Structural Engineering and Mechanics, Vol. 17, No. 3-4 (2004) 331-346
DOI: http://dx.doi.org/10.12989/sem.2004.17.3_4.331

Damage index sensor for smart structures

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(Received February 26, 2003, Accepted May 8, 2003)

Abstract. A new sensor system is proposed for measuring damage indexes. The damage index is a physical value that is well correlated to a critical damage in a device or a structure. The mechanism proposed here utilizes elastic buckling of a thin wire and does not require any external power supply for memorizing the index. The mechanisms to detect peak strain, peak displacement, peak acceleration and cumulative deformation as examples of damage indexes are presented. Furthermore, passive and active wireless data retrieval mechanisms using electromagnetic induction are proposed. The passive wireless system is achieved by forming a closed LC circuit to oscillate at its natural frequency. The active wireless sensor can transmit the data much further than the passive system at the sacrifice of slightly complicated electric circuit for the sensor. For wireless data retrieval, no wire is needed for the sensor to supply electrical power. For the active system, electrical power is supplied to the sensor by radio waves emitted from the retrieval system. Thus, external power supply is only needed for the retrieval system when the retrieval becomes necessary. Theoretical and experimental studies to show excellent performance of the proposed sensor are presented. Finally, a prototype damage index sensor installed into a 7 storey base-isolated building is explained.

Key words: damage index; structural health monitoring; mechanical memory; wireless.

1. Introduction

Structural health monitoring (SHM) systems are getting strong attention for maintaining proper performance of building structures against natural hazards such as large earthquakes as reviewed by Mita (1999). However, simple addition of an SHM system to an existing building is not a smart strategy as the conventional building has many possible damage scenarios. This fact is mainly due to the structural system employed by conventional buildings using the beam-column joints as energy absorbers. The seismic energy is absorbed by the beam-column joints but allowing them plastic deformation. However, the plastic deformation involves sever damage and significant change of load resistant mechanism. Therefore, detecting all possible damage scenarios by an SHM system is by no means feasible.

Instead, we recommend the use of SHM systems for smart structures. The smart structure is defined by the structure consisting of gravity resistant structural components and the structural control devices. The gravity load, i.e. vertical dead load, is supported by the gravity resistant

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structural components. The harmful destructive energy due to an earthquake or a strong wind is taken care of by the structural control devices. This structural system is completely different from the conventional structural systems. In conventional systems, the same structural components should resist gravity as well as earthquakes. Though the concept of providing independent elements for each structural role has been inherently employed by many structural engineers, clarification of the mechanism had not been conducted until recently. Connor and Wada (1997) clarified the concept considering simple shear structures. They called the system damage-controlled building. Although they only considered the passive control devices, active and semi-active control devices have recently become available (e.g. Casciati (Editor) 2003, Conner 2002). Smart structures perform much better during large earthquakes and strong winds. More importantly, they have simpler and fewer damage scenarios. Therefore, detecting damages by an SHM system consisting of reasonable number of sensors may be possible. As the most destructive energy due to an earthquake is taken care of by structural control devices, the most important role for the SHM system is to monitor the integrity of structural control devices.

The most popular passive smart structure is the base-isolated building. The system has been employed for hospitals, residential buildings, data centers, office buildings, school buildings, and so on. In the base-isolated building, all structural control devices are installed in the isolation layer. Buildings with passive dampers as structural control devices have become also very common in Japan and the U.S. for tall steel buildings. However, the number of dampers installed in a tall steel building may easily exceed several hundreds. Validation of health for those devices after a destructive event is extremely difficult. As a realistic and economical means, attaching a sensor that can detect and memorize a damage index to each damper device may be attractive if the cost for each sensor is not expensive. A damage index is defined as a physical value that is well correlated to a critical damage in a device or a structure. Typical damage indexes are peak strain, peak displacement, peak acceleration, story drift, absorbed energy, cumulative deformation, and so on. In addition, if the sensor does not require power supply for detecting the damage index and can memorize the value, the maintenance costs for the sensors will be further reduced. Therefore, the purpose of the research presented here is to develop a damage index sensor that can detect and memorize a damage index without any power supply. In addition, realizing the wireless data retrieval capability is also our important purpose to penetrate the fire-protection materials or cosmetic walls covering dampers. If such a sensor is realized, SHM systems will become very attractive and realistic.

Several peak strain sensors have been proposed recently. The peak strain sensor is one of the most promising damage index sensors. The use of TRIP (TRansformation Induced Plasticity) steel was proposed by Westermo and Thompson (1994) for memorizing the peak strain as the TRIP steel is magnetized when large strain is applied. However, the TRIP sensor is not reusable once the sensor experiences a large strain. In addition, a detector for magnetization level is not simple. Muto *et al.* (1992) studied the relationship between the electric resistance change and the peak strain for CFGFRP (Carbon Fiber Glass Fiber Reinforced Plastics). It was concluded that the change of the electric resistance in the CFGFRP material would be well correlated to the peak strain. This feature is unique as the material itself can function as a sensor. Unfortunately, however, the electric resistance of the CFGFRP is correlated not only to the peak strain but also to the residual strain so that isolation of the peak strain is difficult. Okuhara *et al.* (2001) proposed a better system by replacing carbon fibers by carbon powder. Matsubara *et al.* (2001) reported a possibility to install it into a concrete structure. However, their system still has strong correlation with the residual strain.

Kakizawa and Ohno (1996) proposed the use of the electric resistance of SMA (Shape Memory Alloys) in the hope of using it as a peak strain sensor. However, careful design is required to design the sensor to confine the working range in the region of super-elasticity.

In this paper, a new concept is proposed to memorize damage indexes. The mechanism utilizes elastic buckling of a thin wire. Furthermore, passive and active wireless retrieval mechanisms are proposed. The proposed sensors do not require any power supply for memorizing the damage indexes. Small external power supply is only needed for the data retrieval system when the data become necessary.

