Applied MEMS Micro-vibration Sensors and Structural Health Monitoring

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ABSTRACT

After the Great Hanshin-Awaji Earthquake, interest has been increasing for earthquake disaster prevention awareness and building safety. As a new field of measuring devices, Fuji Electric has created a prototype vibration sensor module that applies MEMS (Micro Electro Mechanical Systems) technology. This vibration sensor is capable of continuous micro-vibration measurements of around 0.1 Gal. It can detect not only damage by earthquakes, but also the alteration of strength in a building caused by age-related deterioration, so it can be applied to structural health monitoring that includes continuous micro-vibration measurements. We are also considering applications in high-frequency/high-acceleration ranges for motor diagnostics.

1. Introduction

Since the Great Hanshin-Awaji Earthquake in 1995 in Japan, disaster awareness regarding earthquakes and concern for building safety has heightened, and in recent years, there has been an increased in the application of structural health monitoring (SHM) to diagnose the health and safety of buildings. Servo acceleration sensors used primarily for this purpose have the excellent characteristics of high detection sensitivity to extremely low-frequency acceleration, and can be used to measure micro-vibrations constantly at high resolution. The extremely high price of these sensors, however, has been one factor preventing them from coming into widespread use. On the other hand, although lower cost sensors that use micro electro mechanical system^{*1} (MEMS) acceleration sensor devices have been developed, they have not yet been used in applications for constant micro-vibration measurement, which is necessary for SHM. Fuji Electric is engaged on developments ranging from sensor devices that apply MEMS technology to vibration sensor capable of 3-axis constant micro-vibration measurement. This paper introduces SHM and then describes MEMS micro-vibration sensors and their applications.

2. Structural Health Monitoring

SHM is a technology, having been researched and developed at universities and the like in recent years, for installing sensors in new construction and existing structures in order to diagnose their structural performance based upon response waveforms. SHM technology is able to utilize the response to unfelt earthquakes, which have a relatively high frequency of occurrence⁽¹⁾, and to constant micro-vibrations (on the order of 0.1 to 0.5 Gal*²), in order to diagnose the performance of structures (having a resonance frequency in the range of about 0.1 to 20 Hz) and in the case of potential damage from large earthquakes (ranging from several hundred to 2,000 Gal), typhoons and the like, to estimate automatically the extent of that damage.

In addition, by accumulating data continuously, the deterioration of a structure due to aging can be understood, and this information can be used when making decisions about maintenance. In contrast to surface or partial inspections such as periodic visual inspections or ultrasonic inspections, SHM allows the status of the entire structure and locations of defects to be estimated. Fig. 1 shows the SHM sequence. With SHM, sensors are installed in the structure to measure



Fig.1 SHM sequence

^{*1:} See MEMS supplemental explanation 1 on page46

^{*2:} Gal is a unit of acceleration, and is defined as 1 Gal= 0.01 m/s^2

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Table 1 Assumed objective of SHM service

Building life cycle	Service objective	
Design, construction, sales	Verification of structural characteristics based on measurement data	
Building management	Diagnosis of building deterioration during normal times	
Repair, reinforcement	Presentation of necessity and timing of large- scale repair and seismic strengthening	
	Presentation of effect of large-scale repair and seismic strengthening	
Disaster	Rapid determination of damage status immedi- ately after disaster	
	Prediction of structural impact in response to predicted earthquake motion at site	
Purchase and sale	Presentation of age-related deterioration of building performance	
	Evaluation of asset value based on measure- ment data	
Change of use, etc.	Pre-measurement and post-evaluation of struc- tural impact that accompanies a change of use	
Discontinuing usage, Rebuilding	ning Presentation of service life based on measure- ment data	

(Source: Comprehensive Technology Development Project, MLIT)

the acceleration (or velocity, displacement, etc.) of the structure, and transmit the data to a server to manage. From the transmitted acceleration data, the vibration mode of the structure is analyzed, and based on the computed natural frequency and the like of the structure, a diagnosis is made and the results are displayed. Using the diagnostic results obtained by SHM, the various services shown in Table 1 can be provided for each phase of the life cycle of the building.

In this way, with SHM, the acceleration due to unfelt earthquakes and constant micro-vibrations is measured to understand the shaking of the overall structure. Therefore, the vibration sensors used with SHM are required to have a high resolution of at least 0.01 Gal, and a high-precision time synchronization function of 1 ms or less among the sensors installed in the structure.

