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Identification of Multiple Cracks from Eddy-Current Testing Signals With Noise Sources by Image Processing and Inverse Analysis

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***Abstract*—This paper proposes a novel method for identifying the number and positions of cracks and reconstructing crack shapes. It assumes that two-dimensional scanned eddy-current testing (ECT) signals obtained from a steam generator tube are a picture image, then a template matching method with the help of genetic algorithms predicts the number and positions of cracks. The present method employs the superposition of crack signals and a nonlinear scaling technique of a signal profile on the crack length that are verified by numerical simulation. The number and positions of the cracks are satisfactorily predicted. The crack-shape reconstructions from the predicted positions with the help of inverse analysis are achieved with a satisfactory degree of accuracy.**

***Index Terms*—Eddy-current testing, inverse problem, multiple cracks, support plates, template matching.**

I. Introduction

EDDY-CURRENT testing (ECT) is used for the in-service inspection of tubes in steam generators (SGs) in pressurized water reactor type nuclear plants. The testing methods need to not only have a high degree of sensitivity and detectability but also need to provide quantitative evaluations of positions and shapes of shallow cracks. SG tubes are supported by support structures. One such structure is a support plate, which is made of ferromagnetic material. Detection of cracks becomes difficult because of the noise caused by the support plate being detected as ECT signals.

In previous studies [1]–[3], it was shown that even when a crack is under influence of a support plate, a single crack can be detected and a crack shape can be reconstructed. However, reconstruction of multiple cracks from ECT signals, including support plates, has not been addressed. This paper discusses identification of positions and shapes of cracks under influence of support plates.

This paper proposes a method for identifying the number and positions of cracks using a template matching method, one of the image recognition methods. The method is verified through application to experimental ECT signals of multiple cracks. The number and positions of cracks are predicted based on two-dimensional scanning ECT signal as an image picture. Genetic algorithms (GAs) are used as search algorithms to improve computation time for identification. Finally, crack shapes are reconstructed with the help of inverse analyses using the predicted positions of cracks.

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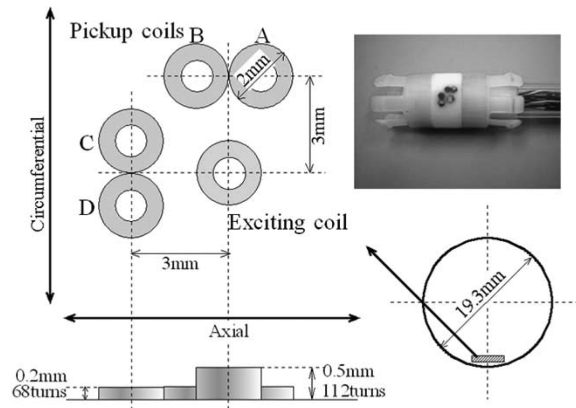


Fig. 1. Geometry of a differential TR probe.

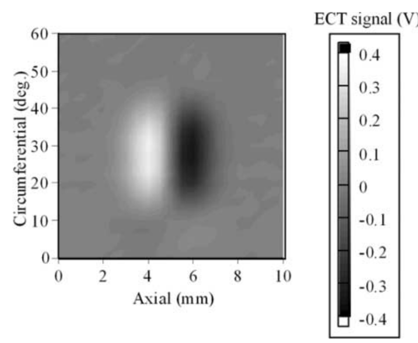


Fig. 2. ECT signal using the differential TR probe.

II. Detail of Experiment

A differential transmit–receive (TR) probe [4] developed by the authors was used for this experiment, as shown in Fig. 1. This probe possesses the feature that the direction of the defects can be identified. Circumferential and axial cracks are detected by a circumferential channel (A, B) and an axial channel (C, D) separately. Fig. 2 shows the y component of output voltage obtained from the circumferential channel. The y component is associated with $\pi/2$ phase difference between the input voltage and the output voltage, while the x component is associated with one that is in phase. This signal is obtained from an electrical discharge machining (EDM) crack of 5 mm in length and 0.2 mm in width and an OD (Outer Defect) of 40% of the thickness in

TABLE I
PROPERTIES OF THE SG TUBE AND THE SUPPORT PLATE

	Testpiece	Support plate
Material	Ni alloy 600	SS400
Conductivity σ (S/m)	1.0×10^6	4.0×10^6
Permeability μ_r	1	70
Length (mm)	300	24.1
Inner radius (mm)	19.69	22.7
Outer radius (mm)	22.23	40.0

