Development of Sensor Devices for Structural Health Monitoring of Buildings and Civil Infrastructures

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Abstract **- This paper reports the results of health monitoring of a building in Battleship Island and a structure of Angkor Wat, registered as World Heritage Sites. In addition, necessary functions for structural health monitoring of World Heritage are listed, and research on desirable sensor device is described. Specifically, the development of an autonomous time synchronization sensor equipped with a Chip Scale Atomic Clock (CSAC) that can hold accurate time information is reported.**

Keywords-Time Synchronization; Chip Scale Atomic Clock; Earthquake Observation; Structural Health Monitoring; Micro Electro Mechanical Systems; World Heritage

I. INTRODUCTION

Hashima Island in Nagasaki City in the south of Japan was registered as a World Cultural Heritage in 2015 [1]. The island was an offshore city that prospered as an undersea coal mine from the 1800s, and had a population density higher than that of Tokyo. The shape of the island resembles that of a battleship, so it is also referred to as “Battleship Island”. Also, the World Heritage Site of Angkor Wat is part of the Angkor Ruins located in the northwestern part of Cambodia [2]. The structures registered as heritage sites are expected to be maintained and managed for centuries. However, heritage sites are subject to serious crises that damage these universal values, including armed conflict, natural disasters, large-scale construction, urban development, tourism development, and commercial poaching. To maintain and manage World Heritage Structures, an understanding of the condition should be obtained by monitoring heritage sites. Monitoring should be performed in accordance with the environmental needs and circumstances of each site.

In this paper, we develop an autonomous time-synchronization sensing system on which a Chip Scale Atomic Clock (CSAC) is mounted as an ideal sensing system to maintain high-precision absolute time information [3] [4]. Even if the CSAC-mounted sensor module/data logger is installed over a wide area and at high density, it is possible to acquire measurement data with time synchronization without relying on a network or a GPS signal. In this paper, examples of health monitoring at Battleship Island and Angkor Wat and the research and development of the CSAC-mounted sensor module are introduced.

Section II and Ⅲ show the results of structural health monitoring of a building in Battleship Island and a structure of Angkor Wat, respectively. Further, Section IV describes necessary functions for structural health monitoring of World Heritage are listed, and research and development of desirable sensor device is described.

II. MONITORING OF A BUILDING IN BATTLESHIP ISLAND

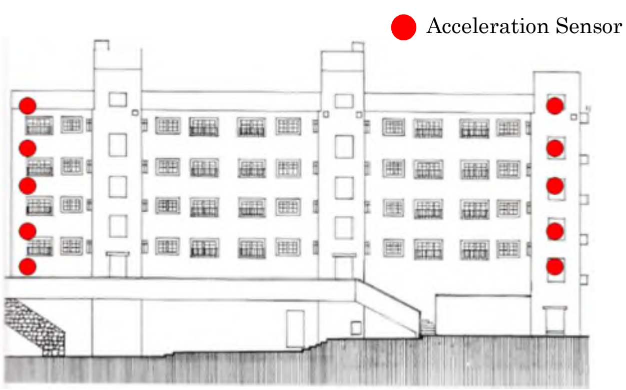
A. No.3 Building of Battleship Island

No. 3 Building on Battleship Island, shown in Figure 1, is a 4-story reinforced concrete housing complex constructed in 1959. It is located at the highest point on Battleship Island, and is a symbolic building that has a silhouette similar to that of a battleship. The building is relatively new on the island, with little sign of aging and damage. On the rooftop of No.3 Building, a wireless antenna for maritime radio communication with the Battleship Island Museum on the opposite shore, a solar panel, a storage battery, and cameras that capture images of the surrounding area, are installed. These serve as communication bases for the monitoring system.

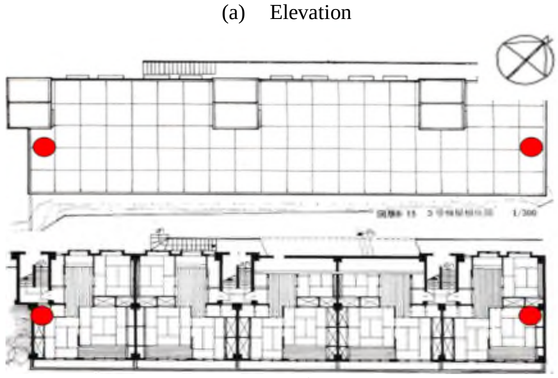
Figure 1. No.3 Building in Battleship Island.

