Finite Element Modelling of Conventional and Pulsed 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

Overview

- Introduction:
  - Main components of CANDU® fuel channels;
  - Eddy Current Technology;
  - Experiential apparatus (probe).
- Problem statement and motivation.
- Numerical models for Eddy Current Probe:
  - Analytic solution;
  - COMSOL FEM models.
- Results.
- Discussion.
- Summary.

Background: CANDU® Fuel Channel

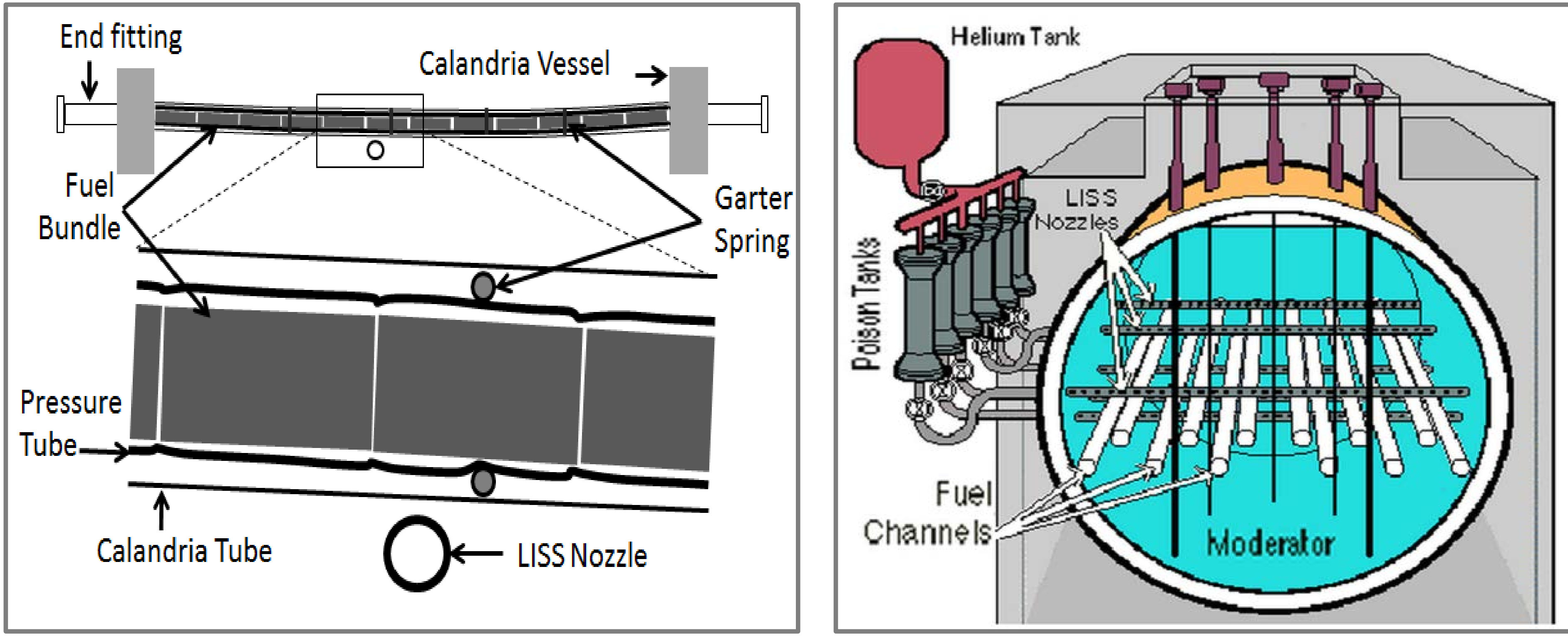


Figure 1: A schematic of a CANDU individual fuel channel (left) modified from [1] and a schematic of the entire CANDU® fuel channel assembly (right) [2].

Motivation

- Hydride Blistering
- 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 to the CT.
- Eddy Current technology offers the most economical solution to this problem.

