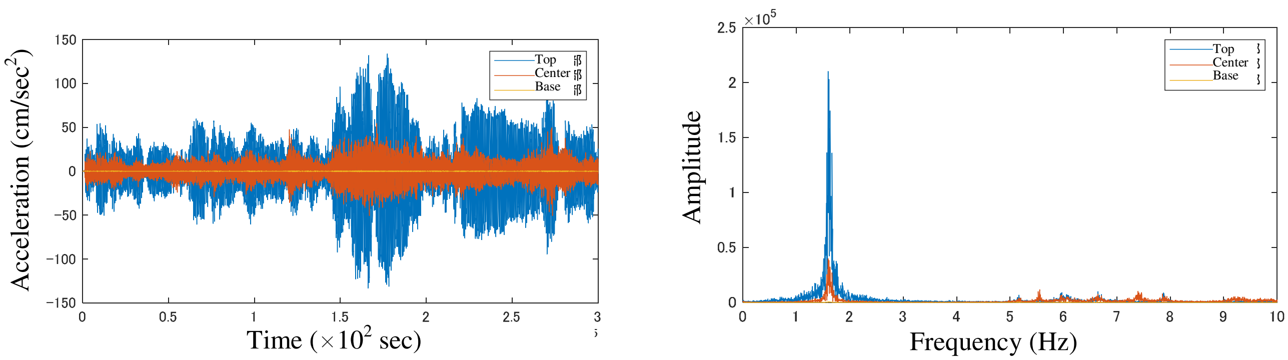


Figure 7. Fourier spectra of measured data obtained by high-precision accelerometer during the measurement period (y direction).

The steel tower structure analyzed in this study is subject to temperature effects, and its vibrations are induced by external wind forces. In the present measurement campaign, no sensors were installed to record temperature, wind speed, or wind direction. Therefore, meteorological data collected by the Japan Meteorological Agency (JMA), a national institution, were used as a reference for the investigation. The JMA operates approximately 50 meteorological observatories and weather stations across Japan, conducting meteorological observations and providing weather information. The observed parameters include temperature, humidity, atmospheric pressure, precipitation, wind direction, and wind speed, which are recorded continuously on a 24-hour basis, with data collected in real time. The accumulated data are archived and made publicly available via the web. The steel tower under investigation is located in Numazu City, Shizuoka Prefecture, and the nearest observation point is the Mishima Weather Station.

Figure 8 shows the average, maximum, and minimum temperatures recorded at this station during the measurement period. The maximum temperature reached 36.3°C, the minimum temperature was -3.5°C, and the average temperature varied gradually between 4°C and 30°C, remaining slightly above the normal seasonal range. No extreme temperatures that could significantly affect the structural performance of the steel tower were observed.

Figure 9 presents the average and maximum wind speeds recorded during the measurement period. From February to March, westerly seasonal winds prevailed, with an average wind speed of approximately 3.8 m/s. In April, the wind direction shifted to the south, and from May to August, southerly winds predominated, with wind speeds decreasing to around 3 m/s, the lowest values recorded throughout the year. In September, due to the influence of typhoons and other factors, easterly winds gradually increased, and in October, easterly winds became dominant, accompanied by a slight increase in wind speed. The Fourier spectra shown in Figures 3 and 4 indicate no temporal variation in the natural frequencies, suggesting that changes in wind speed and direction did not have a significant influence on the structural behavior.

