Fundamental Tests on a Structural Health Monitoring System for Building Structures Using a Single-board Microcontroller

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Abstract

Aiming at the extension of structural health monitoring systems, a new monitoring system with low cost and easy installation was developed in this study. The proposed system includes MEMS acceleration sensors for measuring, a single-board microcontroller GR-SAKURA for processing, and a wireless device, XBee-PRO, for communicating. Acceleration data are collected by microcontroller and transferred by wired or wireless devices to a PC for real-time monitoring. To verify the measuring performance of the proposed system, fundamental shaking table tests were conducted on a small-scale three-story specimen. Data collection and measuring accuracy were verified. The system’s applicability to structural health monitoring systems was assessed. Experimental results showed that the response accelerations and natural frequencies of the specimen measured using the proposed system coincided well with those measured using a conventional data logger. GR-SAKURA has sufficient processing capability. XBee-PRO was confirmed to satisfy basic communication requirements equal to a wired system. Therefore, the proposed system is applicable for structural health monitoring systems with high cost-performance and simple construction.

Keywords: monitoring system; microcontroller; wireless; acceleration sensor; natural frequency

1. Introduction

During and after the Great East Japan (Tohoku-Chiho Taiheiyo-Oki) Earthquake and Tsunami (Architectural Institute of Japan, 2011), many small and medium-sized structures had severe damage caused by earthquake vibrations and tsunami. In recent decades, assessing structural performance during a building’s life cycle has become increasingly important, especially because of the considerable effects of earthquake-induced vibrations.

Studies on dynamic characteristics of building structures have been conducted recently. Jiang et al. (2009) reported the importance of employing displacement as a performance quantifier in performance-based design. Natural frequencies in both experimental tests and numerical simulations change when damage occurs. Then they decrease as the damage accumulates (Xing et al., 2010). Field tests have been conducted to investigate the vibration frequency, damping ratio, and root-mean-square acceleration, all of which should be considered during design (Xiong et al., 2011).

Structural health monitoring systems using strain gages or acceleration sensors have been studied experimentally in Japan. In addition, some communication technologies such as RFID and wireless networks have been introduced into monitoring systems by Tani et al. (2007), Murakami et al. (2007), and Ugaji et al. (2008). In those studies, proposed systems and calculation methods of story displacement and natural periods proved to be effective with sufficient accuracy.

Some structural health monitoring systems have been applied in practice. However, many such systems have been used only in high-rise buildings. They have not been used in general buildings because of their low cost performance and complicated wiring. Therefore, extensive structural health monitoring systems must provide high cost performance and easy installation.

With the rapid development of information and communication technology (ICT), many sensor systems using micro electro mechanical systems (MEMS) have become cheaper and smaller. Consequently, these systems have been widely applied for handheld devices, car navigation, and robots because of their special features such as their compact size, low cost, and commercial availability.
To achieve the objectives stated above, the authors carried out studies on the development of a structural health monitoring system using MEMS sensors, and conducted fundamental experiments. The applicability of these sensors to structural health monitoring systems has been discussed (Liang, Q. et al., 2011, 2012). In previous studies, most sensor systems remained connected to a general data logger with a wired communication system.

Based on an earlier study (Liang, Q. et al., 2013), the authors use a single-board microcontroller as a data processor and recorder to replace the conventional data logger. The proposed system comprises a single-board microcontroller, MEMS acceleration sensors, a portable battery, a wired or wireless transmission system, and a PC for real-time monitoring. The microcontroller and wireless devices selected for this study are GR-SAKURA and XBee-PRO because of their special features: compact size, high processing capacity, low cost, and power consumption.

For this study, small-scale shaking table tests were used to verify the basic measurement performance of the proposed system. Furthermore, the communication capacity is investigated because data dropouts and loss were observed in wireless systems reported by a number of researchers. Based on results obtained from the tests, the applicability of the proposed system as an important addition to current structural performance monitoring systems was verified and discussed.