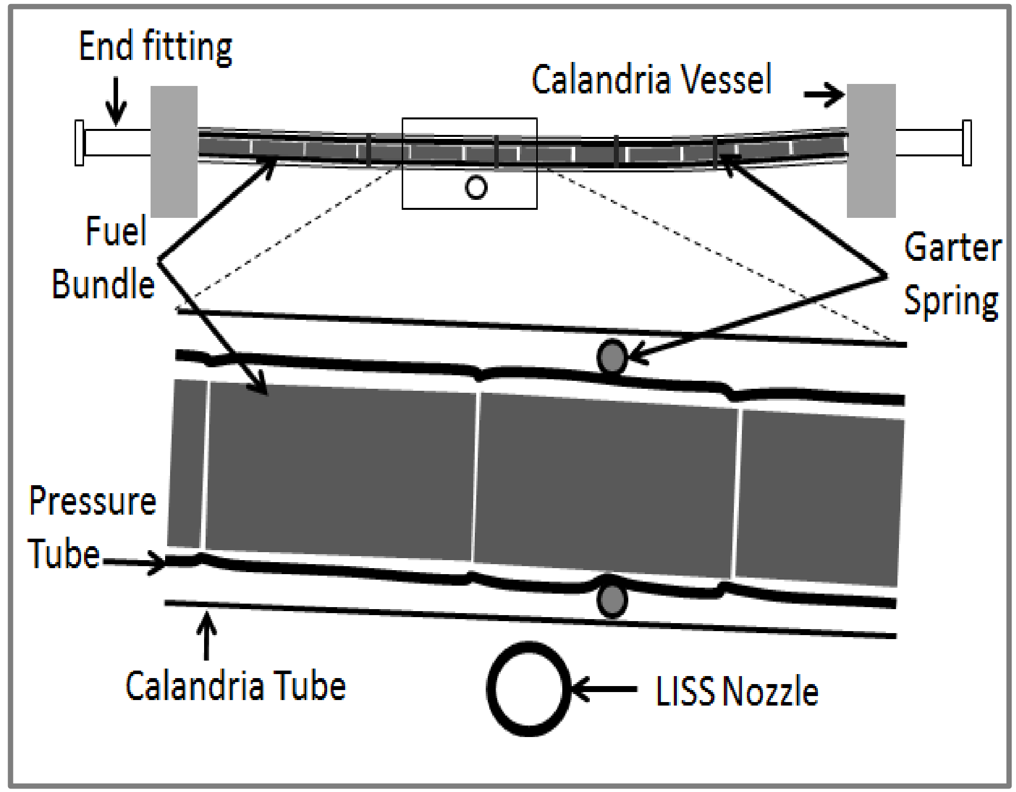


Figure 4: A schematic of an individual fuel channel (right) modified from [2].

Eddy Current Technology

- **Eddy-current testing** is a non-destructive testing technique that uses electromagnetic induction to detect flaws in conductive materials
  - Conventional;
  - Pulsed.
- Advantages:
  - Non-destructive;
  - Inexpensive;
  - Can decipher geometric sub-structures.
- Disadvantages:
  - Only conductive materials are detectable;
  - Depth of penetration limited by material conductivity;
  - Limited range (~1-2 cm);
  - Analytic solutions difficult for certain geometries.