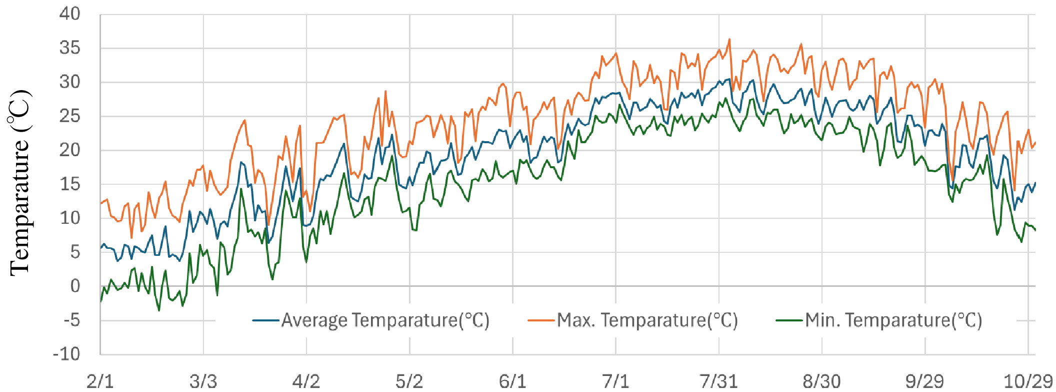


Figure 8. Average, maximum and minimum temperatures observed at JMA observation station.

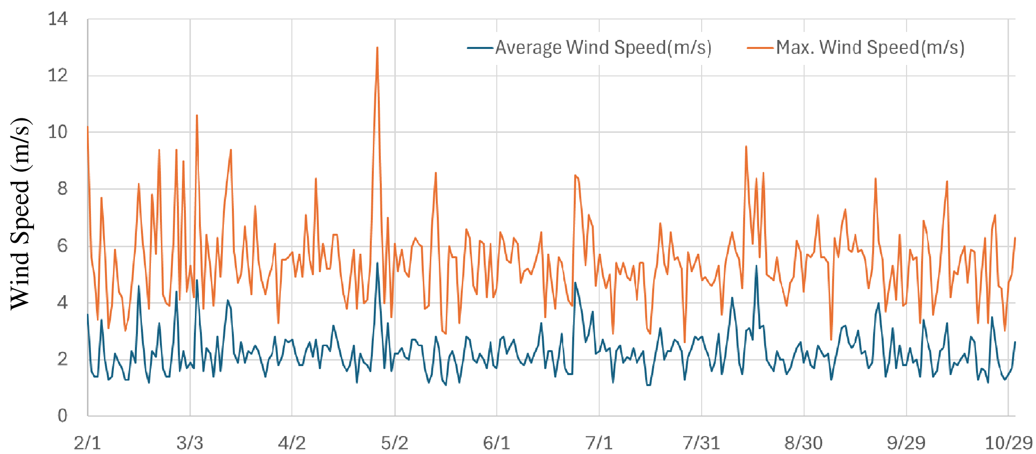


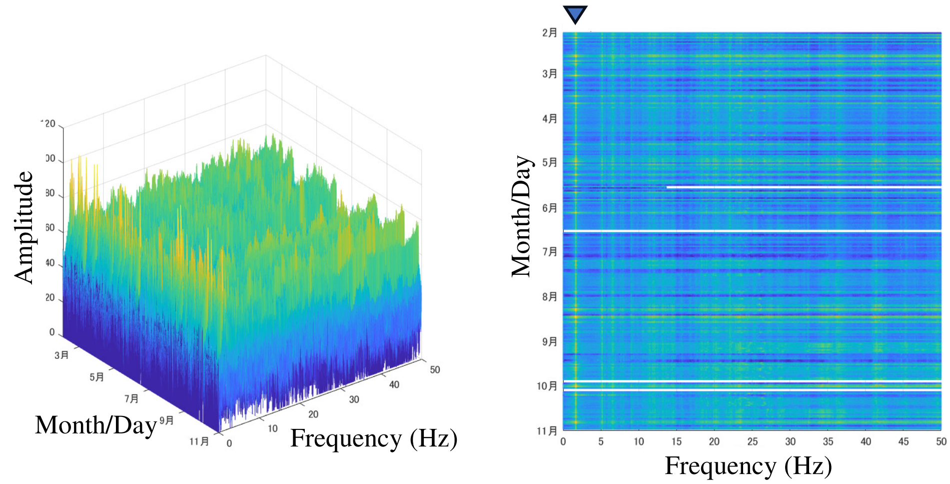
Figure 9. Average and maximum wind speeds observed at JMA observation station.

