Finite Element Modeling of Conventional and Pulsed Eddy Current Probes for CANDUÈ Fuel Channel Inspection

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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 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.

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. The reactor's fission reaction rate may be controlled from a Liquid Injection Shutdown System (LISS), which injects neutron poison into the moderator surrounding the fuel channels [1]. The injection nozzles are just exterior to the CTs. For inspection purposes, a non-destructive probe is necessary to evaluate the following:

- The PT-to-CT gap;
- The axial location and proximity of the LISS nozzles relative to the CT.

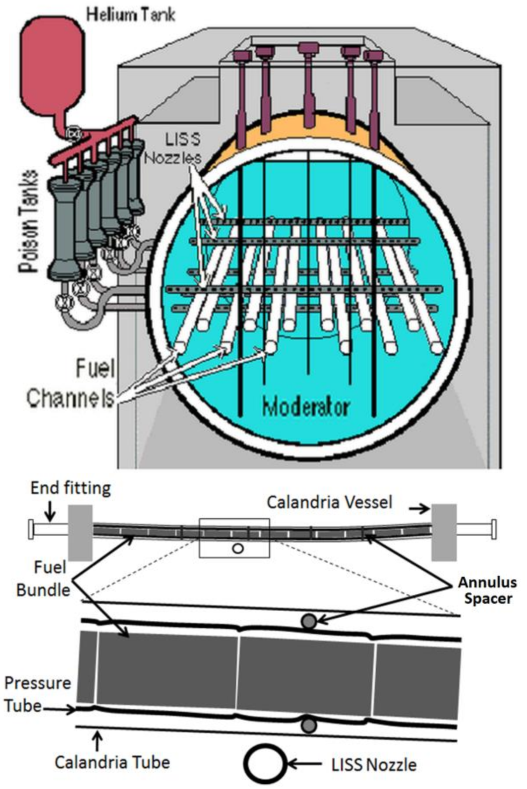

Figure 1: A schematic of a CANDU® fuel channel assembly (top) [1] and a schematic of an individual fuel channel (bottom) modified from [2].

As shown in Figure 2, the prototype pulsed EC probe consists of one drive coil and one receive coil mounted in plastic casing designed to fit inside the PT. A spring system connects both halves of the casing to provide a snug fit for varying PT inner diameter conditions. Not shown in Figure 2 is a copper plate behind the coil, which shields the probe from other electromagnetic field interactions (see Figure 3). The drive coil is excited from a power supply, while the pickup coil is electromagnetically coupled to the drive coil via the magnetic field in the test-piece.

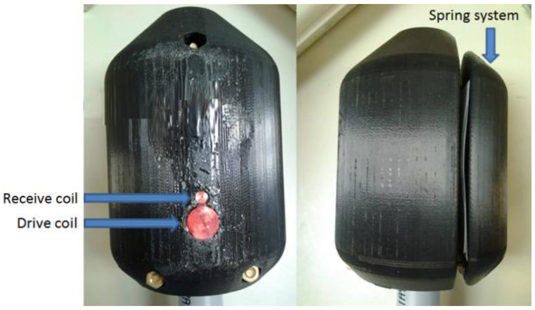

Figure 2: A photograph of the experimental PEC probe showing its basic components.

It should be noted that 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]. Rigorous numerical models of the probe function can be used to evaluate the effects of parameters that may affect the inspection outcome [4].

2. Analytic Model

An analytic solution for low frequency conventional EC developed by Dodd et al. [5] was used to validate the COMSOL models. These solutions considered pancake coils near flat plates. To calculate the solution of a transmit-receive type probe, the magnetic field from the free-space coil component of the Dodd and Deeds equations [5], was subtracted from the overall solution. This difference in magnetic fields was replaced by adding magnetic field from the Biot-Savart solution for the transmit coil. In doing so, the analytic solution made the following assumptions:

- Coils were modelled as integral sum of 3D, axially-symmetric Dirac-delta coils [5]
- The PTs and CTs have infinite parallel-plate geometries [6];
- The copper shielding is an infinitely long rectangular slab [6];
- No skin effect[1] in the coil windings [5]

