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ECT signal modeling and evaluation for steam generator defects with deposit

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1. Introduction

Steam generator (SG) tubes in nuclear power plants (NPPs) undergo regular inspections in order to monitor the condition of SG tubes, while providing evidence of their safe operation. Eddy current testing (ECT) is widely adopted for the detection of defects and deposits in the steam generator tubes of a nuclear power plant [1]. The ECT could determine the risk of the defects. However, difficulties in the diagnosis of defects are caused by non-uniform distribution of deposits on the tube surface. It takes a lot of time and cost to experimentally obtain the reliability of ECT signals using a mock-up. A very efficient alternative method to solving this problem is the use of a simulation experiment. Therefore, the purpose of this study is the development of a more accurate measurement technique for an ECT signal using a finite element method and numerical analysis. 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 older NPPs, some deposits are sometimes formed on the outer surface of tubes. These deposits are composed of magnetite and copper elements in the most part, and they are one of the causes of noise in ECT signal due to their electromagnetic properties. In the case of the deposits, it is difficult to detect the cracks accurately even if signal processing technique is applied [2]

In this study, we theoretically predicted eddy current signals of defects with deposit by using the AC/DC module (electromagnetic numerical modeling tool) in COMSOL Multiphysics. And then, we evaluated the optimum frequency for search the various defect signal.

2. Methods and Results

2.1 Evaluation Modeling

The depth at which the eddy current density is reduced to 37% of its surface density is called one standard depth of penetration (SDP). This is a theoretical approximation. The SDP is expressed as δ and can be readily calculated using the following approximate equation for a very thick conductor:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (1)$$

Where δ is depth in m, f is test frequency in Hz, σ is electrical conductivity in mhos/m and μ is magnetic permeability in H/m. As can be seen from the above equation, SDP decreases with increase in electrical conductivity, magnetic permeability and frequency [3].

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 (2).

$$\Delta \cdot \mathrm{H} = J \qquad (2)$$

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

2.2. Experimental Method

The schematic diagram of the 2D axi-symmetric model is shown in Fig. 1. 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. Defect of inner (ID) and outer (OD) are simulated with or without deposit of 1.86 mm thickness. 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.

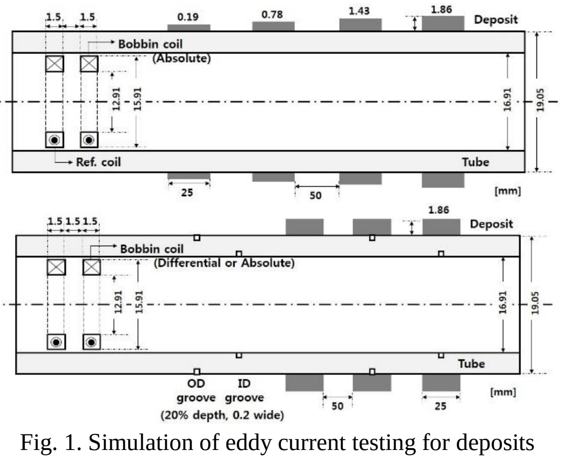

Fig. 1. Simulation of eddy current testing for deposits with/without defect at the outer diameter of the tube.

The materials of model are classified as SG tube (Inconel 600) with/without defects, coil (copper), deposit (magnetite), and surrounding air. Table 1 shows the material properties such as relative permeability, relative permittivity and electrical conductivity. The simulation was carried out using current frequency of 35 kHz.

Table I: The material properties

	Relative permeability	Relative permittivity	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}
Magnetite	7	5.39	166

2.3. Results and discussion

The magnetic vector potential distribution induced the ECT Coil in SG tube with deposit is simulated as shown in Fig. 2. When one of the two coils reaches the deposit, the potential distribution becomes asymmetrical shape. 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, 5].

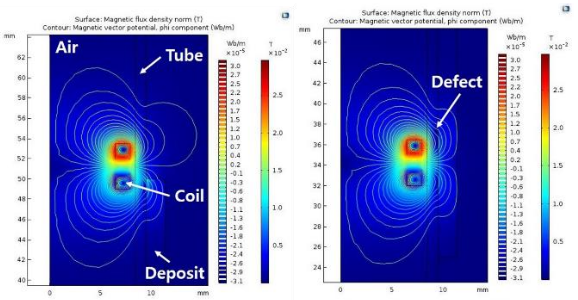

Fig. 2. The distribution of magnetic vector potential of the deposit (1.43 mm height) and defect on the tube.

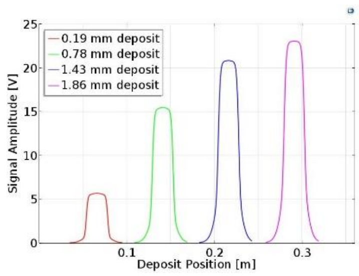

Fig. 3. Impedance magnitudes as different deposits.

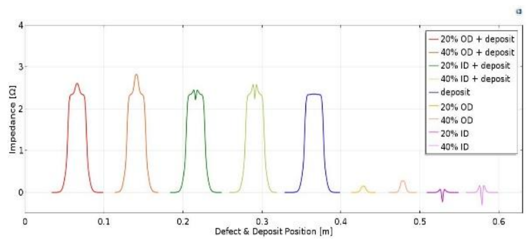

Fig. 4. Impedance signals of defects with deposit.

Fig. 3 and 4 shows the ECT impedance signals according to the thickness of the deposits and various types of defects. 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.

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.

The purpose of this study is the development of a more accurate measurement technique for an eddy current signal using a finite element method and numerical analysis. The impedance signals from the instrument and simulation are relatively consistent from a quantitative point of view (±9.9% error).

We perform the modeling verification by comparing the ECT signal with the modeling result, and then theoretically predict various deposit signals and distinguished the mixed signals including the defects under the deposit. The results of this simulation experiments could apply to analyze the defect signals in the presence of noise sources such as deposit.

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