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Eddy Current Signal Analysis for Transmit-Receive Pancake Coil on ECT Array Probe

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Abstract In this paper, the eddy current signals come from a pair of transmit-receive (T/R) pancake coil on ECT array probe are analyzed with the variations of the lift-off and of the distance between transmit and receive coils. To obtain the electromagnetic characteristics of the probes, the governing equation describing the eddy current problems is derived from Maxwell's equation and is solved using three-dimensional finite element method. Eddy current signals from T/R coils on ECT array probe have quite different characteristics compared with ones from impedance coil on rotating pancake coil probe. The results in this paper can be helpful when the field eddy current signals from ECT array probe are evaluated.

Keywords: ECT array probe, eddy current testing, FEM, T/R coil

I. Introduction

Steam generator (SG) tubes in a nuclear power plant have an important role in blocking radioactivity as well as in heat exchange between nuclear reactor and turbine generator. So the maintaining the reliability of the SG tubes is very essential and periodical examination using nondestructive testing such as ECT has to be executed. In the area of ECT, bobbin probe is widely used for the examination of SG tubes because of its fast inspection speed and accumulated vast experimental data. But the axis of pancake coil of bobbin probe is parallel to the axis of SG tube, it is hard to detect the signals from the circumferential defect. So to inspect more precisely the SG tubes, rotating pancake coil (RPC) probe is used. As it has three or more coils with different axis, it can detect more precisely defect signals. But the weak points of this RPC probe are very low speed of inspection and the limited inspection area. As the probe moves along the pipe with the rotation, its inspection speed is very slow. Because of its geometrical limitations the inspection region is restricted near the tube sheet and it can not reach and inspect the U-bend region. To overcome these limitations, ECT array probe is developed (Cecco, 1995). It has many pancake coils and these coils are divided into two kinds of coils according to its operation mode. The one group is transmit coil which generates the magnetic fields and induces eddy currents in the specimen. The other group is receive coil which detects the magnetic fields and gathers signals concerning to the defect. The merits of ECT array probe are high speed of inspection, high ability of defect detection. ECT array probe can inspect 40 times faster than RPC and it can inspect everywhere of pipes including U-bends, tube sheet and tube support intersections (Obrutsky, 2004).

To properly analyze the field ECT array probe data, we have to establish database of eddy current signals with various defects. It will be the best choice if we obtain the eddy current signals by

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experiment with mock-ups. But making the mock-up with various defects is very difficult, tedious and expensive work. And the numerical method such as FEM is very efficient alternative method for obtaining eddy current signals and is very widely used in engineering field. So in this paper, FEM is suggested for electromagnetic numerical analysis and eddy current signal generation (Biro, 1989). And the signals from the one set of transmit-receive coils on ECT array probe are obtained using 3-dimensional FEM and analyzed with the variation of lift-off and distance between transmit and receive coil.

Ⅱ. Numerical Method for Electromagnetic Analysis

Physically ECT can be modeled as an eddy current problem in electromagnetism. From the following Maxwell's equation and constitutive relations neglecting the displacement current, the governing equation for the eddy current problem in terms of the magnetic vector potential can be obtained (Rao, 1999).

$$\nabla \times \vec{H} = \vec{J}_s + \vec{J}_e \quad (1)$$

$$\nabla \times \vec{E} = -j\omega\vec{B} \quad (2)$$

$$\nabla \cdot \vec{B} = 0 \quad (3)$$

$$\vec{B} = \mu\vec{H} \quad (4)$$

$$\vec{J}_e = \sigma\vec{E} \quad (5)$$

where $\vec{H}$, $\vec{B}$, and $\vec{E}$ are magnetic field intensity, magnetic flux density, and electric field intensity, $\vec{J}_s$, and $\vec{J}_e$ are source current density and induced eddy current density, ω, μ and σ are angular frequency, magnetic permeability and electric conductivity, respectively.

From eqns. (3) and (2) the magnetic vector potential $\vec{A}$ and the electric scalar potential V are derived.

$$\vec{B} = \nabla \times \vec{A} \quad (6)$$

$$\vec{E} = -j\omega\vec{A} - \nabla V \quad (7)$$

From eqns. (1), and (4) through (7) the governing equation can be derive as shown in eqn. (8).

$$\nabla \times \frac{1}{\mu}\nabla \times \vec{A} + \sigma\left(j\omega\vec{A} + \nabla V\right) = \vec{J}_s \quad (8)$$

But eqn. (8) contains two variables, so we have to add one more equation shown in eqn. (9) known as current continuity condition.

$$\nabla \cdot \sigma\left(j\omega\vec{A} + \nabla V\right) = 0 \quad (9)$$

To guarantee of the unique solution of magnetic vector potential $\vec{A}$, the divergence and curl of vector have to be defined. The divergence is defined in eqn. (6), but the curl is not defined. Usually for the curl of the magnetic vector potential, Coulomb gauge condition is used as shown in eqn. (10).