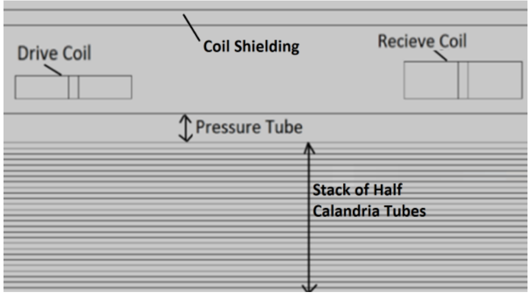

Figure 3: A drawing of the model used by the analytic calculation of an EC probe. Coil-coil spacing is exaggerated for ease of visualization

It should be noted that in the special case of low excitation frequencies (< 4 kHz) and a small coil-coil spacing, the effects of PT and CT curvature are negligible. This is due to a localized circumferential electromagnetic field around the drive coil.

3. Use of COMSOL Multiphysics

The following sections describe three 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 and make the following assumptions:

- The coils were modelled as multi-turn coils, with the drive coil connected to a 1A current AC-source (same excitation as used in analytic model).
- The pickup coil was excited by a 0 A AC source (open circuit configuration).
- The magnetic potential vector ***A*** has a zero magnitude as an initial value.

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:

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

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[1] The skin effect is the tendency of an alternating electric current to become concentrated at the surface of a conductor, decreasing exponentially at greater depths in the material. The depth of penetration is related to the frequency of excitation and the electromagnetic properties of the conductor [5].

$$\boldsymbol{B} = \nabla \times \mathbf{A} \tag{2}$$

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:

$$\mathrm{J_e} = \frac{NI_{cir}}{A}\boldsymbol{e_{coil}} \tag{3}$$

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.

3.1. 3D COMSOL model with planar geometry

As shown in Figure 5, a FEM model with planar geometry was created to approximate the analytic model. It should be noted that to keep a consistant mesh for a variable PT-CT gap parameter sweep, a stack of “half CTs” was created. At any given gap measurement, only two of these “half CTs” were made of the CT material, while the rest were air. In addition to the assumptions described in section 3, this model applied a perfect conductor boundary condition at the extremities of the model to prevent surface currents from forming at the model’s boundary faces. According to the COMSOL solver [6], the external boundaries were constrained by Equation 4:

$$\boldsymbol{n} \times \boldsymbol{H} = 0 \tag{4}$$

Where $\boldsymbol{n}$ is the vector orthonormal to the plane made by the boundary faces of the model and $\boldsymbol{H}$ is the magnetic field.

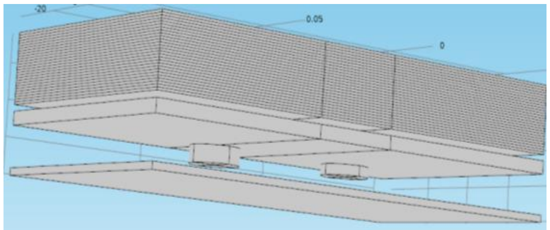

Figure 5: A screenshot of the 3D COMSOL model assuming fuel channel consisted of planar geometry for a conventional probe modelled from [3].

3.2. 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. This model also included a perfect conductor boundary condition on the external faces of the model. Eventually, the results from this model will be compared against experimental data for validation.

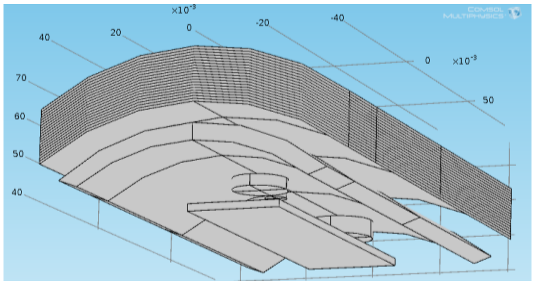

Figure 6: A screenshot of a FEM model with the exact dimensions of a conventional EC probe modelled from [3].

