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

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Introduction

Corrosion and its by-products can develop in SG tube support structures used in CANDU® nuclear reactors, causing the reactor to lose efficiency [1]. As a result, a method to non-destructively evaluate support structure condition from within SG tubes is required for SG maintenance programs.

Motivation

Current inspection methods have limited capability to examine the condition of support plates with regards to corrosion and build up of corrosion products. Pulsed eddy currents (PECs) have been proposed as a method to characterize the condition of support structures from within SG tubes. Recent work on the application of PEC has demonstrated its sensitivity to conducting and ferromagnetic structures at large lift-offs [2,3]. 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 [2]. A finite element (FE) model of the probe is shown in Figure 1. Figures 2 and 3 show examples of SG tube support structures.

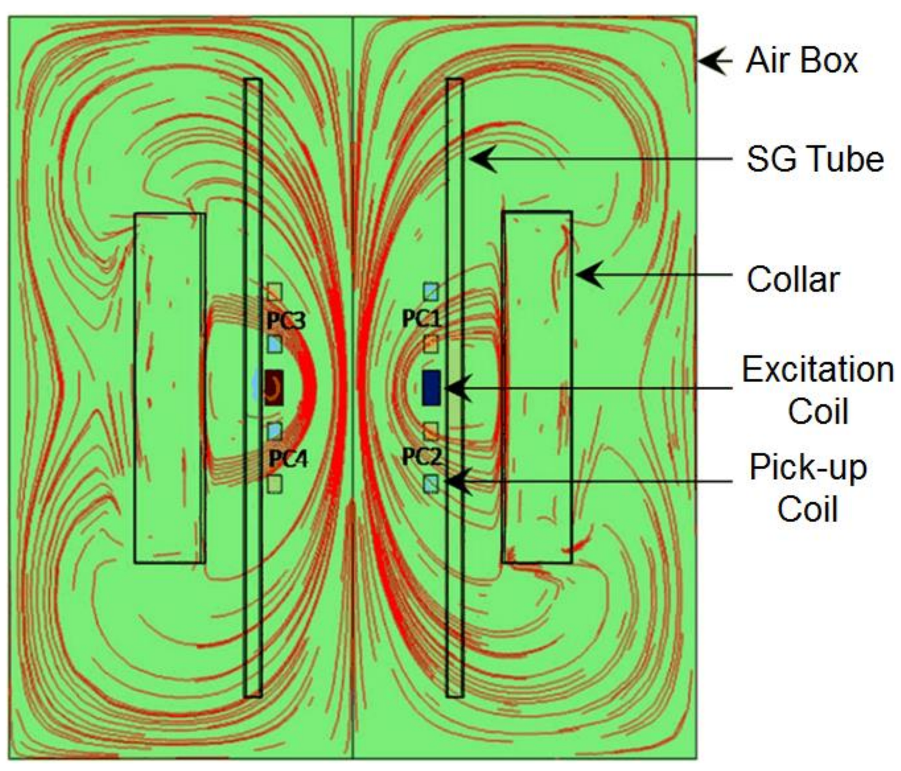
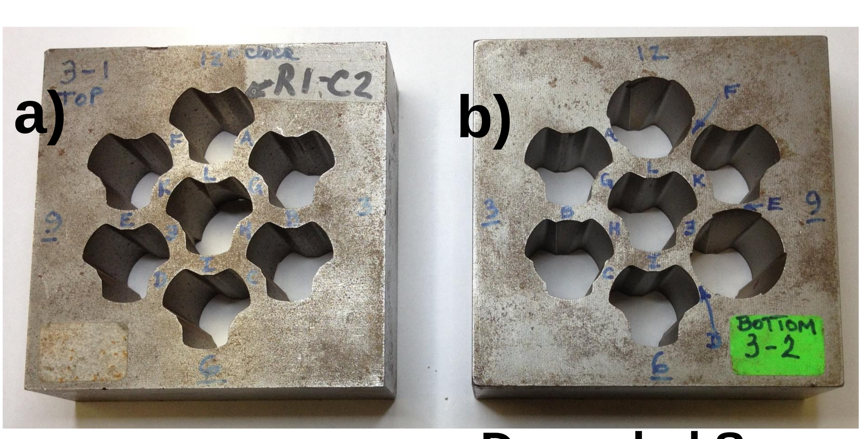
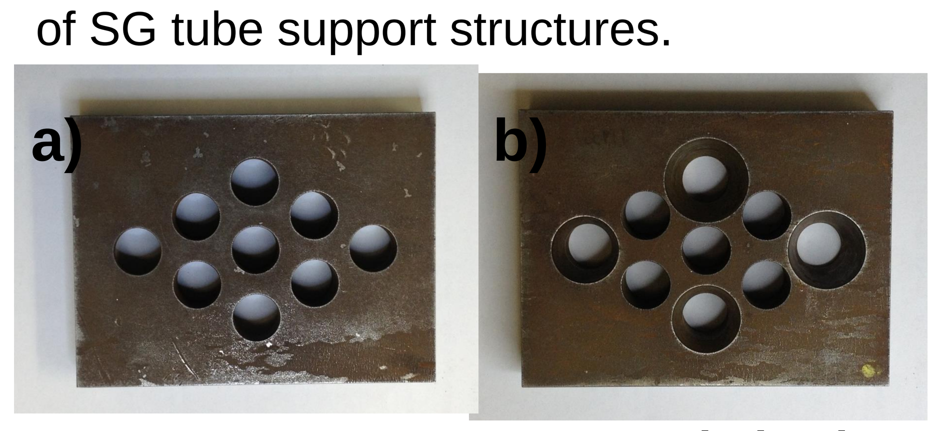


