

# Structure Health Monitoring System Using MEMS-Applied Vibration Sensor

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## ABSTRACT

Recently, studies have come to be increasingly energetically conducted on structure health monitoring (SHM), which involves diagnosis of the structure performance of buildings based on response waveforms to earthquakes and microtremors. Fuji Electric has commercialized a vibration sensor that applies micro-electro-mechanical systems (MEMS) and a primary diagnosis monitoring system that makes use of the sensor. Use of the MEMS-applied vibration sensor instead of a servo acceleration meter allows building of low-cost systems. At present, for the purpose of practical application of the SHM system, Fuji Electric is conducting research and development for estimating an index (feature quantity) that represents the soundness of buildings.

## 1. Introduction

In Japan, many of social infrastructures represented by bridges, tunnels and expressways constructed one after another in the period of rapid growth have existed for 40 to 50 years and are obviously aging. Japan is an earthquake-prone country, and seismicity is required on buildings. To maintain the performance of these social infrastructures and buildings and increase their longevity, inspections and maintenance must be performed at a proper timing. In case of a disaster, it is necessary to conduct primary diagnosis to instantaneously determine the soundness of buildings and inform users of whether they must evacuate from them.

In the past, visual inspections by engineers were the main inspections of structure, and it was difficult for engineers to carry out all works because there were many number and types of structure constructed. In recent years, there has been increasing demand for preventive maintenance, which is intended to detect abnormalities early and take action to increase the longevity of buildings.

In this situation, structure health monitoring (SHM), which, by means of such sensor technology as acceleration sensors, diagnoses the structural performance of buildings from response waveforms to earthquakes and microtremors (constantly produced faint vibrations that people do not feel) has been introduced. Research and development of SHM was conducted mainly by universities and research institutions. With the increase of social capital stock and the occurrence of great earthquakes and infrastructure accidents, and progress of with low-cost acceleration sensors applying micro-electro-mechanical systems (MEMS) as well

as diagnosis technology, SHM systems adopting SHM technology for evaluating the soundness of structure are expected to rapidly develop.

In 2012, Fuji Electric commercialized a MEMS-applied vibration sensor for measuring acceleration and a primary diagnosis monitoring system adopting this sensor and is committed to further carry out research and development of SHM systems. This paper outlines an SHM system for buildings and its element technologies.

## 2. Structure Health Monitoring System

### 2.1 Overview

An SHM system refers to a system for evaluating the soundness of structure from response waveforms of earthquakes and microtremors by installing acceleration sensors, etc. on them, in order to provide users with information for safety and security. This system consists of the functions of data acquisition, primary diagnosis in case of an earthquake, analysis (state estimation), diagnosis, provision of diagnosis results and accumulation and management of SHM information (see Fig. 1).

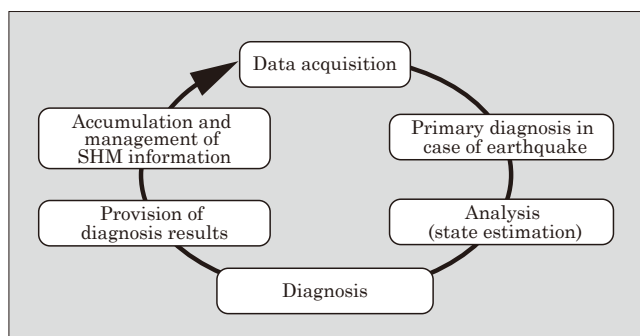


Fig.1 Functional configuration of SHM system

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Fuji Electric has been participating in the Structure Health Monitoring Consortium\*1 under the initiative of Keio University developing SHM systems. The development covers a system covering steps from data acquisition to primary diagnosis and a system responsible for analysis (state estimation) and accumulation and management of SHM information.

The features of Fuji Electric's SHM systems are shown below.

