Performance Evaluation of High-Accuracy Time Synchronization Sensor Device Using Indoor GNSS Time Information Delivery System for Structural Health Monitoring of Buildings and Civil Infrastructures

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***Abstract*—The purpose of this research and development is to realize structural health monitoring for increased efficiency in the maintenance of buildings and civil infrastructures, and observations to prepare for natural disasters, such as earthquakes. The most difficult and interesting issue is the realization of inexpensive time-synchronized measurements. It is necessary to install numerous sensors in a building or civil infrastructure and to acquire measured data whose time synchronization is ensured. Although Global Navigation Satellite System (GNSS) time information is generally only available outdoors, the authors designed a system capable of using GNSS time information indoors. This system can deliver time information to a building by using existing TV coaxial cables. The authors further developed a sensor device able to receive indoor GNSS time information and to add high-accuracy time information to measured data. This paper describes the development of a sensor device that adds high-accuracy time information to measured data by using a system to deliver GNSS time information indoors. The performance of the developed sensor device equipped with a mechanism for receiving GNSS signal-based time information was verified from the results of a shaking table experiment. It was shown that it can be applied to structural health monitoring of buildings and civil infrastructure and seismic observation.**

Keywords; time synchronization; GNSS; structural health monitoring; earthquake observation.

I. Introduction

Japan has suffered serious damage from natural disasters, such as the Great Hanshin Earthquake and the Great East Japan Earthquake. While technologies are being developed to reduce damage at the time of a disaster, one of the most important issue to be addressed is the automation of operations, such as the structural health evaluation of buildings and civil infrastructures after earthquakes, and assessments of damage situation of cities. Because structures, such as houses and other buildings and infrastructures, such as expressways and bridges have deteriorated over time, the automation of inspection for their maintenance is an urgent social issue. To automate such inspection and error detection, data collection is required, using sensors. In order to analyze the data collected by the sensors and so evaluate the structural health of buildings and civil infrastructures, time synchronization between the sensors must be ensured.

In general, dedicated wiring or a wired or wireless network is used to ensure time synchronization for the sensors installed in a building or other structure. Installing wiring over multiple stories of a building is neither easy nor cheap. Because space for wiring and locations for sensors are limited, it is virtually impossible to install sensors in arbitrary locations inside a building. When a wireless network is used, wiring is no longer required. The application of a wireless network is therefore being anticipated now. Applying wireless sensor network technology, the authors developed a sensor device specifically for structural health monitoring and earthquake observations, and verified its performance in a skyscraper [1]–[3]. In a wireless sensor network system, time synchronization was realized through the transmission and reception of wireless packets between sensors [3]. However, with wireless sensor network technology, it is impossible to cover every floor of a skyscraper, or a long structure, such as a bridge, or an extensive area of a city.

Despite these limitations, the problem can be solved fundamentally if the sensors installed in various locations can autonomously hold accurate time information. Using a clock of ultra-high accuracy, namely a Chip Scale Atomic Clock (CSAC) [4]–[6], whose delay time is radically short compared to other devices, such as crystal resonators, a prototype was manufactured of a sensor device that

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autonomously holds accurate time information [7][8]. Improvements were then made to develop and commercialize the prototype, and a sensor device for practical use was developed [9]. In order to apply the developed sensor device to earthquake observations, a logic was implemented to detect the occurrence of an earthquake and store data of an earthquake event only. The functioning of the logic was checked by a shaking table experiment [10] and the logic was applied to an actual building [11]. The sensor device's ability to autonomously hold accurate time information was confirmed, and it was shown that it could be applied to such operations as structural health monitoring and earthquake observations. Autonomous time synchronization sensing using CSAC is the most effective method. In addition, research into and development of a miniature and inexpensive CSAC is underway, and it is expected that a CSAC that can be mounted in a smart phone will be realized. However, the CSAC available at present is quite expensive, which hinders its widespread use.

