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Numerical Evaluation of Correlation between Crack Size and Eddy Current Testing Signal by a Very Fast Simulator

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Abstract–**This paper describes work on the development of a very fast eddy current testing (ECT) signal simulator, and its application to the evaluation of the correlation between cracks and signals. This simulator is developed here based on a reduced magnetic vector potential, edge based finite elements, and the pre-computed unflawed database approach. Using this simulator, three kinds of probes are tested in terms of their linearity and signal to noise ratio.**

Index Terms–**Eddy current testing, steam generator tubes, finite element methods, reduced magnetic vector potentials, pre-computed unflawed database approach.**

I. INTRODUCTION

Eddy current testing (ECT) is used for the in-service inspection of steam generator (SG) tubes in nuclear and conventional power plants. It is particularly attractive because of such features as very high detectability, high scanning speed, and no use of a coupling medium between the probe and the test specimen. Studies for the development of this testing have been performed on such topics as reconstructions and classifications of cracks from their signals, using neural networks[1] or reconstruction methods based on finite elements and optimization theory[2]-[4].

In order to develop this technique, it is important to clarify the correlation between the cracks and their eddy current signals. It had been empirically or analytically recognized that the magnitude of the signals reacts as a function of the crack length, and their phase does with a function of the depth. Three-dimensional numerical simulation methods have recently been used, in place of experiments. Although the high accuracy of some simulation techniques has been demonstrated[5]-[7], a problem still remains in computational time. A large amount of computation is required as the probe moves with various kinds of crack sizes, test frequencies and so on; for the R&D of a new probe, the simulation has requires excessive amounts of time. Hence a very fast solver is necessary, and the pre-computed unflawed database approach based on the reduced magnetic vector potential method and edge based finite elements offers significant advantages in addressing this issue.

In this study, the signals as a function of crack size such as length, depth, and width are predicted using a very fast signal simulator based on the pre-computed unflawed database approach. Three kinds of common probes are tested in terms of linearity and signal to noise ratio(SNR). After describing the application of the pre-computed unflawed database approach to the conventional reduced magnetic vector potential method, examples of the signals are shown, and the consideration of the linearity and the SNR is given.

II. FAST ECT SIGNAL PREDICTION

Using a database approach, the fast ECT signal predictions were made with nodal elements, together with the A-ϕ-Ω FEM[3] and the A-ϕ FEM-BEM[4]. The use of edge based finite elements in the place of nodal finite elements results in a reduction in required computational memory.

The pre-computed unflawed approach developed here is combined with the reduced magnetic vector potential method[2,8]. For the explanation of this database approach, the common magnetic vector potential method is used for simplicity. The governing equations are:

$$\nabla\times\frac{1}{\mu_0}\nabla\times A+\sigma\frac{\partial A}{\partial t}=0 \qquad \text{in conductor,} \qquad (1)$$

$$\nabla\times\frac{1}{\mu_0}\nabla\times A=J_s \qquad \text{in air,} \qquad (2)$$

where μ_0, A, σ and J_s are permeability of air, magnetic vector potential, conductivity and source current density. The gauge transformation ϕ=0 has already been used by introducing edge based finite elements in (1). Additionally, let us define a magnetic vector potential A^u in the case where the conductor is not cracked. If cracks exit, a magnetic vector potential caused by them, A^f, is written as

$$A^f=A-A^u. \qquad (3)$$

This can be considered as the potential due to current dipoles in the flawed region. Using the equations of unflawed and flawed cases, the following equations are obtained:

$$\nabla\times\frac{1}{\mu_0}\nabla\times A^f+\sigma^u\frac{\partial A^f}{\partial t}=(\sigma^u-\sigma^f)\frac{\partial(A^u+A^f)}{\partial t} \qquad \text{in conductor,} \qquad (4)$$

$$\nabla\times\frac{1}{\mu_0}\nabla\times A^f=0 \qquad \text{in air,} \qquad (5)$$

where σ^u and σ^f are conductivity of an unflawed and a flawed conductors. After weak formulation by the Galerkin method, the equations are written as

$$[K+j\omega L]\{A^f\}=[j\omega L']\{A^f+A^u\}. \qquad (6)$$

where $[K]$, $[L]$, and $[L']$ are derived from (4) and (5).

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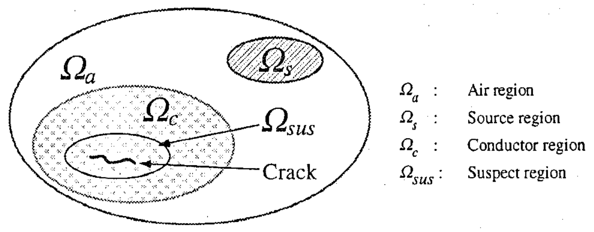


Fig. 1 Definition of the suspect region. This region is much smaller than the whole region including air, source and cracked conductor.