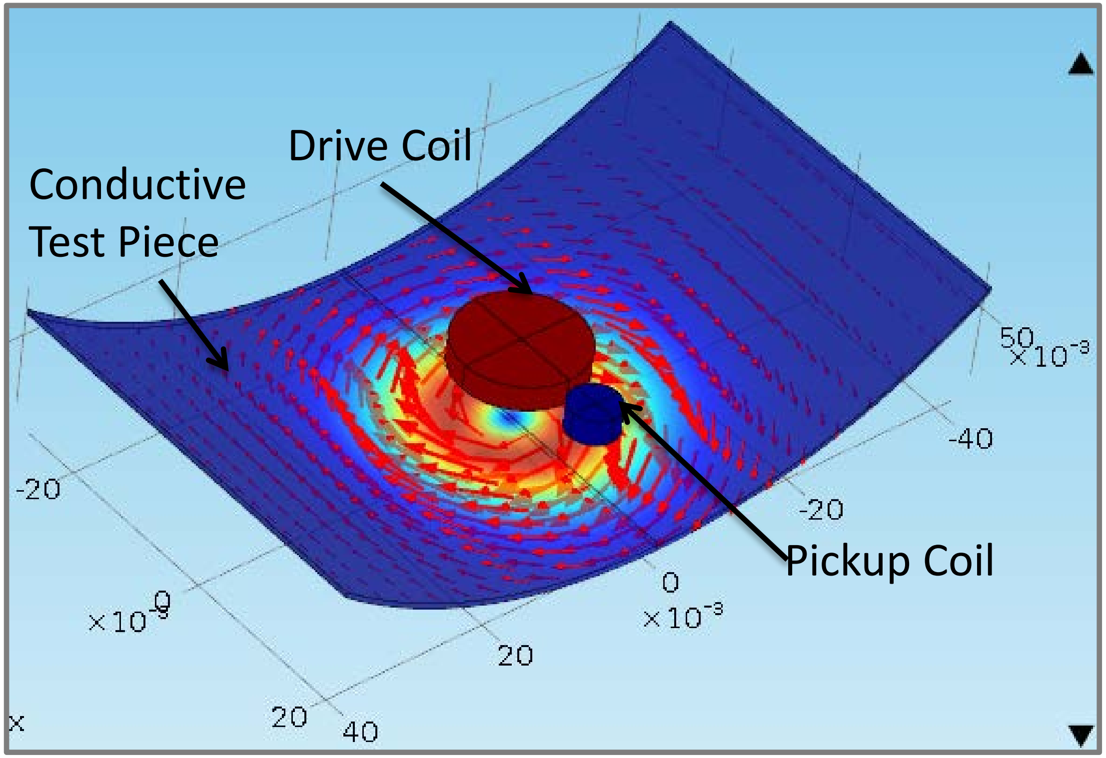


Figure 2: A representation of a typical eddy current distribution in a conductive material for a transmit-receive probe. Colour Axis indicates current density in arbitrary units.

Prototype Pulsed Eddy Current (EC) Probe

Figure 3: A photograph of the experimental EC probe showing its basic components.

Problem Statement and Project Scope

Problem Statement:

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[1]. Therefore, a full understanding of the prototype probe operation is needed before it becomes a commercial product.

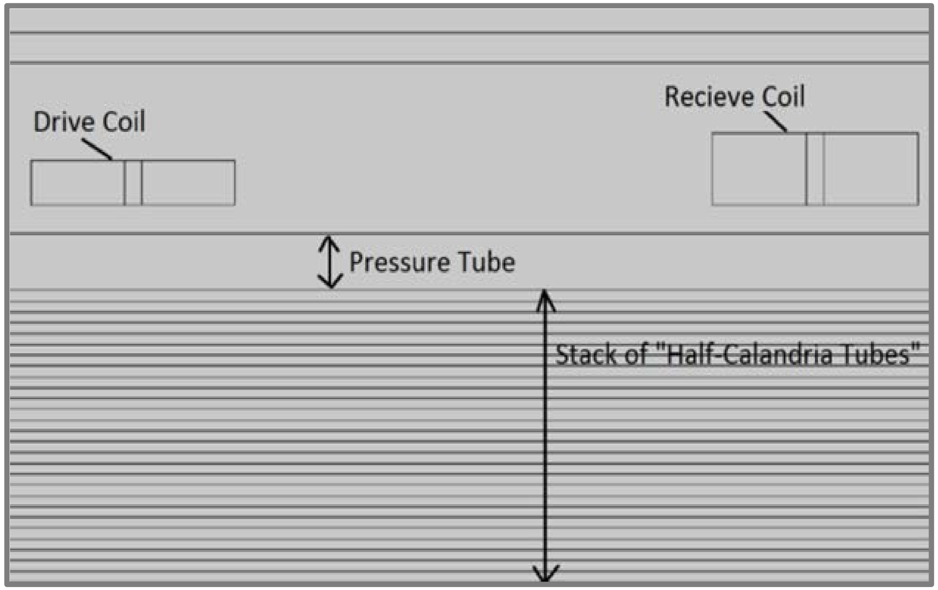


Figure 5: A cross-section of the prototype probe.

Project Scope:

- Develop a COMSOL FEM model to simulate the PT-CT gap response for conventional and transient eddy current probes;
- Compare the relative strengths of both eddy current technologies and create a proposal;
- Finish the above two bullets within a Master's program.