V. COMPARISON OF HIGH-PRECISION ACCELEROMETERS AND MEMS ACCELEROMETERS

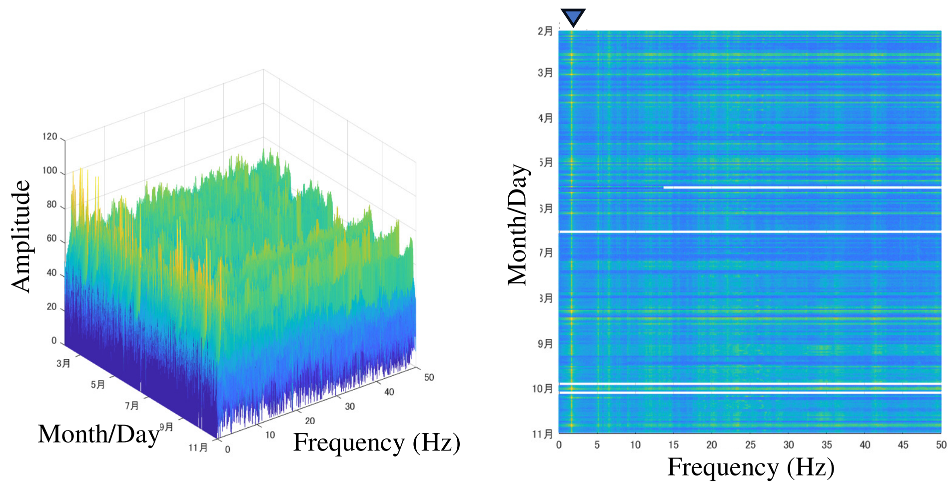
As mentioned above, accelerometers were used to measure the acceleration at the top, center and base of the tower, and both high-precision accelerometers and inexpensive MEMS accelerometers were installed in each part of the tower. Although it is desirable to use high-precision accelerometers for any analysis, in view of the widespread use of measurement systems, it is important to determine the extent to which analysis is possible with MEMS accelerometers which are not highly accurate, but very inexpensive. The following comparisons were therefore made, and the practicality of MEMS accelerometers was examined.

Figure 10 shows the Fourier spectra of the measured data (x-direction) at the top of the tower by the high-precision accelerometer and MEMS accelerometer during the measurement period. As shown in Table II, MEMS accelerometers have a lower noise density performance than high-precision accelerometers, making it difficult to accurately measure small accelerations. Therefore, when comparing the right diagrams in Figures 10(a) and (b), MEMS accelerometers gave a lower overall clarity of the diagram. However, the peaks indicated by ▼ were still captured in the same manner as those of the high-precision accelerometers, and it is possible to discriminate natural frequencies as an indicator of damage risk.

The day when the maximum acceleration of the measurement period occurred is indicated by ▼ in Figure 2. Figures 11 and 12 compare the time history waveforms of the data measured at the top of the tower by the high-precision accelerometer and the MEMS accelerometer at this time. Figures 11 and 12 show that the measurement results from the high-precision accelerometers and the MEMS accelerometers are almost identical, indicating that there are no problems with measurement at large amplitudes, which is important for discriminating natural frequencies as a damage risk indicator. Although the use of high-precision accelerometers is preferable for data analysis, it was confirmed that the use of inexpensive MEMS accelerometers is sufficient in actual practice.



(a) Measurement result by high-precision accelerometer(x direction)



(b) Measurement result by MEMS accelerometer(x direction)

Figure 10. Fourier spectra of measured data at the top of the tower obtained by high-precision and MEMS accelerometer (x direction).