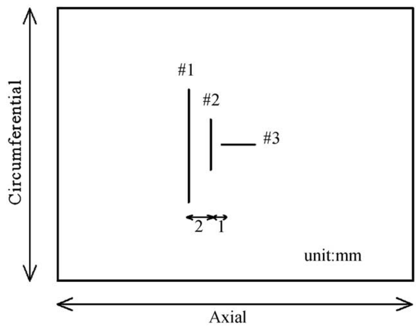
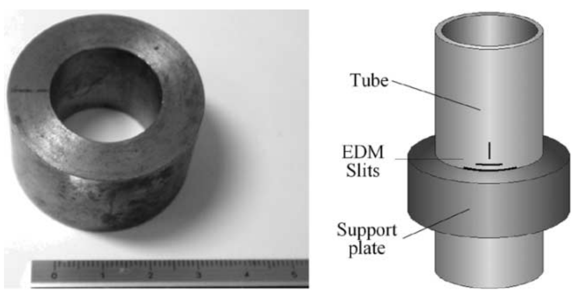


Fig. 3. Positions of EDM slits on the testpiece.



(a) (b)

Fig. 4. Support plate. (a) Photograph. (b) Schematic of the testpiece.

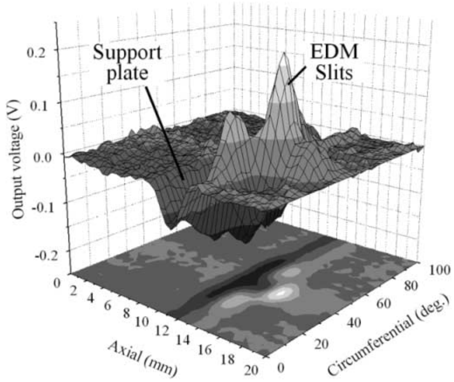


Fig. 5. ECT signal obtained from the testpiece attached to the support plate.

depth. The signal obtained from this probe has two peaks in both sides of the crack, and was used later as a template.

Table I summarizes the characteristics of the testpiece and the support plate [1], [4]. The testpiece has 3 slits on the outside of the tube constructed by EDM. Fig. 3 shows the positions of the slits. The support plate was installed the outside of the testpiece to locate the edge of the support plate right above a slit, as shown in Fig. 4. This support plate is ferromagnetic so that eddy current (EC) is easier to pass into the support plate than the Ni alloy used for the testpiece. A large amount of EC flows into the support plate and a large signal caused by the support plate is detected; thus, it is difficult to detect defects.

Fig. 5 shows the y component of this ECT signal voltage obtained from the SG tube testpiece where the support plate is installed outside. The signal observed at around 12 mm in the axial direction is caused by the support plate.

The employed probe has differentially connected pickup coils so that the support plate has little influence in the axial channel. Therefore, in this paper, reconstruction of crack #3 was not examined and identification was only performed on cracks #1 and #2.

III. IDENTIFICATION OF THE NUMBER AND POSITIONS OF CRACKS

A. Template Matching With the Help of Genetic Algorithms

Template matching with the help of GAs [5] is applied to identify the number and position of the cracks. The lengths and the locations of the crack are expressed in the gene of the GAs. The fitness is calculated by comparing the signals of the template after transformation with the signals of the input image at the location in the gene using a correlation coefficient. Selection, crossover, and mutation are operated based on the fitness of each gene to increase the fitness. After a lot of generation shifts, the gene with the highest fitness is expected to indicate the position of the crack. The features of GAs used in this paper are as follows.

- Initial population: 60.
- Number of generation shifts: 200.
- Crossover rate: 0.9.
- Mutation rate: 0.02.
- Tournament selection.
- Two-point crossover.
- Elite preservation strategy.

After one crack is found, another crack is identified based on the signal from which the template signal is subtracted.

B. Assumptions of the ECT Signals

The following two assumptions are made about the ECT signals.

1) Multiple cracks signals can be expressed as the superposition of single crack signals.
2) Signals of cracks with differential lengths can be scaled based on a template signal.

The former assumption enables a sequential search. The latter is necessary for searching for various length cracks based on one kind of template.