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

Modelling: Analytic model for Conventional EC

- An analytic solution developed by Dodd et al.[2] was used to validate the COMSOL models.
- This analytic solution made the following assumptions:
  - o Coils were modelled as integral sum of three-dimensional, axial-symmetric Dirac-delta coils
  - o The PTs and CTs have infinite parallel-plate geometries;
  - o The copper shielding is an infinitely long rectangular slab;
  - o The skin effect in the coil windings is negligible.
- Assumptions are valid when eddy currents are localized above the coils.

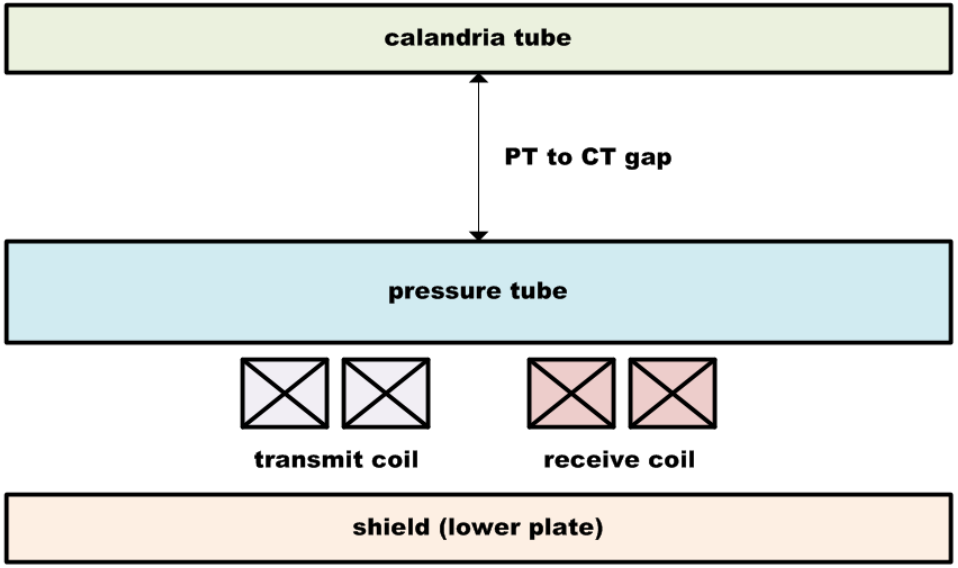


Figure 6: A representation of the geometry modelled by the analytic solution. Modified from [3].

[2]C. V. Dodd, W. E. Deeds, Analytical solutions to eddy-current probe-coil problems, J. of Appl. Phys. 39 (1968) 2829–2839.

COMSOL FEM Models for Conventional EC

COMSOL AC/DC module:

- The coils were modelled as multi-turn coils,
- Drive coil connected to a 1 A current AC-source (same excitation used by the analytic model);
- The pickup coil was excited by a 0 A current AC source (open circuit);
- The magnetic potential vector ***A*** has zero magnitude as an initial value.;
- Perfect conductors placed at model's extremities;
- Equation 1-2 solved everywhere, equation 3 imposed in coils:

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

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

$$J_e = \frac{NI_{cir}}{A}\boldsymbol{e}_{coil} \qquad (3)$$

- Two geometries were considered to quantify the geometric assumptions made by the analytic solutions.

