Actual Application of Ubiquitous Structural Monitoring System using Wireless Sensor Networks

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ABSTRACT :

Ubiquitous structural monitoring (USM) of buildings using wireless sensor networks is one of the most promising emerging technologies for mitigation of seismic hazard. This technology has the potential to change fundamentally the traditional monitoring systems. This paper provides an introduction of wireless sensor network technology for the USM, and reported research activity on development of sensor module. The sensor board which is equipped with the MEMS acceleration sensor selected by the benchmark test was developed and tested. The sensor module which consists of the sensor board and wireless network module was tested by shaking table. It was confirmed that the developed sensor module had enough basic performance for the USM. The USM system which consists of developed sensor modules and PC was installed in a high-rise building. The building's vibration by typhoon was monitored and basic performance of the USM system was verified.

KEYWORDS: Ubiquitous Computing, Structural Health Monitoring, Wireless Sensor Networks, Wind Observation, Earthquake Observation, Smart Sensor

1. INTRODUCTION

Risk of buildings and civil engineering structures from natural hazards is large and growing. The 1995 Kobe earthquake in Japan killed over 6,400 people and the number of completely destroyed buildings and houses was over 100,000. The 2004 and 2007 Niigata earthquake in Japan, tsunami by the 2004 Indian Ocean earthquake, and the 2005 Hurricane Katrina in New Orleans caused heavy damage. Wireless sensor network (WSN) is key technology to realize the ubiquitous computing and networking environment [Morikawa 2005] and it is expected that such an advanced technology will play an important roll for natural hazard mitigation [Kurata et al. 2005]. In this paper, research on ubiquitous structural monitoring (USM) of buildings by using wireless sensor networks is introduced and actual application to high-rise building is described.

2. WIRELESS SENSOR NETWORK TECHNOLOGY

The general purpose of structural monitoring includes hazard mitigation, improvement of safety and reliability of the structural system, sustainability and life cycle cost reduction. The structural monitoring technology consists of sensing, signal processing, health/damage evaluation, and system integration. In recent years a number of conferences have been held in which structural health monitoring for buildings and civil engineering structures has been presented. Some of this work has focused on wireless sensing technology. A wireless sensing unit for real-time structural response measurements has been developed and a series of validation tests have been conducted [Lynch 2002].

"Ubiquitous sensing and computing" is expected to be realized over the next ten years. The interest in sensing technology for various uses has been growing, and new kinds of sensors have been developed by micro electro mechanical systems (MEMS) technology. Environmental information, such as brightness, temperature, sound, vibration, and a picture of a certain place in a building, is evaluated by the network to which a huge number of microcomputer chips with sensors were connected [Morikawa 2005]. A wireless sensor network plays an important role and can be connected to the internet so that this information can be used to monitor structures. Wireless sensors are easy to install, remove, and replace at any location, and are expected to become increasingly smaller (i.e., "smart dust", [Pister et al. 1999]) by using MEMS technology. They will provide a ubiquitous networked sensing environment in building and civil engineering structures. For example, the acceleration and strain at numerous locations on each structural members, temperature and light in each space, images and sounds in desired regions can be obtained by the "smart dust" sensors.

The requirement of a dense array of smart sensors using wireless technology for structural monitoring has been investigated by using the Mote platform [Spencer et al. 2004, Ruiz-Sandoval 2004, Kurata et al. 2005, Gao 2005, Nagayama 2007, Gnawali et al. 2006]. It is an open hardware and software platform for smart sensing and supports large scale, self-configuring sensor networks. Ruiz-Sandoval developed an agent-based framework which is a hardware or software-based computer system that enjoys the properties of autonomy, social ability, reactivity, and pro-activeness for structural health monitoring [Ruiz-Sandoval 2004]. A distributed computing strategy for structural health monitoring was proposed which is suitable for implementation on a network of densely distributed smart sensors [Gao 2005]. A scalable and autonomous structural health monitoring system using smart sensors was developed and the damage detection capability and autonomous operation of the developed system were experimentally verified [Nagayama 2007]. Tenet architecture which simplifies application development for tiered sensor networks without significantly sacrificing performance was proposed [Gnawali et al. 2006]. Its collections of tasklets support data acquisition, processing, monitoring, and measurement functionality. A wireless sensor system using the Mote platform with a developed sensor board was tested on the 4200 ft long main span and the south tower of the Golden Gate Bridge [Kim et al. 2007]. Reference [Lynch and Loh 2006] is a summary review of the collective experience the structural engineering community has gained from the use of wireless sensors and sensor networks for monitoring structural performance and health.

