# Seismic Observation and Structural Health Monitoring of Buildings by Improved Sensor Device Capable of Autonomously Keeping Accurate Time Information

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*Abstract* - **In this research, sensor devices were developed for application to seismic observation to understand damage conditions after earthquakes and to structural health monitoring for the maintenance of buildings and civil infrastructures. To apply the sensor devices, they must be densely installed in a broad area and measurement data with synchronized time must be obtained. It is desirable that the sensor devices themselves keep accurate time information even in environments with no available network or Global Positioning System (GPS) signals. Therefore, a sensor device was developed that keeps accurate time information autonomously using a Chip Scale Atomic Clock (CSAC), which consumes ultra-low power, can be mounted on a small board, and is an ultra-high precision clock. This paper explains the CSAC and a mechanism to add highly accurate time information to the measured data using the CSAC. Next, the paper discusses the process of development from prototype to practical device as well as improvement results to solve challenges identified in the actual use at a bridge. In this paper, a new procedure for time synchronization between devices is described. In addition, the communication system of measurement data newly constructed using "fluentd" which is open source software for data collection is detailed. Finally, the paper demonstrates the usability of the developed sensor device using a case study where seismic observation and structural health monitoring was implemented by installing the improved devices in an actual building. In particular, structural health monitoring of the building based on the evaluation by the inter-story deformation was made possible by the practical device developed in this research securing autonomous time synchronization.**

***Keywords-Time Synchronization; Chip Scale Atomic Clock; Earthquake Observation; Structural Health Monitoring; Acceleration Sensor.***

## I. INTRODUCTION

Due to degradation of buildings and civil infrastructures, such as bridges, and highways over time, automation of inspection for their maintenance and management is an urgent social issue. Also, since there are many earthquakes in Japan, it is required to detect the damage of the structure immediately after the earthquake and to grasp the situation of the urban damage. In order to detect those abnormal situations, data collection and analyses by a group of sensors are necessary [1]. Sensors were developed for seismic observation and structural health monitoring applying wireless sensor network technology, and their performance in a skyscraper was demonstrated [2]-[4]. One important challenge in this research was time synchronization among sensors. To analyze a group of data measured by multiple sensors and assess structural safety, time synchronization among the sensors must be kept. In the wireless sensor network system, the time synchronization was materialized through transmission of wireless packets among the sensors [4]. However, the wireless sensor network technology is not practically applied to multiple buildings, long-span structures, such as bridges, or broad urban spaces. If sensors installed in various locations are capable of keeping accurate time information autonomously, this problem can be solved. Using Global Positioning System (GPS) signals is effective for outdoor situations, but it is not available inside buildings, underground, under bridges, or in tunnels. Therefore, a prototype sensor device capable of maintaining accurate time information autonomously was developed using a Chip Scale Atomic Clock (CSAC) [5]-[7], which is a high-precision clock and very accurate compared with crystal resonators [8][9]. Then, the prototype device was upgraded for higher functionality and practical application to develop a practical device [10].

In addition, in order to apply the developed sensor device to earthquake observation, logic to detect the occurrence of an earthquake and store data of only earthquake events was implemented and confirmed its function in shaking table experiment [11][12]. These tests confirmed the performance of the sensor device that can maintain accurate time information autonomously and showed that the device is applicable to seismic observation and structural health monitoring of buildings and civil infrastructures.

In this article, Section II shows the existing time synchronization methods and describes their problems and achievement of the development of sensor device proposed in this study. Section III describes CSAC and explains the mechanism for providing ultra-high accurate time information to sensor data by the CSAC. Section IV describes the development of a practical module from its prototype. Section V lists problems that were extracted when the practical modules were installed on an actual bridge, and describes details of improvements made to cope with these problems. Further, Section VI shows a new procedure for time synchronization between devices. The communication system of measurement data newly constructed using "fluentd" which is open source software for data collection is detailed in Section VII. Finally, Section VIII shows an example of seismic observation and structural health monitoring by applying the developed sensor device to a real building. In order to obtain the inter-story deformation of the building for the purpose of structural health monitoring shown in this paper, time synchronization of sensors is required. The sensor device developed in this research can hold accurate absolute time information autonomously, so it is easy to secure time synchronization of many sensor devices without wiring or network.

## II. State of the Art

A time synchronizing function is indispensable for sensor devices that are used for seismic observation and structural health monitoring. Unless a data group where time synchronization is ensured is obtained, a time history analysis employing phase information cannot be made. For example, it is difficult to clarify a phenomenon where seismic waves propagate through the ground. Moreover, it is not possible to make a modal analysis or an analysis for damage evaluation of a structure. Many studies have been carried out so far in relation to the time synchronized sensing, including the GPS that makes use of a radio clock or a satellite, and the Network Time Protocol (NTP) [13] designed for time synchronization on the internet. There are also studies where time synchronization is realized by making use of the characteristics of a radio sensor network where a propagation delay is small. For example, time-synchronizing protocols have been studied, which include Reference Broadcast Synchronization (RBS), Timing-sync Protocol for Sensor Networks (TPSN), and Flooding Time synchronization Protocol (FTSP) [14]-[18]. However, although these time synchronizing technologies are widely used even now, they cannot constitute an optimum means for sensor devices for use in seismic observation and structural health monitoring. Specifically, the GPS cannot be used inside a building, and the time synchronizing accuracy of the NTP is not sufficient. The time synchronizing method employing the radio technology is highly useful, but it is not ensured that the radio communication is always available. In particular, if the wireless communication is interrupted at the time of an earthquake, time synchronization cannot be performed.

In this study, a prototype of a sensor module for autonomously keeping accurate time information is developed by making use of a CSAC that is an ultra-high accurate clock, and an improvement is carried out on the prototype for a practical application. Even though a tremendous number of sensors are installed in the buildings and civil infrastructures, in case accurate time information can autonomously be given to the data measured by those sensors, time synchronization can be ensured between the sensors only by collecting the data using an arbitrary means and by realigning the data utilizing the time information. The data group where the time synchronization is ensured by using the sensor device proposed in this paper is available for an analysis intended to grasp a seismic phenomenon or evaluate the damage of a structure.

