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Simulation of Eddy Current Signal from Lift-off and Tilt of a Bobbin Coil Probe in Steam Generator Tubes

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1. Introduction

Steam generator (SG) tubes in nuclear power plants (NPPs) have U-bend regions of various radii. The eddy current testing (ECT) is periodically performed to evaluate the integrity of these tubes. However, the defect detection in the U-bend region is difficult due to a large background noise signal from geometric distortions. The bending may cause a variation in tube dimensions of wall thickness and ovality, and may also affect the trajectory of the probe motion which can be tilted and shifted [1]. These changes caused by the bending process generate wobble signals that obscure the valuable flaw signals. So, it is essential to suppress or discriminate the noise signals for an accurate detection of existing flaw in ECT [2].

Many researchers have studied the problem of eddy current induction by a tilted and shifted coil [2-4]. Zhang *et al* numerically calculated the electromagnetic field and impedance of a cylindrical probe-coil for arbitrary lift-off and tilt angle above a conducting plate [2]. Tai *et al* discussed the effect of tilted angle and excited frequency of a cylindrical air cored coil above a metal foil [3]. Fan *et al* presented the analytical formulation for the off-centered driver-pickup bobbin probe [4].

In this study, simulation of eddy current signal from the commercial bobbin coil probe used for the SG tube inspection was performed based on several previous studies. We theoretically predicted the electromagnetic variation and impedance change due to a coil's lift-off and tilt effect by using AC/DC module (electromagnetic numerical modeling) in COMSOL multiphysics.

2. Methods and Results

2.1 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:

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

$$B = \nabla \times A \quad (2)$$

Where j is the imaginary unit, ω the angular frequency of the applied alternating current, μ and σ the relative magnetic permeability and conductivity of the inspected material, ε the dielectric constant, A the magnetic vector potential, J_e the excitation current intensity, B the magnetic flux density [5].

2.2 Evaluation model and Experiment

The simulation model was built, as shown in Fig. 1. The bobbin coil is generally placed in the center of the tube, with radial lift-off of d ≒ 1 mm. We considered two cases of coil arrangement in tube containing a through–wall drill hole, (1) tilted angle $\theta = 0°$, $0.1 \leq d \leq 1$ mm and (2) lift-off distance d is constant, $-10° \leq \theta \leq 10°$. The coil is excited with current of 1 A and frequencies of 25 kHz or 300 kHz.

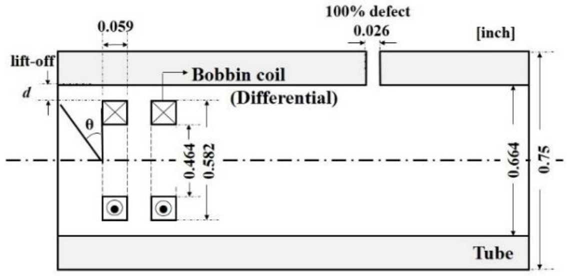


Fig. 1. Schematic diagram of simulation model

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 size of computational domain, including the air around the specimen, was Φ 3 inch×9 inch area. Boundary condition was imposed so that the tangential component of magnetic vector potential was zero.

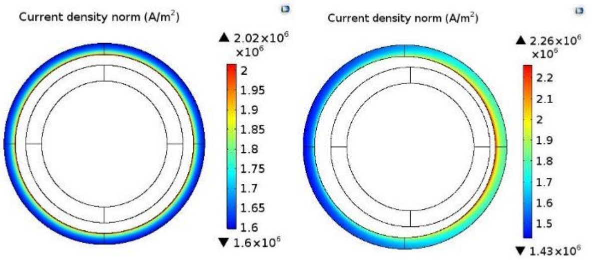
The materials of model are classified into SG tube (Inconel 690), coil (copper) and the other parts (air). Table 1 shows the properties of each material including relative permeability, relative permittivity and electrical conductivity.