- (a) The SHM system can carry out multi-point measurements using low-cost sensors.
  - (b) The SHM system can immediately provide the diagnosis result of the soundness of the building after an earthquake occurs.
  - (c) The SHM system can collect analog data besides acceleration and make it available for diagnosis.
- (1) Primary diagnosis monitoring system

Fuji Electric developed and commercialized a primary diagnosis monitoring system in collaboration with Toda Corporation. A configuration example of the primary diagnosis monitoring system is shown in Fig. 2. This system consists of vibration sensors, a vibration recorder, information monitors and a LAN connecting them. What is required for analysis by SHM is time-synchronizing data. To ensure highly accurate time synchronization between the sensors, the vibration recorder distributes extremely accurate time to the vibration sensors, and also serves as a simplified diagnosis server to collect the acceleration data measured by the vibration sensors and compute the seismic intensity and displacement of the building in real time. Based on these computation results, the primary

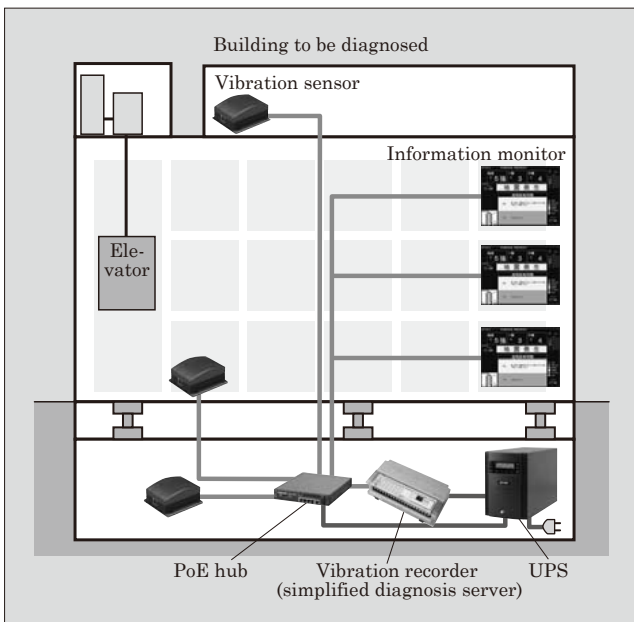


Fig.2 Configuration example of primary diagnosis monitoring system

\*1: URL: <http://www.mita.sd.keio.ac.jp/consortium/index.html>

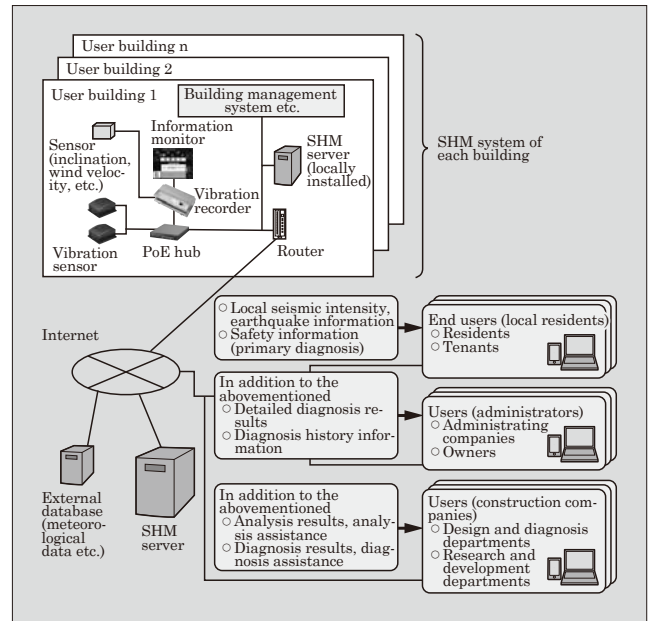


Fig.3 Configuration example of cloud-type SHM system

diagnosis monitoring system displays information about the seismic intensity and estimated soundness of the building for safety and security on the information monitors.

(2) Fuji Electric's SHM system

Based on the SHM system developed by Keio University, Fuji Electric is developing an SHM system that will be applicable to a wider range of fields with the aid of vibration sensors and vibration recorders. This system is capable of diagnosing and evaluating structure from various aspects by collecting analog data, such as inclination, wind direction and velocity and temperature, in addition to acceleration (digital data) from vibration sensors, in synchronization with time. Such data can be collected in a vibration recorder, diagnosed and evaluated in a sophisticated manner on a locally installed SHM server. As shown in Fig. 3, the SHM system can also provide many users with information for safety and security and information about effective maintenance at lower cost by switching the SHM server to cloud-type services installed in a data center, etc.

2.2 Functions and services

(1) Primary diagnosis service

The SHM system conducts diagnosis using data measured inside the building, and provides information about building diagnosis for determining the soundness of the building on an information monitor or by broadcasting just after the occurrence of an earthquake. A screen example of the information monitor is shown in Fig. 4.