## III. Time Stamping Mechanism Using Chip Scale Atomic Clock

A CSAC has time accuracy equivalent to that of a rubidium atomic clock and is very accurate compared with crystal resonators [5][7]. The CSAC can achieve ultra-precision time measurement at a level of some ten picoseconds, consumes low power and is small enough to be mounted on a circuit board (Table I). The development of the CSAC started with the support of Defense Advanced Research Projects Agency, and the commercial product was released by an American company in 2011 and is still available for purchase. Recently, ultra-small atomic clock systems, which can be mounted on general communication terminals, such as smart phones, have been proposed, and further downsizing and price reduction are expected. If the sensor device is equipped with a CSAC and a mechanism that adds time stamping for every sample of measured data, the sensor device can create data having high-accuracy time information. Each sensor device autonomously keeps highly accurate time information even if the GPS signals and network communication are unavailable. Therefore, by collecting the measured data by means, such as 3G, Wi-Fi, Ethernet, etc., a data group ensuring time synchronization can be obtained.

To configure a sensing system composed of multiple sensor devices equipped with a CSAC, one device is set as a master device and other devices as slave devices must be synchronized by defining absolute time information. The main controller of each sensor device is equipped with an input/output connector for 1 Pulse Per Second (PPS) of the CSAC. Using this connector, the master device outputs 1 PPS signal, and each slave device inputs it to synchronize and match the phase of the CSAC in each slave device. The CSAC keeps accurate time, but it does not have absolute time information. Therefore, it must be defined separately. At initial settings, the GPS module installed in the main controller is used. Absolute time information is transmitted from the master device to the slave device by the IEEE 1588 standard. Once all the sensor devices are synchronized at the beginning, they continue keeping highly accurate time information autonomously. It is only necessary to install the sensor device in an arbitrary place and collect data. As mentioned above, any means of data collection, such as Ethernet, Wi-Fi, or 3G, are available as the measured data records accurate time stamping.

TABLE I. Specifications of CSAC

| Model | SA.45s |
|---|---|
| RF output | 10 MHz |
| 1 PPS output | Rise/fall time: < 10 ns<br>Pulse width: 100 μs |
| Power consumption | < 120 mW |
| Outside dimensions (mm) | 40 × 35 × 12 |
| Frequency accuracy | $\pm 5 \times 10^{-11}$ |
| Aging | $< 9 \times 10^{-10}$/month |

The sensors are also suitable for use as mobile measurement and a mobile sensing system because the sensors can measure and collect data even if GPS signals are not available, and a wireless or wired network cannot be used.

## IV. Development of Sensor Device Equipped with CSAC

The general sensor device is composed of a sensor chip, CPU, filter, A/D converter, memory, and network interface, and a crystal oscillator is used as the clock of the CPU. If CSAC is installed in the sensor device and measurement is performed while correcting the clock of the CPU, a delay occurs because CSAC's clocking accuracy is too high. Therefore, a mechanism having a special Field Programmable Gate Array (FPGA) was developed to add time information from the CSAC to the data measured by the sensor directly. The FPGA not only adds the time information of the CSAC to the measured data but can also incorporate logic, such as seismic detection. A prototype device was developed first to identify challenges, and then a practical device that has solved the challenges was developed.

### A. Prototype Device

Fig. 1 shows the developed prototype device [8][9]. The prototype device is composed of a mainboard, sensor board, and wireless communication board. The mainboard incorporates a CSAC, FPGA, CPU, memory, network interface, etc. The sensor board is detachable. Two types of sensor board were developed, one of which is an acceleration sensor board equipped with a microelectromechanical systems (MEMS) accelerometer, temperature sensor, anti-aliasing filter, A/D converter, etc., and the other is an external sensor board that can connect an analog sensor externally via the Bayonet Neill-Concelman (BNC) connector (Fig. 2). The communication board is also detachable and can collect data using wireless network once mounted on the mainboard. Two types of dedicated board equipped with Wi-Fi or 3G were developed.

### B. Practical Device

The following improvements were made for high functionality and practical use of the prototype device [10]-[12].

1) *3-channeled external analog sensor input interface*
2) *24-bit A/D converter*
3) *Enhanced FPGA*
4) *Separate wireless communication to use commercially available Raspberry Pi*
5) *Time synchronization by IEEE 1588*

The practical device is composed of a board and Raspberry Pi having a wireless communication function (Figs. 3 and 4) and is enclosed in a dedicated case (Fig. 5). As shown in Fig. 3, the board of the practical device is composed of a main control unit and a sensor unit. The main control unit is equipped with a CSAC, FPGA, GPS, CPU, memory, and network interface (Table II). The main control unit controls measurement of the sensor while producing time stamping, based on highly accurate time information from the CSAC. The device sends the measurement data via Ethernet or wireless communication to the network after saving data in an SD card. The device saves two types of data, one of which is regularly measured data and the other is extracted seismic event data. The device sends data containing seismic events solely to the network immediately after an earthquake using the FPGA to detect start and end of the earthquake. A GPS is installed in the device to initialize and adjust the time information. The sensor takes measurements following a command from the main control unit. The sensor is equipped with a 3-axis MEMS accelerometer, 3-channel external analog sensor input interface, temperature sensor, anti-aliasing filter, and A/D converter. The wireless communication uses commercially available Raspberry Pi to enable data collection with wireless communication. Either Wi-Fi or 3G is selectively used for the wireless communication.

Compared with the prototype device, the practical device incorporates a 3-channel external analog sensor input interface and 24-bit A/D converter, so it can connect with a sensor requiring a wide dynamic range, such as a servo accelerometer. In addition, the sensor device can be used as a data logger by connecting with three strain sensors, displacement centers, etc. Using Raspberry Pi for the wireless communication, the device can quickly respond to new wireless communication formats. Furthermore, an interface of IEEE 1588 standard for time synchronization of network was incorporated to initialize measurement timing among sensor devices and synchronize them.