3. UBIQUITOUS STRUCTURAL MONITORING SYSTEM

One of the main purposes of the structural health monitoring is a damage detection of the structure. Because the structural damage is a local phenomenon, a Ubiquitous Structural Monitoring (USM), i.e., high density distributed structural monitoring is essentially needed as shown in Figure 1 [Kurata et al. 2005, Kurata et al. 2006]. A wireless sensor network and a fiber optic network will exist together in future building and many kinds of sensors will connected to the network. From this point of view, the authors have conducted research on wireless sensor network architecture for USM in the next generation, which includes a design of hardware and development of operating system [Saruwatari et al. 2005, Horie et al. 2004].

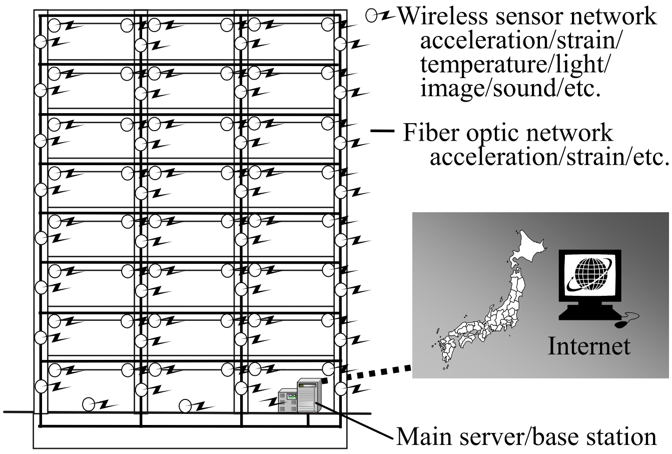


Figure 1 Ubiquitous structural monitoring in building

3.1. Sensor Module for Ubiquitous Structural Monitoring

Developed sensor module for USM consists of sensor board and wireless network module as shown in Figure 2. The sensor board consists of MEMS acceleration sensor, low pass filter and 16 bit A/D converter. 2 MB SRAM is also installed on the sensor board. A platform for wireless sensor networks called Pavenet [Saruwatari et al. 2005] was connected to the developed sensor board. Pavenet module is equipped with a CPU, Microchip PIC18LF4620, and an RF module, Texas Instruments CC1000. Pavenet OS is a hard-realtime operating system for Pavenet module. Required performance of sensor module for USM is listed as shown below.

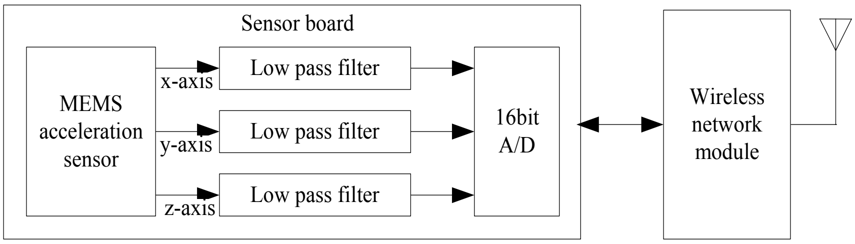


Figure 2 Sensor module for USM

3.1.1 Measurement

Required specifications for acceleration measurement are shown in Table 1. It shows a performance necessary for general seismic observation and vibration measurement of buildings from the moderate earthquake to a large earthquake and typhoon.

