Use of the piezoelectric film for the determination of cracks and defects - The passive and active electric potential CT method -

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Abstract. The passive and active electric potential CT method was proposed by using piezoelectric film for identification of cracks and defects. This method is based on the principle of mutual conversion between mechanical strains and electric potential of piezoelectric material. A smart-layer was constructed using the piezoelectric film, and attached on a structure with a defect. When the structure was subjected to a mechanical load, the electric potential distribution appeared passively on the piezoelectric film due to the direct piezoelectric effect. The defect can be identified from the distribution with the help of inverse analysis. It was found that the crack could be identified reasonably, although the defect depth was not well estimated for the defects located far from the layer. When the electric signal was input to the smart-layer, acoustic wave was actively emitted from the layer due to the inverse piezoelectric effect, and a reflected wave was received on the layer. It was found that the depth of the defect could be estimated well. The simultaneous use of the passive method and the active method is promising for the identification of the defect.

Keywords: electric potential CT method, defect identification, crack identification, passive method, active method

1. Introduction

Structural Health Monitoring (SHM) is a technique that observes and evaluates condition of damage in a structure with various sensors. The SHM is widely recognized as one of the important technical fields for maintenance of structures such as power plants, chemical plant, aircrafts, space structures and bridges to secure reliability and safety. The advantage of SHM is that observation and evaluation of the defect in a structure can be made in real time under use, while general NDT (non-destructive testing) method is applied in frequent checkups. SHM enables us to detect defects and cracks, to monitor the progress of crack, and to reduce the cost and shut-down for inspection. It is possible to detect and identify the damage caused by unexpected load impact in service, using the sensor and actuator built in the structure in manufacturing.

Piezoelectric materials have two characteristics: direct piezoelectric effect converting mechanical deformation into electric charge, and inverse effect converting electric charge into mechanical deformation. This characteristic enables us to use the piezoelectric material as a sensor or actuator. Li
et al [7] proposed the passive electric potential CT method that is one of the bases of NDT method in this study. In this method, a piezoelectric film is glued on the surface of a structural member subjected to mechanical load, and a change in electric potential on the film is induced. If defects exist in the structural member, a characteristic variation of electric potential is observed. This method has two characteristics. One characteristic is that the sensor can be integrated with the structure because a sensor is an extremely thin and light film. The other characteristic is that an inverse method can be introduced as a technique for identifying the defect from information observed on a lot of the measurement points.

In the previous studies [1-3], the passive electric potential CT method was applied to the identification of cracks. For identification of cracks, an inverse analysis scheme based on the least residual method was applied, in which square sum of residuals was evaluated between the measured electric potential distribution and those computed by using the finite element method. Akaike information criterion AIC was used to estimate the number of cracks. Numerical simulations were carried out on the identification of plural cracks and a single crack. The location and size of these cracks were quantitatively estimated by the method. The number of cracks was correctly estimated, even when the plural cracks were closely located and the measured electric potential distribution was similar to that for a single crack. From the previous research, passive electric potential CT method enables us to identify the vertical defects near the top surface accurately. On the other hand, when the crack exists far from the top surface, detection became difficult. When electric pulse is input on the piezoelectric film, pulse-echo is transmitted due to the inverse piezoelectric effect. This method is expected to be useful for the identification of defects far from the top surface. This method can be called the active electric potential CT method using the piezoelectric film.

In this study, a smart-layer is constructed for applying the passive electric potential CT method and the active electric potential CT method. The applicability of the methods is examined.

2. Composition of defect monitoring system for the passive and active electric potential CT method

The present defect identification method is based on two methods. One method is the passive electric potential CT method. When defect exists in a structure subjected to a mechanical load, the distribution of strains on the surface of the structure and those on the film glued on the structure reflect the position and the shape of defect. The strain distribution induces electric potential distribution on the piezoelectric film due to the direct piezoelectric effect. The measured electric potential distribution can be used to identify the defect with the help of inverse analysis.