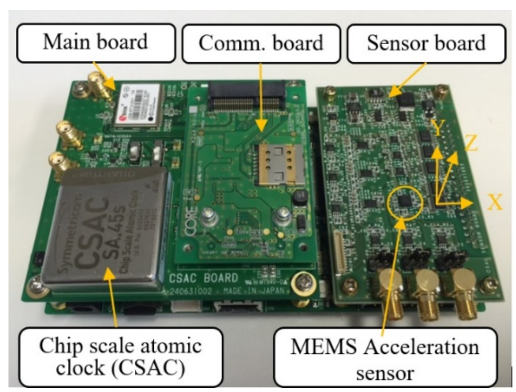



Figure 1. Prototype Device.

Figure 2. External Sensor Board.

## V. Improvement of Practical Device

The developed practical device was installed onto an actual bridge, and measurement was performed for three months to identify challenges in practical use. Based on those challenges, the practical device was improved for higher stability and operability, and the specified performance was confirmed [1]. Improvement items and contents are as follows.

### A. Reduction in Built-in SD Card Access

To avoid failures caused by total service life consumed by the number of rewrite cycles resulting from the quality of the SD card (micro SD card) or compatibility issues, the timing to write in the file system was reviewed. By setting the interval of the write timing to the file system from 5 seconds to 240 seconds, access is suppressed to a maximum of 1/48, as shown in Table III.

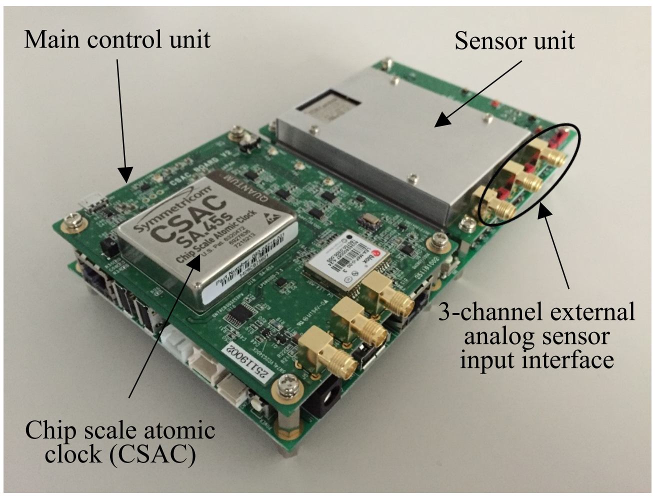



Figure 3. Board Configuration of the Practical Device.

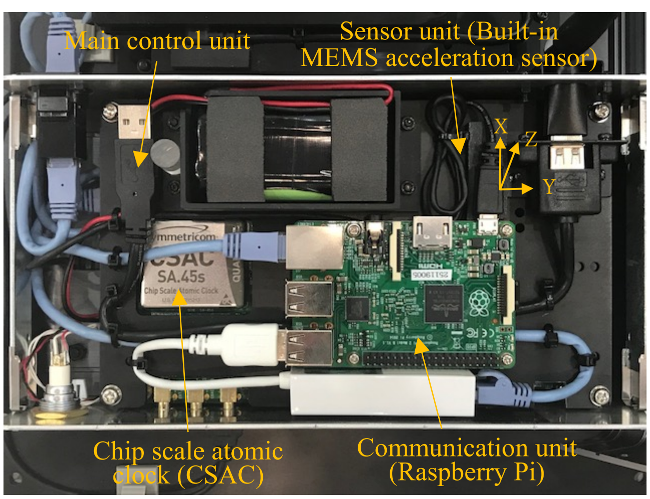



Figure 4. Board Configuration of the Practical Device in Dedicated Case.

However, risk of data loss during emergency black out increases, which means it is a trade-off. Table III shows the effects of reduction in access to the built-in SD card.

Figure 5. Dedicated Case for Practical Device.

TABLE II. SPECIFICATION OF CONTROL UNIT

| | |
|---|---|
| CPU | RZ/A1L<br>CPUcore:ARM Cortex A9 with Neon<br>384MHz (Max)<br>Instruction / data cache: 32KB/32KB<br>L2 cache: 128KB 128MHz |
| RAM (SDRAM) | 128Mbyte CL=2 @64MHz (16bit Bus) x2<br>Micron:MT48LC32M16A2P-75IT |
| RAM (Internal RAM) | 3Mbyte (RZ/A1L) |
| ROM (serial-FLASH) | 64Mbyte Serial Multi I/O x1<br>Spansion: S25FL512SDPMFIG11 (64Mbyte) |
| Ethernet | 10/100BASE-PHY |
| FPGA | XC6SLX45 |
| CSAC | SA.45s CSAC<br>Power consumption: <120mW<br>Volume: <17 cm$^3$<br>Frequency Accuracy: Max. $\pm 5x10^{-11}$<br>Short term Stability(@1000s): < $1x10^{-11}$<br>Aging Rate (Typical): < $9x10^{-10}$ /month<br>Operating Temperature: -10ºC to +70ºC |
| GPS | LEA-M8F |
| Battery | Lithium-ion rechargeable battery (3.7V) 2 cell |
| Outside dimension | 180 × 100 mm |

TABLE III. EFFECTS OF REDUCTION IN ACCESS TO BUILT-IN SD CARD

| | Current | After improvement |
|---|---|---|
| Frequency of writing | Once per 5 second | Once per 240 second |
| Data loss during emergency blackout with sampling rate of 100 Hz | Approx. 500 sampling | Approx. 24000 sampling |