2. Outline of Experiment

2.1 GR-SAKURA and GL-900

The single-board microcontroller GR-SAKURA was used in this study, as presented in Fig.1. A GR-SAKURA is an Arduino-compatible board based on RX63N series 32-bit microcontroller unit (MCU) with on-chip flash memory. Compared to Arduino boards, GR-SAKURA has excellent CPU processing and superior A/D conversion capabilities, enabling it to process data rapidly with remarkable accuracy. Table 1. shows the electronic characteristics of GR-SAKURA and Arduino. In addition to the USB Host/Function, GR-SAKURA has enhanced communication capabilities as shown in Table 2., including an Ethernet connector, wireless port, and Micro-SD card connector, which are convenient for users to choose the appropriate connection mode.

GR-SAKURA is programmable using the USB mass storage mode. It is visible as a drive on a PC. The GNU-based compiler for GR-SAKURA on Cloud also makes it easy to program it on a PC even on an Android device. In this way, users can build an application without complex program installation. To verify the measuring performance of the proposed system, the data logger GL900, with its high performance is used to measure and store observed data of acceleration sensors simultaneously in this study. Table 3. presents the electronic characteristics of GL900.

2.2 Acceleration Sensor

The acceleration sensor used for this study (MMA7361LC) is presented in Fig.2. It is a small accelerometer featuring signal conditioning, g-Select, 0g-Detect and sleep mode. Its sensitivity is factory-configured. Table 4. shows electronic characteristics of the acceleration sensor. This type of sensor has been widely used in handheld devices, car navigation, and robots because of its special features, particularly its compact size (10 mm × 10 mm), low cost, and commercial availability. Previous studies conducted by the authors revealed that the acceleration sensor module has sufficient measurement accuracy for structural health monitoring (SHM; Liang, Q. et al., 2011). Accordingly, this sensor was selected as the acceleration sensor for tests. By measuring the output voltages $V_{out}$ (V), the instantaneous value of acceleration $da$ (g/s.) is calculated using (1), where $V_{r}$ (V) and $Ra$ (mV/g) respectively denote the static output voltage and sensitivity of the acceleration sensor.
2.3 XBee-PRO

The wireless communication module XBee-PRO used for this study is depicted in Fig.3. XBee-PRO, which is based on the IEEE 802.15.4/Zigbee standard, is used to build self-organizing Wireless sensor networks (WSNs). Compared to conventional wireless devices and point-to-point network systems, the XBee-PRO is designed for fast point-to-multipoint or peer-to-peer networking with high-throughput applications. Electronic characteristics of the XBee-PRO Module are shown in Table 5. Low power, low cost, and an appropriate communication range make it suitable for WSNs in structural health monitoring systems.

\[
da = (V_{out} - V_0) \cdot 1000 / R_a \quad (1)
\]

2.4 Test Specimen

The small-scale specimen used in this study is a three-story frame structure fabricated to resemble a three-story building structure. The specimen dimensions are portrayed in Fig.4. The steel plates of each floor have a rectangular configuration with dimensions of 300 mm × 200 mm × 2.3 mm. The columns of the specimen are aluminum bars. The internal length and section size of the columns are, respectively, 250 mm and 20 mm × 2 mm. The plates and columns are connected by steel angles and bolts. An additional weight of 1530 g was added to the plates of each floor. The specimen was installed on a shaking table device. The horizontal vibration direction is perpendicular to the weak axis of the columns. The shaking table system has an 800 mm × 800 mm platform with a single excitation direction.

2.5 Experiment System

An outline and photograph of the experiment system used for this study are shown respectively in Figs. 5 and 6. As the figures show, acceleration sensor A0 is installed on the shaking table. The acceleration sensors A1, A2, and A3 are installed respectively on the plates of the first, second, and third floors. For the proposed system, presented in Fig.5., the measured voltage data are first transformed to acceleration data. Acceleration data are transferred to the PC via USB cable to be displayed on the PC in real time using terminal emulator software. The same acceleration data are also transferred to the PC through XBee devices. Additionally, as stated earlier, acceleration data measured using acceleration sensors are collected and stored simultaneously by a GL900 data logger for performance verification of the proposed system.
As seismic inputs, four earthquake waves were selected: JMA Kobe NS (1995), Taft EW (1952), Hachinohe NS (1968), and El Centro NS (1940). For the proposed system and the data logger, data collection is synchronized. The sampling intervals of data are 0.01 and 0.02 s; the duration of shaking table tests is 20 s. A flowchart of the proposed system is portrayed in Fig.7. An outline of vibration tests is presented in Table 6.