Table 1 Required specifications

Frequency range	0.1～20Hz
Measuring range	±2000 Gal
Measuring resolution	1 Gal
A/D resolution	16 bit
Sampling frequency	100 Hz

3.1.2 Time synchronization

Time synchronization among sensor modules is required to analyze the collected data for structural monitoring. In this system, time synchronization within 1 ms will be sufficient for sampling period of 10 ms and target frequency range of natural period of buildings and dominant period of earthquakes.

3.1.3 Detection of vibration

Sensor modules continuously observe acceleration and correct zero value by average of 1024 sampled data. After the correction of zero value, RMS value of 256 sampled data is calculated for detection of vibration. Though the selected MEMS acceleration sensor is influenced by fluctuation of temperature in environment, this influence could be ignored for measurement during earthquake.

3.1.4 Data transmission

Data loss caused by wireless communication should be considered. Transmission of measured data stored in SRAM on each sensor node is repeated after setting time of 50 ms. All of measured data by sensor modules is collected without loss in this system.

3.2. Benchmark test of MEMS acceleration sensors

The MEMS acceleration sensor was examined for the development of the acceleration sensor board that can be connected with such a wireless network module. Performance of various MEMS sensors is usually confirmed only in the frequency range of 10 Hz or more, though the performance in the low frequency range from 0.1Hz is important intended for the vibration measurement of high-rise building and the observation of long period ground motion. Therefore, the benchmark test of the MEMS acceleration sensors carried out in this study.

Table 1 shows the specifications of the MEMS acceleration sensors. Analog Devices ADXL202 is low cost and used for the standard sensor board for the MICA Mote, however, noise density is large and sensitivity is low as shown in Table 2. SILICON DESIGNS Model1221 is already investigated and tested for the structural health monitoring [Ruiz-Sandoval 2004]. It is listed just as a reference in this case because of the higher cost and the limitation of 1 axis measurement.

Table 1 Specifications of MEMS acceleration sensors

Name	Axis	Max G	Noise Density	Power Supply	Sensitivity (mV/G)	Temperature	Size (mm)
H48C	3	3	1.8mg rms	2.2-3.6	333	-25～75	4.8×4.8×1.5
MXS2200E	2	1	0.2mG/√Hz	2.7-5.25	2000	-40～85	5×5×2
LIS3L02AQ	3	2	50μG/√Hz	2.4-3.6	660	-40～85	7×7×1.8
JA30SA32-25B	3	1.5	0.049 Gal rms/√Hz	4.75-5.25	1000	-10～60	14×11×5
Model1221	1	2	5μG/√Hz	4.75-5.25	2000	-55～85	3.5×3.5×1.05
ADXL202	2	2	200μG/√Hz	3-5.25	167(3V) 312(5V)	-40～85	5×5×2

The MEMS acceleration sensors, Hitachi H48C, MEMSIC MXS2200E, ST Microelectronics LIS3L02AQ, Japan Aviation Electronics Industry JA30SA32-25B, SILICON DESIGNS Model1221, and the traditional acceleration sensor as a reference, were fixed on the shaking table and carried out the benchmark test. The shaking table is 1.8m×1.5m and can be excited according to the sine wave and the external input wave. In the test, the swept sine wave with 0.2 to 20 Hz was input to the shaking table. Fourier spectrum ratio of the measurement result of each MEMS acceleration sensor and the reference sensor was shown in Figures 3 to 6. H48C shows linear characteristics on amplitude and phase, however, noise performance is low. Though MXA2200E has a good sensitivity, it shows strong non-linearity. LIS3L02AQ and JA30SA32-25B has a good performance on amplitude, however, phase lag was observed in the results of JA30SA32-25B. Model1221 shows the best performance and LIS3L02AQ has an equivalent performance with Model1221. Finally, LIS3L02AQ was selected as the MEMS acceleration sensor for the sensor board.