### B. File Compression of Measured Data

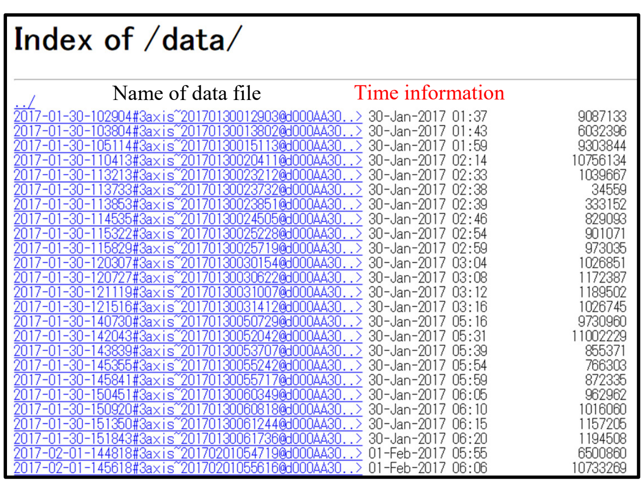
In the actual work installed onto the bridge, transmission time for the measured data must be reduced. To reduce the data transmission time and achieve storing long-term measurement data, a file compression function was added. From the viewpoint of durability, it is desirable to use a relatively small capacity SD card, which is considered to be manufactured in a stable production line rather than a large capacity one which might be manufactured in a premature production line. The file compression function is important as a means to materialize long-term data recording in a small capacity SD. The software was improved to compress the measured data to be recorded in the SD card after 75 minutes.

### C. Change of Local PC Collecting Display

A tool was developed to collect the measured data saved in the built-in SD card of the practical device placed in the LAN, which was temporarily installed on the site into a local PC using a browser. However, there was a possibility that time information not related to measurement data might be displayed depending on the startup environment in the measurement data download screen (Fig. 6). Specifically, by adjusting the time of Raspberry Pi with the FPGA on the baseboard, improvements were made so that the correct time information of the measurement data is displayed regardless of the activation environment. However, even without this improvement, there is no effect on the high precision time information recorded in the measurement data.

### D. Correction of PTP Control Software

The Precision Time Protocol (PTP) defined in the IEEE-1588 standard is a means to synchronize time of computers on a LAN highly accurately. The CSAC is a high precision clock, but it does not keep absolute time information. Therefore, clock adjustment was made with the CSAC and then the absolute time was set to the timer counter of the FPGA by the PTP in the practical device as described in detail in Section VI.



Index of /data/

| Name of data file | Time information | |
|---|---|---|
| ../ | | |
| 2017-01-30-102904#3axis~20170130012903@d000AA30..> | 30-Jan-2017 01:37 | 9087133 |
| 2017-01-30-103804#3axis~20170130013802@d000AA30..> | 30-Jan-2017 01:43 | 6032396 |
| 2017-01-30-105114#3axis~20170130015113@d000AA30..> | 30-Jan-2017 01:59 | 9303844 |
| 2017-01-30-110413#3axis~20170130020411@d000AA30..> | 30-Jan-2017 02:14 | 10756134 |
| 2017-01-30-113213#3axis~20170130023212@d000AA30..> | 30-Jan-2017 02:33 | 1039667 |
| 2017-01-30-113733#3axis~20170130023732@d000AA30..> | 30-Jan-2017 02:38 | 34559 |
| 2017-01-30-113853#3axis~20170130023851@d000AA30..> | 30-Jan-2017 02:39 | 333152 |
| 2017-01-30-114535#3axis~20170130024505@d000AA30..> | 30-Jan-2017 02:46 | 829093 |
| 2017-01-30-115322#3axis~20170130025228@d000AA30..> | 30-Jan-2017 02:54 | 901071 |
| 2017-01-30-115829#3axis~20170130025719@d000AA30..> | 30-Jan-2017 02:59 | 973035 |
| 2017-01-30-120307#3axis~20170130030154@d000AA30..> | 30-Jan-2017 03:04 | 1026851 |
| 2017-01-30-120727#3axis~20170130030622@d000AA30..> | 30-Jan-2017 03:08 | 1172387 |
| 2017-01-30-121119#3axis~20170130031007@d000AA30..> | 30-Jan-2017 03:12 | 1189502 |
| 2017-01-30-121516#3axis~20170130031412@d000AA30..> | 30-Jan-2017 03:16 | 1026745 |
| 2017-01-30-140730#3axis~20170130050729@d000AA30..> | 30-Jan-2017 05:16 | 9730960 |
| 2017-01-30-142043#3axis~20170130052042@d000AA30..> | 30-Jan-2017 05:31 | 11002229 |
| 2017-01-30-143839#3axis~20170130053707@d000AA30..> | 30-Jan-2017 05:39 | 855371 |
| 2017-01-30-145355#3axis~20170130055242@d000AA30..> | 30-Jan-2017 05:54 | 766303 |
| 2017-01-30-145841#3axis~20170130055717@d000AA30..> | 30-Jan-2017 05:59 | 872335 |
| 2017-01-30-150451#3axis~20170130060349@d000AA30..> | 30-Jan-2017 06:05 | 962962 |
| 2017-01-30-150920#3axis~20170130060818@d000AA30..> | 30-Jan-2017 06:10 | 1016060 |
| 2017-01-30-151350#3axis~20170130061244@d000AA30..> | 30-Jan-2017 06:15 | 1157205 |
| 2017-01-30-151843#3axis~20170130061736@d000AA30..> | 30-Jan-2017 06:20 | 1194508 |
| 2017-02-01-144818#3axis~20170201054719@d000AA30..> | 01-Feb-2017 05:55 | 6500860 |
| 2017-02-01-145618#3axis~20170201055616@d000AA30..> | 01-Feb-2017 06:06 | 10733269 |

Figure 6. Local PC collecting tool display screen.

In the actual work at the bridge, there was a risk that the absolute time set by the PTP may be initialized due to plugging and unplugging of the LAN cable. Such phenomenon is not desirable for the practical device although it follows the standard implementation and specifications of Linux as the PTP must be operated with a LAN cable connected. Therefore, the settings were corrected so that the absolute time would not be initialized and would be kept between two practical devices (master device and slave device) whose absolute time had been set by the PTP even if the Ethernet cable was plugged and unplugged.