2. Mechanism of damage index sensor

2.1 Mechanical memory for peak values using elastic buckling

The ideal sensor response of a damage index sensor that can memorize a peak value as a damage index is plotted compared with a conventional sensor in Fig. 1. In this case, the maximum strain was taken as an example of the damage index. The ideal sensor retains the peak value even when the physical value in the object material is released. This feature can be realized by using a material that has pure plastic response against applied force for a sensor element. To realize such plastic response, we propose the use of elastic buckling of a thin wire as a mechanical memory as shown in Figs. 2 and 3. The mechanism of the proposed sensor is explained in the following.

For the mechanism presented in Fig. 2, the left-hand end of a thin wire is attached to a conductive block. The right-hand end of the wire is sandwiched by a conductive block resulting in a certain level of friction force. At the initial phase, no tension is applied to the wire. When the left-hand block is pulled to the left direction, the wire is stretched. Under the condition that the tension force in the wire reaches beyond the static friction force, the wire is pulled out from the right-hand conductive block. When the tension force is removed, the wire may retain the extended length

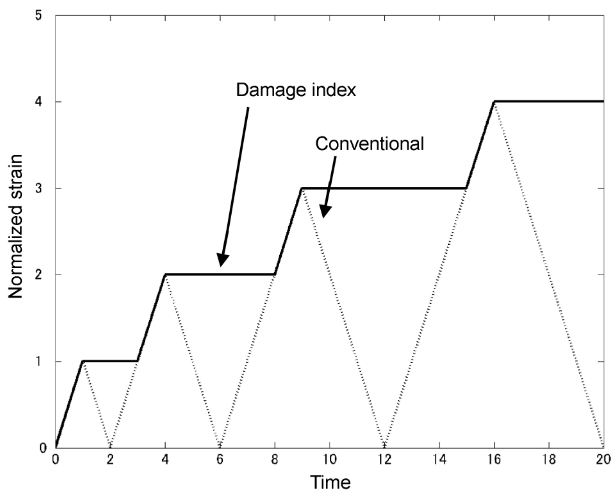

Fig. 1 Ideal response of damage index sensor

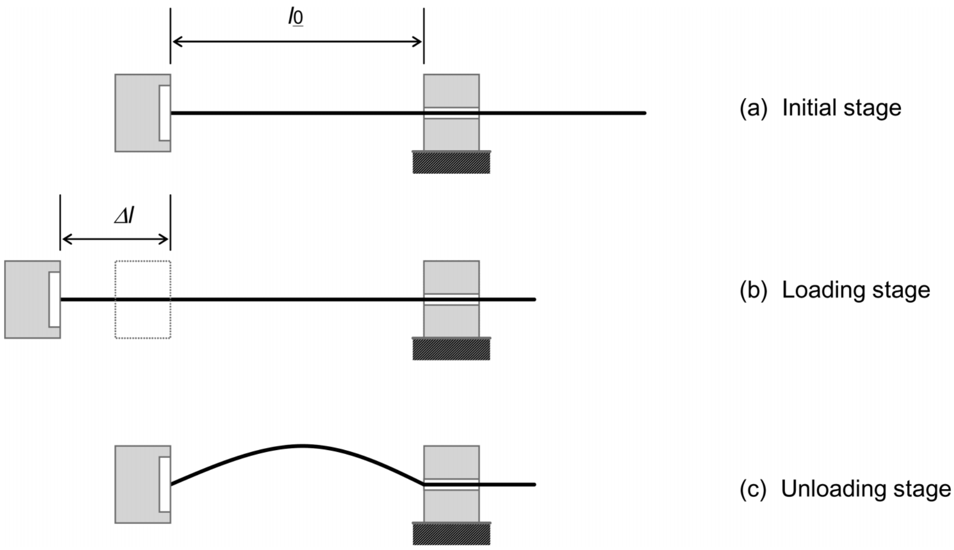

Fig. 2 Mechanism of memory using thin resistant wire

provided that the static friction force is larger than the elastic buckling force for the extended wire. Thus the peak value is mechanically memorized in the form of the length of the thin wire. If the thin wire is electrically resistive, its length is easily obtained by measuring the electrical resistance of the wire.

A slightly different mechanism is shown in Fig. 3. In this case, a variable element such as a variable capacitor, a variable inductor or a variable resistance is used as a mechanical memory. The length of the thin wire in this case is kept the same all the time except the elastic elongation. The peak strain is memorized in the variable element with the help of inherent friction force. The sensor is sensitive in only one direction. In the opposite direction, the sensor is made insensitive by the buckling of the thin wire. In both systems, accuracy of the sensor is highly dependent on the trade-off relation between tensile rigidity and the buckling force. In both cases, the static friction force should be larger than the buckling force.

For the mechanism depicted in Fig. 2, the change of resistance ΔR from the initial resistance R_0 is given by

$$\frac{\Delta R}{R_0} = \frac{\Delta l}{l_0} + 2\nu\frac{\Delta l^e}{l_0} \tag{1}$$

where ν is Poisson's ratio. The initial length of the resistant wire is assumed to be l_0. The increment of the length Δl consists of two components.

$$\Delta l = \Delta l^e + \Delta l^p \tag{2}$$

The superscript e represents elastic elongation. The superscript p indicates the component associated with the plastic or permanent elongation. The typical but exaggerated response of the sensor is shown in Fig. 4. In this case, the dynamic friction coefficient was assumed to be half of the static friction coefficient. The buckling stress was assumed to be negligibly small. In the segment 1, only