3. MEMS Vibration Sensor

3.1 Vibration sensor

To make possible the constant measurement of micro-vibrations, as is required for SHM, a MEMS 3-axis acceleration sensor device, having sensitivity in the low-frequency and low acceleration regions, and its peripheral circuitry were developed and a prototype was built. Fig. 2 shows the appearance of the vibration sensor, Fig. 3 shows the appearance of the MEMS 3-axis acceleration sensor, and Fig. 4 shows a cross-sectional schematic of the sensor device.

The MEMS 3-axis acceleration sensor device is capacitive, and as shown in Fig. 4, detects the displacement of a movable electrode in response to a change in



Fig.2 Vibration sensor appearance



Fig.3 Appearance of MEMS 3-axis acceleration sensor device



Fig.4 Cross-sectional schematic drawing of sensor device

acceleration as a change in electrostatic capacitance. Displacement along the X and Y axes is detected as a change in electrostatic capacitance between a movable electrode and a fixed electrode formed on a silicon on insulator (SOI) substrate, and displacement in the Z axis is detected as a change in electrostatic capacitance between the movable electrode and a fixed electrode formed on a glass substrate.

Figure 5 shows the structure of a vibration sensor and Table 2 lists the development target specifications of these vibration sensors.

As shown in Fig. 5, the vibration sensor uses a low pass filter (LPF) that cuts off signals above 20 Hz and a 24-bit $\Delta \Sigma$ type analog-to-digital converter in each of the 3 axes to realize high resolution of 0.01 Gal. Because clock error exists among the individual vibration

sensor CPUs, the PC transmits a time synchronization packet every 10 seconds in order to achieve time synchronization, and in compared to the specification value of 1 ms as the time synchronization error between sensors, an actual error value of less than 0.5 ms has been attained.

In the connection example shown in Fig. 6, vibration sensors are connected via a power over Ethernet (PoE) hub to a personal computer (PC), and powered using an Ethernet^{*3} LAN cable (Up to 24 sensors may be connected).

3.2 Building measurement example

In order to obtain experience and knowledge regarding the application of vibration sensors to SHM, a field test was conducted by installing vibration sensors on the 1 st and 4th floors of a 5-story building (Fig. 7) located in the same district as Fuji Electric's Tokyo business place, and micro-vibrations were measured constantly. The vibration sensors were positioned in alignment with the long-side direction as the X-direction and the short-side direction as the Y-direction. The measurements obtained included vibrations from



Fig.5 Configuration of vibration sensor

Table 2	Development target	specifications o	f vibration sensor
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Item	Specification
Detection direction (number of axes)	3 components (3 axes of X, Y, Z)
Measurement range	±2,000 Gal * (Acceleration: approx. 600 Gal at period of 1 s, and equivalent to Japanese earthquake scale of 7)
Resolution	0.01 Gal
Frequency	0.1 to 20 Hz (structural vibration is primarily 1 to 20 Hz)
Sampling period	100 Hz
AD conversion	24 bit
Time synchronization	1 ms or less
Power source	Supplied by PoE (Power over Ethernet), 48 V, 4 W

 \ast Gal: Unit of acceleration, where 1 Gal=0.01 m/s^2

*3: Ethernet is a trademark or registered trademark of Fuji Xerox Co., Ltd.

an earthquake originating in the Pacific Ocean off the coast of Japan's Tohoku region. Fig. 8 shows the acceleration waveform at the 1 st and 4th floors at the time of the earthquake, and the acceleration waveform of the constant micro-vibrations immediately prior to the earthquake (enlarged view of interval from 0 to 10 s). Additionally, Fig. 9 shows the Fourier spectral ratio of the 1 st and 4th floors before the earthquake, and Fig. 10 shows the Fourier spectral ratio of the 1 st and 4th floors for the time interval from 70 to 100 s when the amplitude is relatively constant during the earthquake. From Fig. 9 and Fig. 10, it can be seen that the natural frequency of the long-side direction (X axis) decreases from 2.21 Hz before the earthquake to 1.95 Hz during the earthquake, and the natural frequency of the short-side direction (Y axis) decreases from 1.90 Hz before the earthquake to 1.66 Hz during the earthquake. In this field test, we were able to measure the natural vibration frequency of a building with the prototype vibration sensors, and to verify the nonlinearity of the amplitude of the natural vibration



Fig.6 Connection example of vibration sensor



Fig.7 Building with installed vibration sensors



Fig.8 Acceleration waveforms of 1st and 4th floors at time of earthquake

frequency.

