Fast Signal Prediction of Noised Signals in Eddy Current Testing

著者	高木　敏行
journal or publication title	IEEE Transactions on Magnetics
volume	36
number	4
page range	1719-1723
year	2000
URL	http://hdl.handle.net/10097/47877

doi: 10.1109/20.877774

Fast Signal Predictions of Noised Signals in Eddy Current Testing

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***Abstract*—This paper describes a new method for the simulation of signals noised by the presence of other materials outside of test materials in eddy current testing. The method developed here, which can treat ferromagnetic materials, is an extension of a pre-computed database approach based on the magnetic vector potential method. It results in much fewer degrees of freedom than those of typical finite element approaches, and the method provides a very fast forward simulator even in the case with ferromagnetic materials.**

***Index Terms*—Eddy current testing, ferromagnetic materials, finite element methods, steam generator tubes.**

I. INTRODUCTION

EDDY current testing (ECT) is used for the in-service inspection of tubes in steam generators (SG) of pressurized water reactor (PWR) type nuclear plants. Here, a difficulty encountered is the processing of the noisy ECT signals. The noise may be caused by the variation of the lift-off of the probe, deposits formed on the outside surface of the tubes, the presence of structures outside the tubes, etc. One of such structures is a support plate, which is made of ferromagnetic material.

In order to develop this technique, it is important to clarify the correlation between the cracks and their eddy current signals. Three-dimensional numerical simulation methods have recently been used in place of experiments. A nonlinear problem should be considered when the model includes ferromagnetic materials. Anyway, linearization can be performed because the electromagnetic field in ECT works with low density and small range. Using this approximation, a numerical method is proposed to evaluate the ECT signals considering ferromagnetic materials outside SG tubes in this paper.

Although the high accuracy of some numerical simulation techniques has been demonstrated, a problem still remains in computational time. Some fast pre-computed database approaches [1], [2] have been proposed, but a problem still exists because it was impossible to treat ferromagnetic materials.

Manuscript received October 25, 1999. This work was supported in part by the Research Committee on Nondestructive Evaluation Technology by Eddy Current Testing of the Japan Society of Applied Electromagnetics and Mechanics through a grant from 5 PWR utilities and Nuclear Engineering Ltd., and the Grant-in-Aid for COE Research (11CE2003).

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Publisher Item Identifier S 0018-9464(00)05061-5.

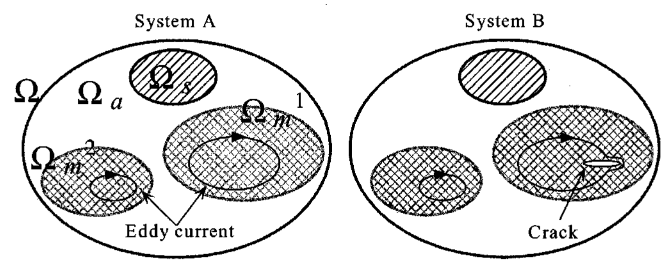

Fig. 1. Schematic diagram of electromagnetic fields of domains including a current source, nonmagnetic and ferromagnetic media.

In this paper, a new method is proposed by the extension of the pre-computed database approach based on the reduced magnetic vector potential method [3]. This method can be applied to the model including ferromagnetic materials. Thus, it can be used to solve the problems of the SG tubes with deposits or support plates. Computational time is reduced and same precision can be achieved as that of a conventional method.

II. FAST ECT SIGNAL PREDICTION

It is usually necessary to consider the whole region including air, coils and conductors to solve the electromagnetic problems of ECT. From the viewpoint of signal evaluation of the cracks, which is obtained as the difference between the models with and without cracks, a finite element domain can be reduced to a much smaller region including the crack and its nearby region [1], [2]. We named it “suspect region.” Using the database of a crack-free model computed in advance, the analysis region is reduced to the inside of the suspect region, and algebraic equations can be obtained on a very small scale compared with conventional magnetic vector potential methods. Moreover, following the reciprocity theorem [4], [5], the signals can be computed using only the unknowns of the suspect region.

