Finite Element Modelling of Eddy Current Probes for CANDU® Fuel Channel Inspection

M. Luloff[1], J. Morelli[2], T. W. Krause[3]
[1]Royal Military College of Canada, Kingston Ontario, Canada, 9msl1@queensu.ca
[2]Queen's University, Kingston Ontario, Canada, morelli@physics.queensu.ca
[3]Royal Military College of Canada, Kingston Ontario, Canada, Thomas.Krause@rmc.ca

Abstract:
A pulsed Eddy Current (EC) probe, which uses the transient response to a step function voltage, is being developed for in-reactor inspection of CANDU® fuel channels. Pulsed EC has the intrinsic advantage of generating a spectrum of discrete frequencies, which allows the simultaneous collection of data from a range of depths (i.e. takes advantage of multiple skin depths) that is unachievable by conventional EC, which can only use a limited number of frequencies obtained from separate time harmonic excitations. A COMSOL multi-physics model was created to characterize the effectiveness of a conventional EC probe and these results were compared against analytic solutions with a simplified (planar) geometry. It was shown that in general, the COMSOL model made predictions similar to the analytic solutions, providing confidence for the efficacy of the COMSOL model. Another COMSOL model was made to incorporate the real geometry of the fuel channel, and it was discovered that the fuel channel curvature manifests itself as a phase rotation of the EC data. This phase discrepancy is not accounted for by the analytical model.

Keywords: Eddy Current Testing, Fuel Channels, Pressure Tube to Calandria Tube Gap

1. Introduction

As shown in Figure 1, CANDU® reactor fuel bundles are immersed in a heat transport coolant within a Pressure Tube (PT) [1]. Surrounding the PT is a gas-filled Calandria Tube (CT), which thermally isolates the PT from the moderator surrounding the fuel channels [1]. Four annulus spacers separate the hot PT (~300 °C) from the cool CT (~50°C) to prevent hydride blistering of the PT, which could occur under contact conditions [1]. Hydride blistering has been known to lead to cracking in the PT. For inspection purposes, a non-destructive probe is necessary to evaluate the following the PT-to-CT gap however the probe response is sensitive to the probe liftoff, PT resistivity and PT wall-thickness. The qualification of an inspection system is a crucial step in evaluating a system's capabilities against its inspection specification requirements and is a nuclear operator regulator requirement [3]. Thus rigorous numerical models of the probe function are required to evaluate the effects of additional experimental parameters that may affect the inspection outcome [4].

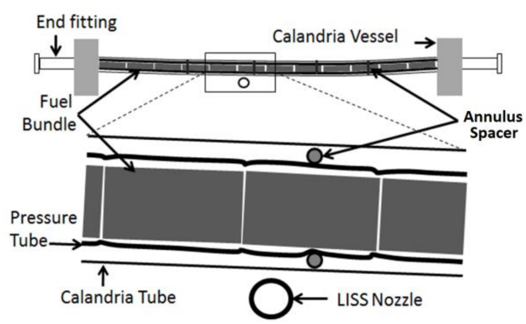

Figure 1: A schematic of a CANDU® fuel channel assembly (top) a schematic of an individual fuel channel (bottom) modified from [2].

As shown in Figure 2, the EC probe consists of a drive coil and a receive coil mounted in plastic casing designed to fit inside the PT. A spring system connects both halves of the casing to ensure the probe is surface riding on the inner face of the PT. The drive coil is excited from a power supply, while the pickup coil is electromagnetically coupled to the drive coil via the ECs in the test-piece.

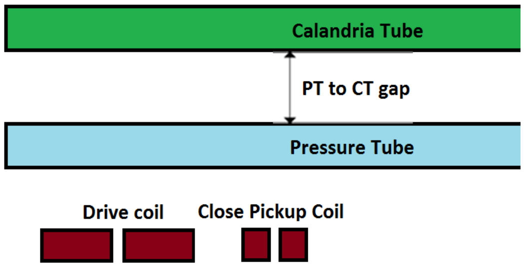

Figure 2: A schematic of the experimental EC probe

2. Use of COMSOL Multiphysics

The following sections describe two Finite Element Method (FEM) models created in COMSOL to simulate the probe for conventional EC. The models differ in geometry. However, both models use a frequency domain analysis to obtain the steady state response. According to the COMSOL solver [7], both models solve "Ampère's Law" in the CT, PT and air between the components as given by Equations 1-2:

$$(j\omega\sigma - \omega^2\varepsilon)\mathbf{A} + \nabla \times (\mu_0^{-1}\mu_r^{-1}\mathbf{B}) = \mathbf{J_e} \quad (1)$$