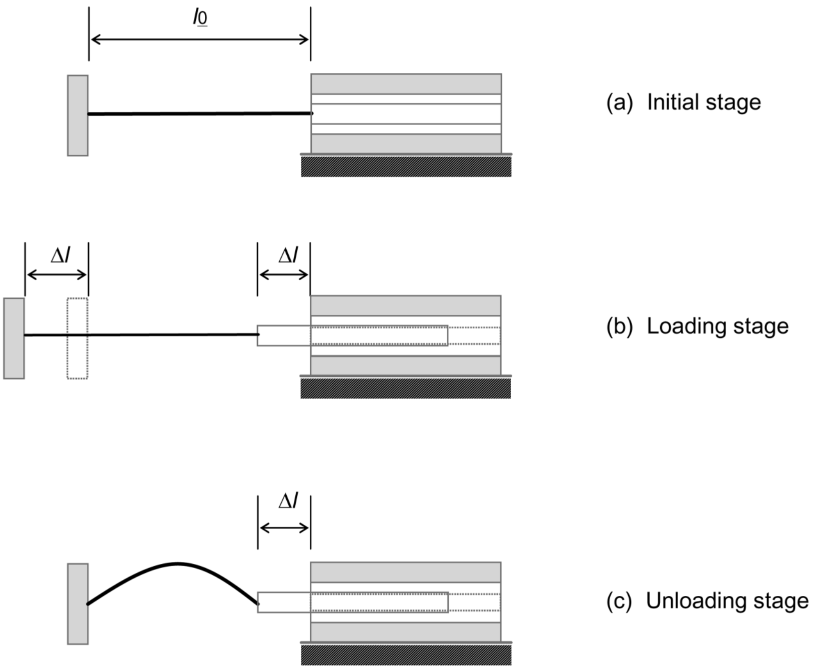

Fig. 3 Mechanism of memory using variable element and thin wire

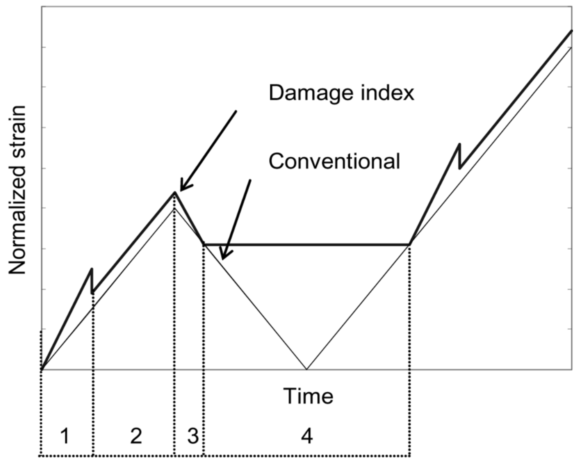

Fig. 4 Typical response of damage index sensor using resistant wire

elastic elongation occurs until the stress in the thin wire exceeds the static friction force. In the segment 2, the friction is reduced to the dynamic friction. The increase of the resistance is due to the plastic elongation. In the segment 3, the elastic elongation is reduced to zero. In the segment 4, the thin wire is buckled so that the same output is retained.

For the mechanism using a variable capacitor and a thin wire depicted in Fig. 3, the expected response is slightly different from the resistant wire based sensor. The response is typically given by in the form of capacitance change ΔC as

$$\frac{\Delta C}{C_0} = \frac{\Delta l^p}{l_0} \tag{3}$$

where C_0 is the initial capacitance. From Eq. (3), it is clearly understood that the response of this sensor is only due to the plastic deformation and not due to the elastic deformation of the thin wire. A simulated response of the sensor consisting of a thin wire and a capacitor is depicted in Fig. 5. In the segment 1, due to the static friction force, the sensor will not give any output before exceeding a certain strain where the resulting stress becomes larger than the static friction. In the segment 2, the tension force is larger than the dynamic friction force so that the variable capacitor will change its capacitance. In the segment 3, the tension force is removed from the thin wire so that the capacitance is kept at the maximum value of the segment 3. The mechanism explained here can be used for peak strain of displacement sensor. By combining the accelerometer, the mechanism can be modified to memorize the peak acceleration. The schematic of the peak acceleration sensor is depicted in Fig. 6.

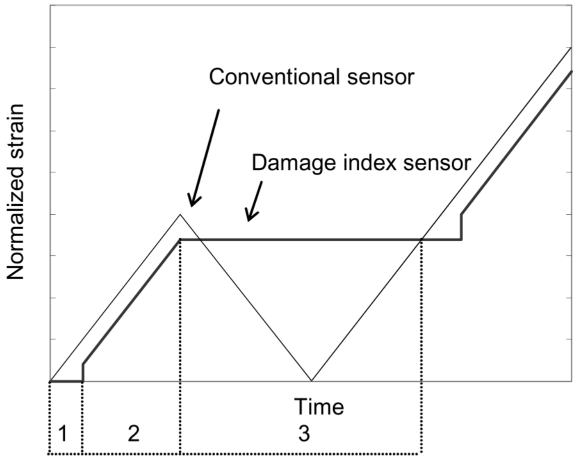

Fig. 5 Typical response of damage index sensor using variable element and thin wire

