Structural Health Monitoring System using Peak Hold Sensor and Wireless Measurement Devices

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ABSTRACT

In recent years, to install sensors in structures for monitoring its performance and health has became common practice, and structural health monitoring system is no longer an exception. However, the initial and operational costs of most of proposed systems are too high for widely spread. In addition, the complexity of its operation is also a great problem that remains to be solved. To solve these problems, we have developed a cost-effective and easy-to-use structural health monitoring system by combining of the peak hold sensor and the wireless measurement device. The peak hold sensor system was developed for prompt health monitoring of structures affected by earthquakes. The mechanical sensor, placed on a structural member, logs the peak value of the movement that result from an earthquake without need for an external power supply. The system enables the non-contact reader to scan the data stored in the system with ease so that the status can be assessed based on measurements made on location. This monitoring system, which is reasonable in price and easy to handle, is ideal for the constant health monitoring of any structure based on its life cycle.

INTRODUCTION

The health monitoring of structures equipped with sensors has become a common practice lately for assessment of the structural performance affected by natural disasters such as earthquakes and typhoons or simply by normal structural aging. This monitoring system, shows the difference between the initial and current status of a particular structure by collecting useful data for prompt assessment of its structural performance, whether it is a sudden change or the result of long-term aging. The monitoring system

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referred to in this paper requires a combined function of a sensor and a measurement device and it is desirable to have secure both mobility and prompt assessment. However, during our study it was difficult to use the systems proposed in the past since these systems were not affordable for wide-scale and operation, as well as difficult to handle. In order for the system to be widely accepted, a new monitoring system with cost effective and easy-to-use functionality was needed. Given these circumstances, the authors designed a structural monitoring system using the inexpensive sensor and simple measurement device for health monitoring of structures affected by earthquakes. The system remains operable even in the event of power loss due to large earthquakes as it has an uninterrupted power supply to record the peak value of structural members at point of attachment. The data stored in the system facilitates access to the measurement data by the non-contact reader for health monitoring of the structure.

OUTLINE OF THE SYSTEM

Structural health monitoring, in installed structures expected to have damages due to external forces such as earthquakes, requires sensors to identify any potential damage. One of the simplest ways is to install the sensor at all points or places where damage is expected. In this term, it was necessary to develop an inexpensive and simple monitoring system with limited functionality by specifying the information that should be obtained by the sensor for technical assessment of the structural status. Specifically, displacement of structural members was determined to be a basic but critical indicator for structural health monitoring. Figure 1 shows the progress of displacement for a structure affected by an earthquake. In particular, the peak and cumulative displacements of structures during a large earthquake should be effective enough to assess potential damages or the expected life of the structure after an earthquake. Moreover, this data may be utilized to design the optimum maintenance program for the affected structure. Thus, it has been desired to develop a sensor for measurement of displacement of structural members and to be available at an affordable price.

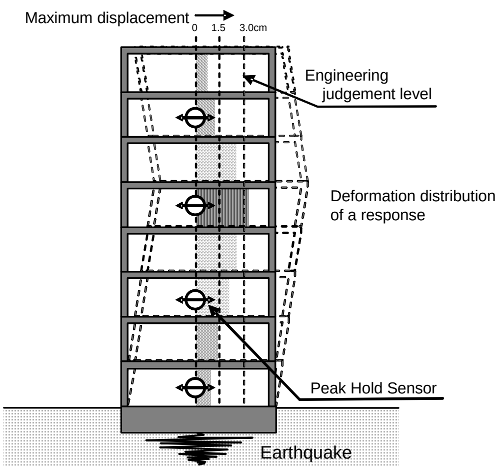


Figure 1: The displacement response and the peak value of a structure affected by an earthquake

The authors aimed to develop a structural health monitoring system using a number of sensors for the target structure which also should be easy to manage. In particular, an inexpensive sensor to store the physical value without the need for power supply was developed. This sensor is equipped with a non-contact device to enable reliable long-term measurement of data without obtrusive cable connections. The device is also designed to conduct the health monitoring on-site. It was important to consider that the system should be convenient to use in terms of functionality for managers without special training to be able to monitor the status of the structure.

SYSTEM CONFIGURATION

Measurement System

Figure 2 shows the appearance and specifications of the peak hold sensor system described in this paper. The system is comprised of the sensor to store the displacement data of structural members and the measurement device to assess the readings. The sensor, without power, is designed to be installed on seismic members so as to monitor and store the peak/cumulative displacement data of the members controlling the vibration energy of the building. Table 1 shows specifications of the system. The measurement device is comprised of the communication device (transmitter) connected to the sensors for scanning the stored data and the non-contact reader (receiver) to supply power to the transmitter without contacting, and to receive the data. The transmitter is preprogrammed to set the sensor ID, calibration value and threshold value for each structural member. One of the major features of this system is to enable users to conduct the health monitoring assessment of members using the threshold value obtained on the spot upon completion of a measurement. The receiver shows the data provided by the transmitter (values for measurement and assessment). A series of such measurements and assessments are completed in about two seconds. Figure 3 shaws the system block diagram. The transmitter and receiver are comprised of general-function electronic parts using a PIC-type microcomputer, which is small and inexpensive. The non-contact power supply employs a coil-type electromagnetic system (transmitable distance is 1cm). A wireless AM modulation is utilized for communication. Note that the sensor output is converted by 4-input A/D (resolution 10bit).