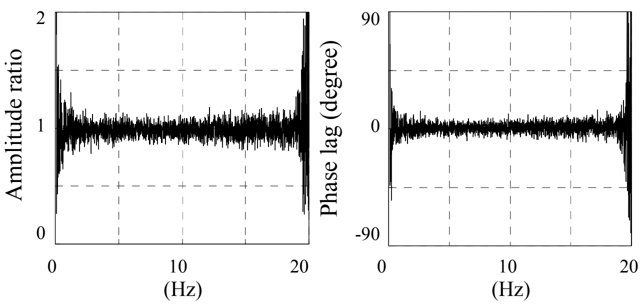


Figure 3 H48C

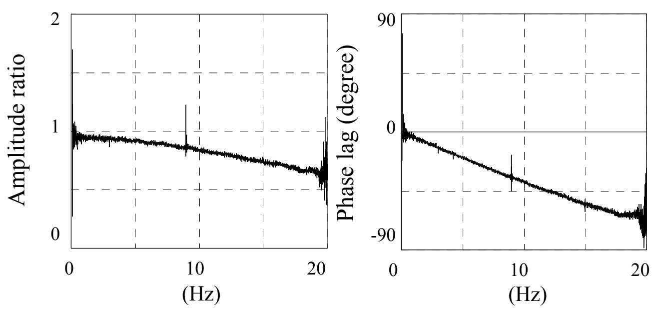


Figure 4 MXA2200E

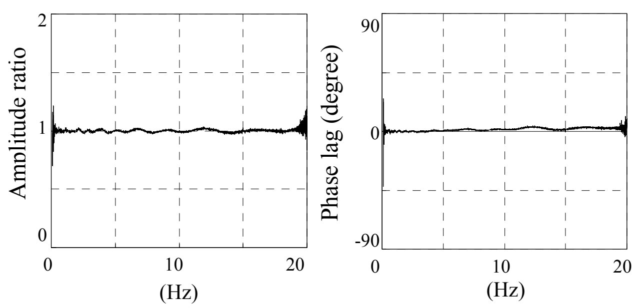


Figure 5 LIS3L02AQ

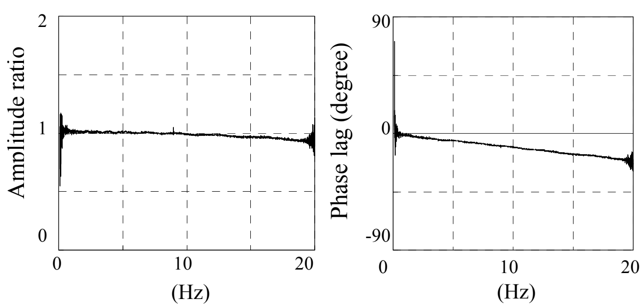
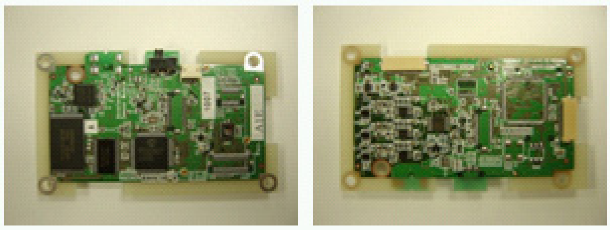


Figure 6 A30SA32-25B

3.3. Developed sensor board and performance test

The authors developed sensor board equipped with selected MEMS acceleration sensor, low pass filter, 16 bit A/D converter and 2MB SRAM (see Photograph 1). Shaking table test was carried out to recognize the performance of developed sensor board. Ten sensor boards and reference acceleration sensor were fixed on the shaking table as shown in Photograph 2. In the test, the swept sine wave with 0.2 to 20 Hz was input to the shaking table. Fourier amplitude spectrum ratio of the measurement result of each developed sensor board and the reference sensor was shown in Figure 7. The measurement result by the sensor board is corresponding to the result by the reference sensor well.



Photograph 1 MEMS acceleration sensors

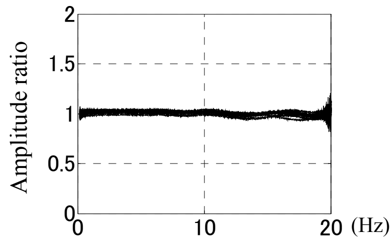


Figure 7 Fourier amplitude spectrum ratio

3.4. Ubiquitous Structural Monitoring System

The USM system consists of a sink node with a PC and sensor nodes as shown in Figure 8. The sink node manages time synchronization among the sensor nodes, detection of vibration and data transmission. It broadcasts time information periodically, and sensor nodes adjust their local clock according with received information. The sensor nodes continue to measure acceleration and store the data in SRAM on them. When the sink node detects the vibration and recognizes the end of it, then, the sensor nodes begin to send measured data to the sink node wirelessly. Finally, the sink node stores the received data to the PC.

