Experimental Study on Applicability of Passive Electric Potential CT Method for Identification of Three-Dimensional Surface Crack

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In this paper, we examine the applicability of the passive electric potential CT (computed tomography) method to the quantitative identification of three-dimensional cracks in structures. In this method, a piezoelectric film is glued on the surface of structures. The electric potential values on the piezoelectric film change due to the strain distribution on the surface of the structures, when the structures are subjected to an external load. The strain distribution induces an electric potential distribution on the piezoelectric film. Then, this method does not require electric current application, and passively observed electric potential values on piezoelectric film can be used for crack identification. The electric potential distribution on piezoelectric film was investigated numerically and experimentally. It was found that the electric potential distribution shows a characteristic change corresponding to the shape of the surface crack. An inverse method based on the least residual method was applied to crack identification from the electric potential distribution. In this inverse method, the square sum of residuals is evaluated between the measured electric potential distributions and those computed from the electric potential distribution of the piezoelectric film. Three-dimensional surface cracks were identified from the measured electric potential distribution. It was found that the location and size of the crack can be quantitatively estimated using a two-dimensional distribution of electric potential.

Key Words: Nondestructive Testing Method, Passive Electric Potential CT Method, Inverse Problem, Crack Identification, Piezoelectric Material

1. Introduction

In recent years, the aging degradation of infrastructures, such as bridges, power plants and chemical plants used for a long time, has become a serious social problem. Nondestructive and real-time damage monitoring, and health monitoring of infrastructures has received considerable attention(1). Conventional Nondestructive testing (NDT) methods such as the ultrasonic method, radiation method and electric potential method have difficulties in application to health monitoring of the structures, because these methods require certain physical stimuli for damage detection. These methods have limitations in their applications for automatic and remote monitoring in severe environment.

Passive NDT methods such as the acoustic emission method use certain waves or vibrations corresponding to the mechanical degradation and damage propagation for the damage detection. Passive methods provide us continuous and real-time assessment of structural integrity and also give us warning signals of damage propagation before catastrophic failure of the structure. Passive NDT methods have a lot of advantages in development of health monitoring.

Health monitoring is a function of smart structures(2). Smart structures consist of structures and devices with sensors, control capabilities and actuators like a human body. Smart structures have functions such as self-sensing, active structural control and structure damping. Several studies on health monitoring have been carried out. Piezoelectric film has been used as a sensor of strain...
and an actuator for smart structures. Several investigations have been conducted on the development of smart structures using piezoelectric materials. Galea et al. (3) showed the possibility of the use of piezoelectric PVDF (poly vinylidene fluoride) film as a sensor for detecting and monitoring damage in composite materials, in which the replacement of the piezoelectric film for strain gages in smart structures was investigated.

Kubo et al. (4)–(6) proposed the active electric potential CT (computed tomography) method for quantitative identification of two- and three-dimensional cracks, by applying inverse analyses to electric potential distributions observed under electric current application. On the basis of the principle of the active electric potential CT method, Li and some of the present authors (7) developed the passive electric potential CT method which does not require electric current application using piezoelectric materials. In this method, piezoelectric film is glued on the structure subjected to mechanical load. The piezoelectric film generates an electric change proportional to a change in mechanical strain. The crack in the body induces a characteristic strain distribution. This strain distribution is reflected on electric potential distribution on the piezoelectric film. Therefore the quantitative crack identification was made from the distribution of electric potential, observed on the surface of piezoelectric film, based on an inverse method. In this inverse method, the square sum of residuals are evaluated between the measured electric potential distributions and those computed using the finite element method.

The present authors showed the feasibility of the passive electric potential CT method for identification of a two-dimensional crack (8), (9) in elastic material and two-dimensional delamination defects in composite material (10), numerically and experimentally.