The other method is the active pulse-echo method. When the pulse voltage is applied to the piezoelectric film, the piezoelectric film vibrates due to the inverse piezoelectric effect, and the ultrasonic wave pulse is excited. The incidence pulse in the structure is reflected and diffracted by the boundary like the defect. The reflected and diffracted ultrasonic pulse is converted into the electric signal due to the direct piezoelectric effect. The defect can be identified from the electric signal.

2.1. Composition of smart-layer

To build-in the piezoelectric material in structure as a sensor and actuator, and to compose a system that enables multi-point measurement, it is necessary to mount the network composed of the piezoelectric material on structure. Network consists of electrode and wiring that is light, compact, and stubborn. The smart-layer requires a technique satisfying the above-mentioned demand. The smart-layer is constructed by accumulating the piezoelectric film, the FPC (Flexible Printed Circuit) that is composed of electrode and wiring pattern as shown in Figure 1. FPC forms the circuit pattern of conductor foil on the polymer materials such as the polyimide and polyester. PET (PolyEthylene Terephthalate) film of 50 (µm) in thickness is used as polymer material. Aluminium of 10(µm) in thickness is used as conductor foil.
Figure 1. Schematic illustration of integrating actuators/sensors network on aluminium specimen in the form of a smart-layer

Figure 2. Details of smart-layer

The following reason shows that the layer constructed by piezoelectric film and FPC can be a smart-layer that has the function of the sensor of strain distribution and ultrasonic wave transducer in the structure. At first, strain distribution on the surface of structure is converted to the electric potential on the piezoelectric film because smart-layer has flexibility, and epoxy adhesive couples piezoelectric film with the structure mechanically. Secondly, epoxy adhesive has the role of couplant that sonically couples the piezoelectric film with the structure. When the smart-layer is used as ultrasonic wave transducer, the influence of the adhesive layer is small, because electric input/output is transmitted and received in the high frequency region from several MHz to tens of MHz, and adhesive layer is very thin. For the electrical output of the low frequency obtained by using the smart-layer as a sensor of strain distribution, the influence of adhesive layer did not occur fundamentally because the charge output is converted into the voltage output by using a charge amplifier.

The feature of the built-in smart-layer is described as follows.

- The smart-layer is light because its thickness is very small from tens of μm to 100(μm).
- Smart-layer has strength reliability, because it is simple, highly flexible, and it does not contain fragile materials such as the conductive resins and the piezoelectric ceramics.
- Because a common ground connects with each electrode, the wiring pattern suffices for the measurement of potential distribution.
- Smart-layer can be built-in beforehand or installed later in the structure.
- Automation of manufacturing process is easy, and it does not contain costly process. Therefore, smart-layer enables to mass produce at low-cost.
3. Passive electric potential CT method

The smart-layer is set up on an aluminum specimen that has a vertical defect. By measuring electric output from piezoelectric film, the applicability of the smart-layer for passive electric potential CT method was examined.

3.1. Experimental procedure

A2024 aluminum specimen with a vertical crack shown in Figure 3 is used in experiment. The width of the specimen is 20 (mm), and thickness is 10 (mm). The crack is penetrated in direction of width of specimen by electric discharge machining. Half-length of the crack is \( a = 3 \) (mm). Crack depth, defined by the distance from specimen surface to the upper tip of the crack, is \( h = 2 \) (mm).

The smart-layer is constructed by accumulating the piezoelectric film and the FPC. The thickness of piezoelectric film is 52 (\( \mu m \)). FPC is composed of the electrode formed by etching and the pattern. The FPC pattern has the terminal of lead line shown in Figure 2. The epoxy adhesive for the strain gauge (EC-30) was used for the adhesive. The rolling direction of piezoelectric film corresponds to the longitudinal direction of the specimen. Specimen and FPC patterns other than electrode part are electrically insulated by PET film. The size of electrode is \( 1.5 \times 4.0 \) (mm) and the pitch of electrode is 2.0 (mm). The two rows of electrode in load direction are arranged by shifting the rows by 1 (mm). The longitudinal direction of the specimen is denoted as \( x \). It was set that the position of the defect to be \( x = 20 \) (mm).

