Digital Sensing Platform with High Accuracy Time Synchronization Function for Management of Buildings and Cities

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***Abstract* - In this paper, a diverse and robust digital sensing platform is proposed as a practical smart sensing system for maintenance management of ageing buildings and cities. High-accuracy time information is added to measurement data to obtain sets of digital sensing data with time synchronization for use in multimodal analysis of risk. As a first step, this paper describes the development of a sensor device for performing high accuracy time synchronization sensing on civil infrastructure, such as bridges and building structures using a digital high-accuracy acceleration sensor. An ultra high-accuracy clock, such as a Chip Scale Atomic Clock (CSAC) is mounted in the sensor device, and using its time measurement accuracy, a mechanism is implemented for time stamping the output of the digital sensor. The measurement accuracy of the chip scale atomic clocks is too high, so if the CPU of the sensor device adds the time stamp, tracking cannot be performed. Therefore, a dedicated Field-Programmable Gate Array (FPGA) for adding the time stamp is provided. Tests were performed on the developed sensor device using a shaking table, and the time synchronization performance was checked by comparing the measurement results of multiple sensor devices and a servo type acceleration sensor.**

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

I. INTRODUCTION

Aging of civil infrastructure, such as bridges, expressways, and high-rise buildings, is advancing, and automation of inspection for maintenance and management of these structures is an important civil task. Also, Japan is subject to natural disasters, such as earthquakes, so it is necessary to detect the damage to structures and identify the damage status immediately after occurrence of a disaster. To automate the detection of such abnormal events, it is effective to collect and analyze data from groups of sensor devices.

The authors have developed sensor devices for earthquake observation and structural health monitoring by applying wireless sensor network technology, and have verified the performance on high-rise buildings [1][2]. One of the important tasks in this verification was time synchronization between sensor devices. Ensuring time synchronization between sensor devices is essential for analysis of sets of data measured by multiple sensor devices to evaluate the structural safety of a structure. In a wireless sensor network system, time synchronization is realized by transmitting and receiving wireless packets between the sensor devices [2]. However, wireless sensor network technology cannot cover large structures, such as buildings and bridges or a wide urban area.

On the other hand, if the sensor devices installed at the various locations can autonomously maintain accurate time information, this problem can be resolved. The use of Global Positioning System (GPS) signals is effective outdoors, but within a building, underground, on the substructure of a bridge, in a tunnel and others, this is not possible. Therefore, a prototype sensor device autonomously maintaining accurate time information using an ultra high-accuracy clock, namely a Chip Scale Atomic Clock (CSAC) [3]-[8], was produced [9][10]. Next, improvements were made to increase the performance and stability of the prototype sensor device, and a device for practical use was developed [11]. In addition, in order to apply the developed practical sensor device to earthquake observation, the logic for the detection of occurrence of earthquakes and storage of data for seismic events was implemented, and the performance was checked using shaking table tests. From these, the performance of the sensor device capable of autonomously maintaining accurate time information was confirmed, indicating that the sensor device can be applied to seismic observation and structural health monitoring of civil infrastructures and buildings. Furthermore, the developed sensor device was installed on actual buildings and bridges, and applied to seismic observation and evaluation of structural health [12]. However, a Micro Electro Mechanical Systems (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 to mount a digital acceleration sensor in the sensor device, to eliminate the risk of noise. A camera sensor can be connected to the digital sensor device described in this paper, with the aim of developing a diverse digital sensor platform.

In this paper, Section II shows the existing time synchronization methods and describes their problems and achievement of the development of the digital sensing platform proposed in this research. Section III describes the mechanism for providing ultra-high accurate time information to digital sensor data by the CSAC, and explains the configuration of the digital sensing platform and the development of the actual sensor device. Further, Section IV describes the performance confirmation tests on the time synchronization of the developed sensor device, and it is confirmed that time synchronization among the developed digital sensor devices is achieved.