In this study, we examine the applicability of passive electric potential CT method to the identification of a three-dimensional crack experimentally. A three-dimensional surface crack existing on the side opposite the measurement side where a piezoelectric film is glued, is identified from electric potential distribution on the piezoelectric film. The detection and evaluation of these cracks are indispensable for the maintenance of the inner surface of structures such as pipes. In this paper, the effects of the location and size of the surface crack on the electric potential distribution are investigated by FEM (finite element method). The electric potentials on piezoelectric film are measured, and the crack in the specimen is identified from the measured electric potential distribution, based on the proposed inverse analysis method.

2. Electric Potential Distribution on Piezoelectric Material

2.1 Analysis model

When a piezoelectric film is glued on the surface of the plate subjected to mechanical load, a change in electric potential distribution is observed on the surface of the piezoelectric film. A FEM computer analysis scheme was developed for the coupled elastic and electric potential problem to investigate the relationship between the changes in crack parameters and electric potential distribution (11).

The FEM model employed in this study is shown in Fig. 1. This model consists of an objective elastic material and a piezoelectric PVDF film. The dimensions of the elastic material and film are set as follows: \( w: 30 \) (mm), \( l: 40 \) (mm), \( h_{\text{elas}}: 5 \) (mm), \( h_{\text{p}}: 0.052 \) (mm). The piezoelectric film is glued on the side opposite the material surface where a surface crack is opening. The location and size of the crack are defined by the following crack parameters; \( a: \) surface crack half length, \( c: \) crack depth, \( x_c \) and \( y_c: \) crack center location in the \( x- \) and \( y- \) directions.

The properties of the piezoelectric film and the elastic material are shown in Tables 1 and 2, respectively (12), (13). It is seen in Table 1 that piezoelectric materials show anisotropy in the elastic properties and piezoelectric effects. The piezoelectric film shows the largest change in electric potential in direction “1”. The piezoelectric film was glued on the elastic material, so that the direction “1” corresponds to the \( x- \) axis. The potential on the interface

![Fig. 1 Model used in FEM analyses](image-url)
Table 1 Properties of piezoelectric PVDF film

|            | $g_{11}$ | $g_{12}$ | $g_{33}$ | $g_{34}$ |
|------------|----------|----------|----------|----------|
| Elastic properties, (GPa) | 3.61     | 1.61     | 1.42     | 0.55     |
| Piezoelectric properties, (C/m²) | 4.10 x 10² | -1.62 x 10² | -1.59 x 10² |
| Dielectric properties, $\times 10^{12}$ (C/V/m) | 65.1     | 71.3     |

Table 2 Properties of elastic material

| $E_{\text{elas}}$ | $G_{\text{elas}}$ | $\nu_{\text{elas}}$ | $\rho_{\text{elas}}$ |
|-------------------|-------------------|---------------------|---------------------|
| 72.4 (GPa)        | 27.1 (GPa)        | 0.33                | 27.7 x 10³ (kg/m³) |

between the elastic material and the piezoelectric film was set to be 0. The electric potential distribution on the surface of the piezoelectric film was computed, when the mechanical tensile load of 2940 (N) in the $x$-direction was applied to the model.

2.2 Results and discussion

For evaluating the effect of the crack length $a$ on electric potential distribution, electric potential distributions computed by FEM for three combinations of crack parameters, i.e., $(a, c) = (1, 2), (2, 2)$ and $(3, 2)$ while maintaining crack depth $c$ constant, and they are compared with each other. $x_c$ and $y_c$ representing the location of the crack center were maintained at 10.0 (mm) in all cases.

The calculated electric potential distributions on the piezoelectric film are shown in Figs. 2 and 3. In Fig. 2, the electric potential distributions are represented by a contour map. The numbers in Fig. 2 indicate the values of potential, and the dotted line indicates the location and size of crack. In Fig. 3, the electric potential distributions along

![Fig. 2 Effect of crack length $a$ on electric potential distribution](image-url)
Fig. 3 Effect of crack length $a$ on line profile of electric potential distribution

$y = 10.0$ (mm) and $x = 10.0$ (mm) are shown. The electric potential computed in the case of no crack is also shown by dashed lines for investigating the effect of the existence of cracks. The following are observed from Figs. 2 and 3.