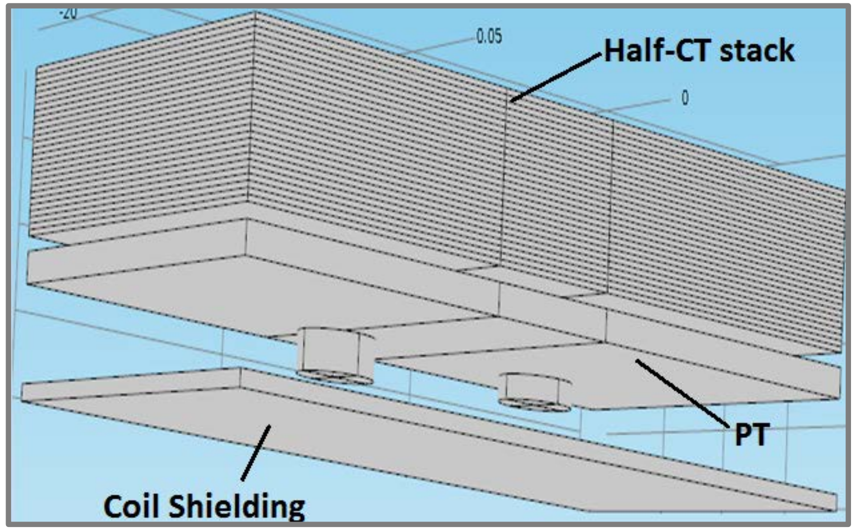


Figure 7: A screenshot of the 3D COMSOL model assuming a planar fuel channel

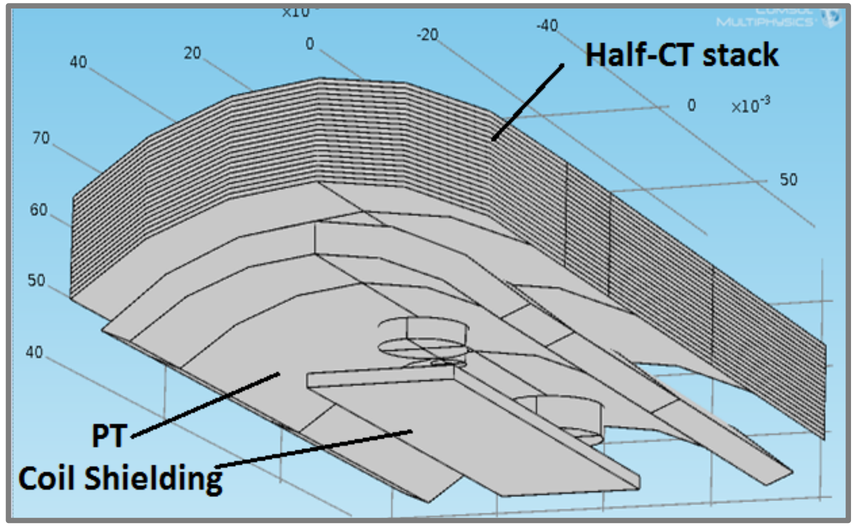