II. State of the Art

Methods for ensuring time synchronization between measurement data from multiple sensors include the method of transmitting and receiving wireless packets [13][14], the method using a network, such as IEEE 1588 [15], the method using a GPS signal, and the Network Time Protocol (NTP) [4] designed for time synchronization on the Internet. However, these have the restrictions that they cannot be used without wireless communication, cable network connections, and an environment where GPS signals can be received, respectively. When sensors are installed on high-rise buildings or civil infrastructure, it is difficult to cover all the installations with a single method. For example, with the method of transmitting and receiving wireless packets, the convenience is high as cables are not required, and if a multi-hop ad hoc wireless function is implemented it is considered that this can be used on structures within a single building [2]. However, if multiple sensors are deployed over long and large structures, such as high-rise buildings and bridges or a wide area urban space, it is not possible to ensure long term stable operation with wireless technology. It is likely that the most stable system can be constructed with cable network connections, but laying dedicated cables for time synchronization is difficult from the cost point of view. Also, the method of GPS signals can be easily used outdoors, but GPS signals cannot be used in such places as indoors, on bridge substructures, underground and in tunnels.

Even if GPS signals cannot be used, wireless transmission and reception is unstable, and cable network connections are not possible, in order to stably acquire sets of sensor data with time synchronization, the ideal method is to enable each individual sensor itself to autonomously maintain accurate time information. In other words, if it is possible to add accurate time information (time stamp) to the measurement data from each sensor, sets of data with time synchronization can be acquired. Therefore, it was decided to develop a sensing system that autonomously maintains accurate time information, by applying high-accuracy clocks, namely CSAC [3]-[8]. The size of CSACs has been miniaturized so that they can be mounted in boards, and they can realize ultra high-accuracy time measurement in the order of several tens of picoseconds. Development commenced in 2001 with support from the Defense Advanced Research Projects Agency (DARPA) of the USA, and in 2011 the commercial product was put on the market. Applications include countermeasures against obstruction of GPS positioning using jamming signals, high-accuracy positioning by mounting the product in such devices as smartphones, and high-level identification of disaster status, and it is expected that the cost will be further reduced as the use spreads. The error in time measurement by CSACs is 4 to 8 orders of magnitude smaller than the error in time measurement by crystal oscillators or the error in time synchronization by NTP or GPS signals. If this CSAC is mounted in each sensor device and a mechanism for adding a high-accuracy time stamp to measurement data that is sampled individually is implemented, sets of sensor data with time synchronization can be acquired even when GPS signals cannot be used, wireless transmission and reception is unstable, and cable network connections are not possible.

In previous developments, the sensor device was equipped with a MEMS acceleration sensor and an external input interface that can connect to any analog sensor. However, the accuracy of a built-in MEMS acceleration sensor is not high and it cannot measure microtremors. High-accuracy servo acceleration sensors can be used via the external input interface, but a risk that noise will be mixed into the analog signal remains. Therefore, in this research, it is decided that a fully-fledged digital sensing platform shall be developed. Specifically, a high-accuracy digital acceleration sensor will be 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 addition, it is intended for a camera sensor to be connected in the next development step, with the aim of developing a diverse digital sensing platform.

III. DESIGN OF DIGITAL SENSING PLATFORM

The sensor device normally consists of a CPU that controls the measurement, sensors, a memory device, a network interface, etc., and the CPU uses a crystal oscillator. When a CSAC is mounted in this device, the CPU of the sensor device is corrected using the time information of the CSAC as-is, and when measurement is performed, a delay occurs due to the high-accuracy time measurement of the CSAC. Therefore, a mechanism provided with a dedicated integrated circuit, Field-Programmable Gate Array (FPGA), was developed for directly adding the CSAC time information to the digital sensor measurement data at the hardware level. In this way, the measurement data with the CSAC time information added by the FPGA is stored in memory without load on the CPU, and the data can be collected via a network. Also, the FPGA is programmable, so logic for detecting abnormal events using the measurement data can be incorporated while handling the CSAC time information. In the development to date, it has been assumed that analog sensors will be used, but in this paper the development of a mechanism for adding an accurate time stamp from the CSAC to the output of digital sensors is described.