- Electric potential values near the crack are smaller than remote values $\phi_0$.
- Contour curves of electric potential near the crack are near-elliptical.
- Electric potential takes a minimum value $\phi_{\text{min}}$ at the location of the crack center $(x_c, y_c) = (10, 10)$. The electric potential on the line of $y = 0.0$ (mm) has a peak value $\phi_{\text{max}}$ for two values of $x$. Electric potential values far from the crack agree with the value $\phi_0$ for the case of no crack.
- The minimum value of electric potential $\phi_{\text{min}}$ decreases with increasing $a$. The distance $H$ between two peaks is constant irrespective of the change in $a$.

For evaluating the effect of crack depth on electric potential distribution, electric potential distributions were computed by FEM for three combinations of crack parameters, i.e., $(a, c) = (2, 1), (2, 2)$ and $(2, 3)$ while maintaining $a$ constant. $x_c$ and $y_c$ were maintained at 10.0 (mm) in all cases.

The calculated electric potential distributions and those on the line of $y = 10.0$ (mm) and $x = 10.0$ (mm) are shown in Fig. 5 (a) and (b), respectively. The distribution in the case of no crack is also shown by dashed lines in Fig. 5. Figures 4 and 5 show the following.

- The width along the $x$-axis of the closed contour curve for a certain potential value, such as 8.6 (V), decreases with increasing $c$.
- The minimum value of potential $\phi_{\text{min}}$ at the location of the crack center decreases with increasing $c$.
- $H$ between two peaks taking the value of $\phi_{\text{max}}$ increases with increasing $c$.

It is found that the existence of surface crack and the change in crack parameters induce characteristic changes in electric potential distribution near the crack. Thus, it is considered that the three-dimensional crack shape can be estimated from the electric potential distribution by the inverse method.

3. Measurement of Electric Potential on Piezoelectric Film

The piezoelectric film was glued on the surface of a specimen. The electric potentials on the piezoelectric film were measured when the specimen was subjected to an external load.

3.1 Specimen and piezoelectric film preparation

The geometry of the specimen used in the experiments is shown in Fig. 6. The elastic substrate material is JIS A2040 aluminum alloy. A semielliptical slit was introduced as a crack by electrical discharge machining. Two specimens with different cracks, i.e., “Crack 1”: $(a, c, x_c, y_c) = (2, 3, 10, 10)$, and “Crack 2”: $(a, c, x_c, y_c) = (3, 2, 10, 10)$ were prepared. The piezoelectric film was glued on the specimen using gauge cement as shown in Fig. 6.

3.2 Measurement method

A schematic illustration of the apparatus used in this experiment is shown in Fig. 7. A noncontact-type electric potential measurement method was used for measuring the electric potentials on piezoelectric film(9). In this method, the electric potentials on the piezoelectric film were measured with an electrostatic voltmeter, which can measure electrostatic charge on polymers, fabrics, and paper. The electrostatic voltmeter can accurately measure surface voltage, because no charge transfer and loading of voltage source can occur without physical contact. The noncontact-type method does not require electrodes and wires on the surface of the piezoelectric film to connect the piezoelectric film to the contact voltmeter. A lot of measurement points per unit area can be placed on the piezoelectric film in the noncontact-type method. The piezoelectric film, as supplied, has coatings on both sides with a thin layer of vacuum-deposited conductive NiCu metal.
The thin layer of conductive NiCu metal film was deleted from the top surface of the piezoelectric film by etching. The electric potential on the processed surface was measured, and the bottom surface coated with NiCu metal was glued on the surface of the specimen.

The periodic load was applied to a specimen with an electrohydraulic machine. The loading conditions are as follows; mean load: 1470 (N), stress ratio: 0.0, and fre-
frequency: 2.0 (Hz). The measured output voltage of the piezoelectric film changes corresponding to the periodic load. Then, the amplitude of the output voltage of the piezoelectric film is used as the electric potential $\phi$. The periodic load has an advantage over static load for excluding the remanent polarization from an output voltage. When static strain is applied, the output voltage consists of polarization by mechanical strain and that by remanent polarization. Therefore, the electric potential distribution reflecting the change in strain distribution cannot be observed with good accuracy when the static load is applied.

