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# DEVELOPMENT OF SENSOR MODULE FOR SEISMIC AND STRUCTURAL MONITORING WITH A CHIP-SCALE ATOMIC CLOCK

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## *Abstract*

In this paper, aiming for the application of seismic monitoring and structural monitoring, I discuss research and development regarding an autonomous time synchronization sensing system that maintains high-precision time information by a chip-scale atomic clock (CSAC). To realize next-generation seismic observation systems and maintenance management systems for building and civil structures, it is necessary to obtain measurement data in which time synchronization is achieved. For this purpose, it is desired that sensor modules themselves maintain accurate time information without depending on networks and GPS signals. Therefore, I developed a sensing system that maintains accurate time information autonomously, equipped with a CSAC, which is an ultrahigh-precision atomic clock that can be implemented in a substrate because of its ultralow power consumption and ultrasmall size. In this paper, the development of a practical sensor module that is an improvement of a previously developed prototype model is reported. First, the concepts of autonomous time synchronization and the CSAC are explained, and then a mechanism to append ultrahigh-precision time information to sensor data using a CSAC and the development of a prototype sensor module is described. In addition, improvement of the sensor module is explained in detail. The shaking table tests are performed on the improved sensor modules equipped with MEMS acceleration sensors, and the amplitude performance from a comparison with the measurement results of a servo-type acceleration sensor for controlling the shaking table is confirmed. In addition, from test results in which multiple improved sensor modules are placed on the shaking table while oscillation is added to those modules, it is confirmed that time synchronization within 0.001 seconds is realized for 100 Hz sampling. Furthermore, tests are performed in which the output from the displacement sensor in one module is branched to connect to eight improved sensor modules through the external analog sensor input interface in each module, and it is confirmed that the measurement results are in excellent agreement. From these results, it is confirmed that an autonomous time synchronization sensing system can be constructed, regardless of whether the built-in MEMS acceleration sensor or the external analog sensor input interface is used, which can be connected to various sensors. In conclusion, the developed autonomous time synchronization system enables the realization of high-density seismic observations in wide areas including underground and subsurface areas and structural health monitoring of building and civil structures.

*Keywords: time synchronization, earthquake observation, structural health monitoring, chip-scale atomic clock*

## 1. Introduction

A ubiquitous structural monitoring system has been developed, in which a wireless sensor network and MEMS (Micro Electro Mechanical Systems) is utilized, and this system was applied to real structures [1-3]. In this system, sensor modules are placed densely, and how to accurately detect damage in structures is studied. Unless time synchronization [4-6] is achieved among data measured by multiple sensor modules, the data cannot be mutually compared and analyzed in detail. In that study, the time synchronization problem is resolved by sending and receiving wireless packets between sensor modules [3]. However, such a wireless sensor network technology can be used only when one structure is considered, and in many cases, the problem cannot be resolved when there are multiple structures, a large civil infrastructure such as a bridge, or a wide area of urban space. In the outdoor environment, we can use GPS signals, but we cannot use them underground or in tunnels. To obtain measurement data in which time synchronization is achieved wherever and however sensor modules are placed, it is desirable that sensor modules themselves continue to maintain accurate time information, without depending on signals from a network or GPS. For this purpose, by mounting a chip-scale atomic clock

(CSAC) [7-9], which is an ultrahigh-precision clock whose delay is substantially less than that of crystal resonators and related technologies, in sensor modules, I have developed a prototype sensing system that maintains autonomously accurate time information [10, 11]. In this paper, I describe in detail the development of an improved practical sensor module based on the prototype. In addition, I report test results to confirm the performance of the improved sensor module.

## 2. Autonomous Time Synchronization and a Chip-Scale Atomic Clock (CSAC)

Ideally, when GPS signals and wired network connections are unavailable, and wireless communication is unstable, to obtain a group of sensor data in which time synchronization is stably achieved, each sensor itself should be able to autonomously maintain accurate time information. In other words, if accurate time information (time stamp) can be appended to data measured by each sensor, a group of sensor data is obtained in which time synchronization is achieved. For this purpose, I decided to develop a sensing system that keeps autonomously accurate time information by using a CSAC, whose time accuracy is high and delay is substantially less than that of crystal resonators and related technologies [7-9].