A. Governing Equations when Ferromagnetic Materials Exist

We consider two systems with and without cracks in a testing material, as shown in Fig. 1. Ω, Ω_a, and Ω_s are the whole region, air region and the current source region. The cracks are supposed to exist inside the conductor region Ω_m^1, which is made of nonmagnetic materials. But for the conductor region Ω_m^2 without any cracks, no restriction on materials is needed. Following the same procedure as that in reference [2], a magnetic vector potential $\boldsymbol{A}^u$ is defined in the case when the conductor Ω_m^1 is not cracked. If cracks exit, a magnetic vector potential caused by them, $\boldsymbol{A}^f$, is written as,

$$\boldsymbol{A}^f = \boldsymbol{A} - \boldsymbol{A}^u. \tag{1}$$

This could be considered as the potential due to the dipole current in the crack region. Using the equations of cracked and crack-free cases, the following equations are obtained:

$$\nabla \times \frac{1}{\mu_0} \nabla \times \boldsymbol{A}^f + \sigma^u \frac{\partial \boldsymbol{A}^f}{\partial t} = (\sigma^u - \sigma^f) \frac{\partial (\boldsymbol{A}^u + \boldsymbol{A}^f)}{\partial t} \qquad \text{in } \Omega_m^1 \tag{2}$$

$$\nabla \times \frac{1}{\mu} \nabla \times \boldsymbol{A}^f + \sigma \frac{\partial \boldsymbol{A}^f}{\partial t} = 0 \qquad \text{in } \Omega_m^2 \tag{3}$$

$$\nabla \times \frac{1}{\mu_0} \nabla \times \boldsymbol{A}^f = 0, \qquad \text{in } \Omega_a + \Omega_s \tag{4}$$

where σ^u and σ^f are conductivity when Ω_m^1 is cracked and crack-free. μ and σ are permeability and conductivity in Ω_m^2. $(\sigma^u - \sigma^f)$ is not zero only in the crack. The right side of (2) can be simply comprehended as the effect of the dipole current, which may appear in the crack region only. Following the same steps of conventional edge element based FEM in [3], the algebraic equations can be obtained:

$$[K + j\omega L]\{A^f\} = [j\omega L']\{A^f + A^u\}. \tag{5}$$

The left side matrix is same as the conventional magnetic vector potential method when cracks do not exist. It does not depend on the cracks, in other words, this matrix can be pre-computed before the crack shapes are known. It must be pointed out that the degree of freedom of (5) is still same as the conventional method. An important point is how we decrease the degrees of freedom.

B. Equations of the Fast Forward Simulation Method

Based on the reciprocity theorem, only the results inside the flaw region (or a slightly larger region: suspect region) are needed to compute the ECT signals. That is to say, we want to solve the equations that contain only the unknowns inside the suspect region. All the unknowns are separated into two parts: unknowns inside the suspect region and its boundary are denoted by subscript 1, the others are denoted by subscript 2. Equation (5) can be rewritten using the subscripts into

$$\begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{Bmatrix} A_1^f \\ A_2^f \end{Bmatrix} = \begin{bmatrix} Q_{11} & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} A_1^f + A_1^u \\ A_2^f + A_2^u \end{Bmatrix}. \tag{6}$$

Most elements in the matrix $[Q]$ are zero, and only the elements related to the flaw are not zero. Multiplying by the matrix $[R]$, which is the inverse matrix of $[P]$ in (6), we obtain

$$\begin{Bmatrix} A_1^f \\ A_2^f \end{Bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} Q_{11} & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} A_1^f + A_1^u \\ A_2^f + A_2^u \end{Bmatrix}. \tag{7}$$

Equation (7) can be separated into two independent equations. After arrangement of the equations concerning the suspect region, equations with much smaller degrees of freedom are shown as

$$\{A_1^f\} = [R_{11}][Q_{11}]\{A_1^f + A_1^u\}, \tag{8}$$

which can also be expressed as

$$[I - R_{11}Q_{11}]\{A_1^u + A_1^f\} = \{A_1^u\}. \tag{9}$$

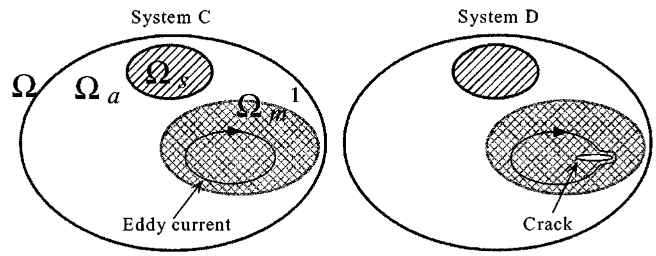

Fig. 2. Schematic diagram of domains without ferromagnetic media.

In (9), $[Q_{11}]$ is the matrix related to the suspect region, and $[R_{11}]$ is a small part of the inverse matrix from a common stiffness matrix. Both $[R_{11}]$ and $\{A_1^u\}$ can be computed in advance because these are independent of cracks, and are used as a database. 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. The equations can be solved by the Gauss method because of its small degrees of freedom.

