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Identification of Crack Depths from Eddy Current Testing Signal

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Abstract—**This paper demonstrates the identification of crack depths using signals obtained from eddy current testing (ECT). The identification method is based on finite elements with the pre-computed unflawed database approach and a meshless crack representation technique, and parameter estimation in non-linear problems. Four different cracks are estimated by using laboratory data.**

Index Terms—**Eddy current testing, steam generator tubes, inverse problems, finite element methods, reduced magnetic vector potentials, pre-computed unflawed database approach, meshless crack representation technique, trust region method.**

I. INTRODUCTION

The development of eddy current inversion techniques is required to identify cracks from detected ECT signals. Signal processing techniques using soft computing techniques such as neural networks or genetic algorithms have been studied for several years. A promising method for achieving this reconstruction was proposed based on combining the corresponding forward problems with optimization theory[1,2]. In this approach, the crack profiles modeled in the forward problem were found by using the gradient method to minimize the difference between experimental measurements and numerical predictions. This was innovative but could not be used to model intricate objects since it used the integration equations assuming a semi-infinite medium. Later, in order to apply it to realistic problems, a nodal finite element approach was substituted for the integral equations[3].

Another method for the inversion was proposed using edge based finite elements[4]. This approach is expected to require much less computational memory than that of nodal finite elements. The trust region method[5] was used instead of the gradient method to find the optimal crack profiles. It was found that while results estimated from laboratory data were in good agreement with the true profiles, this was fairly time-consuming; although recomputation was required in and around the cracks only, large algebraic equations derived from finite elements modeling a much larger region had to be solved repeatedly to obtain the sensitivity of the signals to the crack profiles.

In this study, for improvement on the above method[4], a fast reconstruction for the crack identification is developed based on a very fast forward solver and a simplified method for modeling the cracks. In the forward problem, it is not necessary to compute the eddy current field of the whole region to simulate the eddy current signal due to the crack characteristics. By using a constant database containing the matrices associated with the large unflawed region, the domain is reduced to a small potentially flawed region[6]. Furthermore a method for crack modeling is proposed independent of the generated elements. This makes the representation of the complex profiles easier, and could be also expected to reduce computational time for model construction. After describing the proposed formulation, various estimated crack profiles generated from laboratory data are shown.

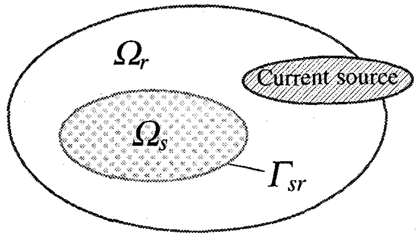
II. CRACK IDENTIFICATION

A. Eddy Current Signal Prediction

For simplification of the modeling task for a moving coil, the reduced $\boldsymbol{A}$ method[7] (referred to as the $\boldsymbol{A}_r$ method) is used. According to this method, the whole problem domain to be dealt with is divided into two parts as illustrated in Fig. 1. Ω_s includes a conductive and/or ferromagnetic material with the standard magnetic potential $\boldsymbol{A}$. Ω_r is the remainder of the modeled domain with the reduced magnetic vector potential $\boldsymbol{A}_r$ which differs from $\boldsymbol{A}$ when an eddy current or magnetization exists in the material in Ω_s. The governing equations are then

$$\nabla\times\frac{1}{\mu}\nabla\times\boldsymbol{A}+\sigma\frac{\partial\boldsymbol{A}}{\partial t}=0 \qquad \text{in } \Omega_s, \tag{1}$$

$$\nabla\times\frac{1}{\mu_0}\nabla\times\boldsymbol{A}_r=0 \qquad \text{in } \Omega_r. \tag{2}$$



Ω_s: Region described by standard magnetic vector potential $\boldsymbol{A}$.
Ω_r : Air region described by reduced magnetic vector potential $\boldsymbol{A}_r$.
Γ_{sr} : Boundary surrounding Ω_s.

Fig. 1. Compuationl domain in the $\boldsymbol{A}_r$ method. In this method, two different potenstials are difined in different regions. One is the air regoin, and the other involves the cracked material.

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The gauge transformation $\phi=0$ has already been used by introducing edge based finite elements in (1).