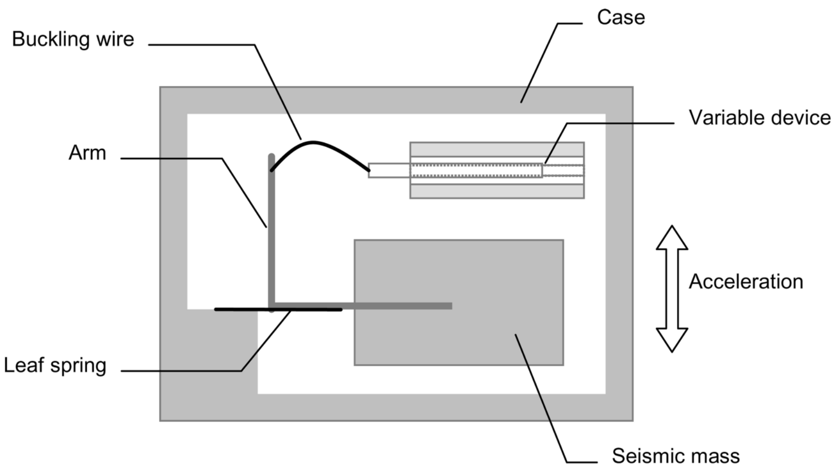

Fig. 6 Schematic of peak acceleration sensor

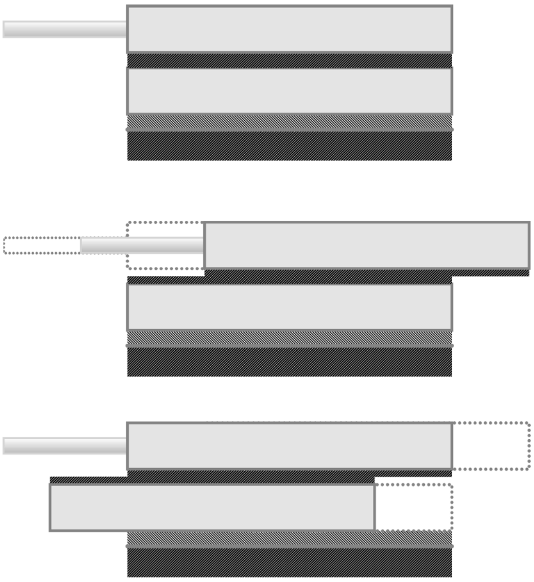

Fig. 7 Schematic of cumulative deformation sensor

2.2 Mechanical memory for cumulative deformation using napped fiber

The cumulative deformation is an important damage index for estimating the level of damage and the remaining fatigue life of a structural component. The mechanism we propose is explained in Fig. 7. The sensor consists of two blocks. On the surface of each block, napped fibers are densely bonded. The cumulative deformation is memorized in the form of position of the bottom block. The bonded fibers are napped into leftward direction for the top block. While, those for the bottom block are napped into the rightward direction. Therefore, the top block can move smoothly into rightward against the bottom block. But the motion into leftward direction against the bottom block is resisted by napped fibers. When the force is applied to the rightward direction for the top block, the friction between two blocks is negligibly small so that no motion is induced in the bottom block. When the top block is moved to the left, the napped fibers cause large friction force larger than the static friction force between the bottom block and the base material. By repeating this process, only the leftward deformation is accumulated and memorized in the bottom block. By detecting the position of the bottom block using a variable element, the cumulative deformation can be easily memorized.

2.3 Wireless data retrieval

Although the simplest configuration for memorizing the peak value would be using a resistant wire as shown in Fig. 2, the use of a variable capacitor or a variable inductor has an additional benefit, that is, wireless retrieval capability. When a variable capacitor or a variable inductor is used, the sensor can be easily modified to form a closed LC circuit by adding an inductor or a capacitor. For a closed LC circuit consisting of a capacitor C and an inductor L, the natural frequency of the circuit is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

This frequency can be detected without touching the wire. The simplest way to measure the frequency is to use a dip meter as explained in Fig. 8. A dip meter generates radio waves at an arbitrary frequency. If the frequency of the sending radio wave approaches to the natural frequency of the closed LC circuit of the sensor (the right circuit), certain amount of the energy is absorbed by the LC circuit. The frequency at which the energy is absorbed is considered to be the natural frequency of the sensor. Thus, the desired value memorized in the sensor can be retrieved wirelessly in the form of natural frequency change using the dip meter. This feature is extremely useful, when the sensor is covered by a fire-protection material or a cosmetic wall. However, in order to identify the dipped frequency the power of the dip meter should be below a certain level as the capacity of the closed LC circuit is limited. That implies that the passive wireless system using the dip meter is applicable only up to a few cm for our application.

For expanding the reachable distance, an active system is proposed as schematically shown in Fig. 9. The power needed to oscillate the closed LC circuit is supplied by using electromagnetic induction as shown in Fig. 9. This power supply system is frequently used to activate the RFID (Radio