C. Computation of the ECT Signals

The signals and noises in ECT are the impedance differences between the cases with cracks or the noise source, and the cases without them. Considering Fig. 1 with real ECT of heat exchange tubes, Ω_m^1 is the test specimen; Ω_m^2 is the noise sources, such as support plates or deposit materials. The signals due to crack only, the noises only, and the noised signals including both these two can be expressed as the differences between system D and system C (ΔZ_{DC}), A and C (ΔZ_{AC}), and B and C (ΔZ_{BC}), respectively, as shown in Figs. 1 and 2. Following the reciprocity theory, ΔZ_{DC} is easy to compute according to the reference [2]. The objective of this study is to evaluate the signal ΔZ_{BC} by the database approach, which can not be evaluated by the previous methods. The same procedure can be used to evaluate the signal ΔZ_{BA} as follows:

$$\Delta Z_{BA} = \frac{1}{I^2} \int_{\Omega_f} \boldsymbol{E}^u \cdot (\sigma^u - \sigma^f)(\boldsymbol{E}^u + \boldsymbol{E}^f)^* \, dV, \tag{10}$$

where $\boldsymbol{E}$ denotes an electric field and * means the conjugate. The signal ΔZ_{AC} can be evaluated by modifying the Biot–Savart's law into more general form as,

$$\boldsymbol{A} = \frac{1}{4\pi} \int_{V_c} \frac{\mu_0 \boldsymbol{J}}{r} \, dV + \frac{\mu_0}{4\pi} \int_{V_m} \frac{\boldsymbol{M} \times \boldsymbol{r}}{r^3} \, dV, \tag{11}$$

where $\boldsymbol{M}$ is a magnetization vector and the second part of the right side shows the contribution of ferromagnetic materials. $\boldsymbol{M}$ can be obtained by $(\mu_r - 1)\boldsymbol{H}$. Signal ΔZ_{AC} can be evaluated by a conventional method such as the method shown in [3], together with (10). Hence the signal ΔZ_{BC} can be evaluated.

$$\Delta Z_{BC} = \frac{1}{I^2} \int_{\Omega_s} \{(\boldsymbol{E}^B - \boldsymbol{E}^A) + (\boldsymbol{E}^A - \boldsymbol{E}^C)\} \cdot \boldsymbol{J}_s^* \, dV = \Delta Z_{BA} + \Delta Z_{AC}, \tag{12}$$

where J_s^* is the conjugate of the current source density. The signal ΔZ_{AC} does not depend on cracks and may be computed once in advance. Since ΔZ_{BA} can be evaluated very fast using the method proposed here, ΔZ_{BC} can be obtained at the same

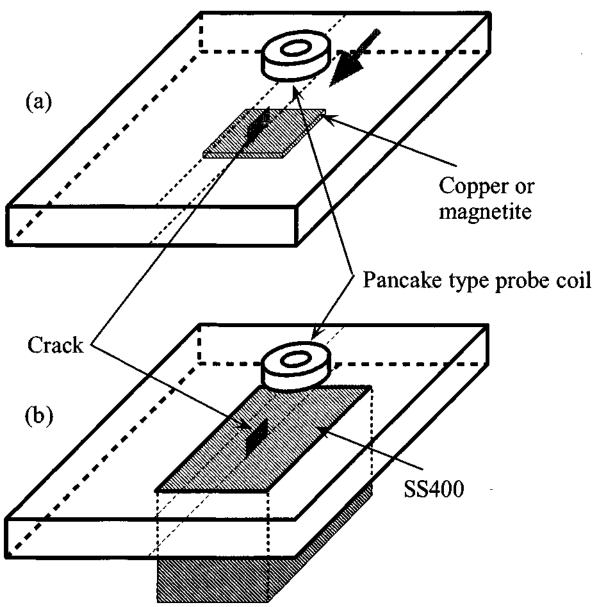

Fig. 3. Schematic diagram of (a) copper or magnetite deposit models, and (b) a support plate.

time. This proposed method has the same accuracy as that of the conventional method [3] because the effect of Ω_m^2 is considered in the formulation. It must be pointed out that ΔZ_{BA} is not the same as ΔZ_{DC} because of the existence of Ω_m^2. Using ΔZ_{DC} instead of ΔZ_{BA} may cause errors in the ECT signals prediction.