Figure 1: COMSOL model showing PEC design of probe in SG tube.



Support Plate **Degraded Support Plate**

Figure 2: a) Support plate used in reactors. b) Support plate showing corrosion.



Tube Sheet **Degraded Tube Sheet**

Figure 3: a) Tube sheet used in reactors. b) Tube sheet showing corrosion.

The design of this probe was optimized for sensitivity to off-centre shift of the SG tube within the support plate and tilt of the tube relative to the support plate center as shown in Figure 4. Shift and tilt occur when 1) the support plate corrodes, 2) the SG tube shifts relative to the center of the support plate, or 3) a combination of both conditions occur.

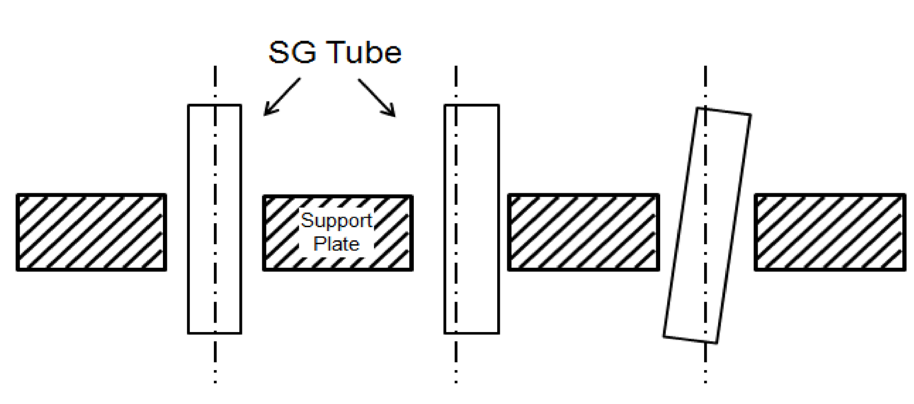


Figure 4: Showing shifted and tilted tube.

Theory

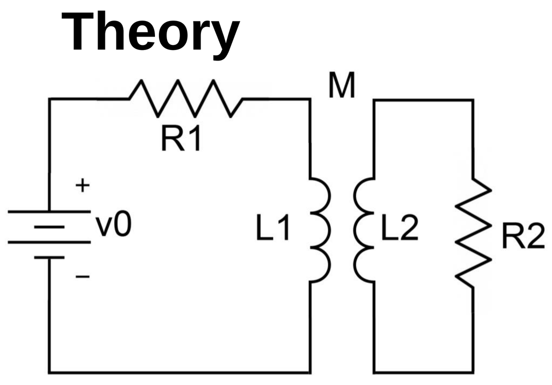


Figure 5: Circuit diagram of probe.