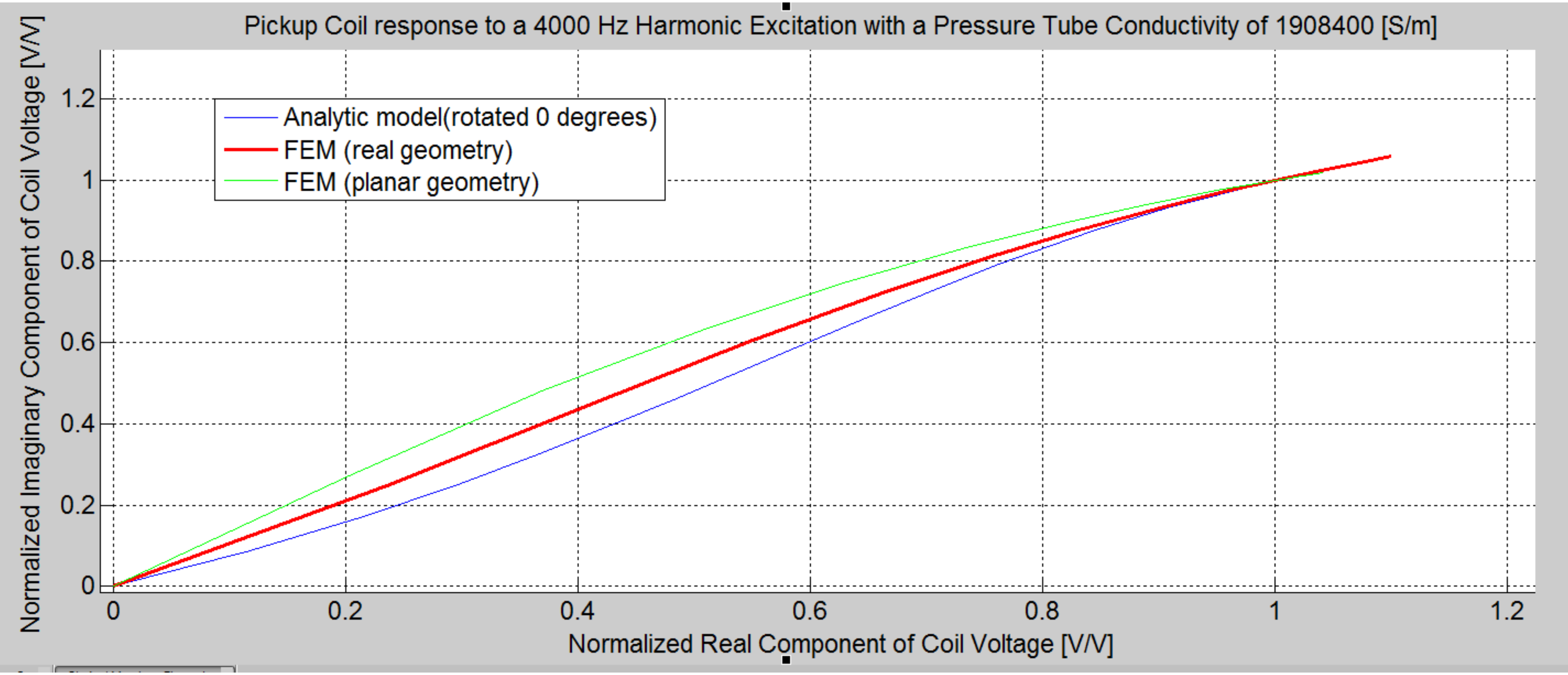
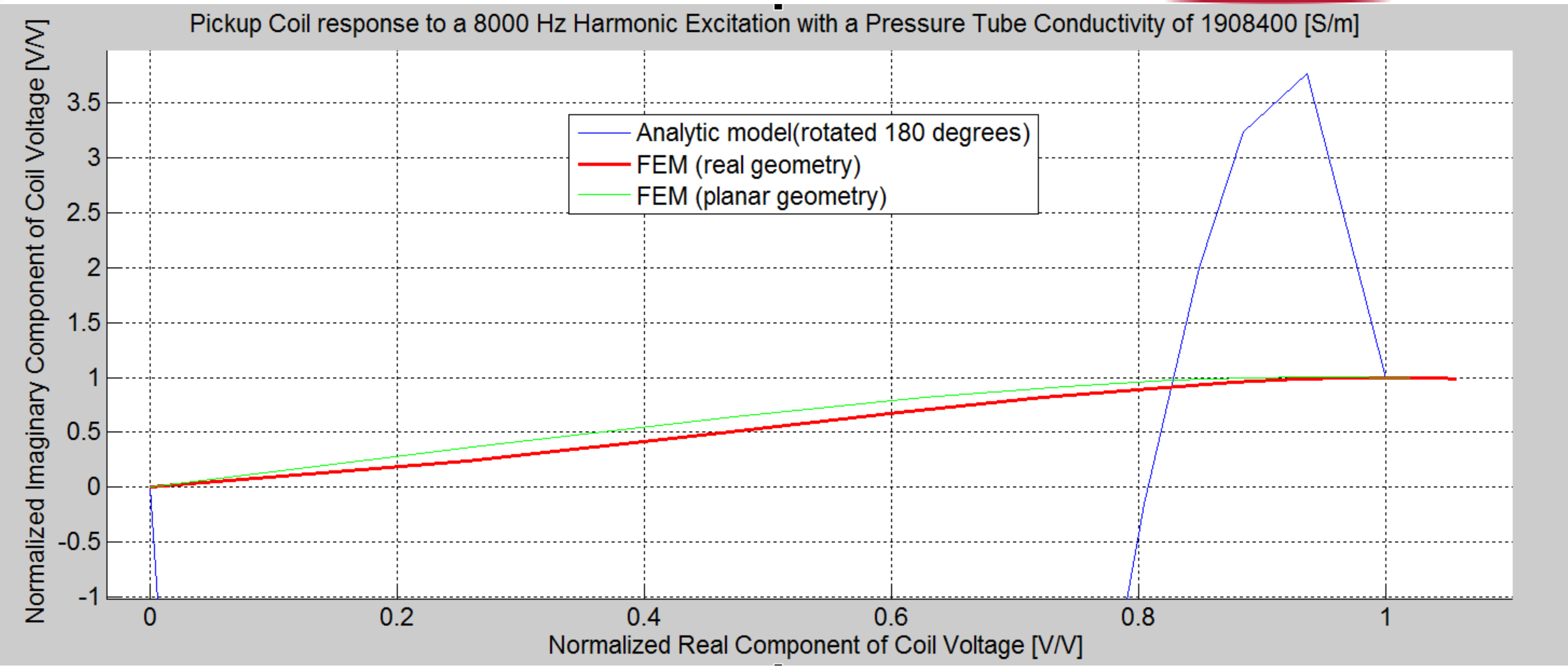


Figure 8: A screenshot of the 3D FEM model with the geometry of the actual probe.