The reduced magnetic vector potential method based on the edge elements [6] is used for verification of the assumptions. At first, the assumption of the superposition of crack signals is verified. Two parallel cracks of OD20% and OD40% were investigated here. They have the same length and width of 10 and 0.2 mm, respectively, and three patterns, at 1, 2, and 3 mm intervals, were computed. The scanning line crosses the centers of the cracks perpendicular to the cracks. Examples of the numerical results are shown in Fig. 6. The correlation coefficients between the superposition of the single crack signals and the

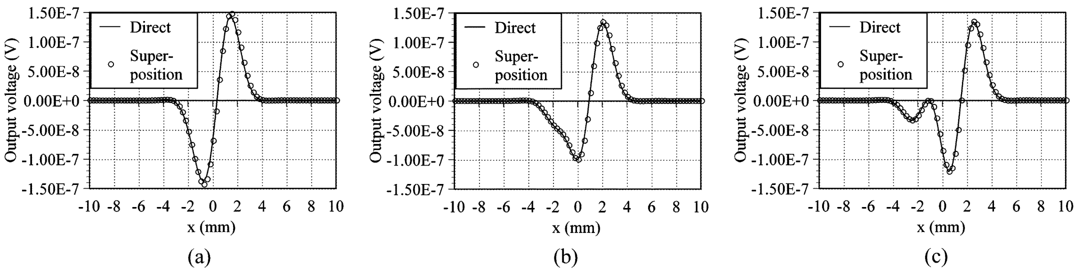


Fig. 6. ECT signals V_x for verification of superposition assumption. (a) 1 mm interval. (b) 2 mm interval. (c) 3 mm interval.

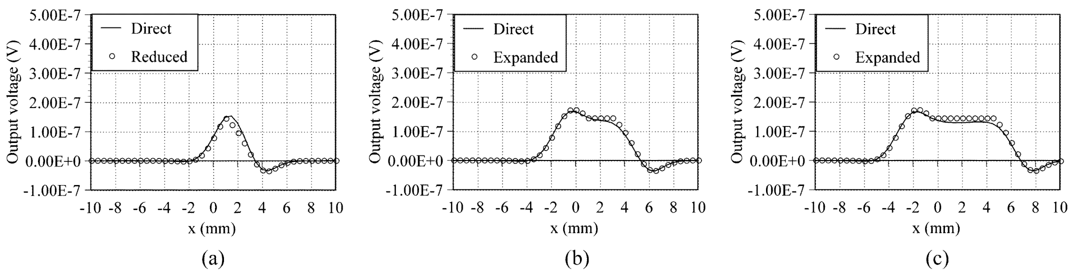


Fig. 7. ECT signals V_x for verification of length scaling assumption. (a) 3 mm length. (b) 7 mm length. (c) 10 mm length.

TABLE II
CORRELATION COEFFICIENTS IN SUPERPOSITION VERIFICATION

Interval of cracks (mm)	Correlation coefficient	Figure
1	0.999775	6 (a)
2	0.999974	6 (b)
3	0.999994	6 (c)

TABLE III
CORRELATION COEFFICIENTS IN LENGTH SCALING VERIFICATION

Crack length (mm)	Crack depth (%)	Correlation coefficient	Figure
3	20	0.993333	
	40	0.989545	7 (a)
	60	0.985233	
7	20	0.999426	
	40	0.999014	7 (b)
	60	0.998457	
10	20	0.998638	
	40	0.997277	7 (c)
	60	0.995720	

two-crack signals are listed in Table II. It is possible to reproduce the signals with very high accuracy in every case. Therefore, it can be concluded that the assumption of the superposition of crack signals is satisfied.

Second, the assumption of crack length scaling is examined. If a crack is long enough with respect to a probe, the signal at the center of the crack must be equal to the signal of a crack having infinite length. If the shape of the crack edge is the same, the signal of the crack edge must always be equal, regardless of the crack length. Based on this intuitive consideration, the crack signal is expected to change depending only on the length of the center. When the crack is expanded, the signal of the crack center is expanded with the value of the center. In contrast, when the crack is reduced, the center of the signal is eliminated.

This assumption is verified using numerical analysis. The signals of cracks of 3, 7, and 10 mm in length are transformed based on the signal of a crack of 5 mm in length. Three kinds of depth, OD20%, OD40%, and OD60%, are examined. The scanning line is parallel to the crack. Examples of the results are shown in Fig. 7. The correlation coefficients between the scaled signals and the signals computed directly are listed in Table III. Thus, the crack length scaling makes it possible to reproduce the ECT signal with high accuracy.

C. Multiple-Frequency Method

The present method is difficult to adapt to ECT signal imaging with some signals except for those caused by cracks, e.g., support plates. Therefore, before examining the present method, the ECT signal is processed for decreasing the signal caused by the support plate and emphasizing only the crack signal.