Measurement system was connected to the smart-layer. Sinusoidal wave load was applied to the specimen by using an electro-hydraulic testing machine. Average load is 784 (N), load amplitude is 735 (N), and load frequency is 3 (Hz). Electric charge at each electrode was sampled. Electrodes that are not used for measurement are connected with the ground. Sampling frequency is 300 (Hz), and the number of sampling point is 1024. The sensitivity of the charge amplifier was set to 7 (pC/V).
3.2. Inverse Analysis Method of Crack Identification

As the inverse analysis method for identification of cracks, the least residual method was applied (Shiozawa et al. 2006). The finite element method (FEM) incorporating the piezoelectric effect was applied to obtain computed electric potential $f^{(c)}$. The computed values $f^{(c)}$ are compared with the measured values $f^{(m)}$ to determine the most plausible crack location and size. As a criterion for crack identification the following square sum $R_s$ of residuals is calculated.

$$R_s(a, h, x_1) = \sum_{i=1}^{M} (f_{i}^{(c)}(a, h, x_1) - f_{i}^{(m)})^2$$

Here $f_{i}^{(m)}$ denotes measured electric potential value at the $i$-th measuring point, and $f_{i}^{(c)}(a, h, x_1)$ denotes the electric potential values at the $i$-th measuring point computed by the FEM for assumed crack length $a$, crack depth $h$, and crack location in $x$-direction $x_1$. $M$ is the total number of measuring points. The combination of crack location and size, which minimized $R_s$, was employed as the most plausible one among all the assumed combinations of the crack location and size. For effective inverse analysis, hierarchical calculation steps (Shiozawa et al. 2006) were introduced.

3.3. Results and Discussion

The charge output of the experiment is shown in Figure 4 (a). Though the amplitude of the charge output is extremely small around 30 (pC), signal-noise ratio of the signal is good. The charge output was converted into electric potential. In the conversion, the thickness $t_p$ and permittivity $\varepsilon_{33}$ of the piezoelectric film was assumed to be 52 (µm) and $1.063 \times 10^{-10}$ (F/m), respectively. The electric potential distribution measured on the piezoelectric film and that calculated by the finite element method (FEM) are shown in Figure 4 (a). Because the accurate value of Young's modulus of piezoelectric film is not known, the potential distribution calculated by the finite element method is calibrated by using the average value of measurements in sound area. It is seen in Figure 4 (a) that the potential distribution obtained by the smart-layer agrees well with finite element results.

In Figure 4 (b), the electric potential measured by the smart-layer is compared with that measured by a non-contact electrometer, which is expected to give a reliable measurement. Measurement by
using the smart-layer compares well with non-contact type measurement shown in Figure 4 (b). The absolute value measured by contact type method is about 20% smaller than the value measured by non-contact type method. This is reasonable because the gain that corresponds to 3 (Hz) of employed charge amplifiers is approximately -1.5 (dB).

From the Figure 4 (a), the electric potential distribution obtained using the smart-layer is close to the FEM results. As a result, passive electric potential CT method can identify the crack with good accuracy. By referring to the previous papers [1-3], the location of the defect in the x-direction can be easily estimated from the point of the local minimum between two local maxima of the electric potential. The size of the defect is reasonably estimated from the height and breadth of the local maxima. The depth of the defect is well estimated when the depth \( h \) is small, while it is not when \( h \) is large.

![Figure 5. Cracked specimen used for experiment of active pulse echo method](image)

4. **Active electric potential CT method (pulse-echo method)**

Smart-layer is set up on an aluminum specimen that has a vertical defect. By using vertical pulse-echo method from the piezoelectric film, the applicability of the smart-layer as the active electric potential CT method is examined.