The CSAC is a clock that realizes ultrahigh-precision time measurement with accuracy of several tens of picoseconds ($5\times10^{-11}$ s) yet whose power consumption is low and size is ultrasmall, so that it can be implemented on a substrate (Fig.1, Table 1). Its development was started in 2001 under the support of the Defense Advanced Research Projects Agency (DARPA) in the United States, and consumer products were released in 2011. Its application includes countermeasures for interruption of GPS positioning due to a jamming signal, high-precision positioning by mounting on smartphones, sophistication in grasping disaster situations, and application to a cloud server. It is expected that its price will be further reduced as it becomes popular. As Table 2 shows, the time accuracy of a CSAC is substantially higher than that of crystal oscillators. If this CSAC is mounted on each sensor module and a mechanism is implemented to append high-precision time stamps to sampling data, a group of senor data can be collected in which time synchronization is autonomously achieved. We can flexibly choose a data collection method, and all we then must do is place sensors—for example, at hotspots of Wi-Fi or 3G.


Fig. 1 – Chip-scale atomic clock (CSAC)

Table 1 – Specification of a 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 |

Table 2 – Various clocks and oscillators

| | Cesium atomic clock | Rubidium atomic clock | CSAC | Crystal oscillator |
|---|---|---|---|---|
| Time for 1-s delay | 50,000 years | 1000 years | 1000 years | One day |
| Size | 0.1 $m^3$ | 1000 $cm^3$ | 1 $cm^3$ | 10 $mm^3$ |
| Power consumption | 50 W | Several 10 W | 30 mW | 10 μW |

## 3. Development and Improvement of a Sensor Module Equipped with a CSAC

A sensor module is usually composed of a CPU (which controls measurement), a sensor, a filter, an analog-to-digital convertor, a memory unit, a network interface, and so on. A crystal oscillator is used for the CPU. If a CSAC is mounted onto this design and measurements are collected by directly correcting the CPU on the senor module using the time information of the CSAC, a delay is generated because the time accuracy of the CSAC is high. Therefore, to append time information of the CSAC directly to measurement data by the sensor using hardware, a mechanism with a field-programmable gate array (FPGA) is developed, which is an integrated circuit specialized for this purpose, and a prototype of a sensor module is produced [10, 11]. Because the FPGA is programmable, we can incorporate logic such as abnormality detection using measurement data by appending time information of the CSAC to measurement data.

As Fig.2 shows, a sensor module is composed of the main control unit, the sensor unit, and the wireless communication unit. The main board is equipped with a CSAC, an FPGA, a GPS, a CPU, a memory unit, a network interface, etc. The main control unit controls measurement by the sensor, appending ultrahigh-precision time information by the CSAC; after saving measurement data to the memory, it transmits the data to a network through Ethernet or wireless communication. For measurement data, two types of data are saved: data measured at all times and data from which only events such as earthquakes are extracted. For the latter, logic to detect the beginning and end of an earthquake is incorporated in the FPGA, and data that contain only the earthquake event are promptly transmitted to a network after the earthquake. A GPS is added to initialize and adjust time information. The sensor unit performs measurement in accordance with commands from the main control unit. The sensor unit is equipped with a triaxial MEMS acceleration sensor, an external analog sensor input interface, a temperature sensor, an antialiasing filter, an analog-to-digital converter, etc. The specifications of the mounted triaxial MEMS acceleration sensor are shown in Table 3. The wireless communication unit enables data collection wirelessly, and either general wireless LAN (Wi-Fi) or 3G can be used selectively. Thus, the basic performance of the developed prototype of the sensor module [10, 11] is confirmed.

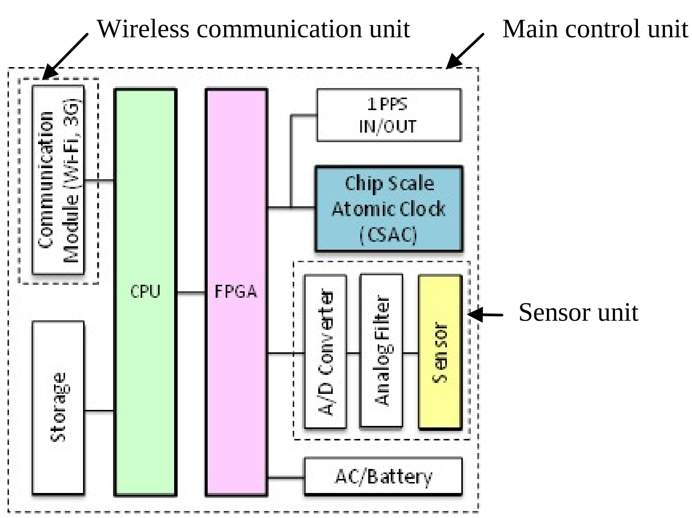


Fig. 2 – Design of the sensor module on which a CSAC is mounted

Table 3 – Specifications of the 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 |

For the developed prototype of the sensor module, to maximize its functionality and practicality, I have made improvements in the following regards:

(1) The external analog sensor input interface has been improved to include three channels.