In order to optimize the profiles, a set of governing equations as in (1) and (2) must be computed repeatedly to obtain the signals from the point of view of sensitivity analysis. However it is not realistic to solve these in typical electromagnetic fields because it is computationally expensive. The signal predictions need the distribution of the electromagnetic fields in the flawed region only, according to the reciprocity theorem. The pre-computed unflawed database method[6] is proposed based on the reduced magnetic vector potential method.

A simple way to model the crack is to assign the finite elements to its geometry, and to give them the same material properties as the air region. If the crack had a complicated shape, it would be tedious to model it. To solve this problem, a meshless crack representation technique is proposed; conductivity is given to each sampling point of the Gauss-Legendre quadrature instead of to each element, as shown in Fig.2.

The signals indicating the presence of the crack are here treated as the impedance change reflected by the disturbance of the eddy current from the presence of the crack. Using the reciprocity theorem, the impedance changes ΔZ due to cracks only are obtained from

$$\Delta Z = -\frac{\omega^2}{I^2}\int_{\Omega_f} A^u \cdot \left(\sigma^u - \sigma^f\right)\left(A^u + A^f\right) dV \quad , \qquad (3)$$

where I, ω ,and Ω_f are a prescribed current, the angular frequency, and the flawed region, respectively. The superscripts "u" and "f" denote the unflawed material and flawed material.

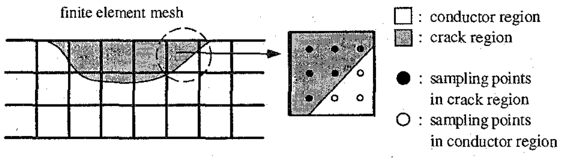


Fig. 2. Sampling points of the Gauss-Legendre quadrature. In the meshless crack representation technique, conductivity is assigned to each of these points.

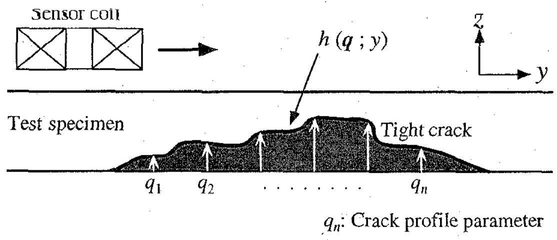


Fig. 3. Paramerization of crack profiles. The profiles are formed by using spline functions in the direction of their depth.

B. Parameter Estimation

For the implementation of the profile identification, the parameters $\boldsymbol{q}$ are defined for characterization of the profiles, as shown in Fig. 3. The lengths of the cracks and the planes where they lie are considered known since these can be easily determined from the signal map. The profiles are represented, using spline functions

$$z = h(\boldsymbol{q};y) = \sum_{i=1}^{N_q} q_i \beta_i(y) \quad , \qquad (4)$$

where q_i and β_i are a bilinear spline function and its coefficient, and N_q is the number of the coefficients. As a result of this definition, it turns out that the signal is a function of the parameters.

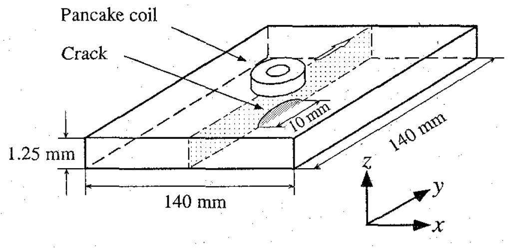
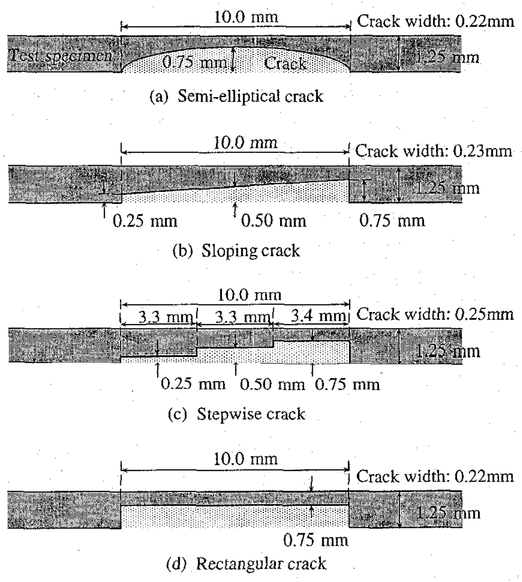


Fig. 4. A coil and a cracked test specimen. These are fabricated to simulate in-service inspection in steam generator tubes in nuclear plants. The coil moves past the crack.