Consider a suspect region which may contain a flaw, as shown in Fig.1. According to the reciprocity theorem, the prediction of the signals due to cracks can be made from the distribution of the electromagnetic field in the flawed region only[3]. Denote the unknowns belong to Ω_{sus} by the subscript 1, the others by the subscript 2. As a result, the whole domain which includes the air region can be drastically reduced to a small computational domain as follows:

$$[I - R_{11}Q_{11}]\{A_1^u + A_1^f\} = \{A_1^u\}, \qquad (7)$$

where $[Q_{11}]$ is the matrix related to the suspect region, $[R_{11}]$ is a small part of the inverse matrix from a common stiffness matrix. Both $[Q_{11}]$ and $\{A_1^u\}$ are computed in advance, and are used as a database. Note that the suspect region must exists in non-magnetic material. Depending on the size of the suspect region, it may be time-consuming to make the database. However, it can be used repeatedly for various kinds of cracks in the suspect region unless the geometry and material properties of the test specimens change.

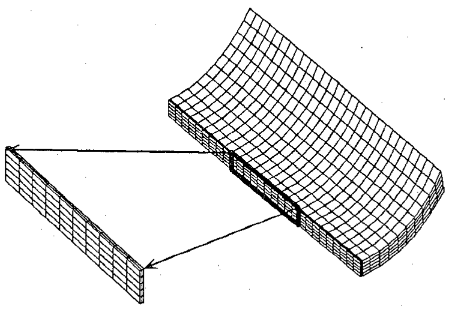
There are two cases in the predictions of eddy current signals. One is the impedance of exciting coils, another is induced voltage of pick-up coils. Using the reciprocity theorem, the coil impedance change ΔZ due to the cracks only is obtained from

$$\Delta Z = -\frac{\omega^2}{I^2}\int_{\Omega_f} A^u \cdot (\sigma^u - \sigma^f)(A^u + A^f)dV , \qquad (8)$$

where I, ω ,and Ω_f are a prescribed current, the angular frequency, and the flawed region, respectively. Similarly, the voltage of the pick-up coils be obtained from

$$\Delta U = -\frac{\omega^2}{I}\int_{\Omega_f} A_p{}^u \cdot (\sigma^u - \sigma^f)(A^u + A^f)dV , \qquad (9)$$

where the subscript "p" denotes an imaginary potential yielded by the pick-up coils. Each of them is assumed to be applied a unit current density. The results from the method developed here were compared with those from the reduced magnetic vector potential method, which has already been demonstrated regarding quantitative predictions of eddy current signals in the JSAEM benchmark problems[5,6].



(a) Suspect region (b) Tube

Fig. 3 Finite element model of a quarter of the tube and a suspect region. First order hexahedral elements are used.

Table I Parameters of crack sizes and frequencies. The sizes are decided from the point of view of possible notches by electric discharge machining

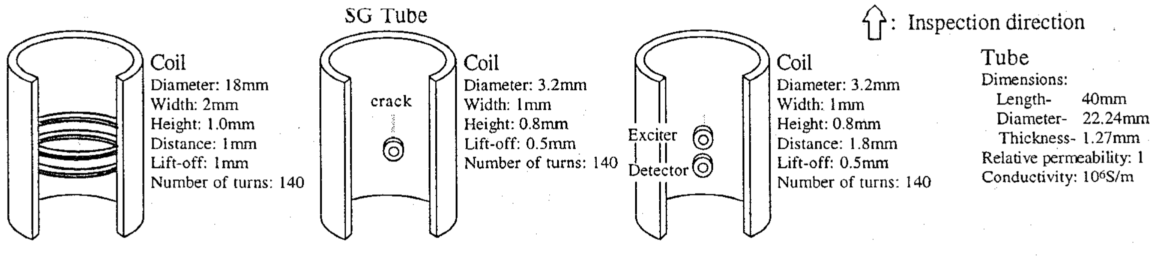
Depth (%)	Length (mm)	Width (mm)	Frequency (kHz)
10, 20, 30,40* 50, 60	2, 4, 6* 8, 10	0.2*, 0.25, 0.3 0.35, 0.4	150*, 300