The multiple-frequency method [7] is used in practical inspection to eliminate the noise caused by support structures. In this technique, the signals, scanned on the same part of the testpiece using more than two frequencies, are expanded, rotated, and subtracted from the signal on the complex plane. The coefficient α to minimize residual noise D of the following formula is calculated using noise S_{f_1} and S_{f_2} at two frequencies f_1 and f_2

$$D_{(\alpha)} = \min \sum_{i=1}^{N_p} \left| S_{f_1}^{p_i} - \alpha S_{f_2}^{p_i} \right|^2$$

where $S_f^{p_i}$ is a signal at the measuring point p_i at frequency f and N_p is the number of measuring points.

Fig. 8 shows the ECT signal image after processing the multiple-frequency method. The test frequencies f_1 and f_2 are 200 and 400 kHz, respectively. According to Fig. 5, it is found that the signal caused by the support plate is eliminated and the crack signal is emphasized. The number and positions of the cracks are predicted based on this ECT signal image of the testpiece having multiple cracks.

TABLE IV
RECONSTRUCTION OF CRACK SHAPES

Detected No.	Estimated depth (%)	True depth (%)	Error of depth (%)	Estimated length (mm)	True Length (mm)	Error of length (mm)	Slit No. in Fig. 3
R1	44.7	44	+0.7	5	4.6	+0.4	#2
R2	29.5	21	+8.5	11	10.3	+0.7	#1

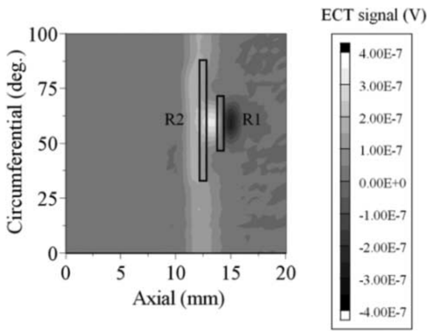


Fig. 8. ECT signal after signal processing obtained from the testpiece attached to the support plate.

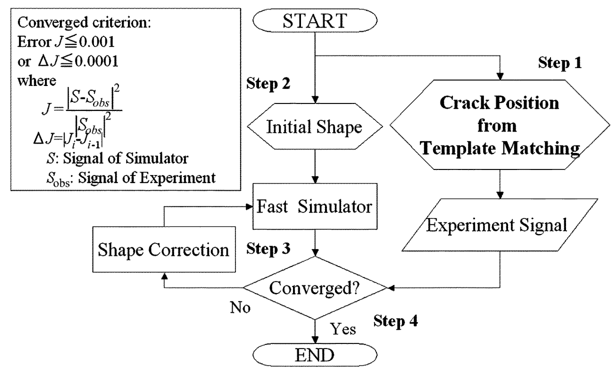


Fig. 9. Flowchart of the inverse analysis.

D. Identification Results

Boxes in Fig. 8 indicate the positions and the lengths of the cracks, which were identified by template matching. It is found that R1 corresponds to the actual crack #2 in Fig. 3 and R2 to #1. The distance between R1 and R2 is 1.875 mm and agrees well with the actual distance of 2 mm between #1 and #2 in Fig. 3.

IV. RECONSTRUCTION OF CRACK SHAPES

The crack shapes were reconstructed based on the positions of the cracks identified by the present method. Huang *et al.* [4] has investigated the method that reconstructs a crack shape when the position of the crack is known. This method requires the position of the crack and the ECT signal at that position to be known. In this paper, the ECT signal is given automatically because the position of the crack is predicted by template matching. Fig. 9 shows a flowchart of crack shape reconstruction. The inverse analysis is conducted according to the following procedure.

Step 1) The experiment signal at the position of the crack identified in the template matching is assumed to be the target signal.

Step 2) The initial crack shape is given to the numerical model and the fast forward simulator obtains the ECT signal.

Step 3) The crack shape is corrected so that the error between the estimated signal and the target signal are smaller and the signal is calculated again.

Step 4) Step 3 is iterated until the error becomes negligible.

The method presented in [4] is enhanced by Step 1. An inverse analysis model of the SG tube, including the support plate, was adapted. Identification of the crack position makes it possible to establish a model by which the positions of the cracks and the support plate are considered. The area where the crack may exist was assumed to be 0.2 mm in width, 16 mm in length, and 100% in depth. The crack shape is expressed using 16 parameters for depth and every 1 mm for length.

Table IV summarizes the shapes of the cracks estimated by the inverse analysis. Both the length and the depth of the cracks show excellent agreement. These results suggest that even if there are neighboring cracks and these cracks are under influence of the support plate, the crack shapes can be reconstructed accurately.

V. CONCLUSION

The possibility of reconstructing crack shapes, in a single system, from scanning a SG tube is demonstrated in this research. A decrement in human errors and faster inspections can be expected by completely automating inspection.

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