The sensor device developed in this research consists of a CSAC board, an FPGA board, and a sensor board, as shown in Figure 1. The CSAC board is equipped with the CSAC, GPS, etc., and it generates accurate time information. The FPGA board controls the measurement by each sensor while adding the ultra high-accuracy time information from the CSAC, and after the measurement data is stored in memory, the data is transmitted to a network through Ethernet, Wi-Fi, or 3rd generation mobile communication system (3G). Two types of data are stored: always measured data, and data that is only measured in an event, such as an earthquake. The

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former is constantly stored on a Secure Digital Memory Card (SD card), and, when a certain quantity is exceeded, old data is deleted to leave space for overwriting with new data. In the case of the latter, logic for detecting the start and end of an earthquake is incorporated in the FPGA, and, after an earthquake, the data for the earthquake event only is immediately transmitted to the network. The sensor board performs the measurements by the sensors in accordance with instructions from the FPGA. The sensors mounted are a digital high-accuracy acceleration sensor and a temperature sensor (-50℃ to +150℃). For checking the time synchronization performance, an external analog sensor interface is provided to which any external analog sensor can be connected via a Sub Miniature Type A (SMA) connector. Table 1 shows the specifications of the digital high-accuracy acceleration sensor mounted in the sensor board. An A/D converter having 16-bit resolution is mounted in the sensor board, and data from signals that have passed through the A/D converter is branched and amplified by a factor of 10, so analog sensors that require a wide dynamic range can also be connected. This has been packaged and developed as a digital sensing platform. Figure 2 shows the produced digital sensor device in which the CSAC is mounted. The CSAC board, the FPGA board, and the sensor board are shown in Figures 3 to 5, respectively.

The autonomous time synchronization digital sensing system is constructed using the developed digital sensor device. The digital sensor devices in which a CSAC is mounted each keep accurate time independently of each other, but, in order to construct a sensing system consisting of multiple devices, it is necessary to define absolute time information in one device as the master device, and synchronize the other devices as slaves. Each main board contains an input output connector for 1 Pulse Per Second (PPS) signal from the CSAC. Using this connector, a 1 PPS signal is output from the master device and input to each slave device for synchronization, so that the phases of the CSAC clocks of the slave devices can be aligned with the master.

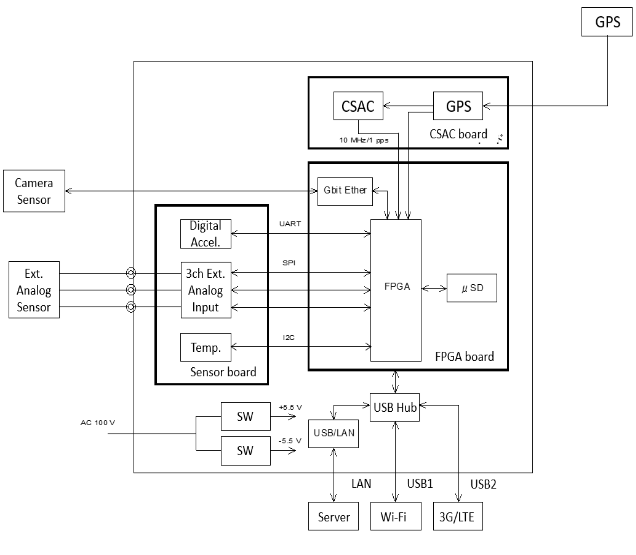

Figure 1. Configuration of digital sensing platform.

TABLE I. SPECIFICATIONS OF DIGITAL ACCELERATION SENSOR

Model	EPSON M-A351AS
Range	±5G
Noise Density	0.5 μG/√Hz (Average)
Resolution	0.06 μG/LSB
Bandwidth	100 Hz (selectable)
Output Range	1000 sps (selectable)
Digital Serial Interface	SPI
Outside dimensions (mm)	24 × 24 × 19
Weight	12 grams
Operating Temperature	-20 ℃ to +85 ℃
Power Consumption	3.3 V, 66 mW
Output Mode Selection	Acceleration, Tilt Angle, or Tilt Angle Speed

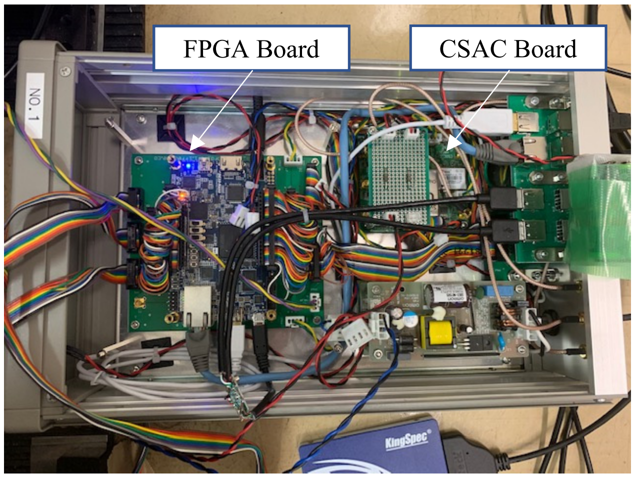

Figure 2. Internal configuration of sensor device.