(2) The analog-to-digital converter has been improved to feature 24-bit resolution.

(3) The FPGA has been reinforced for the above items (1) and (2).

(4) The wireless communication unit has been separated, and it has been built using a Raspberry Pi 2 Model B, which is commercially available.

(5) Time synchronization using IEEE 1588 has been implemented.

Improvements (1) and (2) above enable the connection of a sensor, such as a servo-type acceleration sensor, that requires a wide dynamic range. In addition, it is possible to connect three other sensors, such as a strain sensor or a displacement sensor, and to use the sensor module as a data logger. In addition, realization of the wireless communication unit with the commercially available Raspberry Pi enables price reduction, and it can be rapidly updated to be compatible with new wireless communication methods. Furthermore, to synchronize time by initializing the timing of measurement between sensor modules, the interface of IEEE 1588, which is a standard governing network time synchronization, is also added. Fig.3 shows the improved sensor module.

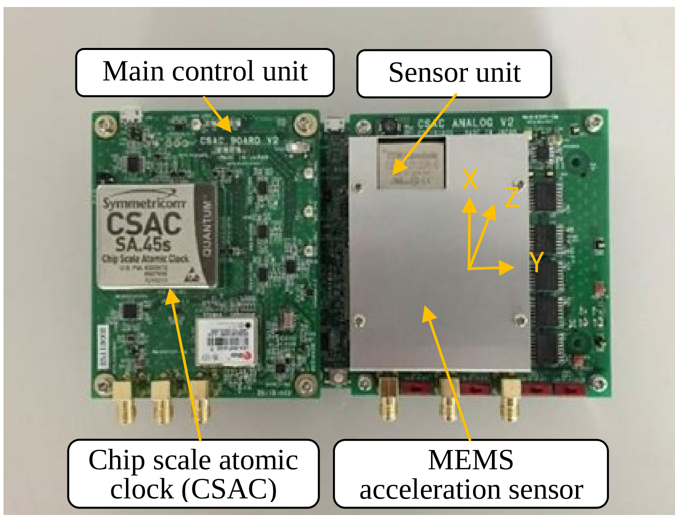


Fig. 3 – Produced improved sensor module with CSAC

## 4. Establishing an Autonomous Time Synchronization Sensing System

Using the sensor modules developed in section 3, an autonomous time synchronization sensing system is established. Each of the sensor modules with CSACs independently has its own accurate time. However, to establish a sensing system composed of multiple modules, we must choose one module as the master module, in which the absolute time information is defined. The other modules are treated as slave modules in which the time is synchronized. The main control unit in each sensor module is equipped with the input–output connector for a 1 PPS (pulse per second) signal for the CSAC. Using this, we can synchronize time by outputting the 1-PPS signal from the master module and inputting this signal to each slave module, and we can adjust the phase of the CSAC clock in each slave module. The time accuracy of a CSAC is high, but a CSAC does not maintain the absolute time information by default; therefore, we must define it. To accomplish this, the GPS module implemented in the main control unit is used. The communication from the master module to the slave modules is achieved by using the IEEE 1588 protocol. In addition, it is possible to obtain the absolute time using the GPS module at the time of the initialization and to synchronize all sensor modules at once. After all sensor modules that compose a sensing system are synchronized in such a way at the initialization, they autonomously continue to maintain high-precision time information. As mentioned previously, accurate time stamps are recorded in measurement data; therefore, we can choose any data collection method such as Ethernet, Wi-Fi, or 3G. In addition, even in a place where GPS signals are unavailable or where there is no wireless or wired network, all we must do is place them anywhere, measure and collect data. Therefore, we can use the system for mobile measurement or as a portable sensing system. Fig.4 shows the configuration of the autonomous time synchronization sensing system. We can freely mix a sensor module equipped with a sensor unit in which an MEMS acceleration sensor is mounted and a sensor module connected with a strain sensor, a displacement sensor, and so on through an external analog sensor input interface of the sensor unit.

