Peak Strain and Displacement Sensors for Structural Health Monitoring

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ABSTRACT

Simple and inexpensive passive sensors that can monitor the peak strain or displacement of a critical structural member were developed. The developed sensors have an ability to quickly assess the degree of damage in a structure when a checkup is needed. The sensors need no power supply for monitoring. The peak values can be retrieved wirelessly if desired. In addition, they can be easily modified to measure other peak values such as acceleration and force.

The mechanism to memorize the peak strain or displacement values relies on the pure plastic extension of sensing section. The pure plastic extension of the sensing section is made possible by introducing elastic buckling. The peak value is detected by measuring a change in electric resistance, inductance or capacitance. In addition, introduction of an LC circuit into the sensor enables wireless retrieval of the data. Theoretical and experimental studies exhibit the feasibility of the developed sensors for structural health monitoring of civil and building structures.

INTRODUCTION

Assessing a correct degree of damages in a large civil structure or a tall building structure is demanded to reduce maintenance costs and to extend the service life of the structure while assuring excellent structural performance. The assessment of a critical infrastructure with appropriate precision and frequency becomes particularly important, as the failure of such a structure should immediately result in fatal accidents and huge economic loss. However, a continuous monitoring system...

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consisting of high-precision sensors and a sophisticated network is not always the solution for that purpose. In some cases, particular damage indexes such as peak strain would be sufficient to detect the potential damages to the structure. Therefore, the purpose of the present study is to develop a peak strain (or displacement) sensor that can memorize peak values ever experienced without external energy supply.

In the past few years, several peak strain sensors have been proposed and developed. The TRIP (TRansformation Induced Plasticity) steel was used as a sensor head as it is magnetized when large strain is applied [1]. However, the TRIP sensor may not be reused once the sensor experiences a large strain. In addition, detection of the magnetization level is rather difficult. In the paper [2], the relationship between the electric resistance change and the peak strain was studied for CFGFRP (Carbon Fiber Glass Fiber Reinforced Plastics). In the paper, 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. However, the electric resistance is correlated to not only the peak strain but also the residual strain so that isolation of the pure peak strain is difficult. The electric resistance of SMA (Shape Memory Alloys) was studied in the hope of using it as a peak strain sensor [3]. However, careful design is needed as the memory capability depends on the magnitude of the strain.

In this paper, a new concept is proposed to memorize the peak strain or the peak displacement. The mechanism utilizes elastic buckling of a thin wire. In addition, the memorized value can be retrieved wirelessly.

**BASIC CONCEPTS**

The ideal sensor response of a peak strain sensor compared with a conventional strain sensor is plotted in Figure 1. The peak strain sensor keeps the peak strain value even when the strain in the object material is released. This feature can be realized by using a material that has a pure plastic response against applied load for a sensor element.

![FIGURE 1. Ideal response of peak strain sensor](image-url)
The ideal response of the peak sensor is achieved by using the elastic buckling of a thin wire as shown in Figure 2. When the change of the electric resistance is used for detection, the peak strain is retrieved from the electric resistance change that is associated with the length of the wire. The mechanism shown in Figure 2 works as follows.

The right end of a thin wire is attached to a conductive block. The left side 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 block is pulled to the left direction, the wire will be stretched. Under the condition that the tension force in the wire reaches beyond the static friction force, the wire is pulled out from the left conductive block. When the tension force is removed, the wire may keep the extended length if the static friction force is larger than the elastic buckling force for the extended wire. Thus the peak strain is obtained by measuring the length of the wire. If the wire is electrically resistive, the length is related to the change of the electric resistance.