For a device, such as a sensor to acquire high-accuracy time information, a Global Navigation Satellite System (GNSS) can be used. A GNSS, such as the Global Positioning System (GPS), Global Navigation Satellite System (GLONASS), or Galileo Satellite Navigation Network (Galileo), measures positions and delivers time information by using signals emitted by satellites. A sensor with a mechanism capable of receiving GNSS signals can add high-accuracy time information to measured data. However, GNSS signals are available only in outdoor places where satellites are not blocked from view. Sensors installed inside a building cannot use GNSS signals. For that reason, the authors designed a system in which signals acquired from an antenna installed on the roof of a building are delivered indoors; GNSS signals can then be used indoors as well as outdoors. The authors also developed a sensor device able to receive indoor GNSS signals, and equipped it with a Micro Electro Mechanical System (MEMS) acceleration sensor.

In Section II of this paper, previous researches into time synchronization methods are described, to show the originality of this research. Section III describes the system for delivering GNSS signals indoors. Section IV describes in detail the development of a sensor device with a mechanism for receiving GNSS signal-based time information. Section V describes a shaking table experiment conducted to check the performance of the developed sensor device, and shows that good acceleration measurement and high-accuracy time synchronization between sensors could be realized.

II. State of the Art

A time synchronization function must be provided to sensor devices to be used in the structural health monitoring of buildings and civil infrastructure, or for earthquake observations. If time-synchronized data sets are not acquired, time series analysis using phase information cannot be performed. For example, it will then not be possible to perform a mode analysis of a structure, or analysis for structural health evaluation, or a wave propagation analysis of seismic waves traveling through the Earth's layers. Many previous studies have been conducted of time synchronization sensing, such as the use of GNSS signals using satellites, and the Network Time Protocol (NTP) intended for time synchronization on the Internet [12]. In addition, as a technology for realizing high-accuracy time synchronization indoors, there is the IEEE 1588 Precision Time Protocol (PTP). In PTP, with an Ethernet cable used for a common Local Area Network (LAN) and others set as a transmission path, a synchronization accuracy is realized of one microsecond or less, using time packets. However, when affected by fluctuations of packet delay or by packet loss due to congestion in a LAN, PTP has difficulty in providing a stable synchronization accuracy. PTP also faces multiple other problems due to the amount of delay being corrected by exchanging packets, such as the limited number of PTP devices that can be connected to the master station, and PTP not being deployable under a Wide Area Network (WAN), in which the amount of delay fluctuates greatly. Some studies realized time synchronization by making use of the wireless sensor network characteristic of small propagation delay. For example, time synchronization protocols, such as Reference Broadcast Synchronization (RBS), Timing-sync Protocol for Sensor Networks (TPSN), and Flooding Time Synchronization Protocol (FTSP) are being studied [13]–[15]. Although these technologies are used for many purposes, they are not the most appropriate method for sensor devices used to monitor the structural health of buildings and civil infrastructures, or earthquake observations. To be specific, as mentioned previously, GNSS signals can be used outdoors only, and the NTP's time synchronization accuracy is not adequate. A time synchronization method using wireless technology is highly convenient, but does not guarantee that wireless communication is always possible. In particular, if wireless communication ceases when an earthquake occurs, it becomes impossible to perform sensing with time synchronization ensured.

In this research, the authors developed a sensor device that retains accurate time information, based on a system capable of using GNSS signals indoors. Even when a huge number of sensors are installed in a building, provided accurate time information can be added to data measured by each sensor based on indoor GNSS signals, time synchronization between sensor data can be ensured simply by collecting data by any method and sorting it by using the time information. Data sets whose time synchronization is ensured by the sensor device developed in this research can be used for analysis of the structural health of buildings and civil infrastructures, or the earthquake observation.

III. Indoor GNSS Time Information Delivery System

Time synchronization using GNSS, of high accuracy and over a vast area, is widely used in mobile communications. For positioning by GNSS, clock synchronization between GNSS satellites and a GNSS receiver is required, which makes it possible to measure the distance between each satellite and a receiver. In other words, positioning using GNSS is realized by highly accurate synchronizing of the controlled atomic clocks mounted in each artificial satellite orbiting the Earth and the clock of a GNSS receiver on the ground. First, the distance (pseudo-distance) between each satellite and the relevant receiver is measured. A pseudo-distance can be obtained by measuring the difference between the time a signal departs from each satellite and the time the receiver receives it. An atomic clock is mounted on the GNSS satellite side, so that the time of day is always kept with high accuracy. The clock of the GNSS receiver is inexpensive, and is synchronized with the satellite time. After the clock synchronization is completed, the use of only one satellite is sufficient for acquiring the time. From the GNSS receiver, Pulse Per Second (PPS) signals are output based on the timing of satellite synchronization.