The circuit shown in Figure 5 represents a simplified circuit model of the simulated probe, shown in Figure 6. The current flowing through the drive coil was compared with two mathematical models. The first model neglected the mutual inductance between the two coils. This equation is given in Equation 1 [4]. The second model included the mutual inductance between the two coils and is shown in Equation 2 [5, 6].

The current flowing through the pick-up coil was also mathematically determined by solving the circuit shown in Figure 5. The equation for the current in the 1st circuit is given in Equation 2 and for 2nd circuit, in Equation 3 [5, 6].

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

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

$$i_2 = \frac{Mv_0(e^{-\alpha_2 t}-e^{-\alpha_1 t})}{(\alpha_1-\alpha_2)(L_1L_2-M^2)} \quad (3)$$

Where α_1 and α_2 are given by [2]:

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

COMSOL

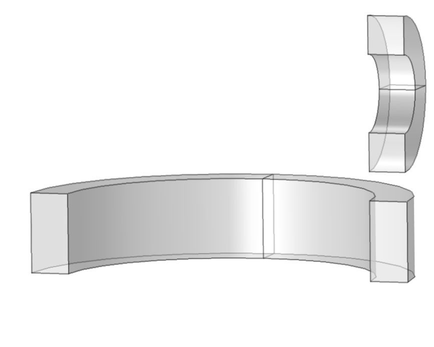


Figure 6: Simplified COMSOL half model.

To compare the analytical model to COMSOL simulated results, a simplified half model was constructed, as shown in Figure 6.

A simulation of the effects of shift was performed using COMSOL. The tube and probe were shifted and tilted relative to the center of the collar. The peak of the differential response was fit with a polynomial function, as shown in Figure 7 and 8, respectively.

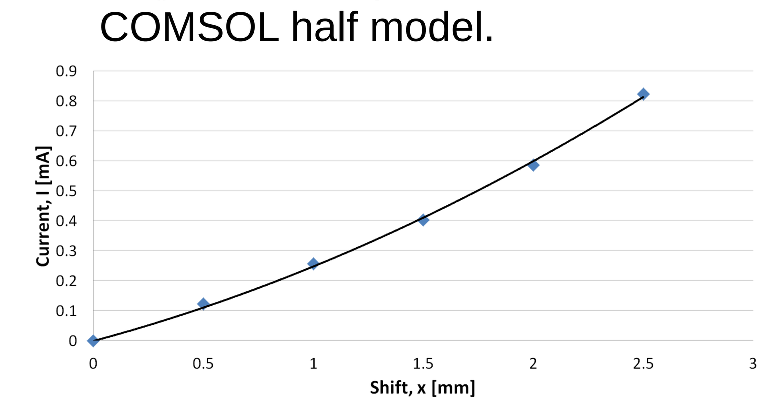


Figure 7: Peak values of differential current as the tube is shifted.

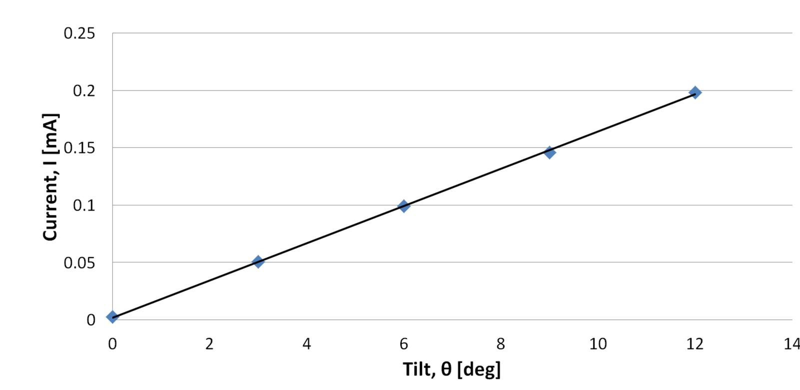


Figure 8: Peak values of differential current as the tube is tilted.

Validation

COMSOL models were validated against two analytical expressions for the excitation coil in air [4, 5, 6]. To compare to experiment, a prototype of the probe was built based on optimum dimensions obtained using COMSOL [2]. A prototype of the simplified PEC probe is shown in Figure 9.