$$\nabla \cdot \vec{A} = 0 \quad (10)$$

To model the eddy current problems, the following equations have to be solved.

$$\nabla \times \frac{1}{\mu}\nabla \times \vec{A} - \nabla\frac{1}{\mu}\nabla \cdot \vec{A} + \sigma\left(j\omega\vec{A} + \nabla V\right) = \vec{J}_s \quad (11)$$

$$\nabla \cdot \sigma\left(j\omega\vec{A} + \nabla V\right) = 0 \quad (12)$$

To solve the equations for eddy current problem, numerical method is used because it is hard to obtain analytic solution with complex geometry. So in this paper, three dimensional finite element method (FEM) is used (Lee, 2000). For the finite element modeling, the problem region is divided into hexahedral elements. Applying the finite element formulation to the above governing equations in eqn. (11) and (12), the following algebraic equation is obtained, and the magnetic vector potential and the electric scalar potential are calculated by solving the algebraic equation (13).

$$\begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{Bmatrix} A \\ V \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} \quad (13)$$

Ⅲ. Numerical Results

To investigate the effect of lift-off and the distance of transmit and receive coils on eddy current signals, numerical analysis is performed by using 3-dimensional FEM. FEM code is implemented using FORTRAN based on the presented theory. The specification of numerical model is described in Table 1 and is shown in Fig. 1. As shown in Fig. 1, the receive coil followed by the transmit coil is moving along X-axis. With the assumption that the size of pancake probe is very small compared to the curvature of the SG pipe, the INCONEL 600 plate is chosen for the base plate with defect. Because of the heavy load of mesh generation, the rectangular shape coils are used. Operating frequency of coil is chosen as 100[kHz]. As the conductivity of the material is 9.860e5[S/m], the skin depth is about 1.6[mm].

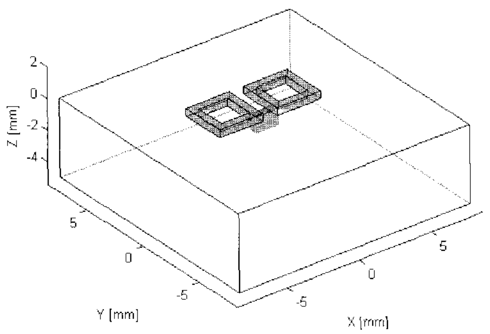


Fig. 1 Analysis Model

Table 1 Model Specification

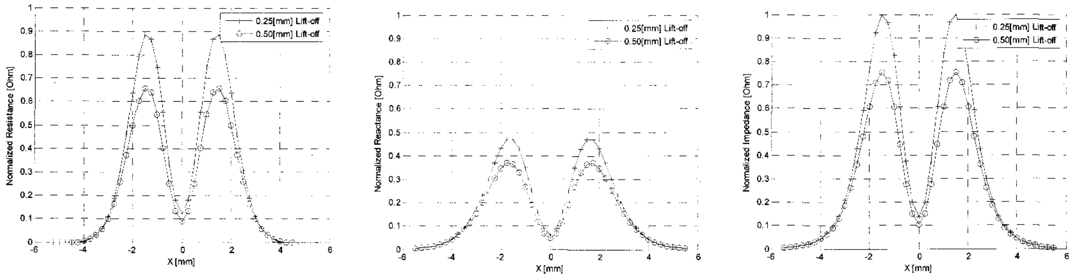
Base Plate and Defect		
Material	Plate Size [X,Y,Z]	Defect Size [X,Y,Z]
INCONEL 600	16[mm]x16[mm] x5[mm]	1.5[mm]x0.5[mm] x1[mm]
Coil		
Frequency	Size [X,Y,Z]	Cross Section
100[kHz]	3[mm]x3[mm] x0.5[mm]	0.5[mm]x0.5[mm]

The lift-off is selected as 0.25[mm] and 0.50[mm]. To perform the FE analysis, the problem region is divided into finite element mesh with hexahedral elements whose length of each edge is 0.25[mm]. More than 6 elements are placed on skin depth. The number of nodes, elements and variables are 173225, 163840 and 608380, respectively. In the conductor region magnetic vector potential and electric scalar potential are used for variables and in the air region only magnetic vector potential is used for variable. To solve the system matrix generated by FEM procedure, iterative solution method of QMR (Quasi-Minimal Residual Method) based on coupled two-term Lanczos with look-ahead is used and two sided SSOR (Symmetric Successive Over-Relaxation) method is used for preconditioning the system matrix. Because of the effect of model boundary, the eddy current signals in the figures are obtained by calculating the signal difference between the signals with defect and signals without defect.

To compare the ECT signals between impedance probe and T/R probe, the eddy current signals of impedance probe is shown in Fig. 2. Because only one coil is used to generate magnetic fields and sense the signals, the shape of impedance signal is symmetric as the shape of defect on the INCONEL 600 plate is symmetric. As the coil moves along the defect, the M-shaped signals are shown in the figures. And the lift-off of the coil increases, the magnitude of signal decreases. The maximum value of signal is reduced to 70% as the lift-off becomes twice.