In an environment where GNSS signals can be received, the GNSS receiver can perform high-accuracy time synchronization and positioning, but cannot be used in an indoor area where GNSS signals cannot be delivered. The authors designed an indoor GNSS time information delivery system that realizes high-accuracy time synchronization by delivering GNSS signals indoors. Specifically, GNSS signals are received on the roof of a building, and delivered as broadcasting into the building by using the transmission path of an existing system, such as a common antenna TV system or cable TV system. A transmitter is installed at any location from which the delivery of GNSS signals into the building is desired, and the signals are sent. The GNSS receiver receiving these signals reads position and time information and outputs high-accuracy synchronization signals (PPS signals). By mounting a GNSS receiver on each sensor device and implementing a mechanism to add high-accuracy time stamps to measured data, it becomes possible to collect data sets whose high-accuracy time synchronization is ensured from indoors. Measured data with accurate time stamps added can be grouped into data sets whose time synchronization is ensured simply by collecting data by any method, such as 3G, 4G, 5G, Wi-Fi, and Ethernet.

The transmission path of a CATV system or cable TV system in a building is used to deliver indoors high-accuracy times synchronized with GNSS satellites. As shown in Figure 1, an indoor GNSS time information delivery system consists of D1 on the roof, D2 inside the building, and D3 at the terminal (a transmitter for delivering GNSS time information indoors). D1 shown in Figure 1 receives a signal from the GNSS satellite, frequency-converts the synchronized time signal, and transmits it into the building. D2 receives time signals from D1 and demodulates them into high-accuracy time synchronization signals (PPS signals). D3 receives data from D2, adjusts the timing, and sends time information to a sensor device. Time information sent from D3 is received by a sensor device to add high-accuracy time information to measured data. By using a hub, it is possible to connect multiple D3s under D2. In addition, by incorporating the transmission function of D3 into D2, space can be saved.

IV. DEVELOPMENT OF SENSER DEVICE ABLE TO RECEIVE INDOOR GNSS SIGNALS

Structural health monitoring of buildings and civil infrastructure is evaluated by analyzing acceleration data from sensor devices that ensure time synchronization. Structural health and damage after an earthquake can be detected by analyzing changes in the natural frequency of the structure and inter-story deformation of the building. A sensor device normally consists of components, such as a CPU that controls measurement, an analog sensor, analog filter, A/D converter, memory, and network interface. In this development, to reduce the risk that noise will enter during measurement, a sensor device was developed with a digital sensor mounted on it instead of an analog sensor. Tables I and II show the specifications of the sensor device and the mounted digital three-axis MEMS acceleration sensor, respectively. The acceleration sensor is a low-noise and low power consumption type, capable of high-resolution vibration measurement. Furthermore, minimal offset drift over temperature, and long-term stability enabling precision applications with minimal calibration are provided.

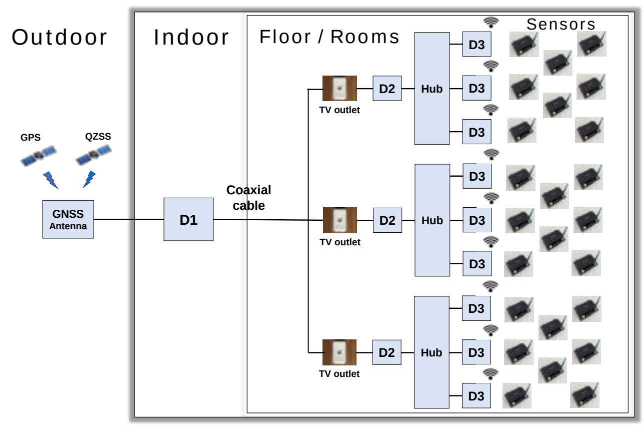


Figure 1. System configuration.