The ability to measure vibrations over a wide range from 0.1 to 410 Gal with vibration sensors, and the ability to measure changes in the natural vibration frequency due to changes in the vibrating state of a building were also verified. Damage caused by earthquakes, as well as changes in characteristics such as degraded building strength due to aging-related deterioration, changes in the natural vibration frequency, and so on can be detected, and vibration sensors are considered to be suitable for application to SHM that includes constant micro-vibration measurement.

In addition, vibration sensors can also be used in SHM applications to rail and road bridges.

4. Application to Earthquake Measurement

After the Great Hanshin-Awaji Earthquake of 1995, the National Research Institute for Earth Sci-



Fig.9 Prior to earthquake (at time of constant micro-vibrations)



Fig.10 During earthquake (70 to 100 s)

ence and Disaster Prevention began development of a nationwide strong-earthquake observation network in Japan. The result of this construction was the Kyoshin Network (K-NET), a strong-earthquake observation network consisting about 1,000 observatories that cover all of Japan with a grid mesh of about 25 km for the purpose of strong-earthquake research and earthquake disaster prevention. Moreover, in order to realize a higher level of disaster preparedness for earthquakes directly underneath urban areas, which was the lesson of the Great Hanshin-Awaji Earthquake, the Earthquake Research Institute of the University of Tokyo has demonstrated the need for carrying out a detailed evaluation of ground characteristics (from several



Fig.11 Illustration of ground measurement



Fig.12 Small-scale earthquake acceleration waveform at Tokyo business place

tens to several hundreds of meters) and to establish disaster prevention criteria for each district through measuring unfelt earthquakes⁽¹⁾ which have a relatively high frequency of occurrence and constant microvibrations. Fig. 11 shows an illustration of the ground measurement implementation.

Detailed seismic measurement requires the use of many seismographs. For estimating ground properties, Fuji Electric is studying the application of MEMStype acceleration sensors which have a cost advantage over the commonly used servo-type acceleration sensors. The specifications required of acceleration sensors for measurement of unfelt earthquakes and constant micro-vibrations are the same as for SHM, that is, high resolution of 0.01 Gal or less and highly accurate time synchronization of within 1 ms among the sensors. For a detailed estimation of ground properties, Fuji Electric installed vibration sensors at 4 locations (points A, B, C and D) in the district of its Tokyo business place, and measured small earthquake acceleration waveforms. Fig. 12 shows the measured acceleration waveforms. Even within the narrow range of these 4 points, which are spaced apart by distances of several tens of meters to several hundreds of meters,

Table 3	Major challenges in application to SHM and
	earthquake measurement

Challenge	Solution
Power supply during power outage	 ○ Built-in battery ○ Change to lower power consumption
Increased cost due to cable installation	Change to wireless technology for cable-free installation
Miniaturization of vibration sensors	Miniaturization of the sensor device and circuit

the appearance of the vibrations differed, confirming that the manner of shaking was also different.

5. Future Developments

SHM and ground property estimation applications are conventionally in the low-frequency, low acceleration region, but Fuji Electric is attempting to use these applications in the high-frequency, high acceleration region. Fuji Electric is studying the use of vibration sensors to replace commercial vibration diagnostic systems for rotating machines, and also their application to motor diagnostic systems for hybrid and electric vehicles. Fuji Electric possesses the MEMS technology and low-noise circuit technology necessary for sensor development, and that makes possible customization and development from the low frequency, low-speed region to the high-frequency, high-speed region. Additionally, Fuji Electric also intends to address the main challenges for application to SHM and earthquake measurement as shown in Table 3.

6. Postscript

Vibration sensors that use MEMS technology and their applications have been introduced in this paper.

As a result of the prototyping and evaluation of MEMS micro-vibration sensors, application to constant micro-vibration measurement appears to be possible. In the future, Fuji Electric intends to perform detailed evaluations of the performance and applicability of these sensors to performance improvements and structural health monitoring, and to contribute to ensuring building safety.

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