The buckling force \( P_{cr} \) to induce the first buckling mode in a thin wire with fixed-end boundary conditions at both ends and of its length of \( L \) is given by

\[
P_{cr} = \frac{4\pi^2 EI}{L^2}
\]

where \( E \) is Young’s modulus and \( I \) is the moment of inertia of an area. The corresponding buckling stress and strain in the wire are given by

\[
\sigma_{cr} = \frac{4\pi^2 EI}{L^2 A}, \quad \varepsilon_{cr} = \frac{4\pi^2 I}{L^2 A}
\]

where \( A \) is the cross sectional area of the wire. The condition required for the peak strain sensor is to keep this buckling force smaller than the static friction force so that the extended length of the wire should be kept. In addition, the buckling strain should be as small as possible since it is associated with the maximum elastic strain induced in the sensor. The elastic component in the response of the sensor should be minimized.

The simplest way to measure the length of the wire is to use a scale. Or as mentioned above, the extended length of the wire can be measured by the change of electric resistance. If one end of the wire is connected to a variable capacitor or a variable inductor, the length can be easily retrieved from the change in capacitance or inductance. This configuration is extremely useful for wireless retrieval of the data as explained later.

![FIGURE 2. Mechanism of memory using elastic buckling of thin wire](image-url)
MECHANISM OF PEAK STRAIN (OR DISPLACEMENT) SENSOR USING VARIABLE CAPACITOR OR VARIABLE INDUCTOR

The mechanism of a peak strain sensor using a variable capacitor is shown in Figure 3. The variable capacitor is made of an outer cylinder and an inner cylinder as schematically presented in the right-hand side of Figure 3. The capacitance will depend on the overlapping length. Both cylinders are made of conductive metal. The static and kinetic frictions in the capacitor are made stable by friction controllers inserted between two cylinders. The peak strain is memorized in the form of a slipping length \( \delta \). The slipping length \( \delta \) can be retrieved from the change of the capacitance. The relation between the extension of the sensor \( \Delta L \) and the memorized length \( \delta \) for the \( i \)-th loading cycle is given in Table I.

In this table, the length \( d_0 \) denotes the initial length of the wire when no strain is applied to the wire. The subscripts \( i-1 \) and \( i \) represent the maximum value in the \( i-1 \)-th and \( i \)-th loading cycle, respectively. The tensile strain \( \varepsilon_s \) is the strain induced in the wire when the force equal to the static friction is applied to the wire. Similarly, the tensile strain \( \varepsilon_k \) is the strain induced in the wire when the force equal to the kinetic friction force is applied to the wire.

In order to show the characteristics of the peak strain sensor schematically, the response of the sensor was simulated and was plotted in Figure 4. In the simulation, the magnitude of static friction was assumed to correspond to the normalized strain of 0.4. The kinetic friction was assumed to be a half of the static friction. Therefore, the normalized strain corresponding to the kinetic friction is 0.2. From this simulation, it is clearly understood that the measured peak value is always smaller than the true peak value by 0.2 due to the kinetic friction. Therefore, to achieve good accuracy, the friction force should be controlled to be as small as possible but keeping the friction force to be larger than the elastic buckling force for the wire.

Instead of using a variable capacitor, a similar mechanism can be achieved using a variable inductor.

| Table I. Response of Peak Strain Sensor |
|-----------------|-----------------|-----------------|
| Status          | Condition       | Response        |
| Loading         | \( \Delta L < \delta_{i-1} + d_0 \varepsilon_s \) | \( \delta = \delta_{i-1} \) |
|                 | \( \delta_{i-1} + d_0 \varepsilon_s < \Delta L < \Delta L_s \) | \( \delta = \Delta L - d_0 \varepsilon_k \) |
| Unloading       | \( \delta = \delta_i (= \Delta L_s - d_0 \varepsilon_k) \) |

![Figure 3. Description of peak strain sensor using variable capacitor](image)
WIRELESS DATA RETRIEVAL

As shown in Figures 2 and 3, the peak strain value can be measured using a variable electric resistor, a variable capacitor or a variable inductor. Although the simplest configuration would be using a variable resistor, 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 as shown in Figure 5. When an LC circuit consisting of a capacitor $C$ and an inductor $L$ exists, the natural frequency of the circuit is given by

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

(3)

This frequency can be detected without touching the wire. The simplest way to measure the frequency would be using a dip meter. A dip meter generates radio waves and detects the frequency at which the energy is absorbed by the LC circuit. The frequency at which the energy is absorbed can be considered to be the natural frequency. The desired peak strain or displacement value is therefore retrieved wirelessly from the measured natural frequency.