TABLE I. SPECIFICATION OF SENSOR DEVICE

GNSS module	FURUNO/GF-8801
Frequency	1555.983-1610.202 MHz
Center frequency	1597.926 MHz
FGGA/CPU	Zynq2 (CPU Dual-core ARM Cortex-A9)
RAM	SDRAM 512Mbyte
ROM	Serial-FLASH 128Mbyte × 2
Power supply	14 W (Typ.)
Size	102（W）× 172.5（D）× 40（H）
Weight	1.65 kg

TABLE II. SPECIFICATION OF MEMS ACCELERATION SENSOR

Model	ADXL355
Measurement direction	3
Maximum acceleration (± G)	2
Outside dimensions (mm)	6 × 6 × 2.1
Consumption current (μA)	200
Stand-by power consumption (μA)	21
Sensitivity	256,000 LSB/G ± 8%
Noise characteristics	22.5 μG/√Hz
ADC Resolution	20 Bits
Operating temperature Range (°C)	-40 - +125

A crystal oscillator is used for the CPU of the general sensor device. However, when an attempt is made to receive indoor GNSS signals and perform measurement while correcting the time information of the CPU, a delay occurs because the clock accuracy is too high. Therefore, in order to add GNSS signal-based time information directly to data measured by a sensor through hardware, the authors developed a mechanism equipped with a dedicated integrated circuit, a Field-Programmable Gate Array (FPGA), to manufacture a sensor device. Because an FPGA is programmable, it is also possible to embed logic for an operation, such as earthquake detection using measured data, while adding GNSS signal-based time information to measured data.

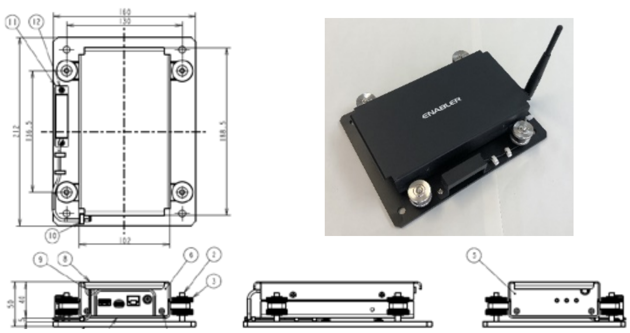


Figure 2. Sensor device.

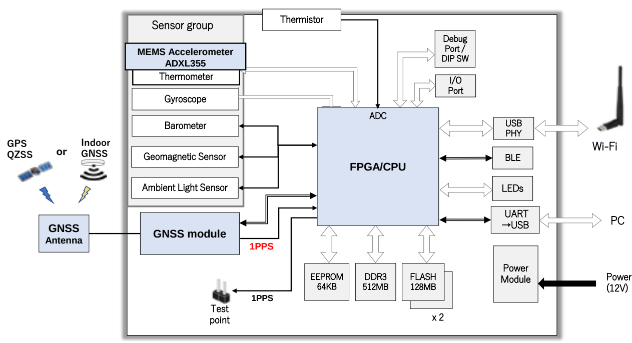


Figure 3. Hardware block diagram.

The sensor device consists of such components as a GNSS receiver, FPGA, CPU, memory, local storage, and network interface. The FPGA controls the sensor's measurement while generating time stamps using GNSS signal-based ultra-high accuracy time information. Measured data is stored in the memory, then sent to the network via Ethernet or wireless communication. Data can be collected using a wired or wireless method. Figures. 2 and 3 show details of the sensor device.