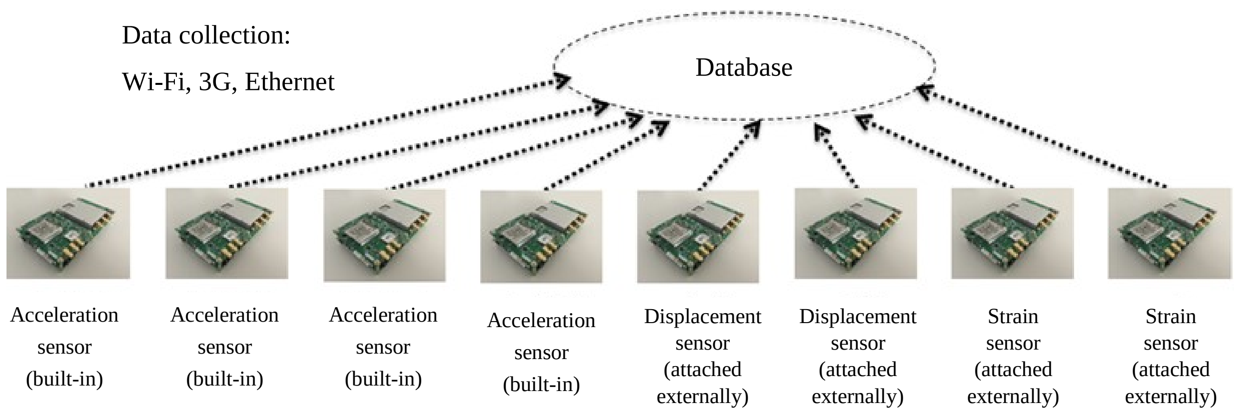


Fig. 4 – Configuration of the autonomous time synchronization sensing system

## 5. Performance confirmation tests of the Improved Sensor Module

### 5.1 Shaking table tests using the built-in MEMS acceleration sensor

To confirm the performance of the improved sensor module developed in section 3, tests were performed using a shaking table. Measurements were taken using the MEMS acceleration sensor mounted in each sensor module. The purpose was to confirm the measurement performance of the MEMS acceleration sensor and the time synchronization performance of the sensor module. As shown in Fig.5, four sensor modules were fixed on a shaking table, the same input wave was added in a horizontal direction, and the measurement results were compared. In the tests, input wave was added to the shaking table using a swept sine wave with a frequency from 0.1 to 2 Hz and from 2 to 10 Hz as shown in Fig.6 The measurement sampling frequency of the sensor modules was set to 100 Hz.

Mechanism of the built-in MEMS acceleration sensor in X and Y direction is same. Vibration was added in the Y direction of the sensor modules, and measurements were taken by the sensor modules and the servo-type acceleration sensor for controlling the shaking table. Fig.7 shows the calculation results of the Fourier amplitude spectrum ratios of the acceleration waveforms measured by the four sensor modules and the servo-type acceleration sensor for control. Compared with the latter, the amplitude of the former four sensor modules is flat in the frequency bands from 2 to 10 Hz, and we see that the MEMS acceleration sensors mounted in the sensor modules have satisfactory performance for the Y component.

Next, I specified one sensor module on the shaking table as the master module, and Fig.8 shows the calculation results of the Fourier phase spectrum ratios of the acceleration waveforms measured by the other three (slave) modules. If there is no phase delay between the sensor modules, and if the time synchronization is achieved, the Fourier phase spectrum ratio should be approximately zero in all frequency bands. In the figure, the phase delay is plotted within 0.001 seconds by the dotted line. Based on the plot, it is concluded that time synchronization within 0.001 seconds between the sensor modules is realized.