### 2.6 Natural Frequency Calculation

In structural health monitoring, measuring the changes of natural periods or natural frequencies of buildings is one of the useful methods to detect structural damage. The proposed system is also desired to ascertain the natural frequencies of structures when applied for structural health monitoring. To identify natural frequencies, Fast Fourier Transform (FFT) analysis is generally performed using measured acceleration data. The predominant values of the obtained Fourier spectrum are determined as natural frequencies of structures.

For this study, FFT analysis is also performed to calculate the natural frequencies of the specimen using absolute response acceleration data of the top floor. Natural frequencies of the specimen identified using the proposed system are also compared with those obtained using the data logger. The identification accuracy of the system was verified.

### 3. Results and Discussion

#### 3.1 Results of Data Collection

Comparison with the data stored in the data logger, revealed no dropouts or missing data collected by the USB mode or XBee mode of the proposed system. Furthermore, no significant difference was found...
Table 7. Acceleration Errors of Specimens (unit: %)

| Input Seismic Wave | JMA Kobe | Taft | Hachinohe | El Centro |
|--------------------|----------|------|-----------|-----------|
|                    | MAX      | MIN  | MAX       | MIN       | MAX      | MIN  | MAX      | MIN     |
| USB (100 Hz)       |          |      |           |           |          |      |          |         |
| GF                 | 5.12     | 3.42 | 4.43      | 0.93      | 0.63     | 9.52 | 2.60     | 0.60    |
| 1F                 | 2.47     | 3.67 | 0.56      | 2.86      | -0.11    | 0.14 | 2.83     | -0.23   |
| 2F                 | 0.59     | 1.28 | 2.50      | 1.67      | 3.93     | 3.74 | -1.88    | 19.80   |
| 3F                 | 2.12     | 2.38 | -0.81     | 0.17      | 2.38     | 1.79 | 0.83     | -0.65   |
| USB (50 Hz)        |          |      |           |           |          |      |          |         |
| GF                 | -7.21    | 1.61 | 11.1      | 1.81      | 5.63     | 0.93 | -6.35    | 9.64    |
| 1F                 | 5.91     | 3.54 | -0.76     | 3.65      | 1.73     | -0.36 | 1.22     | -0.20   |
| 2F                 | 3.74     | 2.84 | 7.98      | 23.6      | -1.79    | -2.01 | -1.91    | -4.07   |
| 3F                 | -0.96    | 0.48 | 3.44      | 2.49      | -0.52    | 14.4  | -3.59    | 0.79    |
| XBee (100 Hz)      |          |      |           |           |          |      |          |         |
| GF                 | 5.66     | 2.86 | 5.63      | 2.90      | -0.24    | 1.29 | -0.80    | 7.92    |
| 1F                 | 9.02     | 5.58 | -0.13     | -0.37     | 1.34     | -0.14 | 3.00     | 3.50    |
| 2F                 | 2.57     | 2.73 | 1.76      | 5.28      | 4.71     | 1.98  | 0.68     | 1.28    |
| 3F                 | 2.56     | 1.89 | 2.17      | 2.03      | 3.71     | 0.40  | 2.56     | 3.01    |
| XBee (50 Hz)       |          |      |           |           |          |      |          |         |
| GF                 | -3.50    | 1.69 | -2.84     | 11.1      | 0.26     | 2.98  | 1.50     | -7.47   |
| 1F                 | 4.69     | -2.18 | -1.27   | -1.66     | -0.67    | -2.55 | 3.40     | 5.91    |
| 2F                 | 5.66     | 5.42 | 0.51      | 11.2      | 1.93     | 0.31  | 8.00     | -0.29   |
| 3F                 | 0.83     | 0.12 | -1.65     | 2.86      | 0.01     | -0.30 | 2.80     | 4.37    |

Fig. 8. Response Acceleration in Case of USB (JMA Kobe)

Fig. 9. Response Acceleration in Case of XBee (JMA Kobe)
between results of sampling frequency 50 Hz and 100 Hz. Therefore, GR-SAKURA is regarded as capable of collecting acceleration data for sampling frequencies up to 100 Hz, and transferring data without loss using wireless communication with XBee.