### E. Minimization of Wiring Delay in the FPGA

Depending on the circuit design of the FPGA, the time stamping may not be correctly recorded due to fluctuation of timing to read and write the memory from the FPGA. The wiring delay of the SDRAM control signal in the FPGA was minimized so that the timing to read and write the memory from the FPGA would not fluctuate. The FPGA circuit was redesigned and implemented in the new practical sensor device. It was confirmed that the continuous operation test for 2 months was conducted for the four devices and the time information was correctly displayed.

## VI. Time Synchronization Procedure among Practical Devices

There are two methods for absolute time synchronization to the practical devices. The first is to synchronize each practical device directly with GPS by absolute time. The second is to synchronize one device (master device) with absolute time by GPS. Thereafter, other devices (slave devices) are synchronized by the master device. For practical reasons, the second method is usually used. The procedure is shown in Fig. 7 and the details are shown below.

In this system, the signal source for clock adjustment and for absolute time definition are called “clock source” and “time source”, respectively. Also, there are “time constant” for determining the follow-up speed to the signal source as parameters related to clock adjustment, and “absolute time synchronization interval” for indicating absolute time synchronization execution as parameters related to the absolute time synchronization.

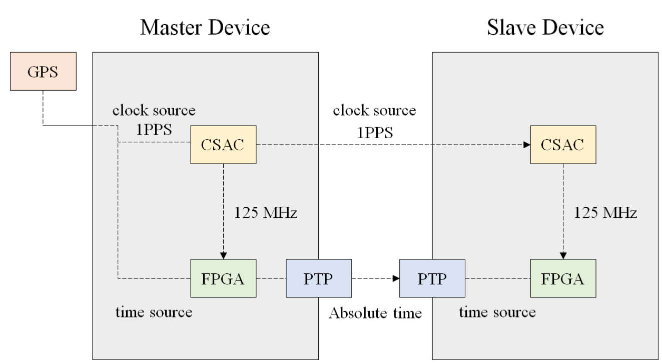



Figure 7. Time Synchronization Procedure among Practical Devices.

### A. Time Synchronization of Master Device

When synchronizing the master device to the absolute time, GPS is used as clock source and time source. Clock adjustment and absolute time definition are performed according to preset time constant and absolute time synchronization interval. By receiving the GPS signal, the master device maintains high clock accuracy and absolute time accuracy. The time constant and absolute time synchronization interval are set to 1,000 seconds and 1,440 seconds, respectively. The absolute time is synchronized with the FPGA timer counter at the time interval set on the basis of 0:00:00 on the day on which this setting was made.

### B. Time Synchronization of Slave Device by Master Device

Clock adjustment of the CSAC of the slave device is performed by utilizing the 1 PPS output of the CSAC of the master device. When the clock adjustment of the CSAC of the slave device is completed, the absolute time is set to the timer counter of the FPGA by the PTP. When absolute time setting by the PTP is completed, more precise time synchronization (less than a second) is performed by using the 1 PPS input of CSAC of the master device again.

## VII. Communication of Sensor Data of Practical Device

The practical device sends the measurement data via Ethernet or wireless communication to the server on the cloud by "fluentd" after saving data in an SD card as shown in Fig. 8. Fluentd is an open source software called a data collector or data log collection tool, and it provides a function to collect log data and convert it to JavaScript Object Notation (JSON) and output it. JSON is one of lightweight data description languages and is designed to be used for passing data between various software and programming languages. "Input function" and "output function" are modularized, and by adding a plug-in module, fluentd can correspond to various data sources and output destinations. Data in the JSON structure in a format conforming to fluentd is transmitted in a binary MessagePack. The continuity and loss of measurement data can be confirmed by sampling period and time stamp. In addition, tag of the data is updated at the start of measurement or at the time of event detection at the date, hour, minute, and second as an identifier for one measurement, and the same tag is given after the end of measurement or the event.

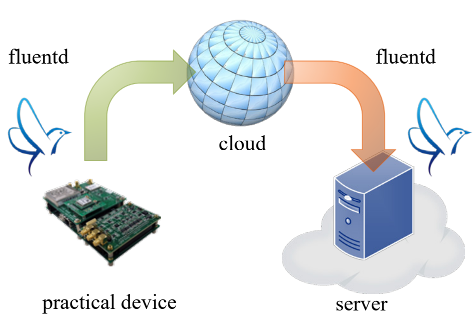



Figure 8. Data transmission from device to server by fluentd.

## VIII. Application to Actural Building

The developed practical devices were installed in an actual building and seismic observation started in October 2017. The building is a three-story reinforced concrete building built in Tsukuba, Ibaraki, Japan (Fig. 9). In each floor, one practical device was installed. Fig. 10 shows the plan of 2nd floor of the building and locations of the practical devices installed. Fig. 11 shows how the devices have been installed. As shown in both figures, dedicated installation space was made next to the staircase from 1st to 3rd floors. At each installation location, the device was screwed to the acrylic plate and it was fixed to the floor with an anchor. The device for the rooftop is fixed on the ceiling of the 3rd floor because the rooftop floor is outside.

The sensor device is able to use the built-in MEMS accelerometer and any analog sensor connected to the external input terminal solely. The device is set to use the built-in MEMS accelerometer. Table IV shows the specifications of the MEMS accelerometer. Because of the excellent noise performance of the built-in MEMS, it is possible to measure building vibrations from small earthquakes as well as large ones. This new practical device can detect earthquake occurrence and save seismic event data. The least square calculation for values measured by the accelerometer in each direction is derived by the following equation.

$$l_{\mathrm{r}} = \sqrt{\frac{1}{N}\sum_{i=N-1}^{0}\{(x_i - r_{xi})^2 + \left(y_i - r_{yi}\right)^2 + (z_i - r_{zi})^2\}}$$

where, $r_x, r_y, r_z$ are correction values of the following zero point.

$$r_x = \frac{1}{N}\sum_{i=N-1}^{0} x_i,\ \ r_y = \frac{1}{N}\sum_{i=N-1}^{0} y_i,\ \ r_z = \frac{1}{N}\sum_{i=N-1}^{0} z_i$$

Figure 9. External appearance of building.