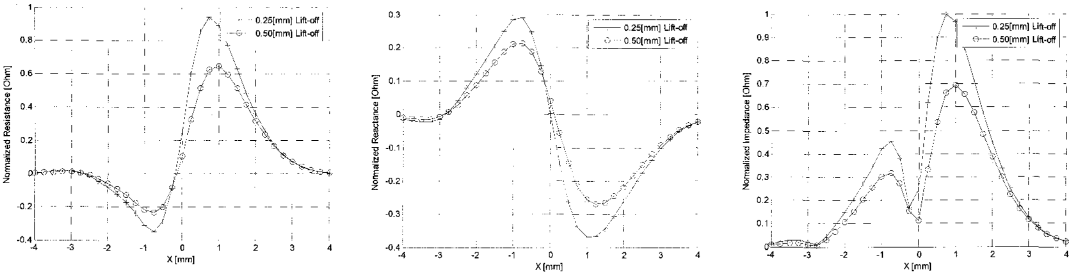
The eddy current signals of T/R probe on ECT array probe are shown in Fig. 3 and Fig. 4 with the variation of lift-off and the distance between transmit and receive coils. The difference between eddy current signals of T/R probe and ones of impedance probe is the asymmetry of the signals. The impedance probe gives symmetric shape of signals. The value of X-axis of the figures is the distance from the center of T/R coils to the center of defect. Figure 3 shows the signals when the difference between T/R coils is zero. This means the pitch between T/R coils is 3[mm] because the width of each coil is 3[mm]. The magnitude of eddy current signals when the probe departs the defect is bigger than that of signals when the probe approaches the defect.

Figure 4 shows the eddy current signals when the difference between T/R coils is 1.5[mm]. The impedance signals with 1.5[mm] distance looks similar to ones with 0[mm] distance in shape. But as the distance between T/R coils is increasing, the pitch between peak points in the resistance and reactance signals is also increasing. The pitch of eddy current signals with 1.5[mm] T/R coil distance is wider than that of 0[mm] T/R coil distance. Figure 5 shows the maximum values of eddy current signal with the variation of the distance between transmit and receive coils. In this figure the magnitude of signal is almost linearly decreased as the difference is increased.



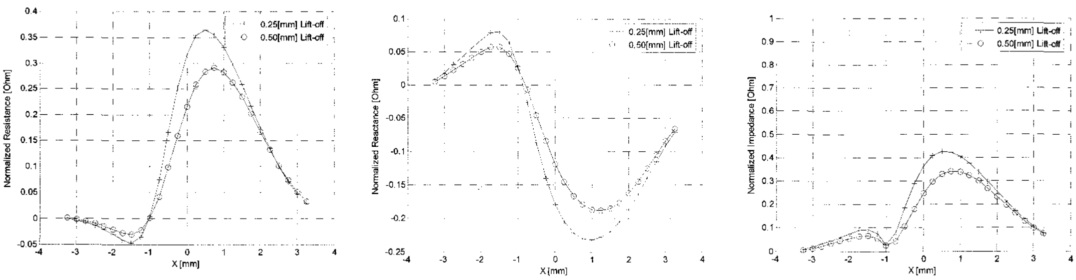
(a) Normalized Resistance (b) Normalized Reactance (c) Normalized Impedance

Fig. 2 Normalized eddy current signals of impedance probe



(a) Normalized Resistance (b) Normalized Reactance (c) Normalized Impedance

Fig. 3 Normalized eddy current signals of T/R probe with 0[mm] distance



(a) Normalized Resistance (b) Normalized Reactance (c) Normalized Impedance

Fig. 4 Normalized eddy current signals of T/R probe with 1.5[mm] distance

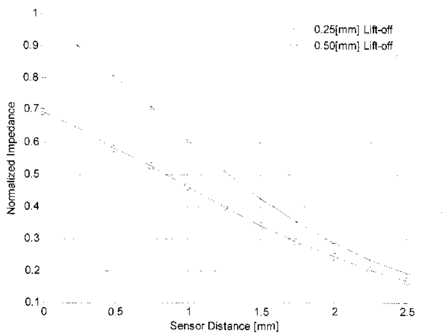


Fig. 5 Comparison of maximum signals with the variation of distance

Ⅳ. Conclusion

The eddy current signals come from a pair of T/R pancake coil on ECT array probe are analyzed with the variations of the lift-off and of the distance between transmit and receive coils. To obtain the eddy current signals, 3-dimensional FEM with hexahedral element is used. To investigate the characteristics T/R probe, the eddy current signals are compared with signals of impedance probe. The main difference of eddy current signals is that the signal shape of impedance probe is symmetric but that of T/R probe is asymmetric. As the lift-off varies, the maximal magnitude of eddy current signals are also varies. And as the distance of transmit and receive coils increases, the magnitude of eddy current signals decreases. In this paper the results of a pair of T/R coil on ECT array probe are shown and these results will be helpful to analyze the ECT array probe.

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