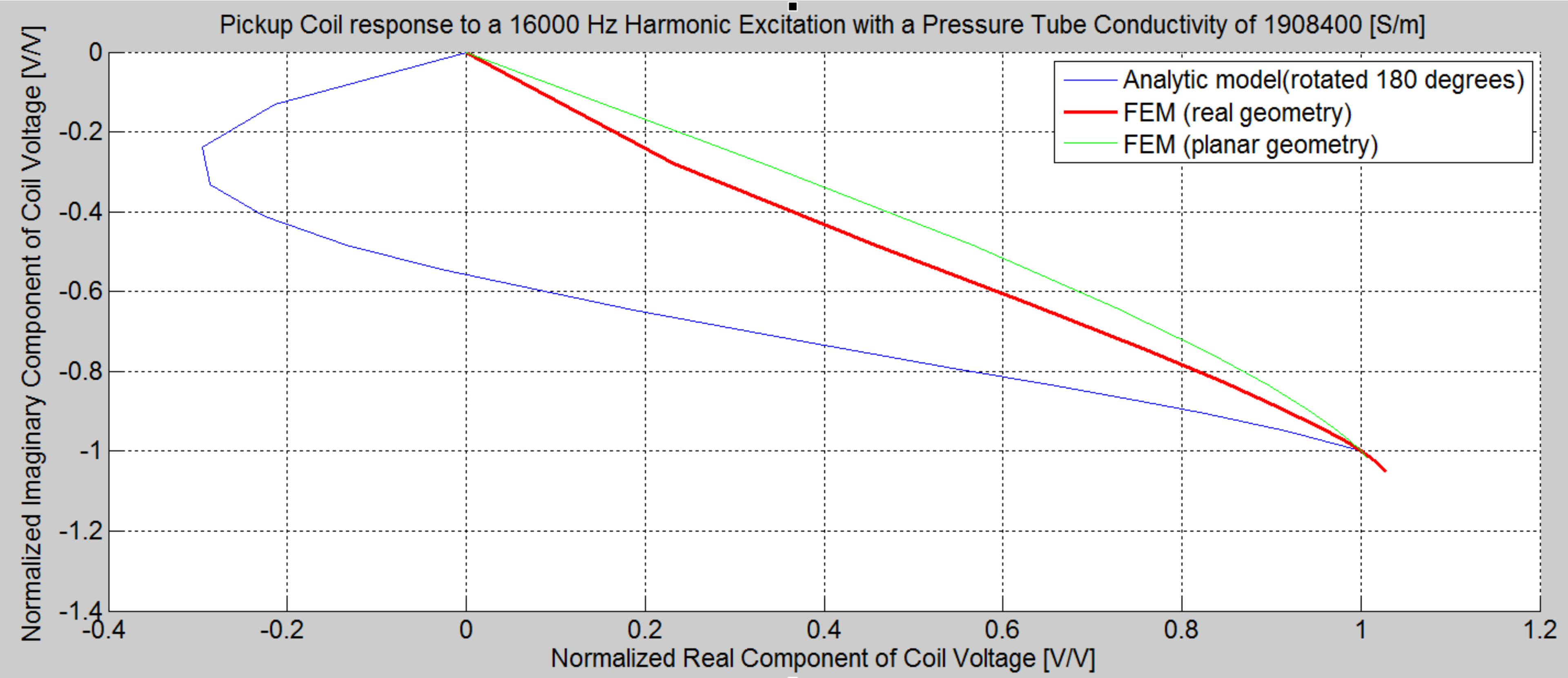
Results: Comparison of FEM to Analytic Solutions



Results: Continued



Results: Continued



Discussion

- In general, the calculated FEM responses qualitatively match the analytic.
- There is little difference between the pickup coil response with and without the coil shielding
- This may infer that:
  - The presence of the coil shielding has a negligible effect on the pickup coil response.