Table 1: Specifications of the System

Measurement Device	Peak Hold Sensor
Power Supply and Communication : Non-contact power supply (Communicable 1cm) Wireless communication Connection sensor : Voltage Output or Resistance Display: judgement lamp and Measurement Value Size: W90 x D135 x H35mm (Non-contact Reader) W50 x D68 x H30mm (Transmitter)	Maximum Displacement Hold: Maximum Stroke ±5cm Hold Type Maximum, Minimum and Current Value Resettable System Cumulation Displacement Hold: Maximum ±200cm Resettable System Size: W140 x D500 x H65mm

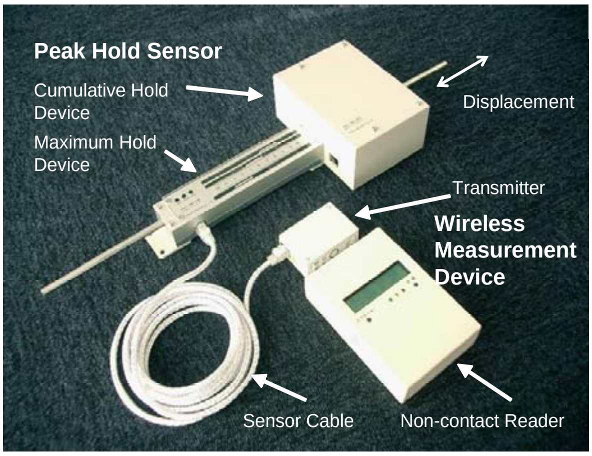


Figure 2: Appearance of Peak Hold Sensor System

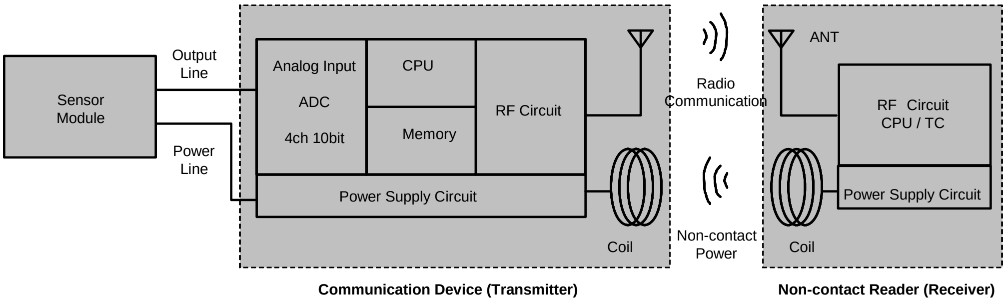


Figure 3: System Diagram

Mechanism of Sensor

The peak hold sensor is designed to hold three kinds of displacement, maximum, minimum and current value (residual) without power supply, utilizing the function to hold the position against friction of movable members and the resistance change of a long resistant member to the moving direction (linear potentiometer). The rolling bearing is equipped with a one-way clutch, which is in contact with the moving member to make the resistance member (rolling potentiometer) roll solely in one way in order to hold the cumulative value for the two directions. The displacement is indicated as the voltage proportional to the partial pressure resistance for displacement. The maximum peak hold sensor and the cumulative hold sensor in the system are separately produced so that the peak hold sensor may be used solely or be combined with the cumulative hold sensor.

PERFORMANCE OF THE SYSTEM

Basic Characteristics of Sensor

The values of displacement monitored by the system and the reference laser-type displacement gauge were compared to review the characteristics of the displacement measurement of the system. For comparison, displacement of the target on a movable stage in a static state was monitored by the peak hold sensor and the laser-type displacement gauge, which are connected to the data storage device with a cable and placed on a fixed base, at the same time. The result is as shown in Figure 4. The solid line in Figure 4 (measurement: cable connection) shows the measurement (of the peak hold sensor) against the reference value (the laser-type displacement gauge) when the target dislocates when the sensor is moving for a full stroke from -50mm to +50mm. This figure shows only the current value of the five kinds of outputs. The figure indicates, which implies that the reference value and measurement are almost identical so that the sensor of this system is effective to measure the displacement with certain accuracy.