* Standard parameter

III. RESULTS AND DISCUSSION

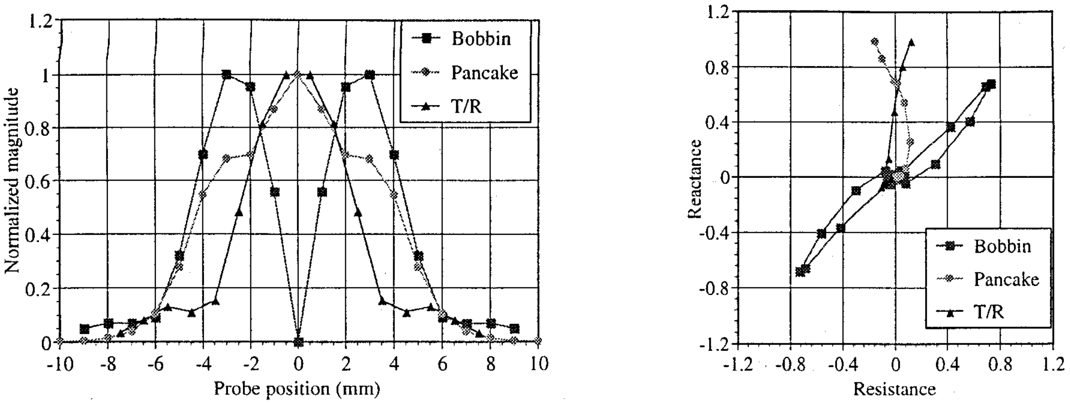
A. Simulated ECT Model

ECT applied to the inspection of the SG tubes is simulated. The test specimen and three kinds of probes, a conventional bobbin type probe, a pancake type probe[6], and a transmit-receive (T/R) type probe[9] are shown in Fig. 2. The bobbin type probes have been used in the in-service inspection of the tubes for a long time. Their scanning speeds are fast. However they are lacking in resolution into the position of cracks in the circumferential direction of the tubes in comparison to other two probes. Although the pancake type probes were developed to supplement the lack of the resolution, they have a disadvantage in the scanning speed. To obtain higher SNR, the T/R type probes were proposed, and studied to make them practicable are being performed[9]. The exciter and detector coils have the same dimensions as



(a) Bobin type probe (b) Pancake type probe (c) T/R type probe

Fig. 2. Tubes and three kinds of probes. The tubes are modeled to simulate SG tubes, and the bobbin type, pancake type and T/R type probes are used in inspection.



(a) Magnitude (b) Trajectory

Fig. 4. Comparision of ECT singnals amomg three kinds of probes. The curves are normalized using maxium values. The dimensions of the cracks are taken from the standard values.

those of a pancake coil. The bobbin coils embedded are much larger than the others, and their axes are parallel to the axis of the tube. Outputs from three probes are the differential impedance of two coils, impedance, and induced voltage of the detector coil, respectively.

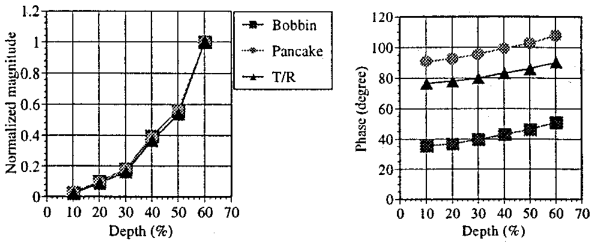
The origin of the probes is defined so as to be the center of the axial crack, and the probe paths run parallel to axis of tube. The sampling points of the signals as the coil moves parallel to the axial cracks are set to 21, from x= -10 mm to 10 mm. The cracks with different shape parameters (length, depth and width) as well as frequencies are summarized in Table I, and all cracks are open on the outer surfaces of the tubes. The standard parameters are marked with "*". Simulations are done with all shape parameters kept to be the standard values except one of them changes as shown in the table.

B. *ECT Signals*

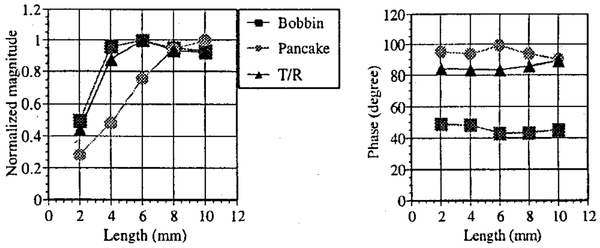
The signals indicating the presence of a crack have various aspects, depending on the used probes. The signals from three probes are compared. In contrast to the bobbin type probe, maximum values at the origin in the cases of the pancake type and T/R type probes. By symmetry, a quarter of the model is constructed using the finite elements as shown in Fig. 3. In this simulation an axial crack is assumed to exist in the suspect region. The parameters of depth, length and width are changed within this region.