III. Results and Discussion

The JSAEM benchmark problem 5 is used as the numerical model [6]. It contains three problems simulating a copper deposit, a magnetite deposit, and a support plate (SS400). The analysis model is shown in Fig. 3 and Table I. The impedance changes with excitation frequencies of 150 kHz and 300 kHz on the condition that the probe coil is located over the center of the test piece are computed using the conventional method [3] to show the accuracy of the method although cracks do not exist in this case. The computational results are plotted on the complex plane in Fig. 4, comparing with experimental results. Both results show good agreement.

Signals considering the noises from deposits and a support plate were computed. In ECT, a crack that is opening on the coil side is called an inner defect (ID), and one that is opening on the opposite side is called an outer defect (OD). The results of the support plate case (150 kHz, OD 40%) are shown in Fig. 5. The curves described in Fig. 5 are the impedance changes (complex numbers) when the coil moves away from the center of the crack along a path parallel to the axial direction. Because of the effect of the support plate, ΔZ_{BA} is different from ΔZ_{DC}, as was mentioned in the previous section. It can also be seen that $(\Delta Z_{BA} + \Delta Z_{AC})$, shows good coincidence with ΔZ_{BC}, which is the target of the simulation, as shown in Fig. 5(b). The results of copper deposit and magnetite deposit cases (150 kHz, OD 40%) are shown in Figs. 6 and 7. The same conclusion can be drawn that $(\Delta Z_{BA} + \Delta Z_{AC})$ shows good coincidence with

TABLE I
Configuration of the Coil and Test Specimen

Models	Deposits	Support plate
Coils	Height: 0.8 mm, Width: 1.0 mm Inner diameter: 1.2 mm Outer diameter: 3.2 mm Applied current: 1/140 A Frequency: 150 kHz, 300 kHz Lift-off 0.5mm	
Test specimens	140mm×140mm×1.25mmt μ_r : 1 σ : 1.0×10^6 S/m	
Other Materials *	Copper 20mm×20mm ×0.08mmt μ_r : 1 σ : 5.8×10^7 S/m	19mm×60mm ×25mmt μ_r : 110 σ : 3×10^6 S/m
	Magnetite 20mm×20mm ×10mmt μ_r : 3 σ : 0.0 S/m	
EDM cracks	Length: 10 mm, Width: 0.2 mm Depth: 40, 60% (Inside or outside)	

* The test specimens touch with the copper sheet/ magnetite block, respectively, or are located at a distance of 0.19mm from ferrous materials.

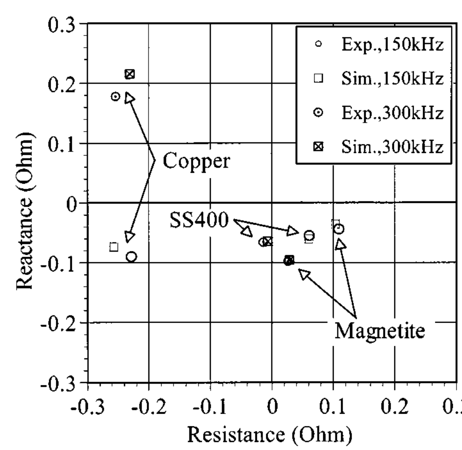

Fig. 4. Comparison of eddy current signals in copper deposit, magnetite deposit and support plate models without crack.

ΔZ_{BC}. As shown in Fig. 6, the effect of the copper deposit is so large that the signals due to cracks are too small to be noticed. This is because the copper deposit has very high conductivity, which is 60 times more as that of the testpiece, and because the copper is in contacts with the testpiece. Most eddy current flows in the copper deposit and this may lower the current density near the cracks. Signal processing must be used to detect the OD's of these noisy cases such as a multi-frequency method. The present method developed here gives us a much faster way to evaluate the total signals including crack signals and noises by a simple superposition of ΔZ_{BA} and ΔZ_{AC}. This will be a strong tool to analyze the cases when noise sources exist.

This fast simulator can be applied to any kinds of cracks inside the suspect region, and only less than 1% of computational

