Finite Element Modelling of a Pulsed Eddy Current Probe for Steam Generator Tube Inspection

S. G. Mokros[1, 2], V. K. Babbar[2], J. Buck[1, 2], P. R. Underhill[2], J. Morelli[1], T. W. Krause[2*]
[1]Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston ON, Canada
[2]Department of Physics, Royal Military College of Canada, Kingston ON, Canada
[*]Corresponding author: e-mail: thomas.krause@rmc.ca

Abstract: Steam generator (SG) tubes in CANDU® nuclear reactors can lose efficiency in the presence of corrosion and its by-products. Current inspection methods used in SG tubes have limited capabilities to determine the condition of surrounding support structures. Condition monitoring of support structures could help direct maintenance activities and thereby increase SG tube lifetime. Pulsed eddy current (PEC) has been proposed as a method to non-destructively determine the presence of defects in support structures. COMSOL Multiphysics was used to study a PEC probe configuration for measurement of SG tube-to-support structure gap, offset and relative tilt. Basic analytical models and experimental results were compared with COMSOL finite element (FE) modeling results. Analytical and FE models were in excellent agreement. FE, which is capable of modeling the more complex electromagnetic interactions between probe, SG tube and support structure, provided an excellent qualitative description of experimental results.

Keywords: Pulsed eddy current, Non-destructive evaluation, COMSOL Multiphysics, Steam generator tubes, CANDU®

1. Introduction

Corrosion and its by-products can develop in the steam generators (SGs) used in CANDU® nuclear reactors, causing the reactor to lose efficiency [1]. As a result, a method to non-destructively determine the presence corrosion and its by-products, present between SG tubes and support structures, is required for SG maintenance programs. In particular, changes in SG efficiency arise when SG tubes shift within support plate holes or corrosion products constrict fluid flow [2]. Changes in design flow occur when SG tubes move relative to the center of support structure holes, when tubes are angled relative to the center of support structures, or when a combination of gap, shift and tilt occurs as shown in Figure 1.

Conventional eddy current testing methods have been successful in locating cracks and corrosion in SG tubes [2,3]. These eddy current methods utilize a sinusoidal excitation of a drive coil, which induces eddy currents in conducting structures according to Faraday's Law [5]. The proximity of ferromagnetic support structures further alters the eddy current probe response [6], [7], but permits only a qualitative assessment of the support structure condition [1].

In pulsed eddy current (PEC) a periodic square pulse excites the drive coil. The corresponding induced eddy currents are transient in nature with long time eddy current decay constants, which enhance depth of penetration in conducting materials [8] as well as increase magnetization of steel components [9]. Recent work on the application of PEC has demonstrated its sensitivity to conducting and ferromagnetic structures at large lift-offs [8, 9].

COMSOL Multiphysics was used to study the configuration of a previously developed probe designed to sense gap, lift-off and tilt of SG tubes within ferromagnetic support structures [9].

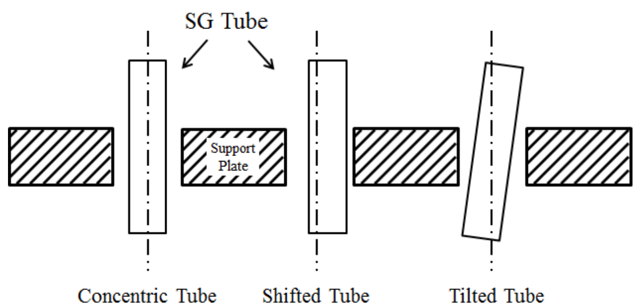

Figure 1: Example showing shift and tilt of the SG tube.

2. Theory

A model consisting of an excitation coil and one pick-up coil was constructed to represent a simplified model of the PEC probe. The circuit diagram shown in Figure 2, was used to mathematically model the probe. Here R1 and R2 are the resistances of the excitation coil and pick-up coil, respectively. L1 and L2 are the inductances for the excitation coil and pick-up coil, respectively. v0 is the input square pulse, and M is the mutual inductance between the two coils. A value for the mutual inductance was determined empirically by applying a least squares minimization in Microsoft® Excel® [11]. The mutual inductance was found to be 126 μH.

Excerpt from the Proceedings of the 2013 COMSOL Conference in Boston

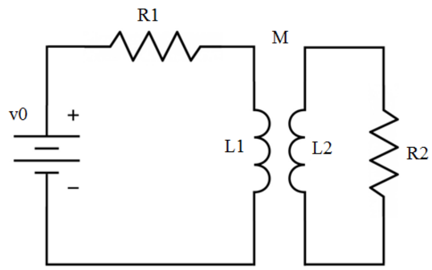

Figure 2: Circuit diagram representing the simplified model used to validate COMSOL's results.