(a) Semi-elliptical crack

(b) Sloping crack

(c) Stepwise crack

(d) Rectangular crack

Fig. 5. Geometries and dimensions of tight cracks. Four different cracks were made by using electric discharge machining.

TABLE I

Configurations of the coil and the test specimen

Coil	Height: 0.8 mm, Width: 1.0 mm Inner diameter: 1.2 mm Outer diameter: 3.2 mm Prescribed current: 1/140 A Frequency: 150 kHz, 300 kHz
Test specimen	Size: 140×140×1.25mmt Conductivity: 1.0×10^6 S/m Relative permeability: 1
EDM crack	Length: 10 mm Opening: 0.22 mm (elliptical) 0.23 mm (sloping) 0.25 mm (stepwise) 0.22 mm (rectangular) Depth: 60% (maximum)

Now using the predictions, we attempt to find the optimal profiles from laboratory data ΔZ_{meas}. The least square function J [4,8] is constructed as

$$J(q^*) = \frac{1}{2}\min\sum_{i}^{N_m}\left|\Delta Z^i - \Delta Z^i_{meas}\right|^2 , \qquad (5)$$

where N_m is the number of the measured points, and the superscript " i " denotes the i th observation point. Finally, the optimal profiles are obtained by minimizing the above equation, using the trust region method[5] which is a kind of the Quasi-Newton method.

III. RESULTS AND DISCUSSION

The reconstructions are performed, using four samples with a tight crack as shown in Fig. 4. Additionally, Fig. 5 shows the crack profiles named semi-elliptical, sloping, stepwise and rectangular. We call them inner cracks which open under the coil, and outer cracks exist on the opposite side. These are proposed as one of the benchmark problems by the JSAEM[9]. Table I summarizes the important dimensions, material properties, and test conditions.

Let us define the origins be the center of each crack and the coil path is along the y axis above the crack; the crack edges are y=-5 mm and 5 mm. By symmetry, a half-model of the problem was formed using the finite elements. Table II summarizes the discrete data and the information on the ICCG method. There are 21 measured points of the signals as the coil moves parallel to the cracks from y= -10 mm to 10 mm, and six depth parameters are located from -5 mm to 5 mm at regular interval, respectively. The admissible parameters are taken as 0.05 mm $\le \{q_i\}_{i=1}^{N_q} \le$ 1.20 mm. For the implementation of the trust region method, a FORTRAN package " OPT2"[10] is used.

The predictions of the signals due to the crack are compared with experimental measurements. Excellent agreement demonstrates the effectiveness of numerical modeling for the forward problem. Both results are highly accurate because these values are under 2 % of the impedance in air.

TABLE II

Discrete data and computational costs

Elements	3,380
Nodes	4,158
Edges	11,645
Unknowns	8,733
Elapsed time	2 hours^a 20 minutes^b
Computational memory (Mbytes)	5^a 3^b

Computer : SUN workstation (CPU, Ultra SPARC 170MHz).

Sampling points in Gauss - Legendre quadrature in an element: 125(=5^3) points.

^{a} database, ^{b} reconstruction.

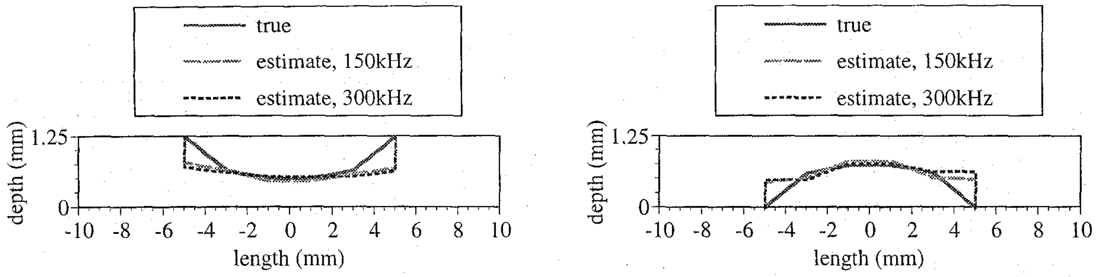
Giving the length, opening, location, and breaking side of each crack is mere assumption for simplification of the modeling. Their locations are presumed from the distribution on the measured impedance map, and the side is predicted in the phases of the signals. The final crack profiles estimated from laboratory data are shown in Fig. 6 in comparison to the true profiles when those of initial guesses are taken as rectangular cracks 50%(0.65mm) deep. The number of iterations is 9 times in the longest case to reach the final results. The estimated results are in good agreement with the true and the estimated profiles in maximum depth, irrespective of shape symmetry of the cracks.