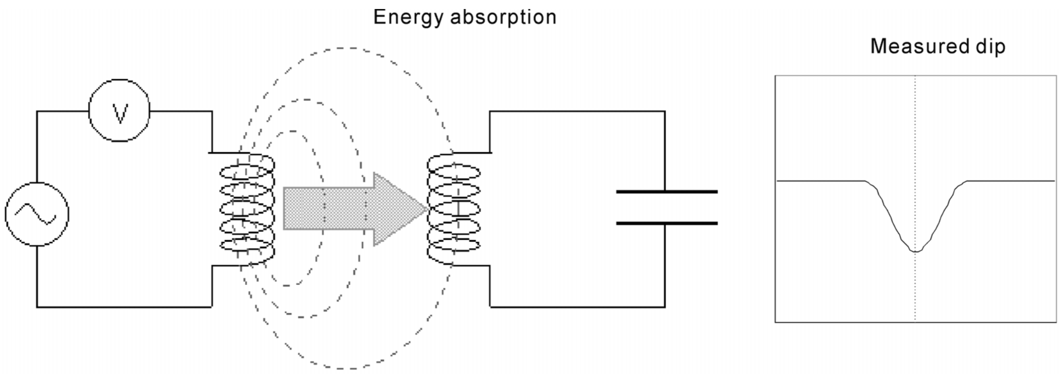

Fig. 8 Mechanism of passive wireless data retrieval system

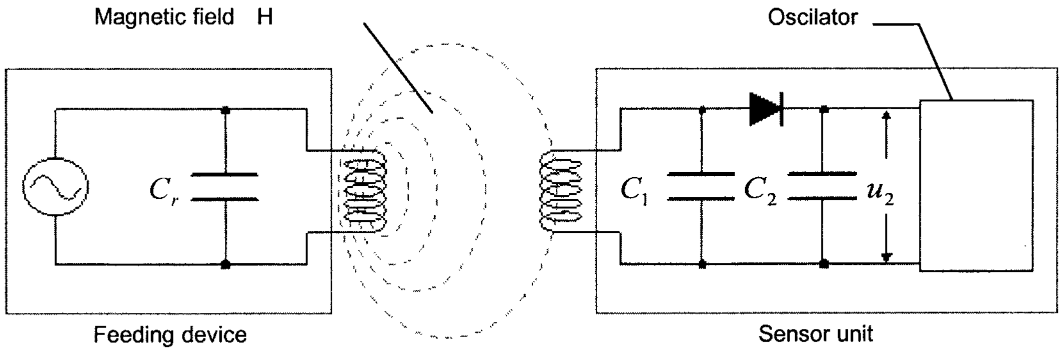

Fig. 9 Mechanism of active wireless data retrieval system

Frequency Identification) tags (e.g. Finkenzeller 2000). The radio wave to supply the electric power is generated by the left-hand oscillator depicted in Fig. 9. The radio wave is received by the circuit of the same oscillation frequency with the power supply radio wave embedded in the sensor. The radio wave is converted into a direct current using a rectifier. The generated direct current is then used to oscillate the variable LC circuit of the sensor. Selecting the frequency of the power supply radio wave different from the frequency to transmit the value of the damage index, the memorized damage index can be retrieved wirelessly. The distance to retrieve the data is much larger than the passive wireless system using a dip meter.

3. Prototype sensors

3.1 Peak displacement sensor using variable capacitor

A prototype sensor consisting of a thin wire and a variable capacitor was fabricated for verification as shown in Fig. 10. The variable capacitor consists of two aluminum cylinders that are separated by a non-conductive material. The capacitance of the variable capacitor can be varied by changing the overlapping length of two aluminum cylinders. The initial capacitance was measured to be 217 pF. An inductor added to the variable capacitor to form a closed LC circuit was 25 μH. Therefore, the natural frequency of the prototype sensor at its initial condition should be 2.16 MHz. The buckling wire was made of a fluorocarbon line to assure high Young's modulus. The diameter of the wire is 0.22 mm. The output from the prototype sensor was compared with the data taken by the laser sensor. The data were retrieved in the form of natural frequency change of the LC circuit. The relation between the frequency change and the displacement induced to the variable capacitor is plotted in Fig. 11. The frequency change was measured by a dip meter. Although the small fluctuation from the analysis result is observed, the measured relation well fits to the analysis. The small fluctuation may result from incompleteness of the variable capacitor.