The measurement points were set on grid points with a distance of 0.5 (mm) over a measured area of 20 (mm) × 20 (mm), which is indicated by the shaded area in Fig. 6.

3.3 Results and discussion

Figures 8 (a) and 9 (a) show the electric potential distribution for the specimen having Crack 1 and Crack 2. The measured electric potential distribution contains some noise due to the defect of gluing of the piezoelectric film. For investigating the tendency in electric potential distribution, the measured electric potentials were normalized by the remote value $\phi_0$. The value of $\phi_0$ was evaluated by averaging the value $\phi$ in the area of $0 \leq x \leq 2$ (mm) and $18 \leq x \leq 20$ (mm). The normalized electric potential distributions for the Crack 1 and Crack 2 are shown in Figs. 8 (b) and 9 (b), respectively.

It is found from Figs. 8 and 9 that the width along the $y$-axis of the closed contour curve for certain potential values, such as 0.90, is larger than that for Crack 1. This change in electric potential distribution is due to the difference in crack length. The width along the $x$-axis of the closed contour curve for Crack 1 is larger than that for Crack 2. This change is due to the difference in crack depth.

4. Inverse Analysis for Crack Identification

4.1 Process for crack identification

As the inverse analysis method for identifying surface cracks, the least residual method\(^{(14)}\) was applied. In this method, computed electric potential values are compared with the measured electric potential values to determine the most plausible crack location and size. As a
criterion for crack identification the following square sum
$R_s$ of residual is calculated.

$$R_s = \sum_i^M (\phi_i^{(c)}(a,c,x_c,y_c) - \phi_i^{(m)})^2$$  \hspace{1cm} (1)

Here, $\phi_i^{(m)}$ denotes the measured electric potential value at the $i$-th measuring point, and $\phi_i^{(c)}(a,c,x_c,y_c)$ denotes the electric potential values at the $i$-th measuring point computed by FEM for crack parameters $a$, $c$, $x_c$, and $y_c$. $M$ is the total number of measuring points. For the identification of a three-dimensional crack, a two-dimensional distribution of electric potential on the film is used. The combination of crack location and size, which minimized $R_s$, is determined as the most plausible one among all the assumed combinations of crack location and size.

For effective inverse analyses, the following hierarchical calculation steps are introduced.

(a) First step: The electric potentials near the crack are smaller than those for a body without a crack. The contour curve of electric potential shows a semielliptical distribution. The location of the minimum point in the electric potential distribution coincides with the location of the crack center. The location of the crack center $(x_c,y_c)$ is determined from the location of the minimum in the electric potential distribution.

(b) Second step: It has been found from previous studies\(^{(15)}\) on the electric potential CT method that the
change in \( R_s \) behaves in a quadratic form of crack parameters near its minimum. It is assumed that \( R_s \) is approximated by the following quadratic function of \( a \) and \( c \).

\[
R_s(a, c, x_c, y_c) = A + Ba + Cc + Da^2 + Ec + Fc^2
\]  

(2)

The coefficients \( A, B, C, D, E, \) and \( F \) are determined by the least-squares method from the values of \( R_s \) for the combinations of three values of crack length \( a \) and three values of crack depth \( c \). The crack location \((x_c, y_c)\) estimated in the first step is used in this step. The combination of \( a \) and \( c \), which minimizes this approximate function \( R_s(a, c, x_c, y_c) \), is employed as the plausible combination in the rough estimation of crack parameters.

(c) Third step: The combination of crack parameters, which gives the minimum \( R_s \), is searched by the modified Powell optimization method\(^{16} \). The crack parameters obtained in the second step are used as the initial values of the crack parameters for the modified Powell optimization method.