V. PERFORMANCE EVALUATION OF THE SENSOR DEVICE ABLE TO RECEIVE INDOOR GNSS TIME INFORMATION

A shaking table experiment was conducted to evaluate the measurement performance and time synchronization performance of the sensor device developed in Section IV. During the shaking table experiment, measurement was performed with the digital three-axis MEMS acceleration sensor incorporated in each sensor device. Figure 4 gives an overall view of the experiment system. A red circle indicates the indoor GNSS time information delivery system, a yellow circle indicates the sensor device and shaking table, and a blue circle indicates the shaking table control system. As shown in Figure 5, the indoor GNSS time information delivery system consists of D1, D2, and D3. As shown in Section III, D1 receives a signal from the GNSS satellites and frequency-converts the synchronized time signal and sends it into the building. Since the purpose of this experiment was to evaluate the performance of the sensor device, the GNSS satellite was not used, and the time signal was generated by the GNSS simulator and input to D1. D2 receives time signals from D1 and demodulates them into high-accuracy synchronization signals (PPS signals). D3 receives data from D2, adjusts the timing, and sends time information to the sensor device via the antenna in Figure 4. The sensor device receives time information sent from D3 and adds high-accuracy time information to measured data.

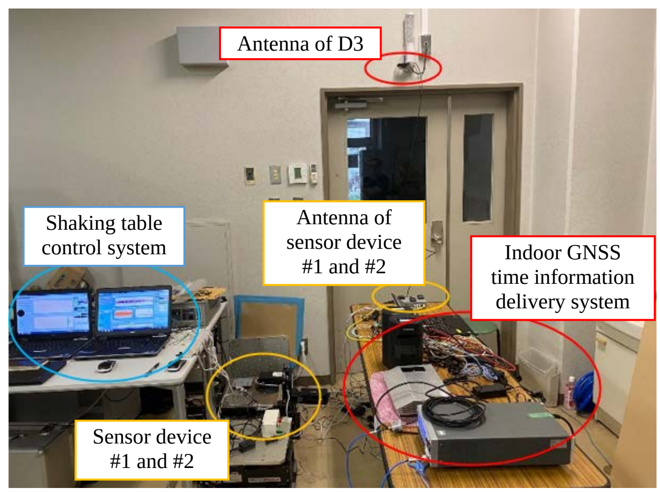


Figure 4. Overall View of Experimental System.

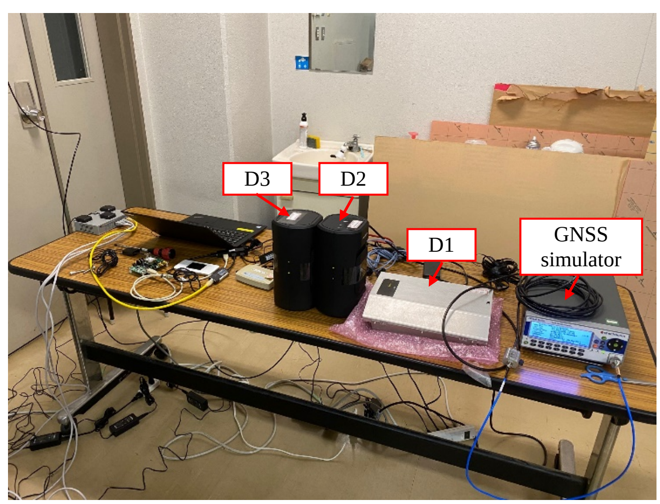


Figure 5. Indoor GNSS Time Information Delivery System.

A. *Sweep Input Experiment*

As shown in Figure 6, two sensor devices and a servo acceleration sensor for comparison were fixed to the shaking table, and the same vibration was applied to compare the results of measurement. The natural frequencies of houses, small buildings, and skyscrapers range from 0.1Hz to 10Hz. In addition, the dominant frequency of seismic motion has a similar frequency component. Therefore, the frequency band from 0.1 Hz to 10 Hz was used as the test target. Two types of input waves were prepared to vibrate with a large acceleration amplitude in each frequency band. In the experiment, 0.1–2.0 Hz and 2–10 Hz swept sine waves (Figure 7) were set as input waves to vibrate the shaking table. The measurement sampling frequency for each sensor device was set to 100 Hz.