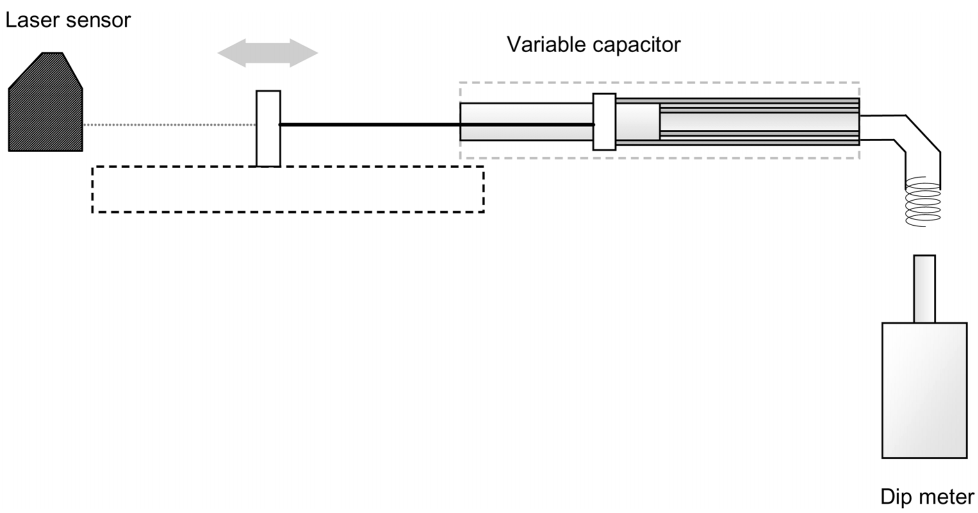

Fig. 10 Prototype peak displacement sensor with dip meter

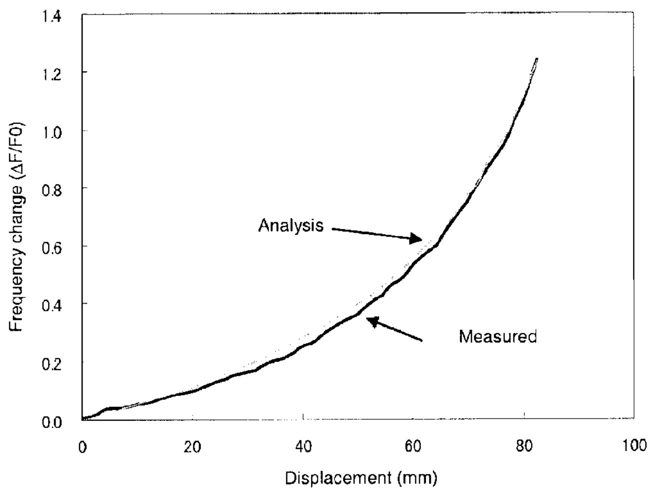

Fig. 11 Natural frequency change versus displacement

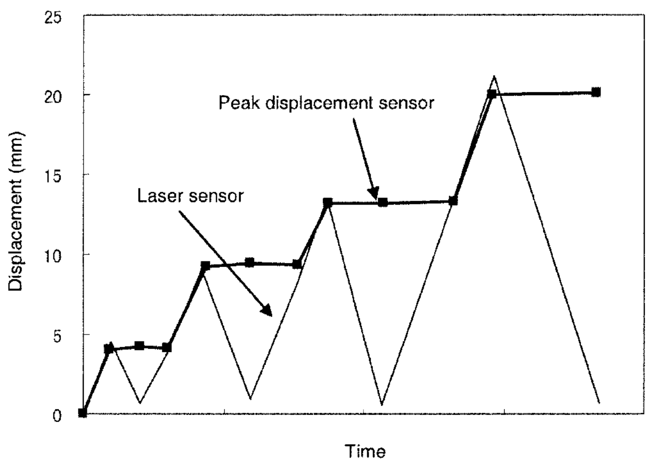

Fig. 12 Response of peak displacement sensor

The measured peak displacement is plotted versus the output from the laser sensor in Fig. 11. It is clearly shown that the peak response is indeed memorized. The friction force was tuned slightly larger that the buckling force. Both forces were found small enough to result in excellent performance. The displacement response was caliculated from the change of natural frequency measured by a dip meter. For example, the initial position corresponded to 2.164 MHz. The largest value of the peak displacement sensor in Fig. 12, 21.1 mm, corresponded to 2.412 MHz. If this sensor is bonded to a material with the initial sensor length of 400 mm to measure the strain, the range tested here corresponds to 0 μ strain to 52,750 μ strain. As the mechanism employed here is very simple, the measurement range can be easily narrowed or widened by changing the length of variable capacitor and wire. The size of the sensor can be as small as a conventional strain gauge and as large as the largest displacement sensor. The mechanism employed here to memorize the peak displacement value can be extended to memorize other physical values such as force, stress, acceleration, velocity, accumulated plastic deformation and so on.

3.2 Cumulative deformation sensor using napped fiber

A prototype of cumulative displacement sensor was made using napped fiber sheets and aluminum plates as shown in Fig. 13. The plates were 100 mm in length, 20 mm in width and 2 mm in depth. On the bottom surface of the top aluminum plate, a sheet with napped fibers was bonded. Similarly on the top surface of the bottom aluminum plate, the same sheet with fibers napped to the opposite direction with the top aluminum plate was bonded. As shown in Fig. 7, the bottom aluminum plate will move only to the leftward direction. The motion of the top aluminum plate was measured by a laser displacement sensor. In Fig. 14, the response of this sensor is plotted versus the cumulative deformation calculated using the measured displacement by the laser sensor. The response of the cumulative sensor well matches to the calculated values. However, the cumulative sensor always indicates slightly smaller response than the calculated ones. This phenomenon is due to the small backlash of the napped fibers.

Fig. 13 Prototype cumulative deformation sensor

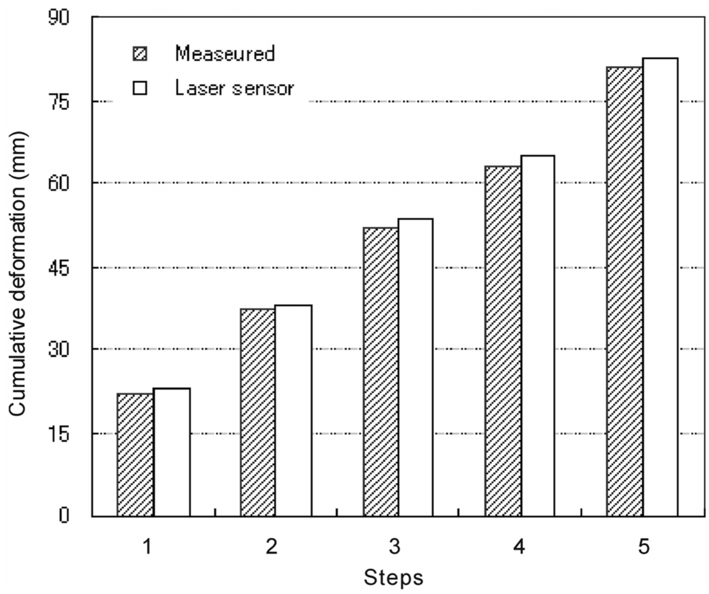

Fig. 14 Response of cumulative deformation sensor

3.3 Active wireless system

The schematic of active wireless system is presented in Fig. 15. The frequency used for the power supply unit is 130 KHz. The oscillating radio wave is supplied to the sensor unit to generate the direct electric current. Using this generated electricity, the LC circuit including a variable capacitor is excited. The emitted frequency is detected by an oscilloscope and an analog amplifier. The frequency emitted from the sensor unit is around 230 MHz that is far away from the frequency used for power supply. The photo of the power supply unit and the sensor unit is shown in Fig. 16. The wooden box was used to imitate a cosmetic wall in a building.