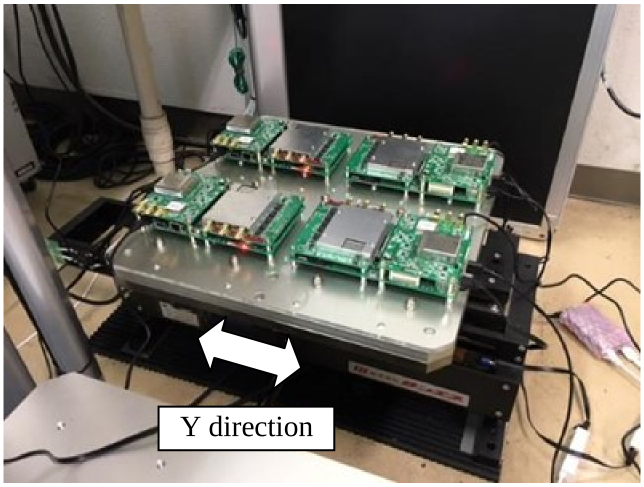


Fig. 5 – Shaking table test in Y direction

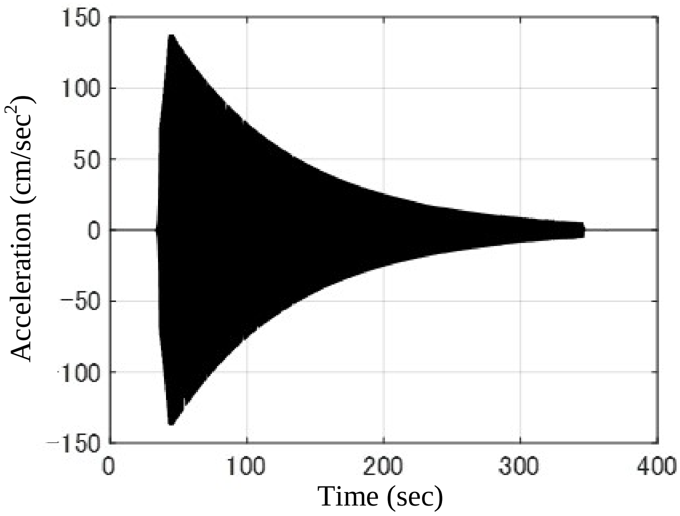


Fig. 6 – Input swept sine wave from 2 to 10 Hz

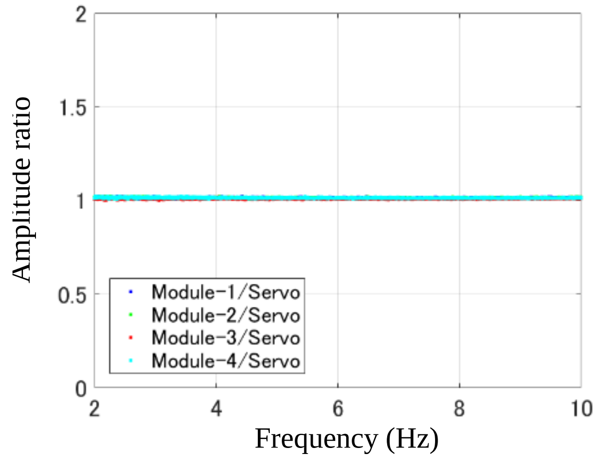


Fig. 7 – Spectrum ratios of Fourier amplitude of the four sensor modules to that of the servo-type acceleration sensor for control (Y direction)

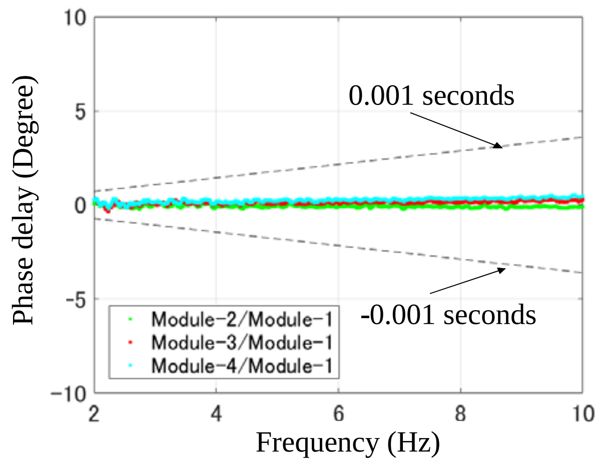


Fig. 8 – Spectrum ratios of Fourier phase of the three slave modules to that of the master module (Y direction)

5.2 Displacement measurement test using the external analog sensor input interface

This test was performed using a displacement sensor to confirm time synchronization performance when using the external analog sensor input interface. As shown in Fig.9, the voltage output from the displacement sensor in one module was branched to connect to eight sensor modules equipped with external sensor boards. In the test, by changing the displacement in approximately 1-cm increments, measurement was performed using the eight sensor modules. Fig.10 shows the measurement results. In the plot, the measurement results obtained by the eight sensor modules are plotted over one another, and time synchronization is realized.