4.2 Results of crack identification

It is found from Figs. 2 and 8 that the measured remote value \( \phi_0 \) is larger than calculated one even when the applied strain is the same. This is due to the difference between the piezoelectric constants of piezoelectric film used in measurement and calculation. It is difficult to measure the piezoelectric constants because the strain field and electric field of piezoelectric film are coupled and the piezoelectric constants have anisotropy in the elastic properties and piezoelectric effects. Thus the reported piezoelectric constants of the piezoelectric films produced under different conditions were used in the FEM analyses. Although the absolute values of measured and calculated electric potential are different, the shape of electric potential distribution shows a common tendency. It is then possible to estimate the location, length and depth of a surface crack from the electric potential distribution normalized by the remote value \( \phi_0 \).

As an example, the process of estimation for Crack 1 is shown below.

It is found from Fig. 8 (b) that the normalized electric potentials decrease near \((x, y) = (10\,\text{mm}, 10\,\text{mm})\) and show the minimum at this point. Therefore, in step (a), \( x_c \) and \( y_c \) are determined as \(10\,\text{mm}\).

In step (b), \( R_s \) was calculated for nine combinations of crack parameters. The crack lengths per width of specimen \(2a/w \) are assumed to be \(1/15, 2/15, \) and \(3/15\), and the crack depths per thickness of specimen \(c/t \) are assumed to be \(0.2, 0.4, \) and \(0.6\). The location of the crack center \((x_c, y_c)\) is assumed to be \((10,10)\) obtained in step (a). \( R_s \) values for Crack 1 are shown in Fig. 10.

It was found that \( R_s \) obtained at \((a, c) = (2,3)\), which was equal to \(0.1996\), was the smallest among \( R_s \) values for nine combinations of crack parameters. The coefficients of Eq. (2) were determined by the least-squares method from the \( R_s \) values for these combinations. A rough estimate of crack parameters is obtained from the minimization of the approximated function \( R_s(a, c) \). The rough estimate of crack parameters and the error in the estimation of \( \Delta a/a, \Delta c/c, \Delta x_c/x_c \) and \( \Delta y_c/y_c \) are shown in Table 3. It is found in Table 3 that the crack length and depth of Crack 1 are estimated within an error of 10%. The locations of the crack center for Cracks 1 and 2 are estimated with good accuracy.

In step (c), the crack parameters were searched by the modified Powell optimization method. The crack parameters in Table 3 are used as the initial values of the crack parameters for the modified Powell optimization method.

The crack parameters and an illustration of the crack shape estimated in step (c) are shown in Table 4 and Fig. 11, respectively. It is found from Fig. 11 that the estimated crack shapes are in close agreement with the actual
crack shapes. Crack length $a$ and the location of the crack center $(x_c, y_c)$ for Crack 1 are identified within an error of 1%. For Crack 2, the location of the crack center is estimated within an error of 3%, and the crack length $a$ and depth $c$ are estimated with approximately 13%.

The error in the estimation of the location of the crack center is found to be small when compared with those of crack length and depth. This is due to the relationship between the location of the crack center and electric potential distribution. The location of the crack center can be determined from the location of the minimum in the electric potential distribution. The location of the minimum in electric potential distribution could be obtained with a high accuracy.

5. Conclusions

The applicability of the passive electric potential CT method to the identification of a three-dimensional surface crack was investigated experimentally. In this method, a piezoelectric film is installed in the structure. The three-dimensional surface crack was introduced on the opposite side of the measurement side, on which the piezoelectric film is glued. The electric potential on the piezoelectric film was investigated by FEM and experimentation. It was found that the electric potential distribution showed characteristic changes corresponding to changes in crack location, length and depth. The crack was identified from the measured electric potential distribution. It was found that the location of the crack center could be estimated within an error of 3%. The error in the estimation of crack length $a$ and crack depth $c$ is approximately 13%. A three-dimensional surface crack can be quantitatively identified by the passive electric potential CT method.

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