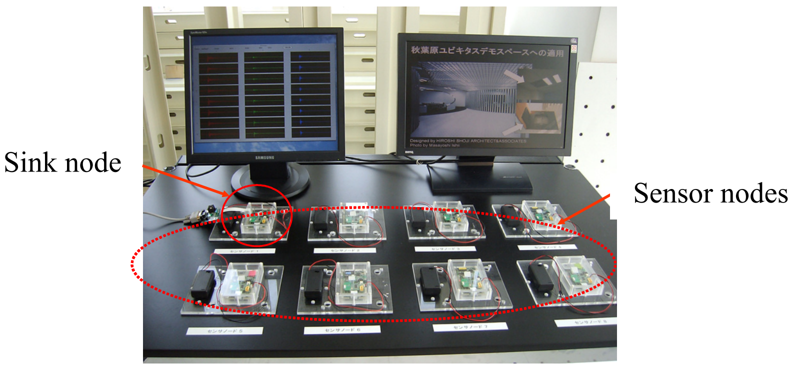


Figure 8 Ubiquitous Structural Monitoring System

Shaking table test was carried out to recognize the performance of developed USM system. A sink node connected to PC, ten sensor nodes, and traditional acceleration sensor as a reference, were fixed on the shaking table. In the test, the swept sine wave with 0.2 to 20 Hz was input to the shaking table. Figure 9 shows comparison between measurement results of developed sensor node and reference sensor. The result of sensor node gave good agreement with the one of reference sensor. Accurate sampling frequency of 100 Hz was realized. Fourier amplitude spectrum ratio of the measurement result of each developed sensor nodes and the reference sensor was shown in Figure 10. The amplitude characteristic of all sensor nodes is almost equal to the reference sensor. Figure 11 shows Fourier phase spectrum ratio of the sensor nodes and the sink node. No phase lag was recognized and time synchronization among sensor nodes was less than 1 ms.