4. Results

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 16 mm for various frequencies and the real and

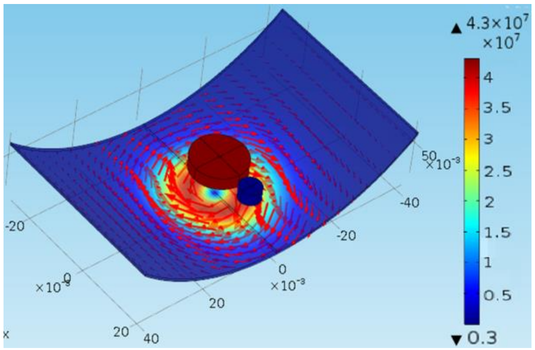

Figure 7: The PT eddy current distribution from a conventional EC probe operated at 16 kHz. Colour axis given in units of A/m^2.

imaginary components of the pickup coil responses were plotted in Figures 8 to 10. Note that the origin corresponds to a ~0 mm gap while data furthest from the origin corresponds to a ~16 mm gap. In general, the trends from the FEM models do not match the analytic solutions.

5. Discussion

The results shown in Figures 8-10 indicate that the FEM models are not in good agreement with the analytic solutions. However, all the models predict an increasing voltage with increasing PT-CT gap and it would seem that the responses predicted by the 3D FEM models are fairly consistent with each other, but deviate slightly with increasing gap. As one would expect, this infers that the planar geometry approximation works best for small PT-CT gaps (<5 mm), when the eddy currents are highly localized in the CT.

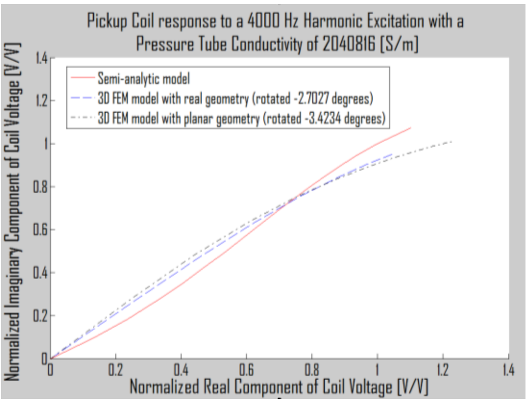

Figure 8: The pickup coil response from a 4 kHz excitation predicted from the three models.

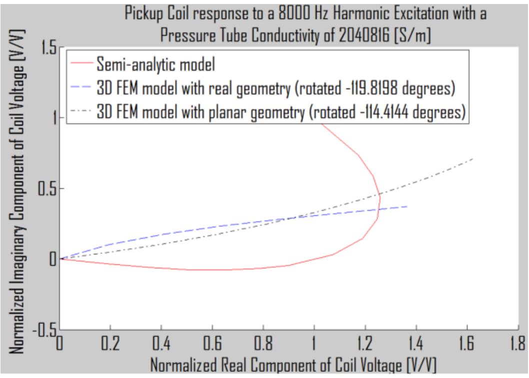

Figure 9: The pickup coil response from a 8 kHz excitation predicted from the three models.

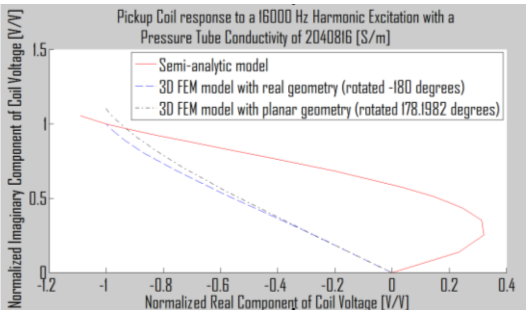

Figure 10: The pickup coil response from a 16 kHz excitation predicted from the three models.

6. 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. Despite some disagreement between the model trends, all the models predict an increasing voltage with increasing PT-CT gap. Further comparison with experimental measurements and other FEM simulation software will be used to validate the COMSOL models.

7. 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.