$$\boldsymbol{B} = \nabla \times \mathbf{A} \quad (2)$$

where ω is the circular angular frequency of excitation, μ_0 is the permeability of free space, μ_r is the relative permeability, ε is the material permittivity, σ is the material conductance, $\boldsymbol{A}$ is the magnetic potential vector, J_e is the current density in a medium and $\boldsymbol{B}$ is the magnetic flux density. According to the COMSOL solver [7], Equation 1 is constrained by Equation 3 for the calculation of the currents in the individual coils:

$$\mathrm{J_e} = \frac{NI_{cir}}{A}\boldsymbol{e_{coil}} \quad (3)$$

Where N is the number of coil turns, I_{cir} is the current in the coil, A is cross-sectional area of the coil turns and $\mathbf{e_{coil}}$ is the unit vector of the current direction. In contrast to the analytic model, these COMSOL models account for the internal geometry of the coil and thus have finite impedances and are susceptible to the skin effect.

2.1. 3D COMSOL model with planar geometry

As shown in Figure 5, a FEM model with planar geometry was created to approximate existing analytic models. It should be noted that to keep a consistant mesh for a variable PT-CT gap parameter sweep, a stack of CTs was created. At any given gap measurement, only one of these CTs were made of the CT material, while the rest were air. Thus activating the CTs would generate the PT-CT gap response without changing the mesh. Similarly, the coils were cut up into fifths and connected in series inside the Electrical Circuit interface. Only five of the coils were activated or connected to a pull up resistor while the other fifth-coils were shorted out with a pull-down resistor. Similarly, turning five of the fifth-coils at a time developed the probe liftoff profile. This model applied a magnetic insulation boundary condition at the extremities of the model and along the plane of symmetry to reduce computational resources.

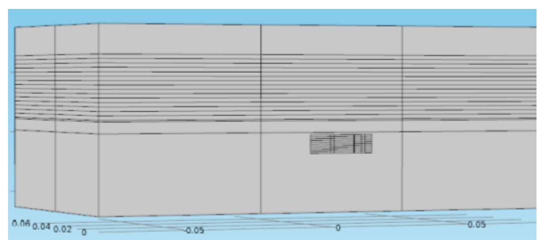

Figure 5: A screenshot of the 3D COMSOL model assuming fuel channel consisted of planar geometry for a conventional probe modelled from [3].

2.2. 3D COMSOL model with tubular geometry

As shown in Figure 6, a 3D FEM model with tubular geometry was created to obtain an accurate model for the probe by using the actual probe dimensions and thus validate the assumptions made by the analytic model.

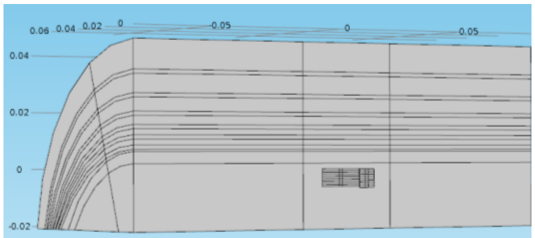

Figure 6: A screenshot of a FEM model with the exact dimensions of a conventional EC probe modelled from [3].

3. Results/Discussion

As shown in Figure 7, one can clearly observe that the eddy currents in the PT are confined to a small area above the drive coil. Therefore the assumption of a localized electromagnetic field spread is confirmed, providing confidence to the assumptions made by the analytic model. The PT-CT gap was allowed to vary from ~ 0 to 20 mm for a 4 kHz excitation and the real and imaginary components of the pickup coil responses were plotted. Note that the origin corresponds to a ~0 mm gap while data furthest from the origin corresponds to a ~20 mm gap. As shown in Figure 8, the effect of curvature manifests itself a phase rotation of the PT-CT gap—an interesting result. The procedure was repeated for different PT resistivities (45-60 uohm*cm) and PT Wall Thicknesses (WT) (3.76-4.38 mm). As shown in Figure 9, the variance of PT resistivity results in a linear offset of the PT-CT gap response while a variance in PT WT rotates and compresses/stretches the PT-CT gap response.

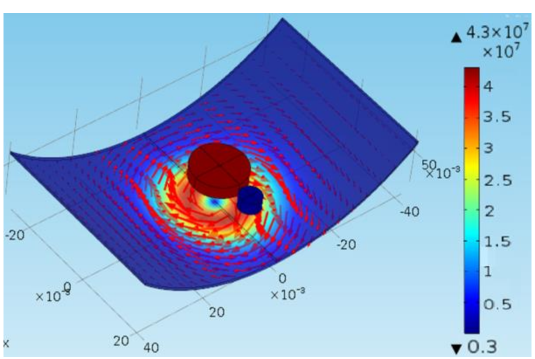

Figure 7: The PT eddy current distribution from a conventional EC probe operated at 16 kHz. Colour axis given in units of A/m^2.