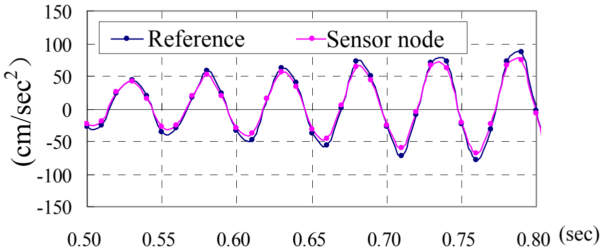


Figure 9 Comparison between developed sensor node and reference

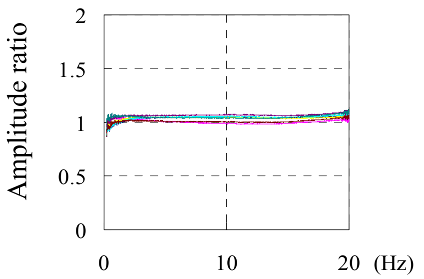


Figure 10 Fourier amplitude spectrum ratio

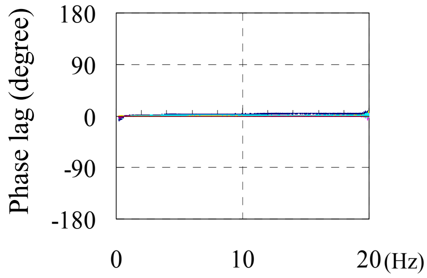
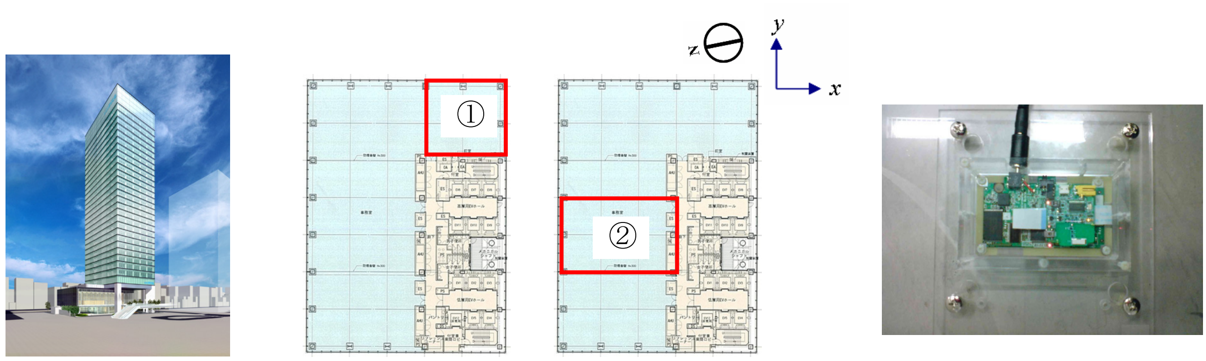


Figure 11 Fourier phase spectrum ratio

4. ACTUAL APPLICATION OF UBIQUITOUS STRUCTURAL MONITORING SYSTEM

4.1. Applied high-rise building

We applied the USM system which consists of a sink node and sensor nodes to actual high-rise building for verification of performance of the system in real apace. Applied 31-story office building is located in front of Akihabara station in Tokyo and is expected to be a new focal point for the Akihabara district, holding areas for Industry-Academia Collaboration, information networking, and attractions for visitors. We installed the USM system in rooms on the 13th and 6th floors in this building as shown in Figure 12.



(a) General view (b) Plan on 13th and 6th floor (c) Installation of sensor node

Figure 12 Applied high-rise building and installation of sensor node

4.2. Vibration detection test by sink node during typhoon

Vibration detection test by the sink node had been carried out in the room ① on the 13th floor in 2007. The vibration of the building during typhoon No. 20 was monitored by installed sink node on October 27th in 2007. The sink node detected the small vibration caused by the typhoon and collected the acceleration data. Figure 13 shows x and y axes acceleration record measured by the sink node and their orbit. Their Fourier amplitude spectrum was shown in Figure 14. In this case, the direction of main vibration of this building was x-direction. Such small vibration, ±2 cm/sec2, in low frequency domain, could be detected and monitored by the sink node. Peaks of the first mode in x and y axis were 0.3 Hz and 0.34 Hz, respectively.