Table I: The material properties

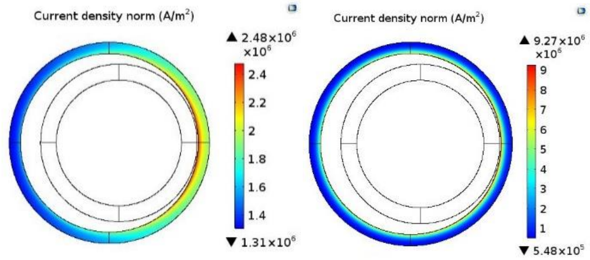
	Relative permeability	Relative permittivity	Electrical conductivity [S/m]
Air	1.00000037	1.000536	$3x10^{-15}$
Coil (Copper)	0.999994	0.9999996	$5.96x10^{7}$
Tube (Inconel 690)	1.01	1	$6.7567x10^{6}$

2.3. Results and discussion

Fig. 2 shows the changes in distribution of induced current density with coil's lift-off. When the coil is the center of the tube, the induced current density has a uniform distribution around the tube circumference. On the other hand, the coil's lift-off movement causes the induced current density to be uneven and to be concentrated in a region close to the coil. As shown in Fig. 2 (c)-(d), the high frequency induces much large concentration of eddy current in local region compared to the lower frequency for the same lift-off distance.



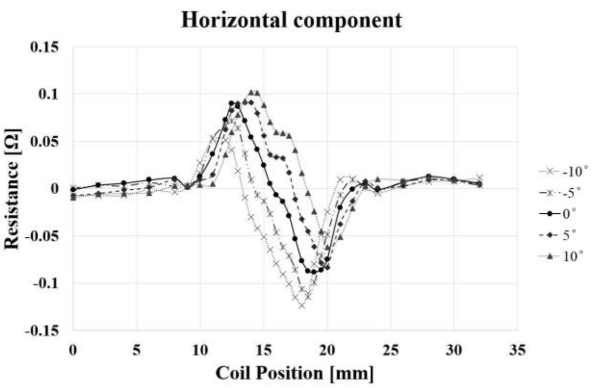
(a) d ≒ 1 mm, f = 25 kHz (b) d = 0.5 mm, f = 25 kHz



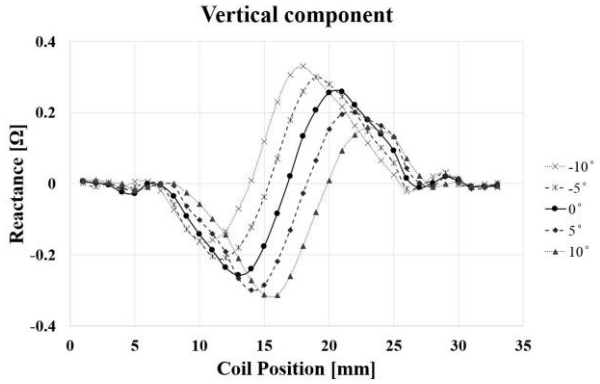
(c) d = 0.1 mm, f = 25 kHz (d) d = 0.1 mm, f = 300 kHz

Fig. 2. The lift-off effect on distribution of induced current density

The horizontal and vertical components of impedance change in differential mode with tilted angles of the coils are shown in Fig. 3. The obliquity of coil has a significant effect on the resistance and reactance components. For θ = 0˚, the maximum-minimum peaks appeared at both sides of the defect location. However, increasing the coil inclination gradually shifts peak signal positions and also changes the max-min peak values of the resistance and reactance components.



(a)



(b)

Fig. 3. The tilt effect on the horizontal and vertical components of impedance change

3. Conclusions

The electromagnetic signal variations due to a bobbin coil's lift-off and tilt in a SG tube were theoretically predicted through the simulation. Results of the analysis show that a coil's lift-off destroys the circumferential uniformity of induced current density, and makes it concentrated in the tube region close to the coil. Increasing the frequency enhances the degree of inhomogeneity in current distribution around the tube circumference and across the tube wall as well. Also, the significant change in impedance with tilt angle of the coil was observed. In future work, we will develop an effective tool for improving the reliability of steam generator tube inspection based on the various results of the simulation and instrumentation.

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