At the shallow parts of the cracks, it is found that there are differences between the true and estimated profiles. An issue arises from low sensitivity at the scanning path above the shallow parts, in comparison to the area where maximum value can be observed around there. However it does not result in improvement although more measuring points are used to cover those parts. This can be considered that it is a matter of sensitivity at the edges. The detectablity of ECT depends on test frequencies by the nature of the skin effect. In the cases of sloping and stepwise cracks from the viewpoint of the sensitivity, this also results in unexpected profiles at high frequency at the corner of shallow depth.

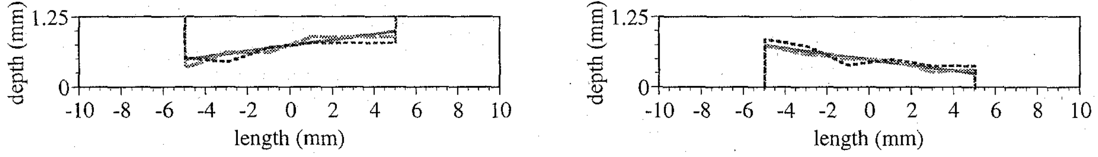
large amounts of computation to predict eddy current signals are required to reach the final results; most of the computational time is originally spent on solving the large algebraic equations from (1) and (2) and this definitely makes it difficult to apply this approach to realistic diagnosis. It took two hours to create the constant database as shown in Table II. However the computational time was reduced to less than 4% of that in the method[4] in terms of the signal prediction, by virtue of the pre-computed unflawed region method and the meshless crack representation technique

IV. SUMMARY

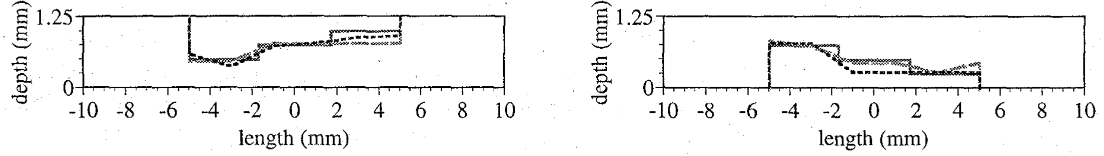
A method for eddy current inversion in ECT was developed, and was used to identify the crack profiles from laboratory data. Summary in this study is: (1)the pre-



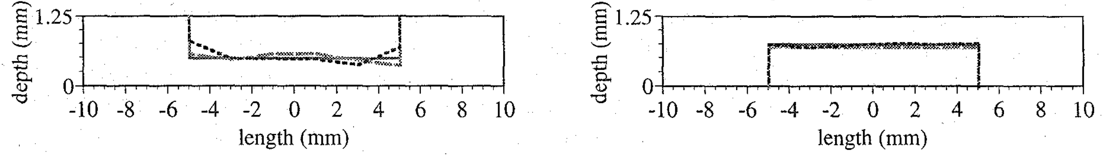
(a) Inner elliptical crack (e) Outer elliptical crack



(b) Inner sloping crack (f) Outer sloping crack



(c) Inner stepwise crack (g) Outer stepwise crack



(d) Inner rectangular crack (h) Outer rectangular crack

Fig. 6. Results of estimated crack profiles. The estimated results are compared with the true profiles of two test frequencies 150 kHz and 300 kHz.

computed unflawed database method was used based on the reduced magnetic vector potential method to develop a fast reconstruction technique; (2)the prediction by the corresponding forward problem was compared with experimental measurements and excellent agreement showed the effectiveness of this method; (3)the crack profiles were formed independent of the finite elements, and the trust region method is used to find the optimal profiles; (4)four different crack profiles were identified by using laboratory data, and these results demonstrated the validity of this approach.

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