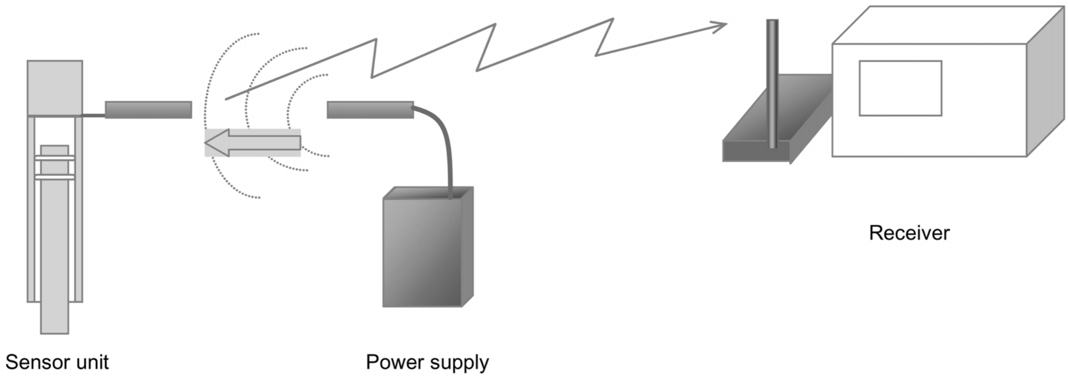

Fig. 15 Schematic of active wireless system

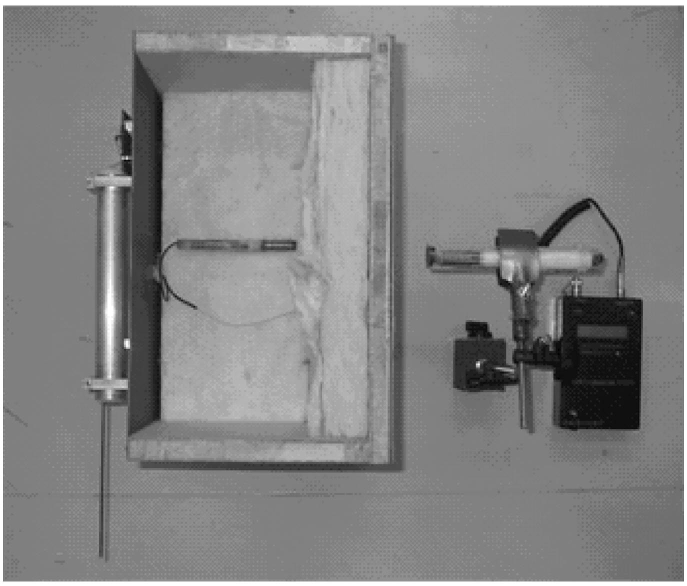

Fig. 16 Active power supply unit and sensor unit with imitation wall

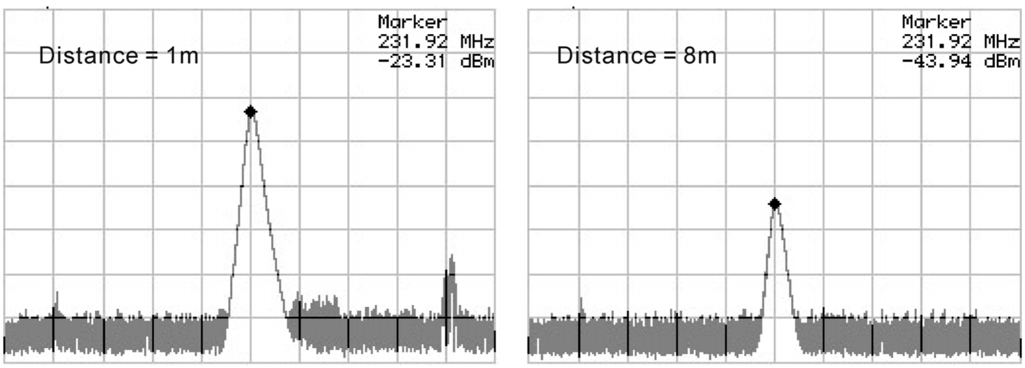

Fig. 17 Spectrum at distance 1 m and 8 m

The maximum distance between the power supply unit and the sensor unit to ensure enough power was about 13 cm. The amplitude of the power spectrum a dBm was measured for several distances. The approximate relation between the distance and the amplitude was obtained from the measured data. The equation is given by

$$a = 147.6 - \log(d) - 20\log(f) \tag{5}$$

Using the oscilloscope and the analog amplifier, the peak oscillation frequency was readable beyond 10 m. The spectrum shapes at the distance of 1 m and 8 m are plotted in Fig. 17. The frequency of the spectrum peak indicates the damage index. We can verify if the height of the spectrum peak follows the relation expressed in Eq. (5) or not from Fig. 17.

3.4 Peak displacement sensor for base-isolated building

The performance of a base-isolated building fully relies on the health of isolation devices that are typically made of elastomeric material. As was indicated by Naeim and Kelly (1999), it is crucial to limit the extreme displacement of the devices within their capacities for keeping their health. Hence, installing damage index sensors to a base-isolated building to measure peak deformation of a device is a rational strategy to ensure the safety of the building.

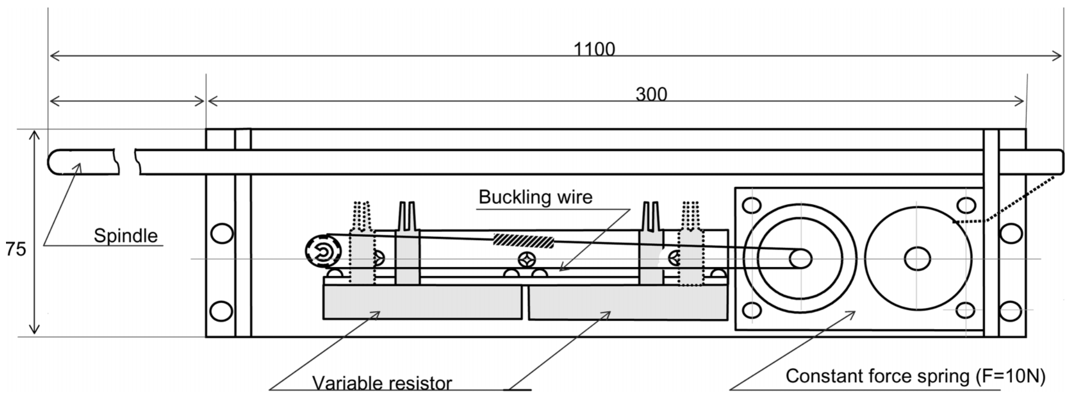

Fig. 18 Peak displacement sensor for base-isolated building

For damage detection of a base-isolated building, a variable resistor based sensor as shown in Fig. 18 was developed. The sensor consists of two precision potentiometers (used as variable resistors), thin wires, pulleys, a spindle and a spring. First, the straight-line motion of the spindle is converted into rotary motion by the right pulley. A spring is attached to this pulley to introduce a constant resistant force for the motion of the spindle. The rotary motion induced in the right pulley is converted into straight-line motion by a thin wire connecting left and right pulleys. One end of a buckling wire is connected to this thin wire. The other end of the buckling wire is connected to a potentiometer. The maximum response is determined from a set of two outputs from the potentiometers; one output indicates peak displacement into leftward direction, the other output indicates peak displacement into rightward direction. The sensor has a 300 mm range in each direction. The resistance change of the potentiometers may be measured by a conventional tester. The measured response of this prototype sensor is shown in Fig. 19. It is clearly understood that the performance of this sensor is excellent.