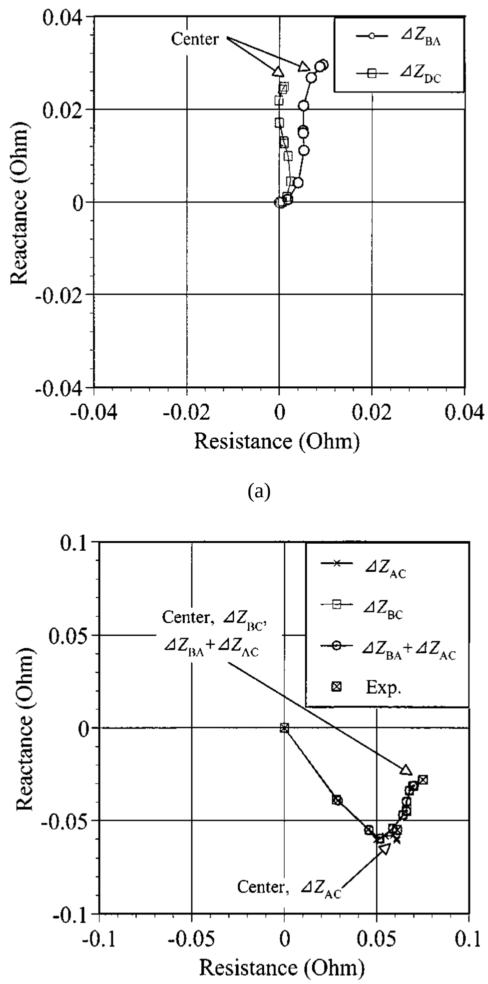

Fig. 5. Eddy current signals in the support plate model. (a) Comparison of crack signals. (b) Comparison of signals including noise.

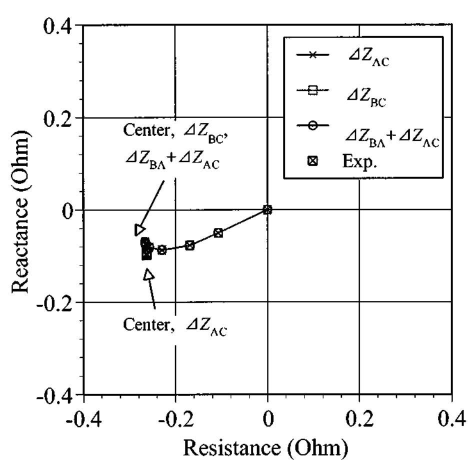

Fig. 6. Eddy current signals in the copper deposit model.

time of the conventional method is needed. The comparison of the computational costs is made in Table II. The data shown in Table II are the values needed for the computation of 11 scan points.

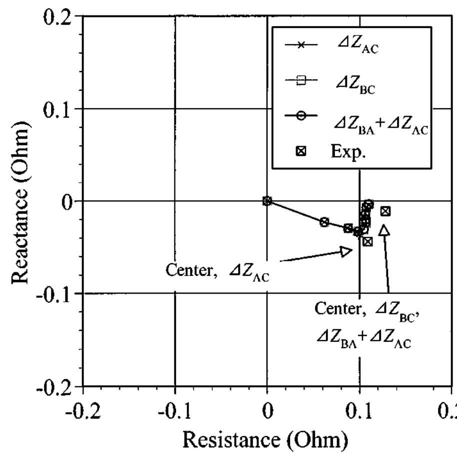

Fig. 7. Eddy current signals in the magnetite deposit model.

TABLE II
COMPUTATIONAL COSTS OF THE PRESENT AND THE CONVENTIONAL METHOD

Models	Methods	Unknowns	Memory (Mbytes)	Time (seconds)
Copper or magnetite deposit	Present method ($\Delta Z_{BA}+\Delta Z_{AC}$)	21,948 [a] 181 [b]	38 [a] 3 [b]	19,800 [a] 45 [b]
	Conventional method (ΔZ_{BC})	21,948	38	5,400
Support plate	Present method ($\Delta Z_{BA}+\Delta Z_{AC}$)	22,812 [a] 181 [b]	38 [a] 3 [b]	19,800 [a] 45 [b]
	Conventional method (ΔZ_{BC})	22,812	38	6,000

Computer: SUN workstation (CPU, Ultra SPARC 300MHz)
[a] Creation of database [b] Signal prediction

IV. SUMMARY

A very fast ECT signal simulation method, which can treat ferromagnetic materials, was developed in this paper.

1) Based on the reduced magnetic vector potential method, a pre-computed database approach was extended to predict the ECT signals of a system including ferromagnetic materials.
2) Instead of computing ΔZ_{BC} directly, the feature of this new approach is the fast simulator to solve ΔZ_{BA} and the simple superposition of ΔZ_{BA} and ΔZ_{AC}.
3) The effectiveness of this fast simulator was verified by applying it to the problem including the noise factor in the ECT of SG tubes. The signals can be evaluated with the same precision as that of the conventional method but much faster.

This approach is useful for the evaluation of signals of different kinds of cracks, and may be of great advantage if used in inverse problem analysis because of its high speed.

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