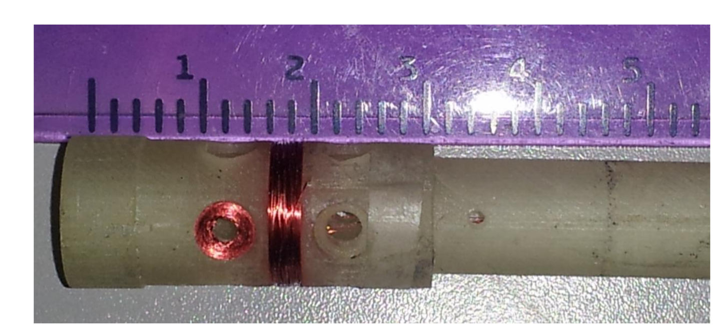


Figure 9: Prototype of simplified PEC probe.

The drive coil and pick-up coil responses are shown in Figures 10 and 11, respectively. The COMSOL model was in excellent agreement with the analytical models for both the drive coil and the pick-up coil. Experimental results for the pick-up coil were in excellent agreement with modeled results, while the drive coil results were in qualitative agreement. The discrepancy in the latter case as shown in Figure 10 was attributed to internal drive circuit capacitance.

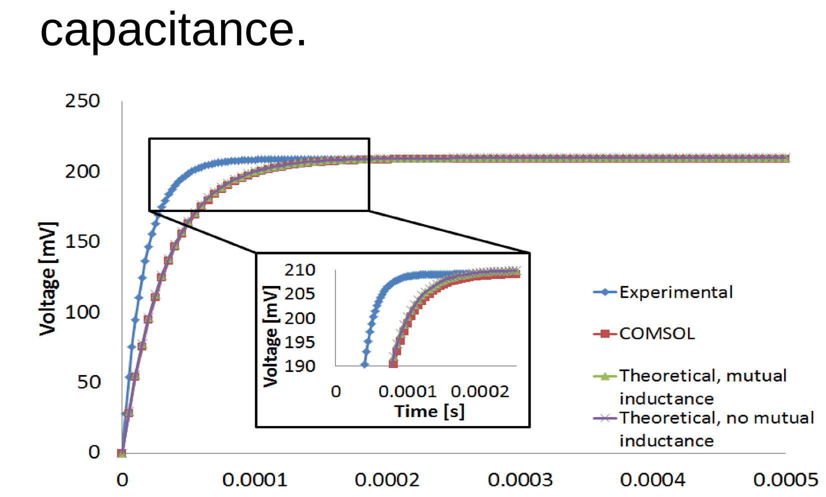


Figure 10: Excitation coil response. Inset showing blown up area.

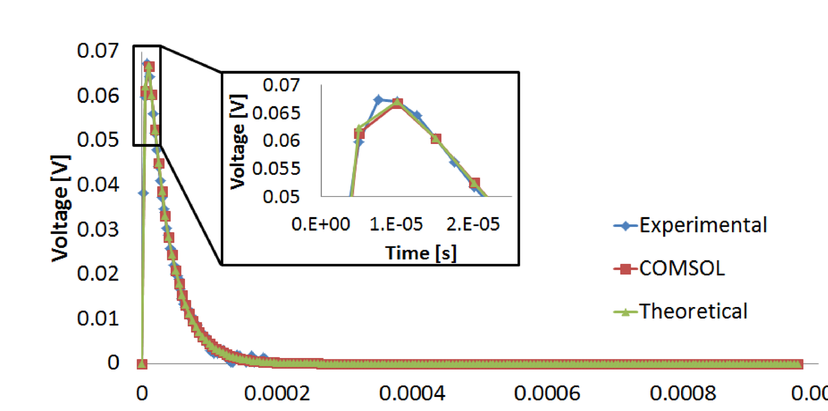


Figure 11: Pick-up coil response. Inset showing blown up area.

Conclusions

It was found that the COMSOL results matched well with the results determined from analytical models. The experimental measured results for the pick-up coil were in excellent agreement while the drive coil were only in qualitative agreement. The discrepancy at early times for the drive coil is believed to be due to an internal capacitance in the circuitry.

A FE model of PEC interactions of SG tubes within support plate structures was used to study probe design for determination of the effects of shift and tilt as well as effects of support plate corrosion simulated as increasing gap.

Future Work

Future research will focus on validating COMSOL results of the probe within the SG tube. In addition, plans are to explore effects from other forms of corrosion, such as fretting and build-up of magnetite.

Acknowledgements

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