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Finite Element Modeling of the ECT Signal for Steam Generator Tubes with Loose Parts

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1. Introduction

Steam generator (SG) tubes in nuclear power plants (NPPs) undergo periodic inspections in order to monitor the integrity of SG tubes, while providing evidence of their continued safe operation. In Korea and foreign NPPs, their operation had been interrupted unexpectedly due to primary coolant leakage from SG tubes. The causes of the degradation in SG tubes were mostly wear nowadays. The fretting wear of tubes can be caused by the physical contact with loose parts and the tube support structures in the secondary side. The presence of residual loose parts has been identified using eddy current testing (ECT) and foreign object search and retrieval (FOSAR) equipment. However, the detection of loose parts from ECT has limitations that depend on the material properties and the condition of contact with the tube [1, 2].

In this study, we theoretically predict eddy current signals of loose parts by using the AC/DC module (electromagnetic numerical modeling) in COMSOL Multiphysics 5.3a, and discuss the optimum test frequency for various loose part materials.

2. Methods and Results

2.1 Standard depth of penetration

The depth at which the eddy current density is reduced to 37% of its surface density is defined as 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:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

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].

2.2 Finite element (FE) model

By using the COMSOL Multiphysics, the coupling of magnetic field and electric field excited by alternating current were modeled. The basic equations of electro-magnetic field are presented as follows:

$$(\mathrm{j}\omega\sigma - \omega\varepsilon)\mathrm{A} + \nabla \times (\mu^{-1}\nabla \times A) = J_e \tag{2}$$

$$\mathrm{B} = \nabla \times \mathrm{A} \tag{3}$$

Where j is the imaginary unit, ω the angular frequency of the applied alternating current, ε the dielectric constant, A the magnetic vector potential, J_e the excitation current intensity, B the magnetic flux density [4].

2.3 Evaluation model and Experiment

The geometrical model was built, as shown in Fig 1. The tube material (Inconel 690) and dimension (0.75 inch in outer diameter, 0.043 inch wall thickness) are the same as those of domestic nuclear power plants. The conductivity of the tube material is 6.76×10^6 S/m, and the relative permeability of the tube material is 1.01. The ECT bobbin coils (0.610 inch in outer diameter) were modeled in both absolute and differential types. The cross section of the coil was 0.059×0.059 inch^2, and the number of turns is 100. The conductivity of the coil material (Copper) is 5.96×10^7 S/m, and the relative permeability of the tube material is 0.999994.

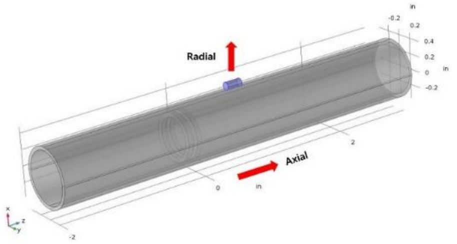

Fig. 1. SG tube model showing radial and axial directions with loose part (blue) in parallel orientation.

The loose part materials used in this simulation are listed in Table 1 along with their relevant type and properties. The geometry of loose part was considered in the wire shape (Φ 0.05 inch, 0.2 inch in height).

The simulation was performed in two cases: (1) The loose part is located to be in contact with the SG tube, and (2) to have the gap between tube and the loose part. The gap was increased in the radial direction from 0 to 3 mm with 1 mm step.

The operating frequencies were determined according to practical procedure used in the field inspections considering the tube material and thickness (eq. 1). In high frequency, it is almost impossible to detect any loose parts on outside surface of tube [5]. Thus, the simulation was carried out in the lower frequency ranges of 10, 15, 20, 35, 50, 75, 100 kHz.

Table I: Type and material properties of loose parts

Material	Magnetic ordering	Relative permeability	Electrical conductivity [S/m]
Austenitic Stainless Steel	Non-Ferro-magnetic	7	1.45e6
Aluminum		1.000022	3.77e7
Carbon Steel	Ferro-magnetic	100	6.99e6
Iron		5000	1.00e7
Nickel		600	1.43e7

The phase of the measured signals in low frequency was calibrated based on carbon steel support ring signals (90±1 deg.) according to the ASME code [6].

2.4 Results and discussion

First test was performed using absolute bobbin coil mode. The loose part was detected in the frequency below 50 kHz. The simulated signals at 75 and 100 kHz could not distinguish the signals from loose parts.

Fig. 2 shows the variation of amplitude values with the frequency for various loose part materials. The amplitude values of most loose parts were the largest at 15 kHz. At all frequencies, the ferromagnetic materials could be detected better than the non-ferromagnetic materials.

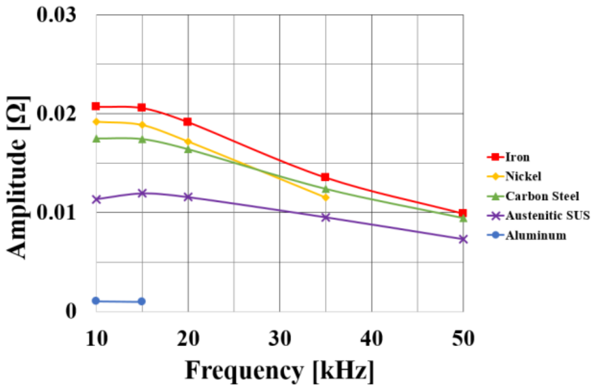

Fig. 2. The variation of amplitude values according to the frequency of various loose parts.

Second test was performed adjusting the gap between tube surface and the loose part from 0 to 3 mm with 1 mm increment. This test used differential bobbin coil mode for comparison with the absolute mode. The amplitude values of signals decreased as the gap between the loose part and the tube increases, as seen in Fig. 3.

From a result of comparing the amplitude values, it is considered that the differential mode (0.024Ω) is easier to detect the loose part than the absolute mode (0.017Ω) because the signal of differential mode is about 30% larger.

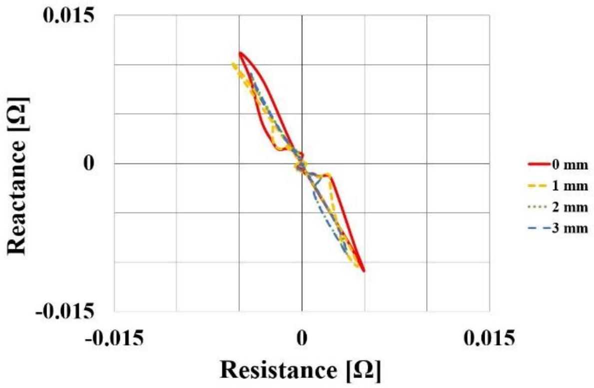

Fig. 3. 15 kHz differential signals of carbon steel wire oriented parallel to SG tube with radial offsets

3. Conclusions

Finite element modeling and results of numerical analysis for ECT of SG tubes with loose parts were described in this paper. Results of the analysis show that the optimum frequency for detecting loose parts was 15 kHz, and the detectability of the loose parts depended on their material and radial distance from the SG tubes as expected. But there are many different types and contact forms of loose parts. Therefore, in future work, we will theoretically predict various signals of loose parts considering more variables, including the types and contact forms. Moreover, we will perform the verification of modeling by comparing with the ECT signal from SG tube mock-up specimens.

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