B. Vibration Measurement System

Figure 2 shows the locations of the accelerometers in No. 3 Building. No. 3 Building has a flat, rectangular shape, with a total of 10 acceleration sensors installed on both sides of each floor. The accelerometers used are JA-70SA manufactured by Japan Aviation Electronics Industry. This accelerometer can measure a wide range of vibrations from microtremors, to strong vibrations during a typhoon or large earthquake. For vibration measurement, a data acquisition device (referred to as a DAQ) having a 16-channel A/D conversion module is used, and synchronization is performed to within 5 μsec by a multiplexer at the preceding stage. Time synchronization is performed by GPS, and the sampling frequency is set to 100Hz. A continuous measurement function that saves 10 minutes of measurement data every 2 hours and a trigger function that stores measurement data when more than a certain level of vibration occurs due to a typhoon or an earthquake are installed. The data stored in the data recorder is transmitted to a data server in the Battleship Island Museum on the opposite shore by a maritime radio communications antenna installed on the rooftop. This data server is accessible via the Internet. Solar panels and storage batteries are installed on the rooftop of the structure to serve as a power source for the vibration measurement system. PCs, the DAQ and accelerometers consume higher power, but they use system power efficiently to provide constant remote monitoring and continuous measurement.



(a) Elevation

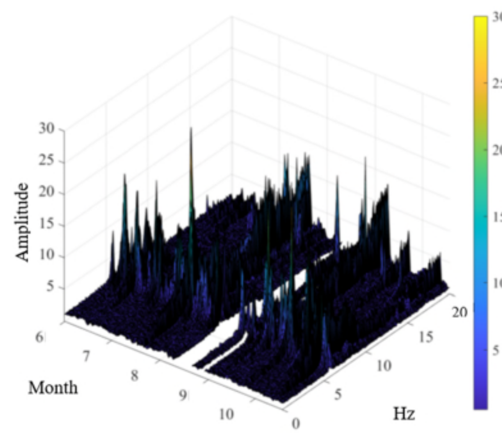


(b) Roof Plan

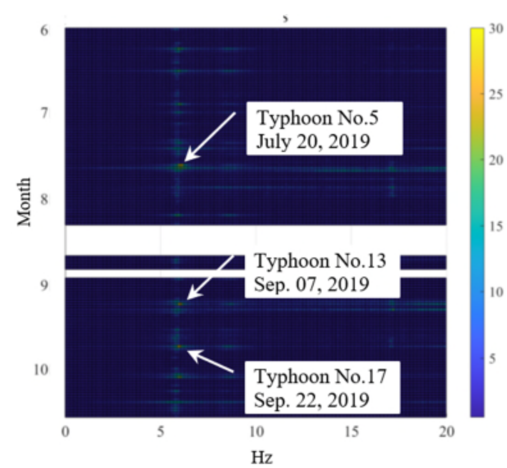
Figure 2. Sensor location.

C. Analytical Results of vibration

Figure 3 and 4 show amplitude ratios of Fourier acceleration spectra on the rooftop and the first floor calculated from acceleration data measured for 10 minutes from 12:00 every day, from June 1 to October 18, 2019. As can be seen from the figures, some parts of the data from August 12 to 19 and August 27 to 28 during the measurement period are missing. In each figure, the measurement dates, frequencies, and ratios of Fourier spectra are displayed in 3D and 2D. In addition, the dates of occurrence of three typhoons that caused strong vibrations in No. 3 Building during the measurement period are shown. Figure 3 shows the analysis results of the long-side components of the sensors installed on the south sides of No. 3 Building. From these figures, it can be seen that the first characteristic frequency clearly appears around 6 Hz during strong winds or a typhoon. In addition, characteristic frequencies of higher-order modes can be observed near 17 Hz. Further, if vibration of the building increases due to strong winds or a typhoon, vibration in the high frequency region of 10 Hz or more increases on the south side.