(2) Analysis (state estimation) and information accumulation and management services

The SHM system removes noise from measured data, adds metadata, and estimates an index (feature



\* Developed in collaboration with Toda Corporation.

Fig.4 Screen example of information monitor

quantity) representing the soundness of the structure concerned. In addition, it manages measured values, analysis (state estimation) results, diagnosis results and other data in a proper manner for the maintenance and management of the structure and provides users with them in visualized form.

### 2.3 Application example

The consortium has installed an SHM system in an apartment building constructed in Tokyo and conducted test operation.

Three vibration sensors and a vibration recorder for temporarily recording data measured by the vibration sensors are installed inside the building, and data measured during microtremors and earthquakes is transmitted via the Internet to the SHM server installed inside Keio University. This data and analysis results will be provided on web screens. A display example of acceleration data and that of power spectrum analysis results are shown in Fig. 5 and Fig. 6, respectively.

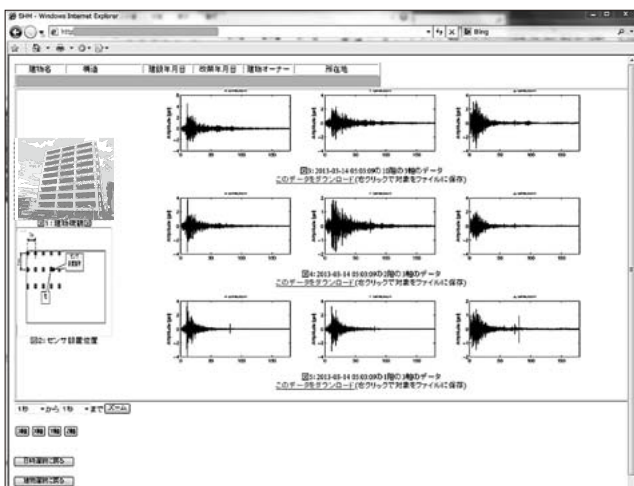


Fig.5 Display example of acceleration data

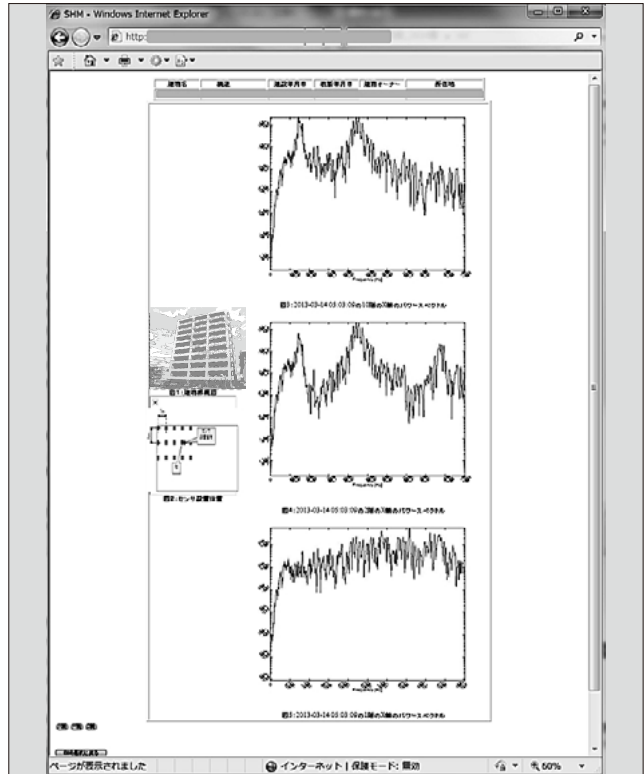


Fig.6 Display example of power spectrum analysis results

Also installed inside the apartment building selected for the test operation is an SHM system equipped with an expensive conventional servo-type accelerometer. The results of the test operation showed that the data measured by the vibration sensor was equivalent to the data collected by the servo-type accelerometer. This fact verifies that an SHM system using low-cost vibration sensors can be constructed.