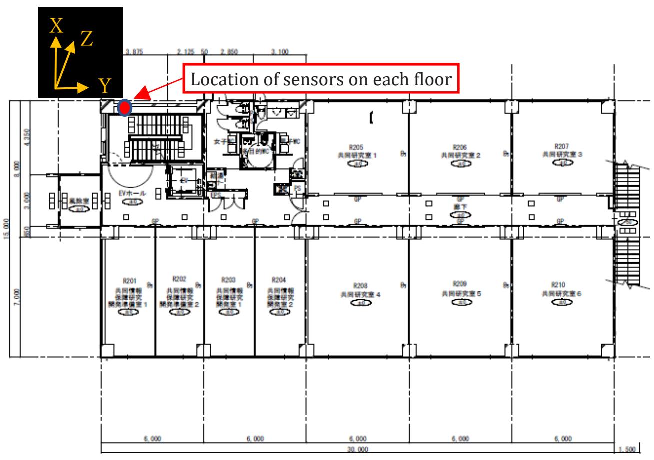



Figure 10. Plan view of 2nd floor of the building and locations of practical device installed.

The device was set to judge that an earthquake has occurred when the least square value $l_r$ for 2 seconds exceeds 1 cm/sec$^2$ and to save the measurement data until the earthquake ends under the condition of a sampling frequency of 100 Hz and a number of correction values of zero point N = 200 in the above equation. The device also saves data 10 seconds before the point that the device judged that the earthquake has occurred and 10 seconds after the earthquake has ended. As shown in Section III, each practical device is equipped with Ethernet, Wi-Fi, and 3G as communication means and can use any of them. For this time, it was decided to use 3G for data transfer to the data server in order to store only the measurement data at the event of the earthquake.

Table V shows a list of seismic records observed from October 2017 when the system was installed to November 2017. When an earthquake with Japanese seismic intensity scale of 1 or more occurred, measurements were made reliably. Figs. 12 and 13 show measured acceleration of an earthquake in the building, which occurred on November 3, 2017 (No. 8 in Table V).

TABLE IV. SPECIFICATIONS OF MEMS ACCELERATION SENSOR

| | |
|---|---|
| Model | LIS344ALH |
| Measurement direction | 3 |
| Maximum acceleration (± G) | 2 |
| Outside dimensions (mm) | 4 × 4 × 1.5 |
| Consumption current (mA) | 0.68 |
| Stand-by power consumption (µA) | 1 |
| Detection sensitivity | 660 mV/G ± 5% |
| Noise characteristics | 50 µG/√Hz |
| Operating temperature (°C) | -40 - +85 |

(a) Ceiling of 3rd floor (Floor of rooftop)

(b) Floor of 1st floor

Figure 11. Photo of how practical devices are installed.

TABLE V. LIST OF EARTHQUAKE RECORD MEASURED BY PRACTICAL DEVICES

| No | Date | Time | Name of Epicenter | Magnitude/ Depth(km) | Local/Max . Intensity |
|---|---|---|---|---|---|
| 1 | 06/10/2017 | 16:59 | Fukushimaken-oki | 6.3/57 | 1/2 |
| 2 | 06/10/2017 | 23:56 | Fukushimaken-oki | 5.9/53 | 2/5 lower |
| 3 | 07/10/2017 | 16:20 | Ibarakiken-nanbu | 3.4/43 | 1/1 |
| 4 | 12/10/2017 | 15:12 | Fukushimaken-oki | 5.2/26 | 1/2 |
| 5 | 15/10/2017 | 19:05 | Ibarakiken-hokubu | 3.0/7 | 1/1 |
| 6 | 18/10/2017 | 07:40 | Ibarakiken-nanbu | 3.7/45 | 1/2 |
| 7 | 02/11/2017 | 22:31 | Ibarakiken-oki | 4.3/74 | 1/3 |
| **8** | **03/11/2017** | **21:38** | **Ibarakiken-hokubu** | **4.8/8** | **2/3** |
| 9 | 05/11/2017 | 17:40 | Ibarakiken-nanbu | 2.9/43 | 1/1 |
| 10 | 15/11/2017 | 01:21 | Ibarakiken-nanbu | 3.8/20 | 1/2 |
| 11 | 26/11/2017 | 15:55 | Ibarakiken-hokubu | 3.9/4 | 1/2 |
| 12 | 30/11/2017 | 22:02 | Ibarakiken-naubu | 3.9/42 | 1/3 |

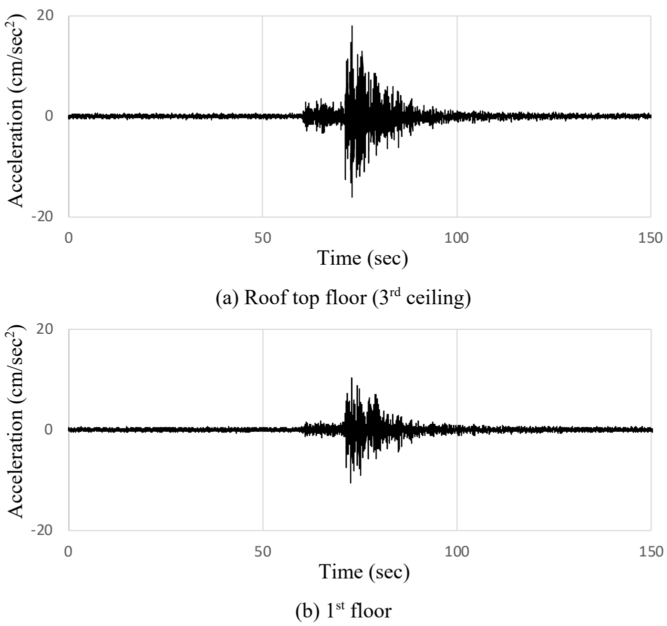



Figure 12. Measured acceleration data (X direction).