### 3.2 Response Acceleration Results

Time history response accelerations of the shaking table and each floor for JMA Kobe with sampling frequency of 100 Hz are presented in Fig. 8. Results collected by GR-SAKURA via USB mode and XBee mode are compared, respectively, with those by data logger in Figs. 8(a)–8(d) and Figs. 9(a)–9(b). It is readily apparent that the results of both types of data collection methods of the proposed system almost coincide with those of a data logger in terms of phases and amplitudes. Small differences between the proposed system and the data logger in terms of amplitude were observed, probably because of the lower A/D conversion capacity of GR-SAKURA. Furthermore, comparatively greater noise was found in results of the proposed system near zero acceleration. The reason for this phenomenon is regarded as the lower electrical precision of GR-SAKURA.

And almost equal magnitudes of noise between USB mode and XBee mode were observed in this study.

Measurement errors of different data collection methods of the proposed system are presented in Table 7. Errors in the table are calculated using (2), where \( \text{ACC}_{\text{USB}} \) and \( \text{ACC}_{\text{XBee}} \) respectively denote the response acceleration collected by USB mode and XBee mode of the proposed system, whereas \( \text{ACC}_{\text{GL900}} \) denotes the acceleration results collected using the data logger. 'Max' and 'Min' in Table 7. denote the errors of maximal and minimal values of measured response acceleration data.

\[
\text{Error}_{\text{USB}}(\%) = \frac{(\text{ACC}_{\text{USB}} - \text{ACC}_{\text{GL900}})}{\text{ACC}_{\text{GL900}}} \times 100
\]

\[
\text{Error}_{\text{XBee}}(\%) = \frac{(\text{ACC}_{\text{XBee}} - \text{ACC}_{\text{GL900}})}{\text{ACC}_{\text{GL900}}} \times 100
\]

### Table 7. Average Errors of Each Case (unit: %)

| Item       | 50 Hz | 100 Hz |
|------------|-------|--------|
| USB mode   | 4.25  | 2.71   |
| XBee mode  | 3.12  | 2.8    |

3.3 Results for Natural Frequency

The results of FFT analysis for JMA Kobe input waves are presented in Fig. 10., in which (a) presents FFT results obtained using data collected by the data logger, whereas (b) and (c) are results obtained using data collected by the USB mode and XBee mode of the proposed system. As the figures show, FFT results obtained using the proposed system have apparent peak values at the predominant period, just as those of the data logger, meaning that natural periods of specimens are identifiable using results obtained using the proposed system.

The first, second, and third natural frequencies of the specimen identified by FFT analyses in all cases are presented in Table 9. Results of the USB mode and XBee mode of the proposed system are also compared to those of the GL900 data logger. Errors are presented in Table 10. The values identified by the proposed

![Fig.10. Results of FFT Analyses in Case of JMA Kobe](image-url)

Table 7. presents the measuring accuracy of four cases: two types of data collection methods of the proposed system and two types of sampling frequencies. It is clarified that results obtained using the proposed system have almost identical accuracy to those obtained using the data logger. Approximately 96% of the results are under 10%; 80% are under 5%. Accordingly, the proposed system using GR-SAKURA is applicable to structural health monitoring systems within the allowable range. However, in some cases, large errors arise, probably attributable to specimen fabrication and measurement system flaws. Average errors of results for four cases are summarized in Table 8. Results for the sampling frequency of 100 Hz were greater than those for 50 Hz, but no marked difference was observed between USB results and XBee results.

![Fig.10. Results of FFT Analyses in Case of JMA Kobe](image-url)
system are fundamentally identical to those obtained by the data logger. The maximum error of the result is approximately 0.6%.

No significant difference was found between results obtained using different data collection methods and different sampling frequencies. It is clarified that the natural frequency is identifiable by acceleration data measured using the proposed system with sufficient accuracy. Furthermore, no significant effect of signal-noise was observed in the results of XBee mode.

4. Conclusions
As described herein, aiming at the development of a structural health monitoring system with convenience and high cost-performance, fundamental tests of performance were conducted on a GR-SAKURA single-board microcontroller and an XBee-PRO wireless device. Based on experimentally obtained results, the following conclusions were obtained.