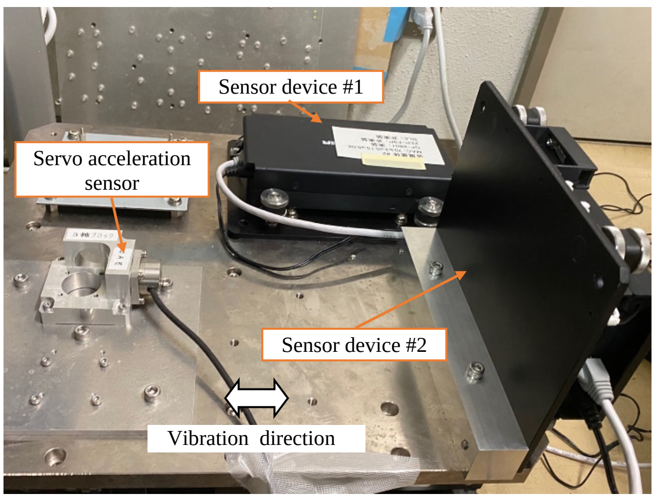
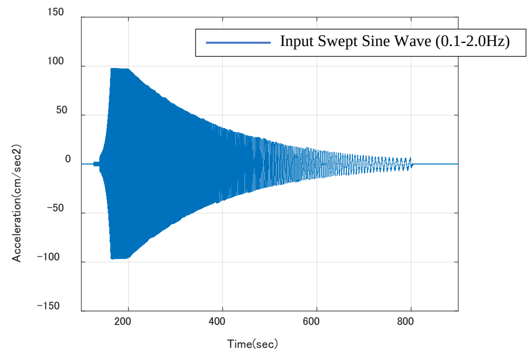
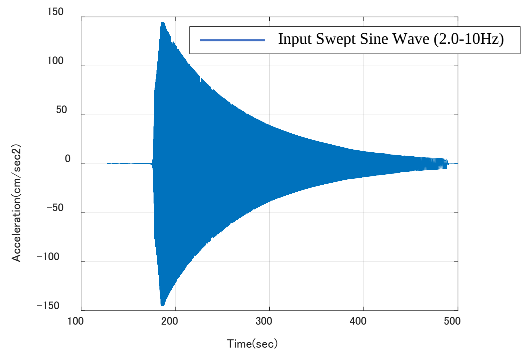


Figure 6. Sensor Device and Shaking Table.

Vibrations were applied to the horizontal direction of sensor device # 1 and the vertical direction of sensor device # 2, and measurements were taken with the sensor device and the servo-type acceleration sensor for comparison. Figure 8 shows the results of Fourier amplitude spectrum ratios calculated for acceleration waveforms measured by the sensor device #1 and the servo acceleration sensor. Compared to the servo acceleration sensor, the amplitude of the sensor device #1 was flat in the 0.1–2.0 Hz and 2–10 Hz bands, showing that the MEMS digital acceleration sensor mounted in the sensor module has good performance in terms of components in the horizontal direction. Figure 9 shows the results of Fourier phase spectrum ratios calculated for the acceleration waveforms of sensor devices #1 and #2 on the shaking table. If there is no phase delay between the sensor devices, and if time synchronization is ensured, the Fourier phase spectrum ratio must be near zero in all vibration frequency bands. In the figure, phase delays within 0.001 seconds are plotted in dotted lines. It can be seen that time synchronization within 0.001 seconds could be realized between the sensor modules.

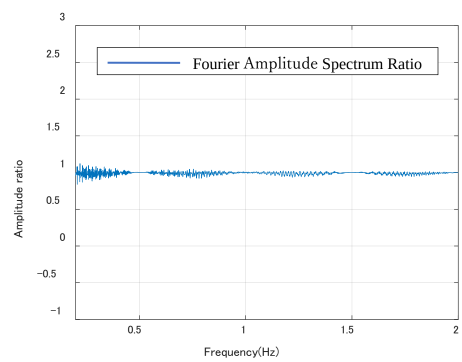


(a) 0.1-2.0 Hz

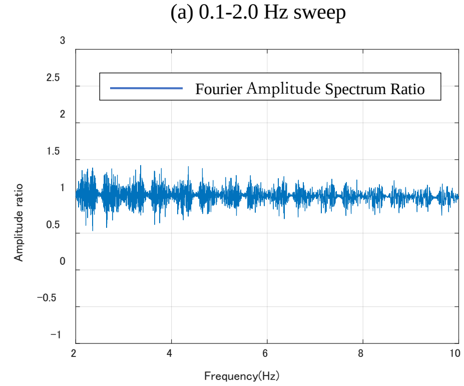


(b) 2.0-10Hz

Figure 7. Input Swept Sine Waves.