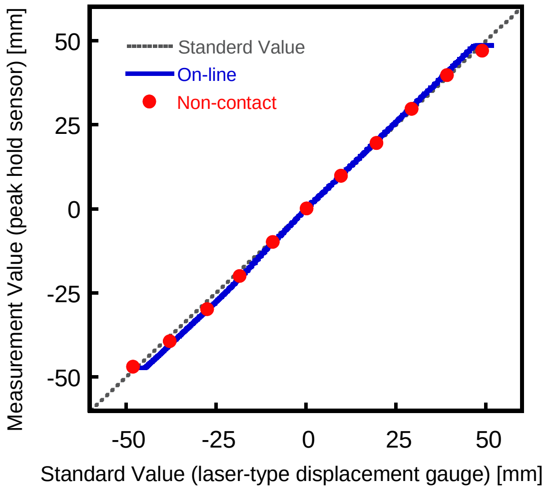


Figure 4: Characteristics of the Sensor: Displacement Measurement

Basic Characteristics of the Measurement Device

The Distance for non-contact measurement was studied in order to examine the measurement properties of the non-contact reader. This assessment was conducted because the risk of potential system failure and loss of functionality, in spite of its advantage using non-contact and convenience of measurement. The distance for practical measurement of the non-contact sensor was targeted to be 1 cm. Then, the measurable distance (a distance practical to accurately measure the data) and the transmission distance (the distance measurable but may not be accurate) were studied for some different distances between the transmitter and receiver, in term of the axis displacement X and the distance Y. The axis displacement direction X was adjusted by changing the number of acrylic plates (2mm in thickness) when the transmitter and the receiver were in a contact position. The test condition was shown in Figure 5. The test result is shown in Table 2. It shows no major data spread for the distance of practical measurement. These results confirm that the measurement distance of the non-contact measurement device of this system is sufficient for the operating conditions assumed.

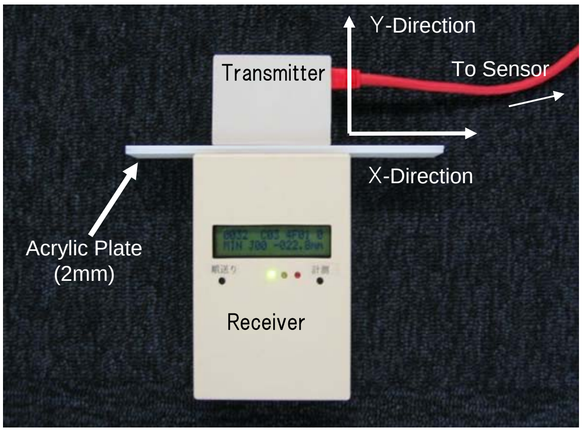


Figure 5: Testing Condition of Measurement Device

Table 2: Test Result of Measurable Distance

	X-Direction Shift	Y-Direction Shift
Measurable Distance	8mm	18mm
Transmission Distance	12mm	20mm

Dynamic Displacement Detection Test

The purpose of the test is to examine the dynamic properties of the sensor using the three-dimensional vibration table. The sensor is anchored to the edge of the vibration table in order to measure the displacement of the target plate placed at the fixed point outside the table. The displacement detection by the sensor is conducted as the detection rod is held by a spring coil to detect the main axis, not the three-axis part, and the pole head is installed in a manner which allows the tip of the rod to slide in all directions save towards the main axis. This mechanism allows the sole monitoring of the major axis displacement, which would prevent the sensor from being damaged due to deformation of parts other than the major axis. As the sensor may be used as a regular displacement sensor by constantly supplying power to it, displacement data are stored in the measurement device using a PC on a real time basis, in using the value of displacement shown in the laser-type displacement gauge as reference. At last, the sensor connection was changed to a non-contact measurement device after receiving vibrations to assess the entire performance of the system itself.

Table 3 shows the test result of the dynamic property of the system when the vibration was raised incrementally. The vibration increased every 80 seconds per test case, and the vibration wave was entered for 4-levels of oscillation. This shows the displacement monitored by the non-contact reader for each test case, which were almost consistent to the reference laser displacement gauge. The cumulative displacement shown in the table, refers to a cumulative calculation of displacement from the measurement of the laser displacement gauge in the positive direction.

Figure 6 shows the vibration wave of the test case shown in Table 3.This is the maximum positive and negative values and the current value of the peak hold sensor affected by vibration during the 4 test cases. It shows that the positive and negative maximum values are stored and retained in line with the increment of displacement. The figure includes the enlarged view of the lateral axis for the maximum vibration, which shows that the displacement data and the current value (compared to the value obtained by the laser displacement gauge) corresponds to the actual deformation.