FIGURE 5. LC circuits for peak strain sensors using variable capacitor or variable inductor
EXPERIMENTAL VERIFICATION

Description of experiment

The schematic of the experiment for a peak strain sensor using a variable capacitor is presented in Figure 6. The photograph of the experimental setup is shown in Figure 7. A variable capacitor is made of two aluminum cylinders of 223 mm long. The initial capacitance of this variable capacitor was measured to be 216.8 pF. The inductor was made from a copper wire and its inductance was 24.96 µH. Therefore, the natural frequency of the peak strain sensor at its initial condition can be calculated using Eq. (3). The theoretical natural frequency was thus obtained to be 2.264 MHz at its initial position. The wire connecting the variable capacitor and the sensor tip is made of fluorocarbon to assure high Young’s modulus. The diameter of wire is 0.219 mm. The length is 100 mm at its initial condition. Two sets of wire were used for connection.

The peak strain values were retrieved wirelessly from the change of natural frequency and using Eq. (3). The natural frequency was measured using a dip meter as shown in Figure 6. The motion of the sensor tip was measured using a laser sensor.

FIGURE 6. Experimental setup for peak strain sensor

FIGURE 7. Photograph of experimental setup
Experimental results

The peak strain sensor was stretched several cycles. At the end of each cycle, the sensor tip was returned to the initial position to verify the performance of the peak strain sensor. A laser sensor was used to detect the motion of the sensor tip. The measured results are shown in Figure 8. The response is presented in the form of tip displacement for the laser sensor and the sliding length of the variable capacitor for the peak strain sensor.

From this figure, it is clearly shown that the peak response is indeed memorized. The friction force was found to be small enough to result in an excellent performance. As the peak response is well memorized, the buckling force for the wire turned to be small enough. The response was measured using a dip meter. For example, the initial position corresponds to 2.1637 MHz. The largest value of the peak strain sensor in Figure 8, 21.1 mm, corresponds to 2.4177 MHz. If this sensor is bonded to a material with the initial sensor length of 400 mm, the range tested here is from 0 μstrain to 52,750 μstrain. The same sensor can be used of course as a peak displacement sensor. 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 the length of 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 strain or displacement value can be extended to memorize other physical values such as force, stress, acceleration, velocity, accumulation of plastic deformation and so on. The accumulation of plastic deformation is particularly useful to estimate the remaining service life of a damper made of low-yielding steel that is a common device to reduce the seismic response of a tall building.

![FIGURE 8. Measured response of peak strain sensor](image-url)
CONCLUDING REMARKS

Simple and inexpensive passive sensors that can monitor the peak strain or displacement were proposed. The mechanism to memorize the peak strain or displacement value relies on the pure plastic extension in the sensing section. The pure plastic extension is achieved using the elastic buckling of a thin wire. The change in the length of the sensing section is converted into a change in electric resistance, inductance or capacitance. When a variable capacitor or a variable inductor is used, wireless retrieval of data becomes possible. Adding an inductor or a capacitor to form a closed LC circuit introduce an inherent natural oscillatory frequency of the system. As this natural frequency can be measured using a dip meter, wireless sensing capability is realized.

A prototype peak strain sensor consisting of a variable capacitance and a fluorocarbon wire was fabricated. The sensor data was retrieved successfully using a dip meter. The comparison with the data obtained by a laser sensor assured feasibility and accuracy of the system. In addition, the proposed mechanism is applicable to measure other peak values such as acceleration and force. As the proposed sensors need no power supply for monitoring, employing the proposed sensors would be helpful to realize a reliable and robust health monitoring system with a minimum cost.

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