Measured acceleration data can be collected using the proposed system in both wired and wireless communication methods with sampling frequency up to 100 Hz, roughly equivalent to that of a conventional data logger. Acceleration waveforms measured using the proposed system approximately coincide with those by the data logger in terms of amplitude and phase. Overall errors of maximal and minimal values of measured results are less than 5% of those of the data logger.

No loss and no high level of noise was observed in the measured data transferred by XBee devices. These results have approximately the same accuracy as those transferred through the USB cable. No significant difference was found between results with sampling frequencies of 50 Hz and 100 Hz. Natural frequencies of specimens can also be identified using data measured using the proposed system within acceptable measuring errors: less than 4.25%, on average, compared to the data logger.

In this study, GR-SAKURA is considered to have basic collection and processing performance. XBee is regarded as satisfying the basic communication requirements for a SHM system. Therefore, the proposed system is applicable to build a SHM system with high cost-performance and easy construction. However, the processing limits of GR-SAKURA, as well as effects of transmission distance and obstacles such as walls on XBee must be investigated in future studies.

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Table 9. Natural Frequency (unit: Hz)

| Data Collection Method | Input Seismic Wave | Sampling Frequency 100 Hz | Sampling Frequency 50 Hz |
|------------------------|-------------------|--------------------------|--------------------------|
|                        | 1st   | 2nd     | 3rd     | 1st    | 2nd     | 3rd     |
| JMA Kobe               | 1.440  | 4.199   | 5.981   | 1.428  | 4.199   | 5.981   |
| Taft                   | 1.526  | 4.199   | 5.969   | 1.526  | 4.211   | 5.957   |
| Hachinohe              | 1.648  | 4.223   | 5.981   | 1.648  | 4.223   | 5.969   |
| El Centro              | 1.453  | 4.236   | 5.969   | 1.452  | 4.236   | 5.969   |
| JMA Kobe               | 1.434  | 4.199   | 5.981   | 1.428  | 4.196   | 5.981   |
| Taft                   | 1.532  | 4.199   | 5.969   | 1.526  | 4.199   | 5.966   |
| Hachinohe              | 1.642  | 4.224   | 5.975   | 1.648  | 4.218   | 5.981   |
| El Centro              | 1.459  | 4.236   | 5.965   | 1.453  | 4.236   | 5.975   |
| JMA Kobe               | 1.447  | 4.199   | 5.975   | 1.434  | 4.199   | 5.981   |
| Taft                   | 1.532  | 4.199   | 5.963   | 1.535  | 4.199   | 5.960   |
| Hachinohe              | 1.648  | 4.230   | 5.975   | 1.645  | 4.218   | 5.978   |
| El Centro              | 1.459  | 4.230   | 5.969   | 1.459  | 4.233   | 5.975   |

Table 10. Natural Frequency Errors of Specimens (unit: %)

| Data Collection Method | Input Seismic Wave | Sampling Frequency 100 Hz | Sampling Frequency 50 Hz |
|------------------------|-------------------|--------------------------|--------------------------|
|                        | 1st   | 2nd     | 3rd     | 1st    | 2nd     | 3rd     |
| USB                    | -0.417 | 0.000   | 0.000   | 0.000  | -0.071  | 0.000   |
| JMA Kobe               | 0.393  | 0.000   | 0.000   | 0.000  | -0.285  | 0.151   |
| Taft                   | -0.364 | 0.024   | -0.100  | 0.000  | -0.118  | 0.201   |
| Hachinohe              | 0.413  | 0.000   | 0.101   | 0.016  | 0.000   | 0.101   |
| El Centro              | 0.486  | 0.000   | -0.100  | 0.200  | 0.000   | 0.000   |
| Xbee                   | 0.393  | 0.000   | -0.101  | 0.590  | -0.285  | 0.050   |
| JMA Kobe               | 0.000  | 0.166   | -0.100  | -0.182 | -0.118  | 0.151   |
| Taft                   | 0.413  | -0.0142 | 0.000   | 0.482  | -0.071  | 0.101   |
| Hachinohe              | 0.000  | 0.000   | 0.000   | 0.000  | 0.000   | 0.000   |
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