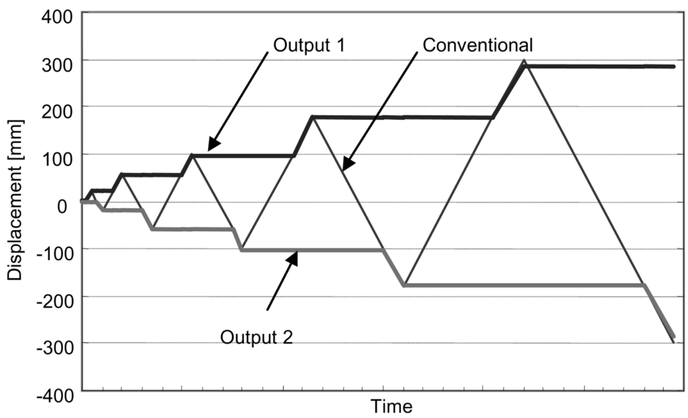

Fig. 19 Response of peak displacement sensor for base-isolated building

Fig. 20 7-storey school building at Keio University

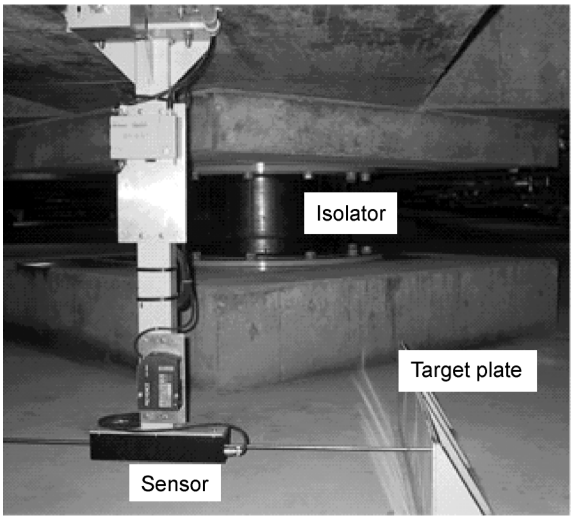

Fig. 21 Sensor installation for isolator

The developed sensor was installed into a school building at Keio University (see Fig. 20). The building is a 7-storey seismic isolated building with the gross floor area of 18,606 m^2. The height is 31 m above ground level. It utilizes high-damping rubber bearings of 750 mm and 900 mm diameter as the isolation devices between the base and the 1^{st} floor. The peak displacement sensor was installed into one of the isolators as shown in Fig. 21. A smooth Teflon coated plate was used as a reference for the base. The Teflon coated plate was also used as a target for a laser displacement sensor so that the performance in the practical environment can be verified.

4. Conclusions

A new sensor system was proposed for measuring damage indexes and memorizing the data using a mechanical memory. The damage index is a physical value that is well correlated to a critical damage in a device or a structure. The mechanism proposed here as a mechanical memory utilizes elastic buckling of a thin wire without any external power supply. The external power supply is needed only for the data retrieval system when the data is required. Furthermore, passive and active wireless data retrieval mechanisms using electromagnetic induction were proposed. The passive wireless system was achieved by forming a closed LC circuit to oscillate at a certain frequency using a dip meter. The active wireless system could transmit the damage index wirelessly much further than the passive system at the sacrifice of slightly complicated electric circuit for the sensor device. Theoretical and experimental studies exhibited excellent performance of the proposed sensor. A prototype damage index sensor has been already installed into a 7 storey base-isolated building for field verification.

References

Casciati (Editor) (2003), *Proceedings of the Third World Conference on Structural Control*, John Wiley & Sons.

Conner, J. (2002), *Introduction to Structural Motion Control*, Prentice Hall.
Connor, J.J., Wada, A., Iwata, M. and Huang, Y.H. (1997), "Damage-controlled structures. I: Preliminary design methodology for seismically active regions", *J. Struct. Eng.*, **123**(4), 423-431.
Finkenzeller, K. (2000), *RFID Handbook : Radio-Frequency Identification Fundamentals and Applications*, John Wiley & Sons, Inc.
Kakizawa, T. and Ohno, S. (1996), "Utilization of shape memory alloy as a sensing material for smart structures", *Proc. Advanced Composite Materials in Bridges and Structures*, 67-74.
Matsubara, H., Shin, S.-G., Okuhara, Y., Nomura, H. and Yanagida, H. (2001), "Application of the self-diagnosis composite into concrete structure", *Proc. SPIE*, **4234**, 36-43.
Mita, A. (1999), "Emerging needs in Japan for health monitoring technologies in civil and building structures", *Proc. Second International Workshop on Structural Health Monitoring*, Stanford University, 56-67.
Muto, N., Yanagida, H., Nakatsuji, T., Sugita, M., Ohtsuka, Y. and Arai, Y. (1992), "Design of intelligent materials with self-diagnosing function for preventing fatal fracture", *Smart Materials and Structures*, **1**, 324-329.
Naeim, F. and Kelly, J.M. (1999), *Design of Seismic Isolated Structures from Theory to Practice*, John Wiley & Sons, Inc.
Okuhara, Y., Shin, S.-G., Matsubara, H., Yanagida, H. and Takeda, N. (2001), "Development of conductive FRP containing carbon phase for self-diagnosis structures", *Proc. SPIE*, **4328**, 314-322.
Westermo, B.D. and Thompson, L. (1994), "Smart structural monitoring: A new technology", *International Journal of Sensors*, 15-18.