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Eddy Current Simulation for Steam Generator Tube with Deposit

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1. Introduction

Eddy current testing(ECT) is widely adopted for detection of flaws and deposits in the steam generator(SG) tubes of nuclear power plants(NPPs). The ECT method can determine the level of risk for the defects according to the shape and size of the impedance signal. Because varieties in defect signals are important in ECT method, it is common to make defects using the mock-up and obtain signals experimentally. But a very efficient alternative method to solving this problem is to use simulation, because the above way takes a lot of time and money [1]. Thus, one of recent research interests of the ECT is the development of more effective and accurate EC simulation technology by using CIVA, AMPERES, COMSOL Multiphysics, etc.

In SG tubes of NPPs, it has been required that surface cracks, especially outer cracks, must be detected before they grow up. Here, a difficulty encountered is the processing of noised ECT signals. In o1der NPPs, some deposits are sometimes formed on the outer surface of tubes. These deposits are composed of magnetite and copper for the most part, and are one of the causes of noise in ECT signal because of their electromagnetic properties. In the case of the deposits, it is difficult to detect the cracks accurately even if signal processing technique is used [2].

In this study, we theoretically predicted eddy current signals of the deposits by using AC/DC module (electromagnetic numerical modeling) in COMSOL Multiphysics.

2. Methods and Results

2.1. Impedance calculation

The bobbin coil is generally reliable and capable of detecting and sizing volumetric defects such as wear and deposit. In this study, we modeled the differential bobbin probe using the total impedance of two coils as signal. The two coils of same size are placed on the identical axis with a small distance, and the directions of the currents flowing through the coils are opposite to each other. If the two coils pass by the same environment, the magnitudes of the two coil impedances are equal and their sign is opposite, so the sum is zero. However, in case of existing the deposits, there is a difference in the impedance obtained from each coil, so that the signals of deposits can be obtained.

The measured impedance value is defined by the following equation:

$$Z = R + j\omega L = \frac{E}{I} \quad (1)$$

Here,

$$I = \int_{\Omega} J_s \, d\Omega \quad (2)$$

$$E = \frac{d\Phi}{dt} = j\omega\Phi \quad (3)$$

The current is obtained from the given current density, and the induced electromotive force is obtained from the following equation.

$$\Phi = \int B \cdot dS = \oint A \cdot dl \quad (4)$$

Therefore, by calculating the following equation, the impedance is obtained [4].

$$Z = \frac{j\omega \oint A \cdot dl}{\int_{\Omega} J_s \, d\Omega} \quad (5)$$

2.2. Evaluation model and Experiment

We first developed a COMSOL model of the basic geometry. The geometry can be modeled using a 2D axi-symmetric model. The work presented here utilized the AC/DC module in COMSOL 5.2a. The geometry is challenging to model for finite element calculation.

Maxwell-Ampere's Law was applied to realize electromagnetic numerical analysis, and the formula is as shown in (6).

$$\Delta \cdot H = J \quad (6)$$

Where H is the magnetic field and J is current density.

Fig. 1 is the schematic diagram of the 2D axi-symmetric model. The geometry consists of the same material(Inconel 600) and size(19.05 mm in outer diameter, 1.07 mm wall thickness) as a real SG tube of NPPs. The deposits were the mixture with magnetite, and their thicknesses were adjusted to 0.19, 0.78, 1.43, and 1.86 mm, respectively. And the shape of deposits was an annulus with a length of 25 mm. The cross section of the coil was 1.5×1.5 mm^2, and the number of turns is 100.

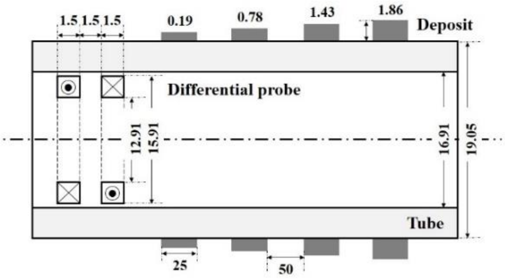

Fig. 1. Parameters in the simulation of eddy current testing for deposits at the outer diameter of the tube.

The materials of model are classified into SG tube (Inconel 600), coil(copper), deposit(magnetite), and the other parts(air). Table 1 shows the material properties such as relative permeability, relative permittivity and electrical conductivity. The simulation was carried out to 35 kHz.

Table I: The material properties

	Relative permeability	Relative permittivity	Electrical conductivity [S/m]
Air	1.00000037	1.000536	$3x10^{-15}$
Coil (Copper)	0.999994	0.9999996	$5.96x10^{7}$
Tube (Inconel 600)	1.01	-	$9.7087x10^{5}$
Deposit (Magnetite)	7	5.39	166

2.3. Results and discussion

Fig. 2 is the distribution chart of magnetic vector potential at the deposits. When one of the two coils reaches the deposit, the potential distribution becomes asymmetrical. And the impedances of the two coils become different. The impedance difference between the coils varies depending on the position of the probe, and appears as a trajectory on the impedance plane. It is referred to as defect signals of the differential eddy current test [4].

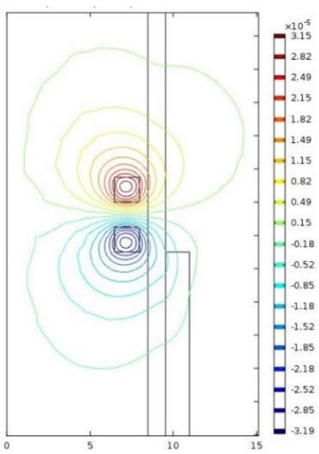

Fig. 2. The distribution of magnetic vector potential of the deposit(1.43 mm height) at the outside surface of the tube.

Fig. 3 shows the defect signals according to the thickness of the deposits. The size of impedance signals increased as the thickness of the deposits increases. This means that the quantification of the deposits is possible using the simulation.

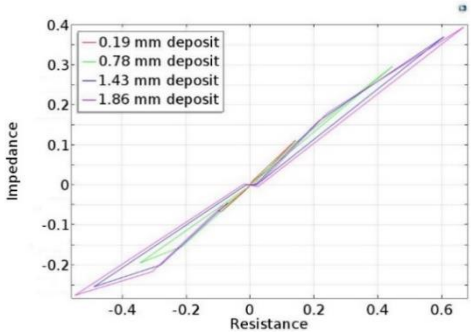

Fig. 3. Impedance plane trajectory.

3. Conclusions

Finite element modeling and results of numerical analysis for ECT of SG tubes with the deposits were described in this paper. As a result of the analysis, it was found that the signal increased according to the thickness of the deposits. But the impedance value changes by various variables such as the probe type, frequency, etc.

Therefore, in future work, we perform the modeling verification by comparing the ECT signal with the modeling result. And then theoretically predict various defect signals according to the change of the variable values, including whether the deposits are exist or not.

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