## 3. Element Technologies of Structure Health Monitoring System

### 3.1 Vibration sensor

The appearance of a vibration sensor is shown in Fig. 7, and its specifications are listed in Table 1. The vibration sensor is equipped with an electric-capaci-

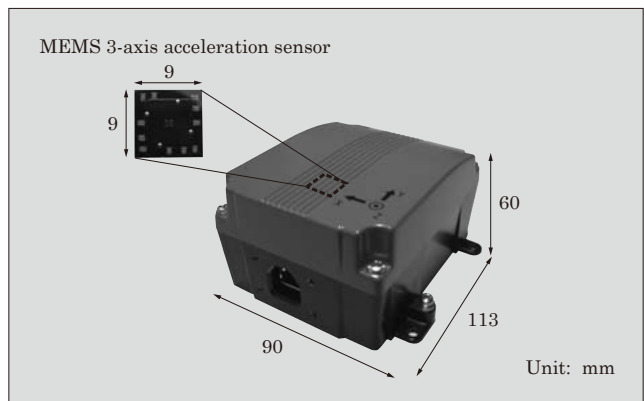


Fig.7 Vibration sensor

Table 1 Specifications of vibration sensor

Item	Specifications
Detection direction (number of axes)	3 components (X, Y and Z axes)
Measurement range	$\pm 2,000 \text{ Gal}^*$
Resolution	X and Y axes: 0.02 Gal, Z axis: 0.07 Gal
Frequency range	0.1 to 50 Hz
Sampling frequency	200 Hz (can be set on 100 Hz)
Time synchronization	Within 1 ms
Power source	PoE supply: 48 V, 4 W

\*: Gal is the unit of acceleration; 1 Gal = 0.01 m/s<sup>2</sup>

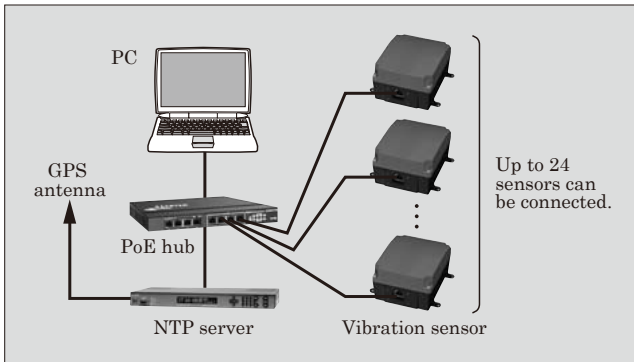


Fig.8 Connection example of vibration sensors

tance-type MEMS 3-axis acceleration sensor, which was originally developed to measure microtremors required for the SHM system and has a sensitivity covering low-frequency and low-acceleration regions, and its peripheral circuit.

A connection example of vibration sensors is shown in Fig. 8. Up to 24 vibration sensors can be connected to a personal computer via a PoE hub\*<sup>2</sup>. These vibration sensors transmit acceleration data on the X, Y and Z axes together with time data. Since the SHM system requires time-synchronizing data for analysis, the NTP protocol or another protocol is used to keep the synchronization error between the vibration sensors within  $\pm 1$  ms. Once an IP address is set to each vibration sensor prior to installation, it will automatically start communication simply by connecting an LAN cable to it, making other setting operations no longer necessary at the time of installation.

### 3.2 Analysis technology

To enable the SHM system to diagnose and evaluate the soundness of the structure concerned, an index appropriate for the purpose of diagnosis needs to be estimated. Various analysis technologies are required for primary diagnosis and analysis (state estimation) because the value of the diagnosis index will be estimated from the values measured by sensors.

\*2: PoE hub: Hub capable of supplying the power by means of an Ethernet communication cable.

Table 2 Diagnosis indices and representative sensors to be used for SHM system

Object to be measured	Example of diagnosis index	Representative sensor to be used for measurement
Overall level	Decrease in frequency of primary mode	One or more acceleration sensor in whole object
Layer* level	Decrease in frequency of each order mode	Acceleration sensors installed on multiple layers
	Local increase in inclination of mode shape	Acceleration sensors installed on multiple layers
	Decrease in layer rigidity	Acceleration sensors installed on multiple layers (Mass of each layer, inter-layer displacement gauge)
	Maximum story drift in excess of threshold	Acceleration sensors installed on multiple layers (Mass of each layer, inter-layer displacement gauge)
	Interleaving frequency	Three acceleration sensors
	Maximum deformation, cumulative deformation, cumulative energy	Acceleration sensors installed on multiple layers
Component level	Others	Acceleration sensors installed on plural layers
	Torsional mode	Two or more acceleration sensors installed on the layer concerned
	Others	AE sensor, strain gauge, etc.