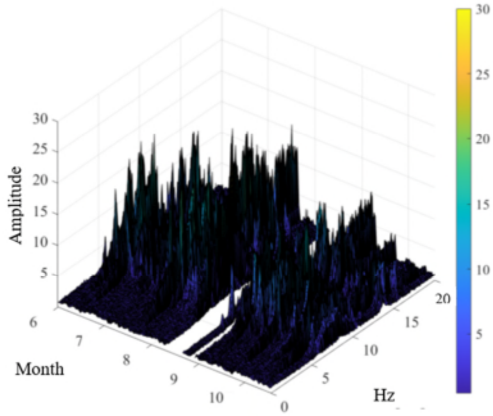


(a) South side (3D)

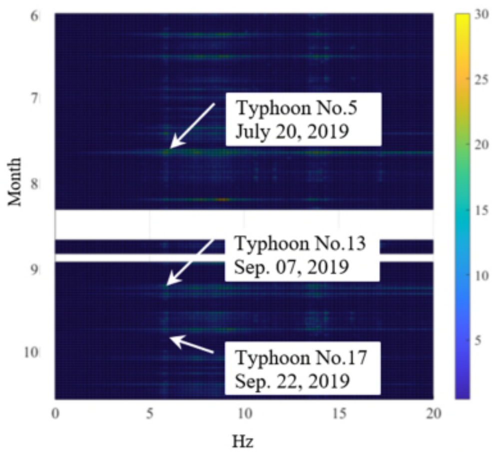


(b) South side (2D)

Figure 3. Fourier amplitude spectrum ratios of the acceleration data (Long-side component)



(a) South side (3D)



(b) South side (2D)

Figure 4. Fourier amplitude spectrum ratios of the acceleration data (Long-side component)

Figure 4 shows the analysis results of the short-side components of the sensors installed on the south sides of No. 3 Building. From these figures, it can be seen that characteristic frequencies appear at around 9 Hz and 14 Hz in addition to 6 Hz during strong winds or a typhoon. Further, when vibration of the building increases due to strong winds or a typhoon, the vibration on the south side is larger than that on the north side, and on the south side, vibration in the high frequency region of 10 Hz or more increases.

III. MONITORING OF A STRUCTURE OF ANGKOR WAT

A. *Angkor Wat*

The World Heritage Site of Angkor Wat (Figure 5) is part of the Angkor Ruins located in the northwestern part of Cambodia. The structure is a Hindu temple, and is regarded as a masterpiece of Khmer architecture. An image of the structure is displayed in the center of the Cambodian flag. The premises are surrounded by moats that are 1,500 meters in length from east to west, 1,300 meters in length from north to south, and 190 meters wide. The premises were mainly constructed from sandstone and laterite, and the temple was built by utilizing steelmaking technology in a nearby area. The structures are surrounded by a three-storied corridor. The first story corridor is 200 meters in length from east to west, and 180 meters in length from north to south. The second story corridor is 115 meters in length from east to west, and 100 meters in length from north to south. The third story corridor is 60 meters long on each side, and 13 meters higher than the second story corridor. To enter the third story corridor, it is necessary to climb a steep set on stone steps. In this corridor, five ancestral halls are located in each of the four corners and in the center; the central ancestral hall is 65 meters high.

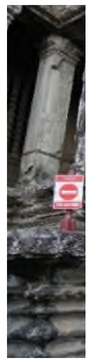
Figure 5. Angkor Wat World Heritage Site.

B. *Measurement of Vibration*

As shown in Figure 6, a constant tremor was measured every 10 minutes at each location point (●) of the first, second, and third corridors of Angkor Wat. Measurements were taken with the single portable high-sensitivity acceleration sensor shown in Figure 7. The sampling frequency is 100 Hz. Measurements at the first and third story corridors are shown in Figure 8.

Figure 6. Floor plan and measurement points of Angkor Wat.

Figure 7. Portable acceleration sensor.



(a) The third corridor

(b) The first corridor

Figure 8. Measurement at the third and first corridor.