Summary

- Preliminary FEM modelling results of EC response to pressure tube to calandria tube gap variation were compared against analytic solutions .
- Agreement between FEM models and analytic model results was not satisfactory in some cases .
- Further work is needed to experimentally validate the PEC COMSOL model.

Acknowledgements

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

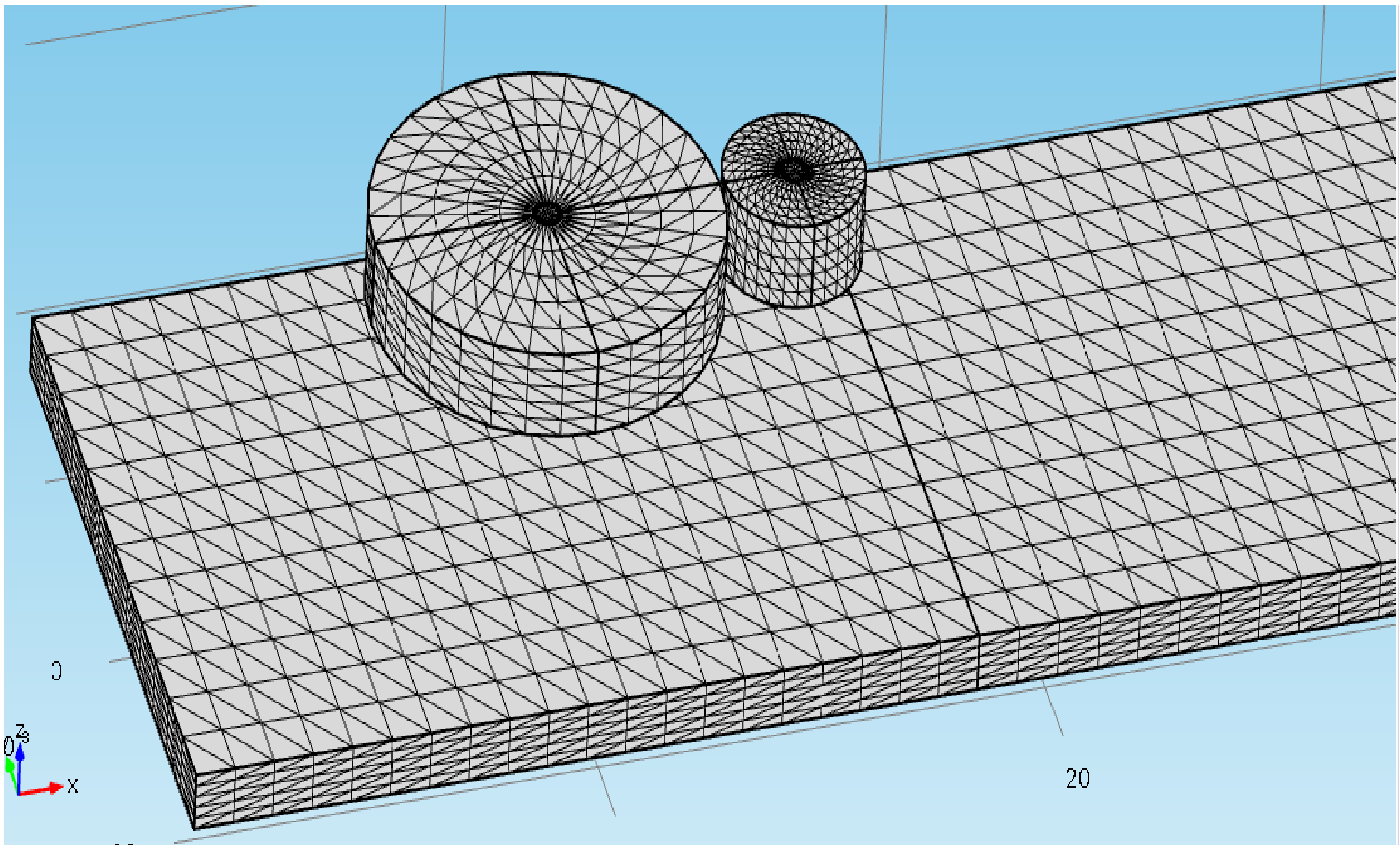
Bibliography

[1] 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.

[2] 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.

[3] 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.


Questions?


0
20
z
x