Table 3: Result of Dynamic Displacement of the Sensor

Test	Vibration Test Acc.(cm/s/s)			Measeure Displacement of Peak Hold Sensor (cm)			Cumulative (cm)
Case	X / Y / Z Direction			Positive Peak	Current	Negative Peak	Positive
1	20	11	12	0.14 (0.17)	-0.02 (0.00)	-0.12 (-0.12)	0.0 (0.8)
2	50	27	31	0.50 (0.49)	-0.01 (0.00)	-0.36 (-0.37)	4.8 (6.6)
3	100	55	61	1.10 (1.08)	-0.01 (0.00)	-0.79 (-0.77)	20.5 (23.1)
4	200	110	122	2.35 (2.30)	-0.14 (0.00)	-1.72 (-1.68)	58.2 (62.8)

Note: A measurement value with the laser displacement gauge that the parenthesis assumed it a reference.

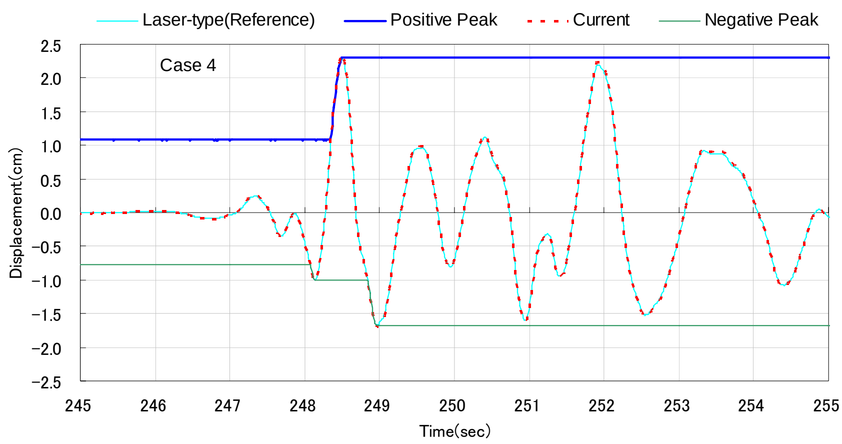
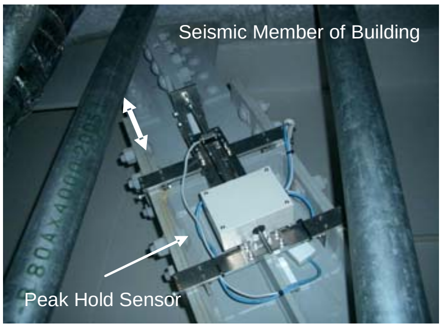


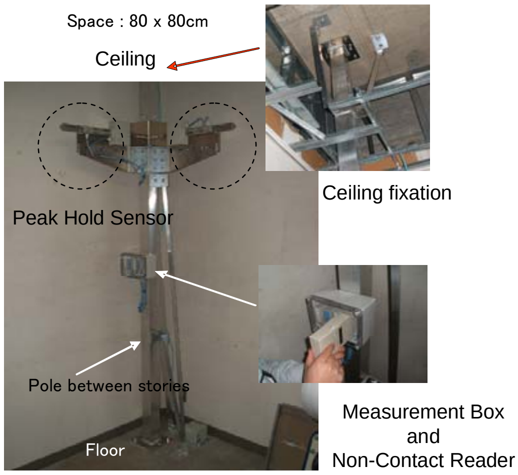
Figure 6: Dynamic Displacement Detection by Earthquake Wave Motion (Case 4)

APPLICATION OF THE SYSTEM TO ACTUAL STRUCTURES

The system has been applied to actual buildings for preliminary structural health monitoring of the buildings affected by large earthquake. Figure 7 shows how to install the sensors. (a) this figure refers to an example of a system installation to a seismic member. In this case, twelve sensors were installed in a 12-story steel structured building. (b) shows the example of the system installed for direct measurement of inter-story displacement of the building. The sensors were attached to the pole to measure the displacement between the stories so that displacement for the two lateral directions (using the ball-head mechanism and spring) can be measured. This is an example of the system as used indoors. However, in most cases, the system tends to be installed wherever invisible areas such as pipe space are available due to location restriction. Currently three buildings have the sensor system as described.



(a) seismic member



(b) inter-story displacement

Figure 7: How to Install Displacement Sensor in a Building

CONCLUSION

The authors have developed the monitoring system comprised of the peak hold sensor and the non-contact measurement device for health monitoring of structures, and various tests were conducted to examine the performance of the system. As a result, the tests confirmed that the system sufficiently functions, displacement measurement and non-contact measurement. The test using the vibration table demonstrated that the system would be capable of retrieving the data of displacement including the residue, maximum and cumulative values of displacement as an effective indicator for structural health monitoring. The system is considered to have the potential to become widely used for buildings thanks to its affordable price and ease of use. Currently, the application of the system to actual buildings has started. Therefore, its long-term durability under real-life conditions will then be assessed in the future as well as its efficiency.

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