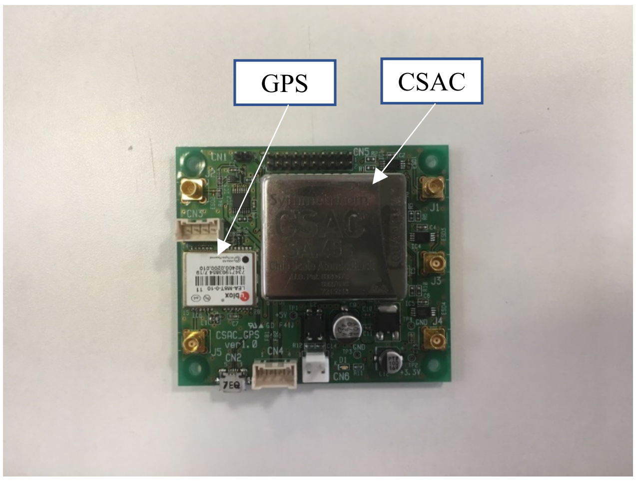

Figure 3. CSAC board.

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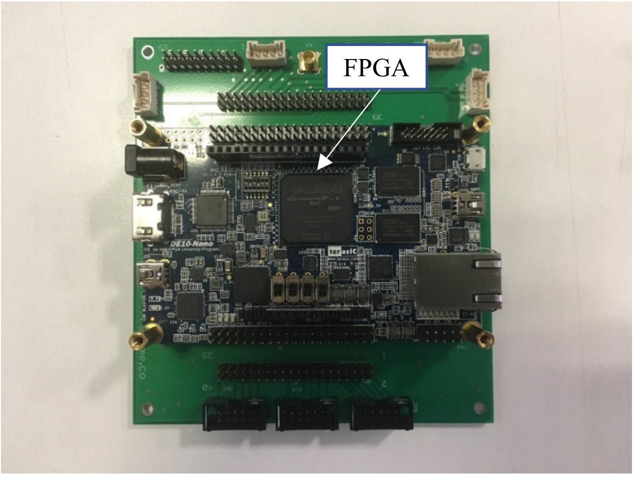

Figure 4. FPGA board.

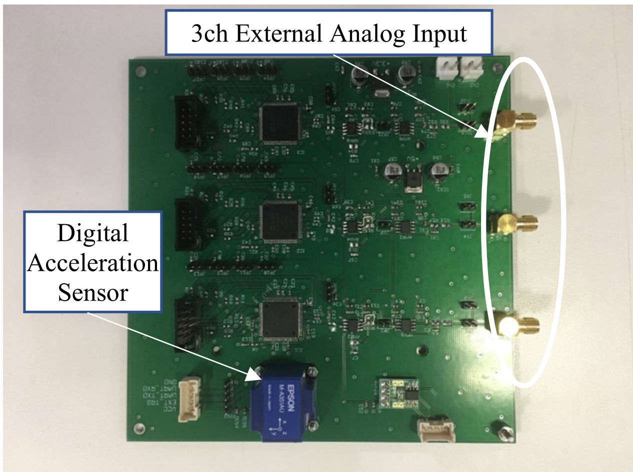

Figure 5. Sensor board.

The time measurement accuracy of the CSACs is advanced, but they do not have absolute time information from the start, so it is necessary that this be separately defined. For this purpose, the GPS device mounted in the main board may be used, or such information may be manually input. Also, during initial setting, all sensor devices may acquire the absolute time using their GPS device and they can be synchronized together. When all the sensor devices from which the sensing system is constituted are initially synchronized in this way, they subsequently continue to autonomously maintain high-accuracy time information, so they can be installed in any location and the measurement data can be streamed or can be stored on an SD card and retrieved at any time. An accurate time stamp is recorded during each sampling process of the measurement data, so a data acquisition method, such as Ethernet, Wi-Fi and 3G, can be selected. Also, even in places where GPS signals or network connection is not available, since just measurement and data collection are required, this system is suitable for mobile measurement or for use as a transportable sensing system.