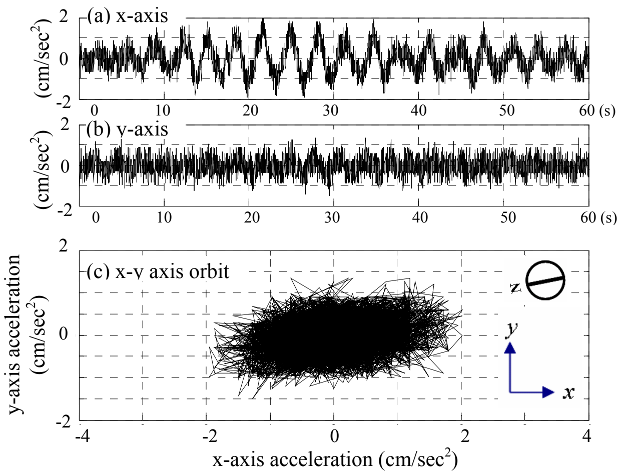


Figure 13 Acceleration record and orbit

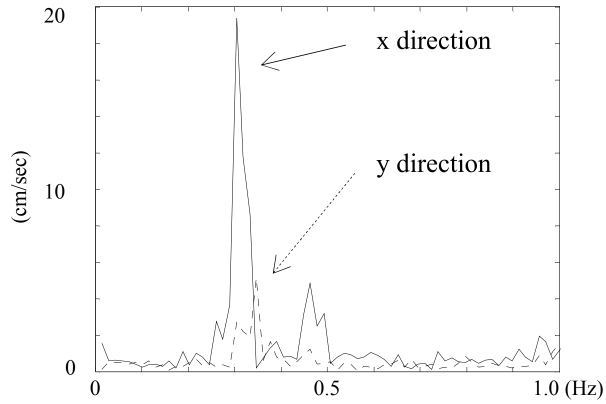


Figure 14 Fourier amplitude spectrum

4.3. Story drift based structural monitoring for earthquake

Story drift based structural monitoring has been carried out in the room ② on the 6th floor. The sink node and sensor node were installed on the floor as shown in the Figure 12(c) and on the ceiling, respectively. The vibration of the building during earthquake occurred on August 8th in 2008 was monitored. The sink node realized the time synchronization with the sensor node. The sink node detected the vibration caused by the earthquake and collected the acceleration data from the sensor node after the vibration without data loss. That was minimum system configuration, however, basic function of applied USM system described 3.4 was recognized. Figure 15 shows x and y axes acceleration data measured by the sink node and the sensor node. Displacement data was evaluated by double integral of acceleration data and story drift was calculated by difference between displacement data of the sink node and the sensor node. Orbit of story drift was shown in Figure 16. According to the Japanese design code for high-rise building, structural members are expected to remain within elastic range for story drift angle of 1/200 or less. It was recognized that the story drift angle during the earthquake remained within 1/2000, therefore, in this case, no damage was evaluated in this space.

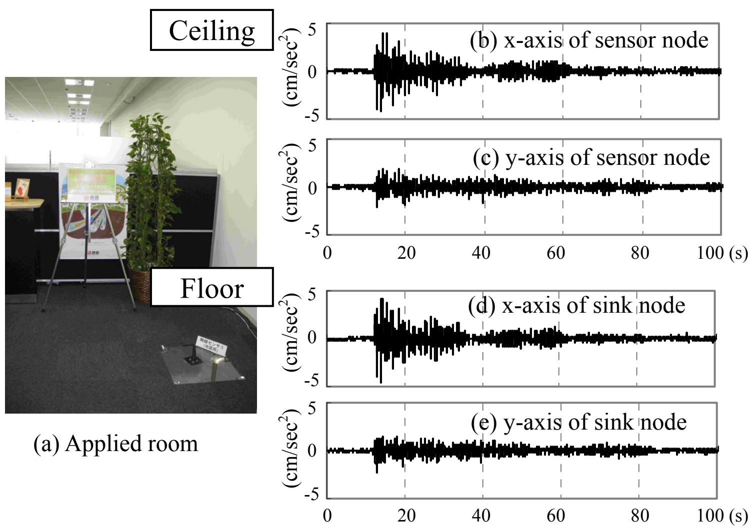


Figure 15 Acceleration data

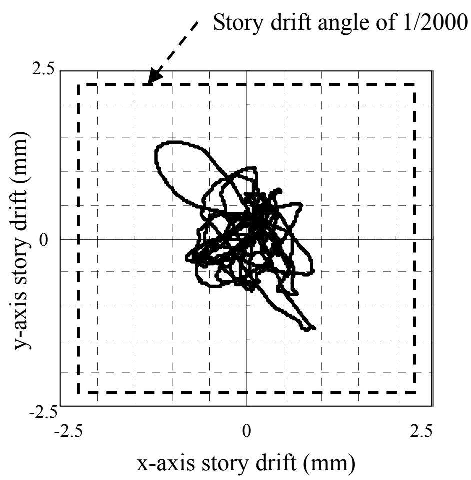


Figure 16 Orbit of story drift

5. CONCLUSIONS

This paper reported research activity on development of sensor module. The sensor board which is equipped with the MEMS acceleration sensor selected by the benchmark test was developed and tested. The sensor module which consists of the sensor board and wireless network module was tested by shaking table. It was confirmed that the developed sensor module had enough basic performance for the USM. The USM system which consists of developed sensor modules and PC was installed in a high-rise building. The building's vibration during earthquake was monitored and basic performance of the USM system was verified.

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