Two theoretical models were used to determine currents in the excitation coil. Kirchhoff's Laws were used to solve the circuit, shown in Figure 2. The first model, given in Equation 1, neglected the mutual inductance between the two coils.

$$i_1 = \frac{v_0}{R_1}\left[1 - e^{-\left(\frac{R_1}{L_1}\right)t}\right] \quad (1)$$

The second model included the mutual inductance. The current was again determined from Kirchhoff's laws. When the mutual inductance was included, two differential equations could be determined and solved by using Fourier transforms, giving Equation 2 [12].

$$i_1 = \frac{v_0}{R_1}\left(1 - \frac{(e^{-\alpha_1 t} + e^{-\alpha_2 t})}{2} - \frac{(L_1R_2 - L_2R_1)(e^{-\alpha_2 t} - e^{-\alpha_1 t})}{2(\alpha_1 - \alpha_2)(L_1L_2 - M^2)}\right) \quad (2)$$

where α_1 and α_2 are given by Equation 3.

$$\alpha_{1,2} \equiv \frac{(L_1R_2 + L_2R_1) \pm \sqrt{(L_1R_2 + L_2R_1)^2 - 4R_1R_2(L_1L_2 - M^2)}}{2(L_1L_2 - M^2)} \quad (3)$$

The current in the pick-up coil requires the mutual inductance. This model was solved in a similar fashion to the solution given for the current in the drive coil when mutual inductance is included. A Laplace transform was applied to differential equations determined from the simplified circuit diagram as shown in Figure 2 and used to obtain expressions for current i_1 and i_2. This is given in the form of Equation 4 [12], [13].

$$i_2 = \frac{Mv_0(e^{-\alpha_2 t} - e^{-\alpha_1 t})}{(\alpha_1 - \alpha_2)(L_1L_2 - M^2)} \quad (4)$$

3. COMSOL Multiphysics

The simplified model of the PEC probe was simulated using finite element (FE) modeling through COMSOL Multiphysics 4.3a. All models were run on a 2.67GHz dual-quad processor with 96GB of RAM. Figure 3 shows the FE model used to compare theoretical to simulated results.

Figure 3: COMSOL simplified half model of PEC probe.

COMSOL was used to determine the ideal location of four pick-up coils relative to the excitation coil [8].

A simulation of the effects of shift was performed using COMSOL. The tube and probe were shifted relative to the center of the collar. The peak of the differential response was fit with a quadratic function, as shown in Figure 4.

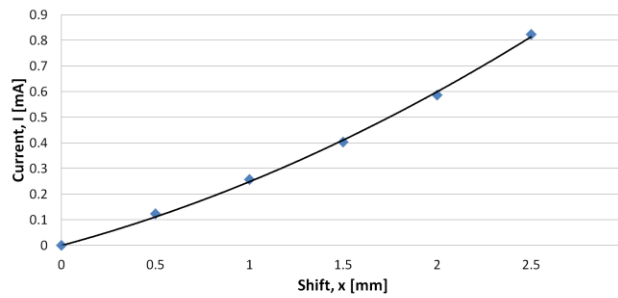

Figure 4: Peak differential response when tube is shifted with respect to the center of the support plate.

A simulation of the effects of tilt was also performed. The tube and probe were rotated with respect to the center of the support plate. The peak of the differential current was fit using a linear function, as shown in Figure 5.

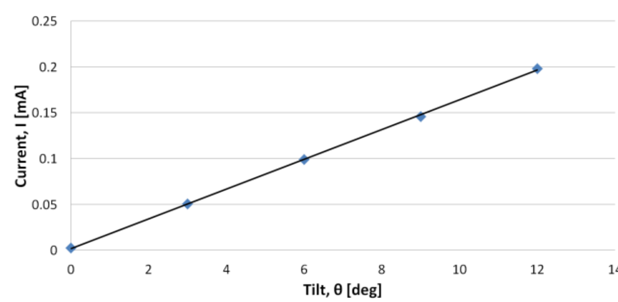

Figure 5: Peak differential response when the tube is tilted with respect to the center of the support plate.

4. Experiment

To compare COMSOL models to experimental data, an experimental setup was constructed. A National Instruments (NI) digital acquisition (DAQ) device was used to excite the drive coil as well as to collect data from the pick-up coils. The signal generated in the pick-up coils was then filtered and amplified for easier analysis.