\* Layer: Story of a building

Examples of diagnosis indices to be used for SHM systems and representative sensors to be used for measurement are shown in Table 2.

(1) Analysis technology that realizes primary diagnosis

In primary diagnosis, the maximum acceleration and maximum story drift of all stories are estimated as soundness indices in order to evaluate the soundness of the building concerned just after the occurrence of an earthquake. Here, the maximum story drift is calculated by integrating acceleration data twice. In this step, various pieces of data are preprocessed and integrated in the frequency region to stabilize integration. In concurrence with this, the soundness indices of all stories are estimated by evaluating the acceleration response of the stories not installed with the sensors based on information about the mode (amplitude pattern of vibrations at the natural frequency) of the building concerned. An example of estimation results is shown in Fig. 9. Through such analysis, diagnosis can be conducted only with several vibration sensors without installing a vibration sensor on all stories.

The maximum acceleration, a soundness index, in excess of the threshold indicates the possibility of damage to the inside of rooms by moving furniture and equipment and to equipment piping, anchors, etc. The

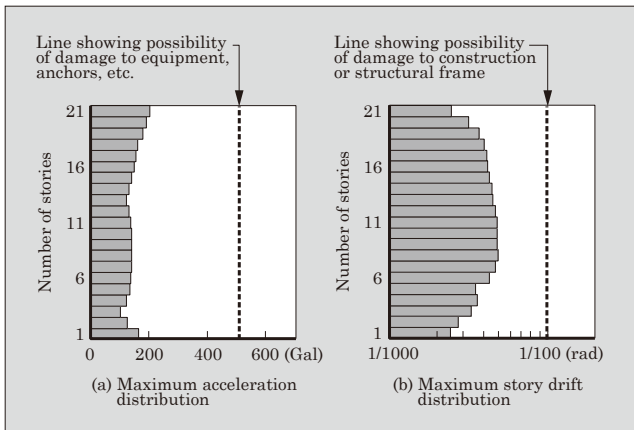


Fig.9 Estimation example of maximum acceleration and maximum story drift in primary diagnosis

maximum story drift exceeding the threshold presents the likelihood that the soundness of the structural frame will be impaired.

Such information will be useful for making decisions such as whether or not to conduct a damage investigation preferentially from the stories with higher maximum acceleration or maximum story drift. Set these thresholds with structure design information, etc. about each building concerned taken into account.

#### (2) Analysis technology for state estimation

Using measured acceleration data, obtain the natural frequency, mode and other vibration characteristics, and then estimate the state of the building from changes in the characteristics. To estimate the state of a building, construct a physical or mathematical model that is best suited to the object to be measured. Correctly determining the orders and parameters of a model expressing the system concerned (building concerned in this case) from input/output data is generally called system identification. The SHM system determines the structure of the model and estimates its parameters by conducting system identification with the acceleration of the first floor as the input and the acceleration of the top floor as the output. The system then estimates the vibration characteristics of the building concerned from these estimation results.

In diagnosis, the soundness of the building can be evaluated based on, for example, a change (decrease) in the estimated natural frequency.

It should be noted that the accuracy of the system identification mentioned above will vary with the set orders of the model or the quality of the data to be used for identification. To avoid this variance, these parameters will be automatically determined by applying an optimization algorithm that uses the orders of the model and the data processing parameters to be used for identification as decision variables and identification accuracy as an evaluation function. In addition, an interactive interface is adopted to enable users to adjust identification parameters, and the combination of this interface and the abovementioned optimization algorithm achieves practical-state estimation.

## 4. Postscript

This paper described the structure health monitoring system using MEMS-applied vibration sensors.

Fuji Electric has commercialized a primary diagnosis monitoring system capable of diagnosing the soundness of buildings just after the occurrence of an earthquake, and has been providing information useful for subsequent decision-making. Fuji Electric is also conducting research and development for the practical use of SHM systems. As the first step, we will construct a system that will provide experts in structures with information necessary for diagnosis, such as analysis results, in a timely manner. We are determined to establish soundness indices based on measured data accumulated in the system, achieve automatic diagnosis, and, above all, make the system applicable to social infrastructure, such as bridges and tunnels, and thereby contribute to the safety and security of society.

In the process of establishing the SHM system, we were given suggestions and guidance from Professor Mita of the Faculty of Science and Technology at Keio University. We also received advice from Toda Corporation and member companies of the consortium. We would like to express our heartfelt thanks to all of them.



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