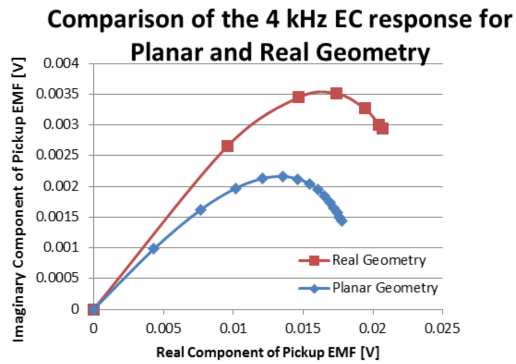

Figure 8: The pickup coil response from a 4 kHz excitation predicted from the three models.

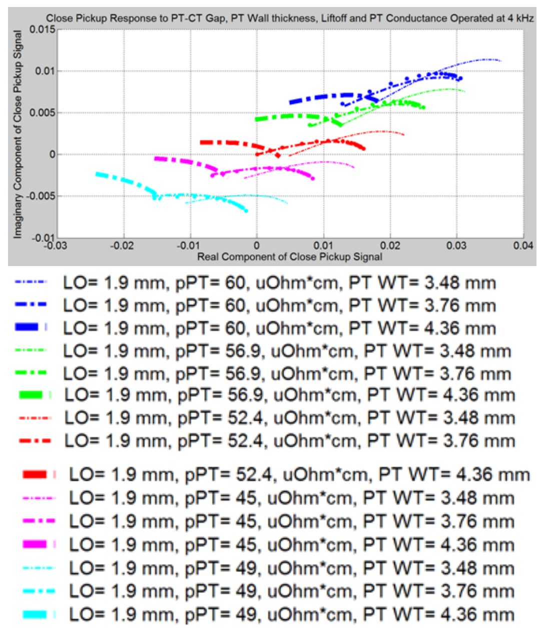

Figure 9: The 4 kHz PT-CT gap response of the probe from varying PT resistivity and PT wall thickness. Note this model assumed a planar approximation.

5. Conclusions

FEM solutions were obtained for an EC driver-receive coil configuration within a multi-layer flat plate geometry and for the actual physical tube-within-tube configuration. Modeled probe responses due to changing gap between PT and CT were compared against analytic solutions for infinite plate geometry. It was found that the curvature of the fuel channel manifests itself as a phase rotation in comparison to the flat-plate approximation and thus at present, the existing analytical models do not account for this discrepancy. Furthermore, the FEM models indicate that the different experimental parameters (PT WT, PT resistivity, etc) have a unique effect on the observed PT-CT gap response, which may allow one to develop techniques to measure or account for these parameters.

6. References

[1] S.T. Craig, T.W. Krause, B.V Luloff and J.J. Schankula, “Eddy current measurements of remote tube positions in CANDU reactors,” in 16th World Conference on Nondestructive Testing, Palais des Congrès, Montreal, Canada, 2004, Aug. 30-Sept. 3.

[2] S. Shokralla, T. W. Krause and J. Morelli, “Surface profiling with high density eddy current non-destructive examination of data,” NDT&E International, vol. 62, March 2014.

[3] J. A. Baron, Qualification of inspection systems in the CANDU nuclear industry, CINDE Journal 35 (1) (2014) 10–14.

[4] European Network for Inspection and Qualification, Luxembourg, ENIQ Recommended Practice 6: The Use of Modelling in Inspection Qualification, 2nd Edition (2011).

[5] C. V. Dodd, W. E. Deeds, Analytical solutions to eddy-current probe-coil problems, Journal of Applied Physics 39 (6) (1968) 2829–2839.

[6] S Shokralla, Sean Sullivan, Jordan Morelli, Thomas W. Krause, “Modelling and Validation of Eddy Current Response to Changes in Factors Affecting Pressure Tube to Calandria Tube Gap Measurement,” NDT&E International, submitted for publication, Sept 4, 2014.

[7] “COMSOL Multiphysics User’s Guide Version 4.3,” COMSOL, 2012. pp. 558-560 [Online]. Available: http://nf.nci.org.au/facilities/software/COMSOL/4.3/doc/pdf/mph/COMSOLMultiphysicsUsersGuide.pdf [Accessed: Sep. 5, 2014].

9. Acknowledgements

The authors wish to thank Ontario Power Generation and Stuart Craig, Atomic Energy of Canada Limited for providing analytical model data. This work was supported by University Network of Excellence in Nuclear Engineering and the Natural Sciences and Engineering Research Council of Canada.