IV. Performance Confirmation Tests on the Time Synchronization Function of Digital Sensing Platform

Tests were performed using a shaking table to confirm the performance of the developed digital sensor device. The objective was to confirm the measurement performance and time synchronization performance of the digital sensor device. Three sensor devices and a servo acceleration sensor for comparison were fixed on a shaking table, as shown in Figures 6 and 7. The same vibrations were applied in one horizontal direction and the results were compared. The analog output of the comparative servo acceleration sensor was input to the sensor devices via the external input interface. In the test, a sweep wave of 2 to 20 Hz, as shown in Figures 8 and 9, was applied to excite the shaking table as an input wave, and the measurement sampling frequency of the sensor devices was set to 1,000 Hz.

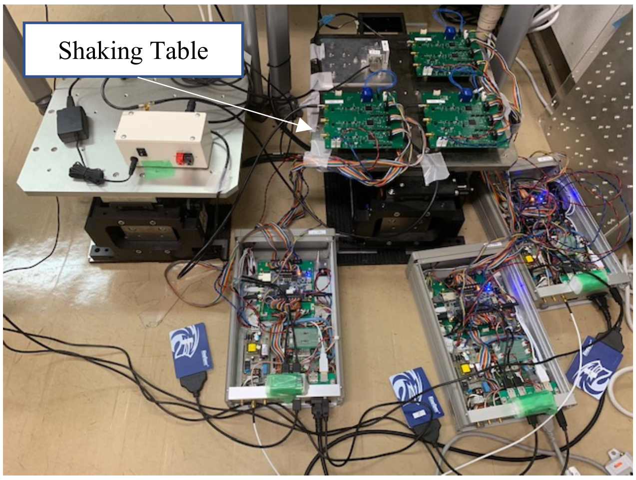

Figure 6. Experimental setup.

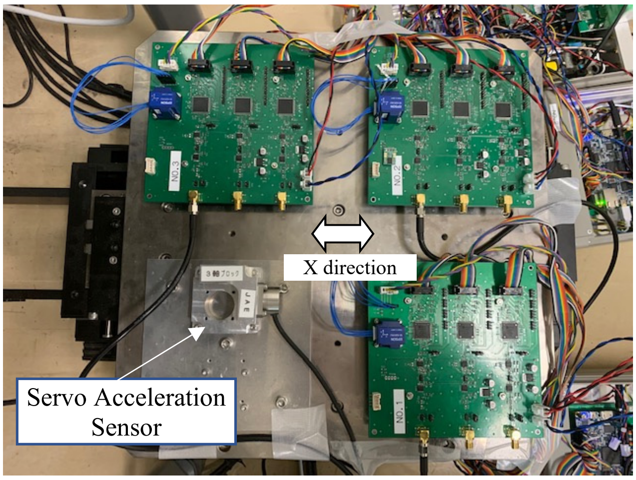

Figure 7. Sensor boards on shaking table.

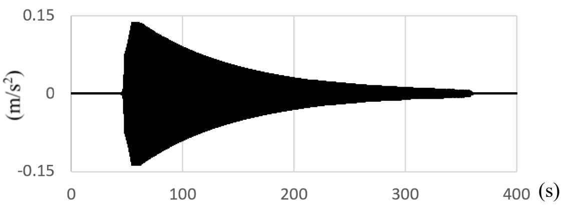

Figure 8. Input swept sine wave (2 to 20 Hz).

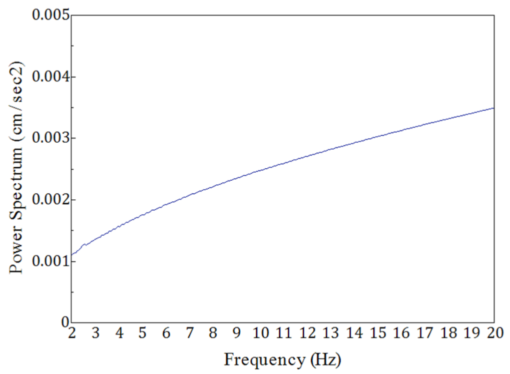

Figure 9. Power spectrum of input swept sine wave

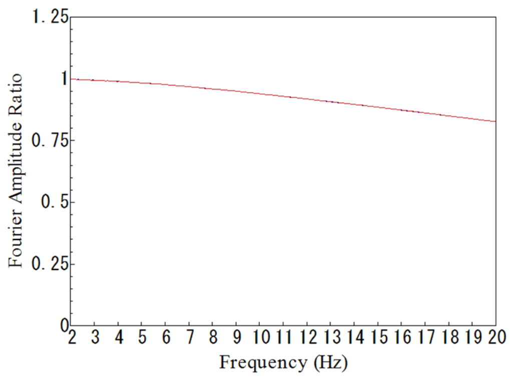

Figure 10. Spectrum ratios of Fourier amplitudes of three sensor modules to servo-type acceleration sensor (X direction).