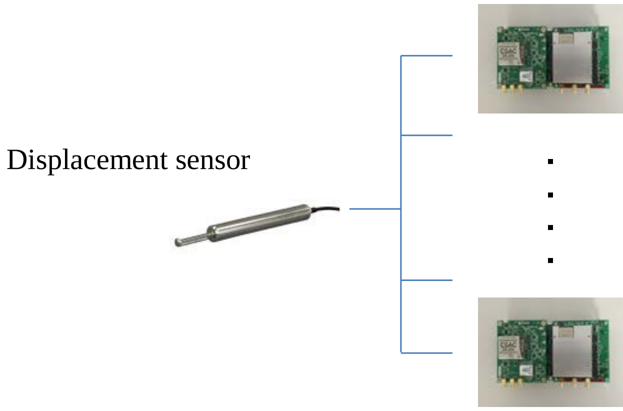


Fig.9 – Test with displacement sensor connected to the external analog sensor input interface

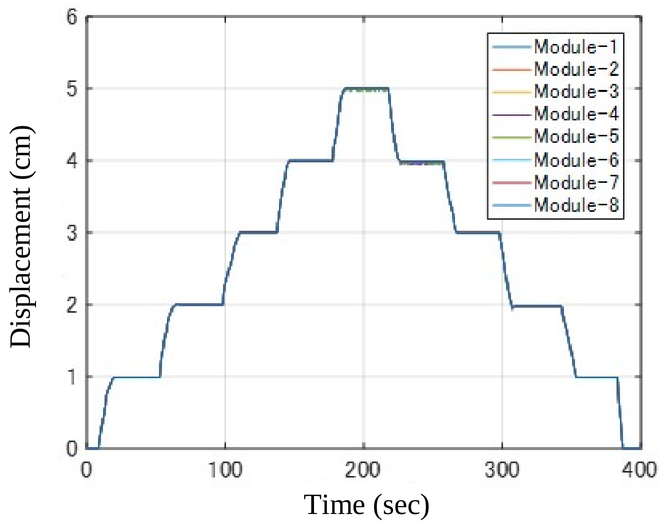


Fig.10 – Measurement test results where the displacement sensor was connected

## 6. Conclusion

In this paper, aiming for the application of seismic and structural monitoring, I reported research and development on an autonomous time synchronization sensing system that maintains high-precision time information by a chip-scale atomic clock (CSAC). First, the concepts of autonomous time synchronization and the CSAC were explained, and a mechanism to append ultrahigh-precision time information to sensor data using a CSAC and the development of a prototype sensor module was described. In addition, the development of an improved sensor module based on the prototype was explained in detail, and the results of tests conducted to confirm the performance of the module were reported. Shaking table tests were performed for the sensor modules equipped with MEMS acceleration sensors, and it was confirmed that the amplitude performance was satisfactory from a comparison with the measurement results by the servo-type acceleration sensor for controlling the shaking table. In addition, from the test results in which the multiple sensor modules were placed on the shaking table while oscillation was added to those modules, it was confirmed that time synchronization within 0.001 seconds was realized for 100 Hz sampling. Furthermore, the developed system is a multi-sensing platform to which various sensors can be connected; for this purpose, three channels were added to the external analog sensor input interface. Next, tests were performed in which the output from the displacement sensor in one module was branched to connect to eight sensor modules, and it was confirmed that the measurement results were in excellent agreement. From these results, it was confirmed that an autonomous time synchronization sensing system can be constructed, regardless of whether the built-in MEMS acceleration sensor or the external analog sensor input interface is used, which can be connected to various sensors. The developed autonomous time synchronization sensing system enables realization of high-density seismic observations in wide areas including underground and subsurface areas.

One of the problems is that CSACs will age in the long term, so I may need to consider how to operate the sensing system, depending on the measurement purpose and subject. Further, although it is expected that CSACs will be eventually used in computers and smartphones and become popular, CSACs are currently produced and sold by only one enterprise in the United States, and they are expensive. It is desired that Japanese enterprises enter the market and CSACs become actively used in various fields. In the future, I will continue basic research such as verifying the time accuracy of a CSAC as an atomic clock and verifying the wireless communication function of the system. I plan to apply the system to actual seismic observations and perform verification tests on structures and bridges.

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