4.1. Experimental procedure

A2024 aluminum specimen with a vertical crack shown in Figure 5 is used in experiment. The width of the specimen is 20 (mm), and thickness is 15 (mm). The slit was penetrated in the width direction of specimen by electric discharge machining. Half-length of crack is \( a=2 \) (mm), crack depth is \( h=10 \) (mm). Large \( h \) value is selected because the passive electric potential CT method does not give good estimate of \( h \) when \( h \) is large. Smart-layer is constructed by accumulating the piezoelectric film and the FPC shown in Figure 2. The composition of the smart-layer is the same as that described in chapter 3. The rolling direction of the piezoelectric film corresponds to the longitudinal direction of the specimen. The position of the defect was set to be \( x=20 \) (mm).

By using measurement system shown in Figure 5, electric signal is input to each electrode by the pulse-echo method. Considering that the sound wave velocity of the longitudinal wave is large and attenuation is small in the specimen, the applied pulse frequency is set to approximately 15 (MHz).

4.2. Results and Discussion

Figures 6 and 7 respectively show the received echo obtained by the active pulse-echo method when a center position of the electrode is set to 18 (mm) in sound area and 20 (mm) above defect. The reflection wave appearing at 5 (\( \mu \)s) in Figure 6 is smaller than that in Figure 7. In addition, the
reflection pulse from the top of the crack is observed at 3.5 (μs) in Figure 7. Because the received echoes in sound part correspond well with each other, the reproducibility of the characteristic of each electrode is good. Therefore, the time axis can be converted into the distance from the surface of the material by using the first reflected wave and second reflected wave. Arrival times of the first and second reflected wave observed in Figure 6 are denoted by $T_A$ and $T_B$, respectively. Then, the wave velocity of the longitudinal wave is calculated by the following equation.

$$v_l = \frac{2t}{T_A - T_B}$$

where $t$ denotes the thickness of specimen. When the distance from the surface of the specimen is denoted by $y$, the equation for $y$ is given as follows.

Figure 6. Reflection signal of smart-layer (above sound part: $x=18$)

Figure 7. Reflection signal of smart-layer (above defect: $x=20$)

Figure 8. Reflection signal of smart-layer (above defect: $x=20$: The time axis is converted into the distance from top surface.)
From Figure 8, $T_A$ is 4.95 (µs) and $T_B$ is 9.69 (µs). The $v_t$ is calculated to be 6329 (m/s). By using these values, a horizontal axis was converted into the distance from the surface of the specimen as shown in Figure 8. From Figure 8, the depth of the upper tip of the crack $h$ can be estimated accurately. The initial response of the pulse-echo remains for 1.6 (µs), which corresponds to 4 (mm) in the depth of the crack. Therefore, the depth of crack that is deeper than 5 (mm) can be estimated accurately.

The active method is expected to be more efficient in the identification of crack parallel with the top surface compared to the identification of vertical crack studied in this study, since the echo is more pronounced for the parallel crack. Encouraging experimental results were already obtained.

5. Conclusions
The passive and active electric potential CT method was proposed for identification of defects by using the piezoelectric film, which has a characteristic property of mutual conversion between mechanical strains and electric potential of piezoelectric material. The smart-layer was constructed using the piezoelectric film, and attached on the structure with a defect. When the structure was subjected to a mechanical load, the electric potential distribution appeared passively on the piezoelectric film due to the direct piezoelectric effect. The defect can be identified from the distribution with the help of inverse analysis. It was found that the electric potential distribution obtained using the smart-layer compared well with results of the finite element analysis. Then the crack can be identified reasonably, although the defect depth was not well estimated for the defects located far from the layer. When the electric signal was input to the smart-layer, acoustic wave was actively emitted from the layer due to the inverse piezoelectric effect, and received signal was also received on the layer. It was found that the depth of the defect could be estimated well from the travel time. The simultaneous use of the passive use and the active use of the piezoelectric smart-layer is promising for the identification of the defect.

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