C. *Measurement at the Thrid Story Corridor*

Figure 9 shows the Fourier spectrum of the accelerogram as measured in the southwestern part of the central tower in the third story corridor (Figure 6, ④ part). Each figure is comprised of north-south (NS), east-west (EW), and up-down vertical direction(UD) components. Frequency peaks are indicated by blue and yellow arrow marks in each figure. Vibrations of 7-8 Hz are considered to be caused by tourist traffic on the stairs externally attached to the third story corridor, and local vibrations. It has been inferred that the structures in the third story corridor of Angkor Wat have a natural frequency of around 3 Hz. Structures resembling a rigid rocky mountain can be seen in the three-storied corridor.

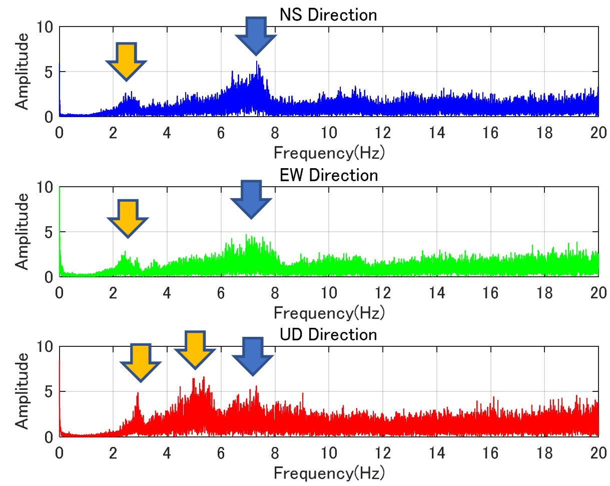


Figure 9. Fourier spectrum of the measured acceleration.

If the natural frequency moves to the lower side, rigidity will be lost, and structural deterioration and damage can be evaluated. In order to accurately evaluate this kind of natural frequency, a time synchronous measurement between the structure and the ground surface should be performed; a division of the frequency domain is required. Measurements should also be taken at the tops of the five ancestral halls (at each of the four corners and the center of the corridor).

IV. Future Direction on World Heritage Monitoring and the Need for Development of Senser Device

Battleship Island and Angkor Wat are typical sightseeing spots that bustles with tourists throughout the year. Therefore, there is heavy damage from tourist traffic in addition to age and deterioration. In order to evaluate the damage, data acquisition and accumulation by constant monitoring or periodic measurement is required. However, under the circumstances, it is not practical to bring in a large energy supply system or to wire the site for the purpose of taking measurements. Therefore, battery-driven sensor devices and data collection methods that are performed without wires are necessary. As well, Micro Electro Mechanical System (MEMS) based sensors that pursue low power consumption and involve high precision will be essential [5].

Furthermore, in order to carry out a highly accurate analysis, it is desirable to take multipoint measurements on the ground surface, at all three stories of the corridor, and on the ancestral halls for Angkor Wat. By simply installing sensors, it is possible to obtain autonomously accurate time information; the technology is expected to perform activities such as acquiring a data group that ensures time synchronization [3, 4]. These measures are also useful for monitoring the site for the management and maintenance of general building structures and social infrastructure. With the application of these methods to World Heritage monitoring in mind, research on the development of an autonomous time synchronization sensor module that holds highly accurate time information has been carried forward by using the CSAC. In order to acquire measurement data that secures time synchronization by installing the sensor devices in a wide area of high density, the sensor module itself should autonomously hold accurate time information without relying on a network or GPS signal. Therefore, a sensing module that autonomously holds accurate time information by mounting the CSAC has been developed (Figures 10 and 11).

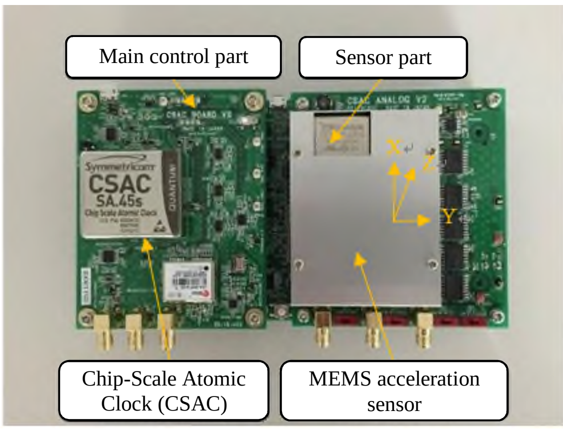


Figure 10. CSAC and sensor board.