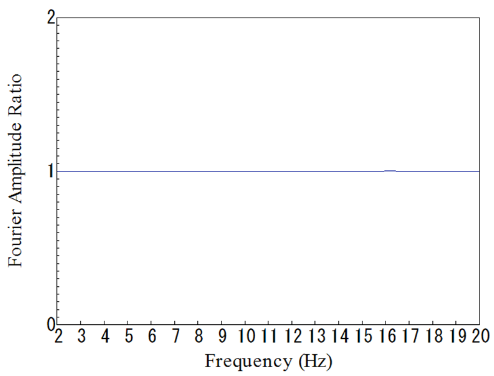

Figure 11. Spectrum ratios of Fourier amplitude of two slave modules to master module (X direction).

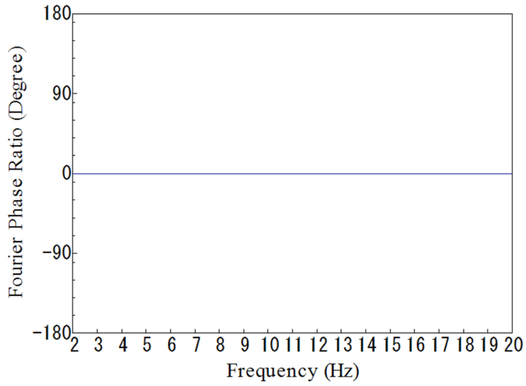

Figure 12. Spectrum ratios of Fourier phase of two slave modules to master module (X direction).

Excitation was applied in the X-direction of the sensor devices, and measurement was performed by the sensor devices and the comparative servo acceleration sensor. Figure 10 shows the results of calculation of the Fourier amplitude spectrum ratios of the acceleration time history measured by the three sensor devices and the comparative servo acceleration sensor. The amplitude of the former three devices relative to the latter reflected the low pass filter characteristics of the digital sensors, so it can be seen that the digital acceleration sensor mounted in the sensor boards have good performance.

Next, Figure 11 shows the results of obtaining the Fourier amplitude spectrum ratios for the acceleration time history from two sensor devices (slaves) on the shaking table when the other sensor device was used as the master. The amplitude of the former two devices relative to the latter was flat over the frequency band 2 to 20 Hz. In addition, Figure 12 shows the results of obtaining the Fourier phase spectrum ratios for the acceleration time history from two sensor devices (slaves) on the shaking table when the other sensor device was used as the master. There is no phase delay between the sensor devices, and, if the time synchronization was maintained, it would be expected that it should be about zero over the frequency band 2 to 20 Hz. From the figure, it can be seen that time synchronization has been achieved between the sensor devices.

V. Conclusion

This paper has reported on research into a digital sensing platform that autonomously maintains high-accuracy time information, by applying CSACs. First, the issues with a system that was developed assuming analog sensors were pointed out, and a system based on digital sensors was proposed and developed as a method of resolving these issues. Autonomous time synchronization using CSACs was described, and the mechanism for adding ultra high-accuracy time information to digital sensor data using a CSAC and the development of the sensor devices was described in detail. In addition, the results of tests performed to confirm the time synchronization performance of the sensor device were reported. Three sensor devices were mounted in a shaking table and tests were performed by applying vibrations simultaneously, and by checking the phase properties of the measurement results it was confirmed that time synchronization was achieved for sampling at 1000 Hz.

In the next development step, we intend to additionally connect a camera sensor, with the aim of developing a diverse digital sensing platform. For absolute time synchronization of the camera sensor, a digital input interface will be additionally installed to the developed sensor device as a digital sensor platform so that a camera sensor can be connected. A function for adding the time stamp to the output of the camera sensor will be added, the same as for the output of the built-in digital acceleration sensor. The developed diverse digital sensing platform will be applied to actual structures, to acquire acceleration and image data with accurate time information.

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