A prototype of the probe was designed based on optimum dimensions obtained using COMSOL. The excitation coil was wound coaxially using 36 AWG wire and four pick-up coils were mounted perpendicularly, two above the drive coil, and two below. The pick-up coils were wound using 44 AWG wire. The differential current was determined by measuring the current in opposing coils mounted 180° apart. The prototype of the probe with only one pick-up coil present is shown in Figure 6.

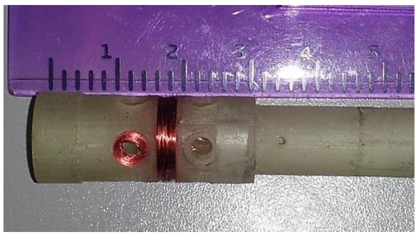

Figure 6: Experimental probe showing excitation coil and one pick-up coil.

The simplified COMSOL model was compared to the experimental probe in air and theoretical models. The drive coil response is shown in Figure 7. The COMSOL model is seen to have excellent agreement with analytical model results; however the experimental measurements show some disagreement on the rise. It is believed that this is due to an internal capacitance in the filtering and amplification stage of the circuitry.

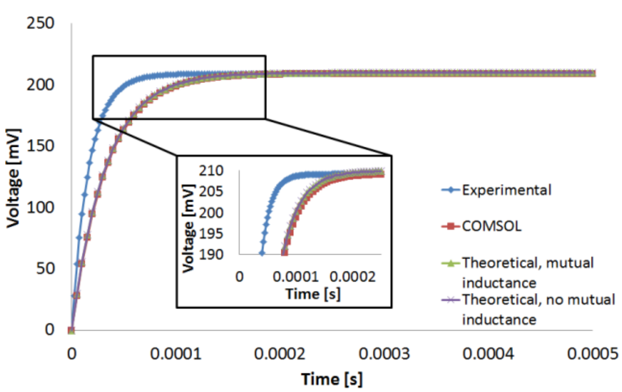

Figure 7: Response of the excitation coil for COMSOL model, experimental and theoretical models.

The response of the pick-up coil is shown in Figure 8. Here excellent agreement is observed between COMSOL simulations and theoretical models. Experimental data was found to be consistent with both COMSOL and analytical theory.

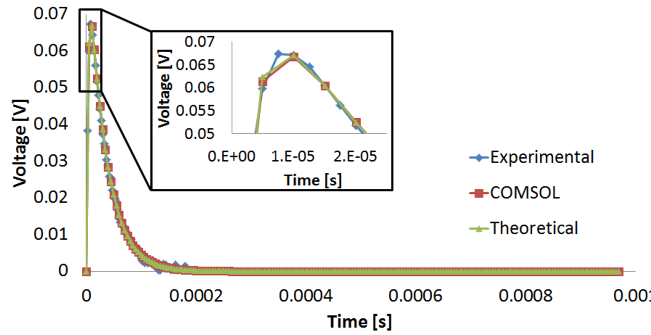

Figure 8: Response of pick-up coil for COMSOL model, experimental and theoretical model.

The results determined from the COMSOL model were compared to the experimentally measured values. These values are summarized in Table 1. It is clear that the majority of the values agree, however the value of the internal resistance of the pick-up coil does not match that found in experiment. This discrepancy requires further investigation.

Table 1: Experimental and simulated results of resistance and inductance for the coils used in the simplified probe design.

Element	Experimental		Simulated	
	Drive	Pick-up	Drive	Pick-up
Resistance (Ω)	7.6	34.2	7.1	78.2
Inductance (μH)	233	300	232	257

5. Summary

A FE model of PEC interactions of SG tubes within support plate structures was used to study probe design for the determination of the effects of shift and tilt as well as effects of support plate corrosion. Peak differential current in the pick-up coil response, when the SG tube was shifted or tilted relative to the center of support structures is presented in this paper. The data obtained when the SG tube was shifted was fit with a polynomial function, and a linear fit was used when the SG tube was tilted.

The PEC probe was represented as a simplified transient circuit. This simplified circuit was used to compare analytical models to COMSOL simulated results and experimental data. The simulated, analytical and experimental results for the pick-up coil were in excellent agreement. However the simulated and analytical results were only in qualitative agreement with the experimentally measured drive coil voltage. It is believed that the discrepancy for the drive coil results was due to an internal capacitance within the physical circuit.

6. Acknowledgments

The authors would like to thank Brian Lepine, AECL, Chalk River Laboratories, for samples and materials. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the University Network of Excellence in Nuclear Engineering (UNENE).

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