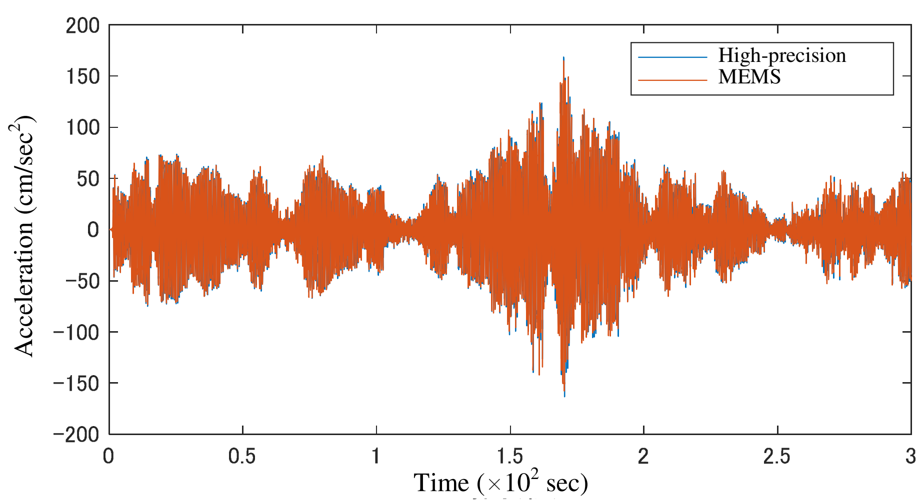


Figure 11. Comparison of time history waveforms of the data measured by high-precision and MEMS accelerometer (x direction).

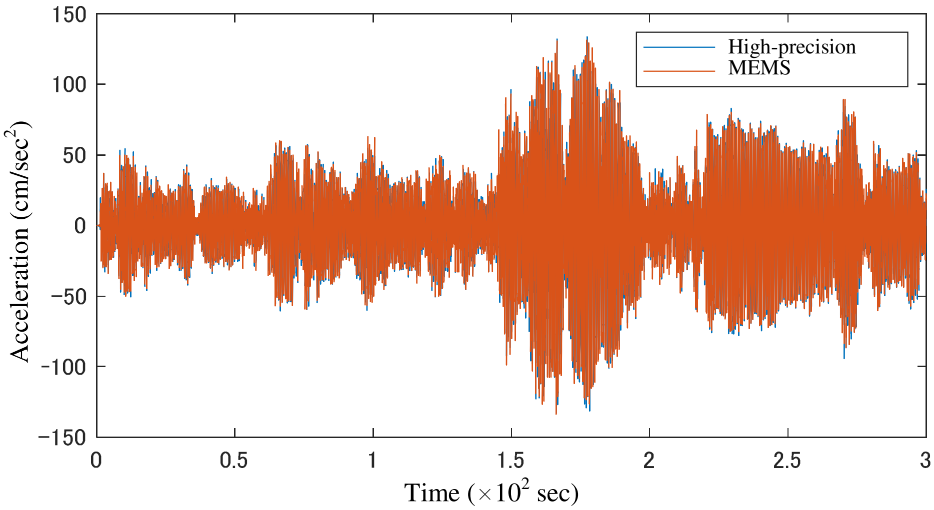


Figure 12. Comparison of time history waveforms of the data measured by high-precision and MEMS accelerometer (y direction).

VI. Conclusion

In the present study, sensors were installed on steel towers, and measurement data was collected and analyzed over a period of several months in order to obtain knowledge useful for monitoring the health of steel tower structures, extending their service life, and equalizing and facilitating reconstruction work. From the measurements and data analysis over a period of nine months, it was found that in the targeted steel tower structures, vibrations at the first-order natural frequencies were dominant, but the higher-order mode natural frequencies were also identified. Continuous monitoring of the natural frequencies of tower structures is considered effective as an indicator of damage risk. If a change in the damage risk indicator occurs, specifically if a trend towards lower natural frequencies is detected, it can be assumed that the rigidity of the structure has decreased, and this can lead to a higher priority for detailed inspection and planned reconstruction work. As a future issue, although the deterioration of the structural performance of the tower over time can be obtained through such fixed-point data measurement and analysis, it would be desirable to acquire data on events during typhoons and other strong winds and earthquakes, when the risk of tower collapse is high, together with video images to understand what events are occurring at that time. and to develop a measurement system to ensure their time synchronization.

Acknowledgment

This research was supported by the Ohata Zaidan, to which the author would like to express gratitude and was partially supported by JSPS KAKENHI Grant Number JP23K04342.

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