Figure 11. Sensor module.

The CSAC is an ultrahigh precision atomic clock that features ultra-low power consumption and ultra-small size, and can be mounted on-board. The module includes the CSAC in addition to the CPU, memory, storage, 3-axis MEMS acceleration sensor, external part analog sensor input interface, temperature sensor, anti-aliasing filter, and A/D converter. It is also equipped with a Field-Programmable Gate Array (FPGA), which is a dedicated integrated circuit that is used so time information from the CSAC can be directly sent to the sensor's measurement data. Although an Ethernet network interface has been provided for data communication, Wi-Fi and 3G/LTE communication functions have been separately added to improve the module's convenience as a sensor device. By developing this kind of autonomous time synchronization sensor module, a health monitoring application has been added to the structure. Furthermore, the developed sensor device was installed on actual buildings and bridges, and applied to seismic observation and evaluation of structural health.

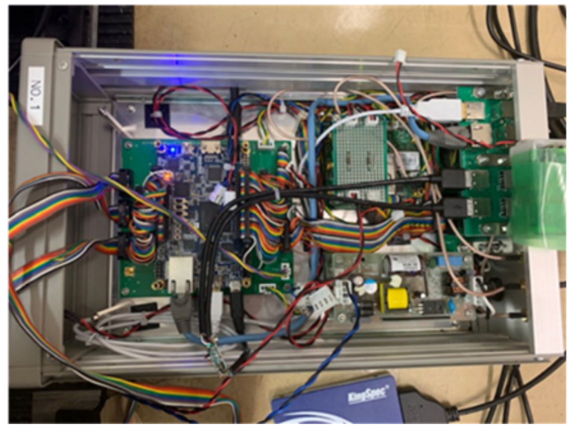


Figure 12. Digital sensing platform.

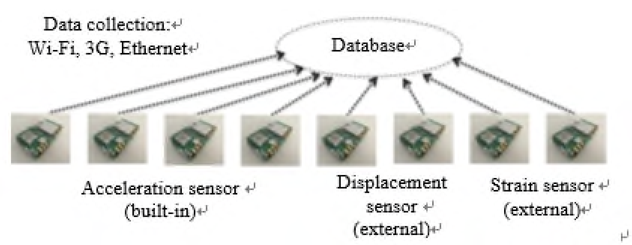


Figure 13. Autonomous time synchronization sensing system.

However, the MEMS acceleration sensor was mounted in the developed sensor device, so it was difficult to measure down to microtremors with high accuracy. The developed sensor device is equipped with an external analog input interface, through which any analog sensor can be connected. High-performance servo acceleration sensors can also be connected, but the risk of noise being mixed into the analog signal remains. Therefore, it was decided that a fully-fledged digital sensing platform (Figure 12) was developed. Specifically, a high-accuracy digital acceleration sensor was mounted in the sensor device to enable accurate acceleration measurements with no risk of noise being mixed in, and technology has been developed to add an accurate time stamp to the digital sensor output using CSACs.

In order to properly maintain and manage World Heritage for centuries by collecting, accumulating, and analyzing the measurement data, it is necessary to develop a sustainable database that copies the entire structure and ruins area from real space to cyberspace in addition to the development of a sensor and communications research

(Figure 13). Ultimately, it will be required to construct a Cyber-Physical Systems (CPS) of a World Heritage. The CPS of this sort can perform real-time sensing, event analysis, and prediction by big data assimilation, and can also control the real space of a site based on those results.

V. CONCLUSION

In this paper, the results of vibration measurement and data analysis of the structures at Battleship Island and Angkor Wat were reported. Structures registered as World Heritage Sites are expected to require maintenance and management for centuries. To maintain and manage a World Heritage structure, it is necessary to obtain knowledge of its status by suitably monitoring the environment in accordance with the structure's circumstances. Furthermore, the future direction on World Heritage monitoring and the need for the development of sensor device were discussed and research and development relating to a sensor device that autonomously retains highly accurate time information by applying a CSAC, was reported.

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