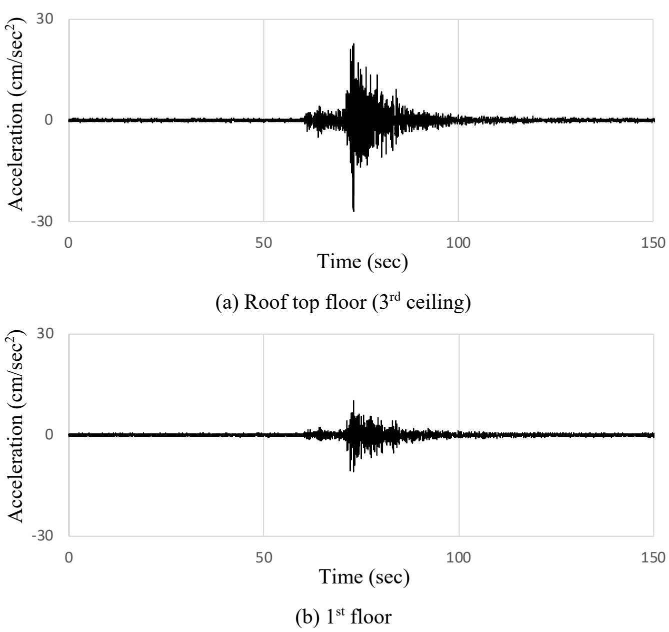



Figure 13. Measured acceleration data (Y direction).

Figs. 12 and 13 show measured results of the 1st floor and the 3rd ceiling (floor of the rooftop) in a horizontal direction X and Y, respectively. For the 1st floor, an acceleration of 10.2 cm/sec$^2$ in X direction and 10.0 cm/sec$^2$ in Y direction at the maximum are observed. For the rooftop, the vibration of the earthquake is amplified and the maximum value of the acceleration is greater. The acceleration amplification factor of rooftop floor for the first floor is about 1.8 times in the X direction and about 2.2 in the Y direction.

Fig. 14 shows a Fourier spectrum of acceleration on the first floor. That is the acceleration of the seismic motion itself which is the input to the building. From this figure, dominant frequencies are observed at 2.4 Hz and 2.9 Hz in the X direction and 3.9 Hz in the Y direction. Figs. 15 and 16 show a transfer function (Fourier spectrum ratio) of the acceleration of each floor with respect to the first floor. Figs. 15 and 16 show the X direction and the Y direction components, respectively. By calculating the transfer function of each floor, it is possible to eliminate the influence of the frequency component of the seismic wave and observe only the dynamic characteristics of the building. It can be confirmed from the figure that the primary natural frequencies in the X direction and the Y direction are around 4.5 Hz and 5.5 Hz, respectively. Observation of the primary natural frequency is important for the structural health monitoring of buildings. If it moves to a lower frequency after the earthquake, it means that the stiffness of the building's structural member has decreased and the building has been damaged.

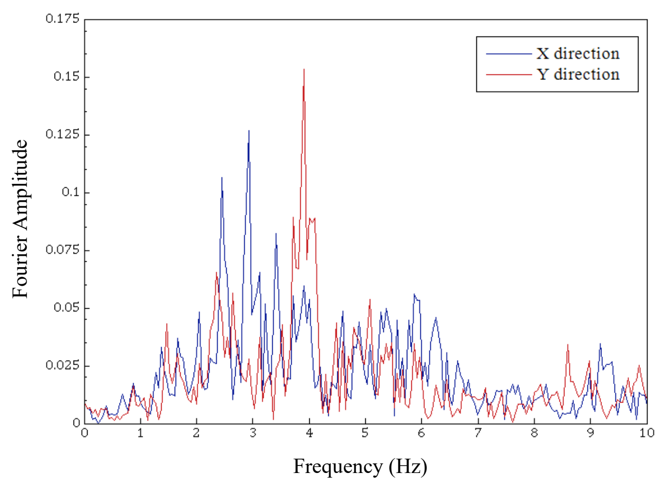



Figure 14. Fourier spectrum of acceleration on 1st floor.

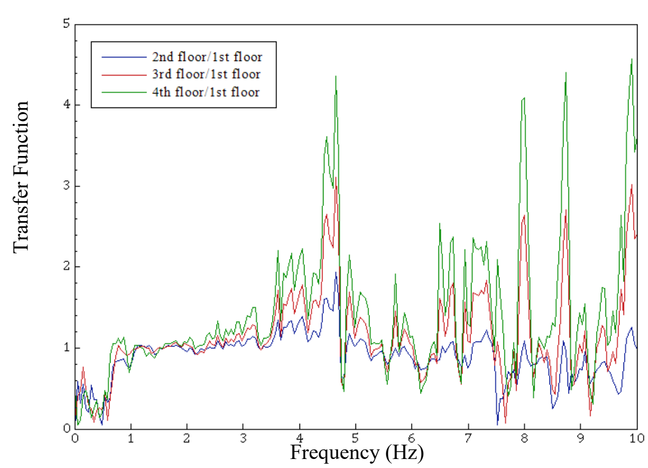



Figure 15. Acceleration of each floor relative to the first floor in X dir.

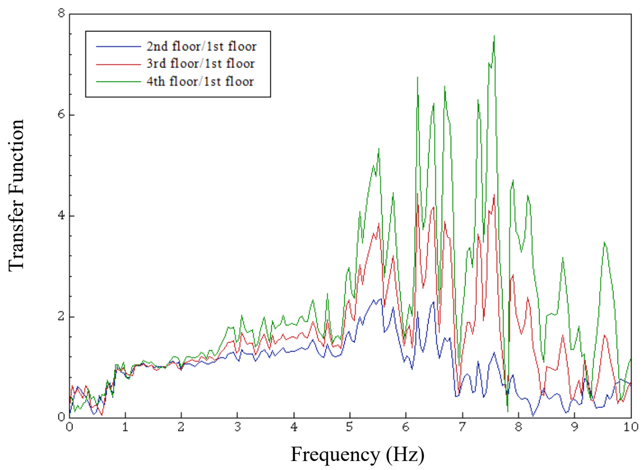



Figure 16. Acceleration of each floor relative to the first floor in Y dir.