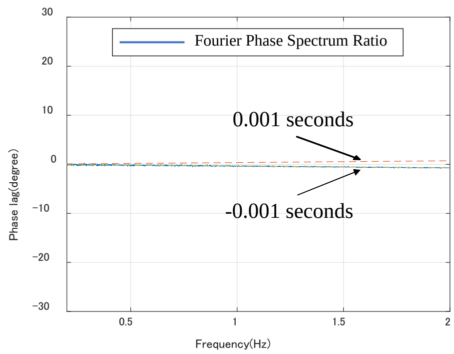


(a) 0.1-2.0 Hz sweep

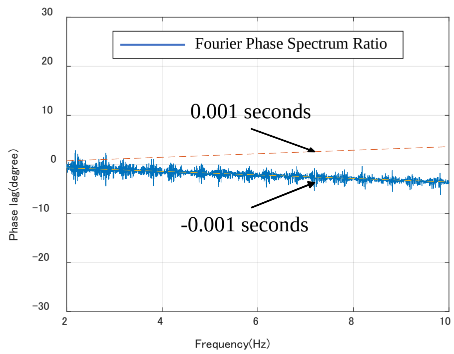


(b) 2.0-10Hz sweep

Figure 8. Fourier Amplitude Spectrum Ratios of Sensor Device #1 Compared to Servo Acceleration Sensor.



(a) 0.1-2.0 Hz sweep



(b) 2.0-10Hz sweep

Figure 9. Fourier Phase Spectrum Ratios of Sensor Device #2 Against Sensor Device #1.

B. Seismic Wave Input Experiment

In order to evaluate the measurement performance and time synchronization performance when inputting seismic waves containing random vibration frequency components, the shaking table was operated using seismic records measured at the Kobe Local Meteorological Office during the Great Hanshin Earthquake. Figure 10 shows the measured time-history waveforms of the horizontal sensor device # 1, the vertical sensor device # 2, and the servo accelerometer for comparison.

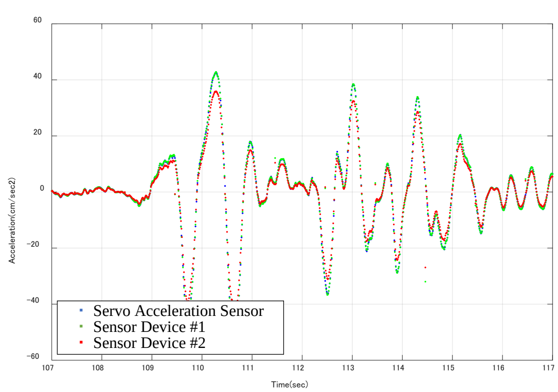


Figure 10. Seismic Wave Input Experiment.

The results in the three cases matched, confirming that the developed sensor device has a good measurement performance, equivalent to that of the servo acceleration sensor, and that time synchronization between two sensor devices was ensured.

VI. CONCLUSION

For the purpose of application to the structural health monitoring of buildings and civil infrastructures, or to earthquake observations, this paper reported a sensor device that adds high-accuracy time information to measured data by using a system to deliver indoor Global Navigation Satellite System (GNSS) time information. A system for delivering GNSS time information indoors was described first. The development of a sensor device with a mechanism for receiving GNSS signal-based time information was then explained in detail. The results of a shaking table experiment conducted to evaluate the basic performance of the sensor device were presented. From the results mentioned above, the measurement performance and time synchronization function of the developed sensor device were verified, to show that it could be applied to such automatic operations as structural health monitoring of buildings and civil infrastructures and earthquake observations. Verification using an actual building is now scheduled to be carried out.

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