Comparison of the signals of three probes is made in Fig. 4, using the standard case in Table I. The magnitude is normalized by maximum values of each signal. In the cases of both the pancake type and T/R type probes, peak values are observed at the position where the centers of the probes overlap those of the cracks. The trajectories of signals are different each other. This simulator makes it possible to evaluate the shapes of the signals from cracks.

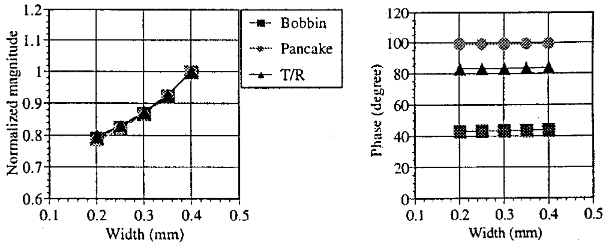
In general, signals due to cracks can be extracted from measured signals noised by the presence of other structures around the tubes or deposits which consists of magnetite, using the multi-frequency processing technique. By contrast, it is difficult to find the cracks in the vicinity of copper deposits because the signal after the processing are declined and is not the sum of signals by a crack and copper deposits[10]. The purpose of this paper is different from those of deposits cases. The question here is whether the linearity between signals and crack sizes exists. If it did, the characterization of the cracks might become easier, based on prepared calibrations.



(a) Depth



(b) Length



(c) Width

Fig. 5. Magnitude and phase of ECT signls as functions of crack depth, lenght, and width.

Fig. 5 shows normalized magnitude and phase as functions of crack depth, length, and width with the exciting

Table II Comparison of three probes in the linearity and the SNR

		Bobbin	Pancake	T/R
Linearity	Depth	×	×	×
	Length	×	O	×
	Width	Δ	Δ	Δ
SNR		×	×	O

O: best Δ: good ×: poor

frequency of 150kHz. The values are at the location where signals take maximum amplitude. The phase of the signals from any probes is not in direct proportion to the depth, and the linearity is not satisfied by nature of the skin effect. In the case of the pancake type probes, the linearity is observed when the length is approximately shorter than two times of the diameter of the coil (6 mm), and then the magnitude is saturated. In the cases of the T/R type and bobbin type probes, the linearity is not clear. However, they have higher detectability of short cracks than the pancake type probes. Although there are fluctuations in phase, they are negligibly small in the case of the length. From the relationship between the width and the signals, the linearity is slightly observed in magnitude, but the phase does not vary with the width in each case. Interests are that the normalized signals varying with the depth and width show the same tendency in each probe even though ways to induce the electromagnetic fields and to detect the signals are completely different as shown in Fig. 4. This means that the effect of cracks on the electromagnetic phenomena in the conductor seems to be same if the exciting frequencies are equal in the different probes.

The SNR which is an important performance parameter of the probes is compared in this paper. It turns out that the SNR of the T/R type probe is more than a fifty times of that of the others in these examples as it has already been pointed out by K. Maeda et al. [9]. Here the noise is defined as the signals of 2 degrees inclination of the probe. The features of these probes for the linearity and the SNR are summarized in Table II.

As discussed above, a large amount of computation is required to evaluate the detection performance. Comparisons of the computational time and memory required for the pre-computed unflawed database approach and the conventional reduced magnetic vector potential method are presented in Table III. The computational time required for the signal predictions is reduced by a factor of 60 by introducing the pre-computed unflawed database approach. Even though the development of the database is computationally expensive, this is very useful for the predictions of various kinds of probes and cracks after creating the constant database once.

IV. SUMMARY

A very fast ECT signal simulation technique was developed, and its application to evaluating the detection performance of the bobbin type, pancake type and T/R type probes was demonstrated.

(1) The pre-computed unflawed database approach was proposed to predict the ECT signals. In this approach, the domain required for computation of ECT signals is reduced to a small potentially flawed region by using the database.

Table III Comparison of the present method (pre-computed unflawed database approach) and the conventional method (reduced magnetic vector potential method only)

	Unknowns	Memory (Mbytes)	Time (seconds)
Present Method	28,064 [a] 362 [b]	40 [a] 6 [b]	32,400 [a] 60 [b]
Conventional Method	28,064	40	3,600

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

[a] Creation of database. [b] Signal prediction.

(2) The linearity between the crack size and signals was evaluated by using the proposed approach. From the SNR, the T/R type probe was superior to the others.

(3) Introducing the pre-computed unflawed database approach, it becomes possible to predict the signals with many parameters in practical computational time.

This approach is useful for the evaluation of new probes which have advantages over the linearity of the signals and detectability, and would enable us to develop fast crack reconstruction techniques.

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