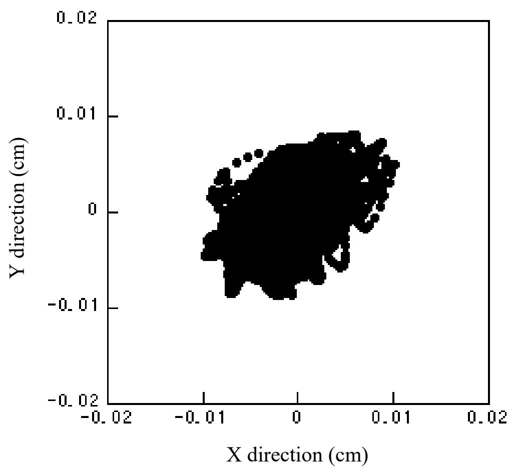



Figure 17. Inter-story displacement (3rd story).

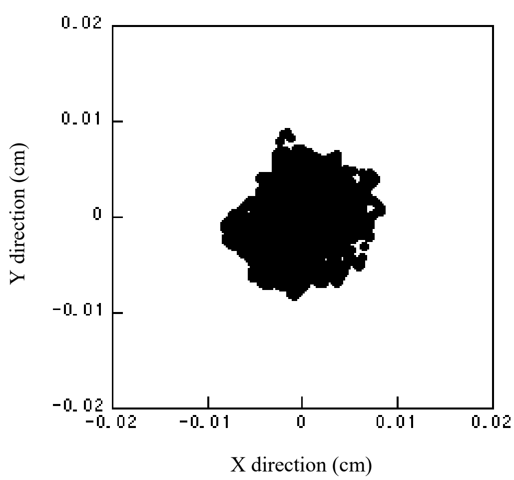



Figure 18. Inter-story displacement (2nd story).

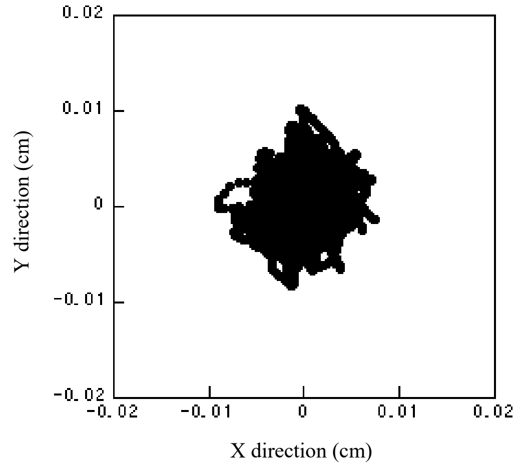



Figure 19. Inter-story deformation (1st story).

Even if many sensors are installed in a building, analysis to evaluate the structural health of the building cannot be performed unless time synchronization between the sensors is secured [19]. Structural health of the building after the earthquake can be evaluated by the amount of deformation of each inter-story by the earthquake. Therefore, in order to evaluate the damage of the building in more detail, the inter-story deformation at each floor must be calculated. The displacement of each floor is calculated by double integration of the measured acceleration. Since time synchronization is ensured for the measurement data of this practical devices, the deformation of each inter-story can be calculated by subtracting the displacement of the upper floor and the lower floor. The value obtained by dividing the inter-story deformation of the building by the floor height is defined as the inter-story deformation angle. The maximum inter-story deformation angle during the earthquake and the damage of the building have the following relation. If the maximum inter-story deformation angle of the building during the earthquake is within 1/200, the building is assumed to be undamaged. The possibility of damage is high if it exceeds 1/100. Figs. 17, 18 and 19 show calculated inter-story deformation of the third, the second, and the first story of the building, respectively. Since the floor height of the targeted building is 380 cm to 390 cm, the inter-story deformation angle of 1/200 means an inter-story deformation of 1.9 cm to 1.95 cm. Since the inter-story deformation shown in Figs. 17, 18 and 19 is much smaller in both the X and Y directions, it can be evaluated that the building is undamaged against this earthquake.

Function and usability of the improved practical device, which was installed onto an actual building, were verified by the case study of seismic observation and structural health monitoring. In particular, such structural health monitoring of the building was made possible by the practical device developed in this research securing autonomous time synchronization.

## IX. Conclusion

This paper describes research and development on the sensor devices that can keep highly accurate time information autonomously using the built-in Chip Scale Atomic Clock (CSAC) for the purpose of application to seismic observation and structural health monitoring of buildings and civil infrastructure. First, a process of development was explained from the prototype, which uses the mechanism that adds highly accurate time information to the measured data with the CSAC to the practical device. Then, challenges in practical use were identified by the long-term measurement implemented by installing the developed practical device onto a bridge. Based on the challenges, further improvements were made for stability and operability of the practical device, and its performance was confirmed. A new procedure for time synchronization between devices and the communication system of measurement data newly constructed using "fluentd" which is open source software for data collection were detailed. In addition, the improved practical device was installed onto an actual building, and its function and usability were verified by the case study of seismic observation and structural health monitoring. Finally, structural health monitoring of the building based on the evaluation by the inter-story deformation was made possible by the improved practical device developed in this research securing autonomous time synchronization.

As one of challenges, the operating method of the sensing system must be considered depending on the objective of measurement because the CSAC is aged over time although it is a highly accurate clock. Another challenge is the high cost of manufacture. The CSAC is expected to be mounted on all computers and smart phones in the near future, but only one American company manufactures and sells it at this time. It is expected that many companies will also participate in the business, and CSACs are actively used in various fields. Further verification will be performed by using the sensing system in actual buildings and civil infrastructures.

## Acknowledgment

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