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

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[1] [illegible]

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INTRODUCTION/MOTIVATION

CANDU® REACTOR FUEL CHANNEL

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

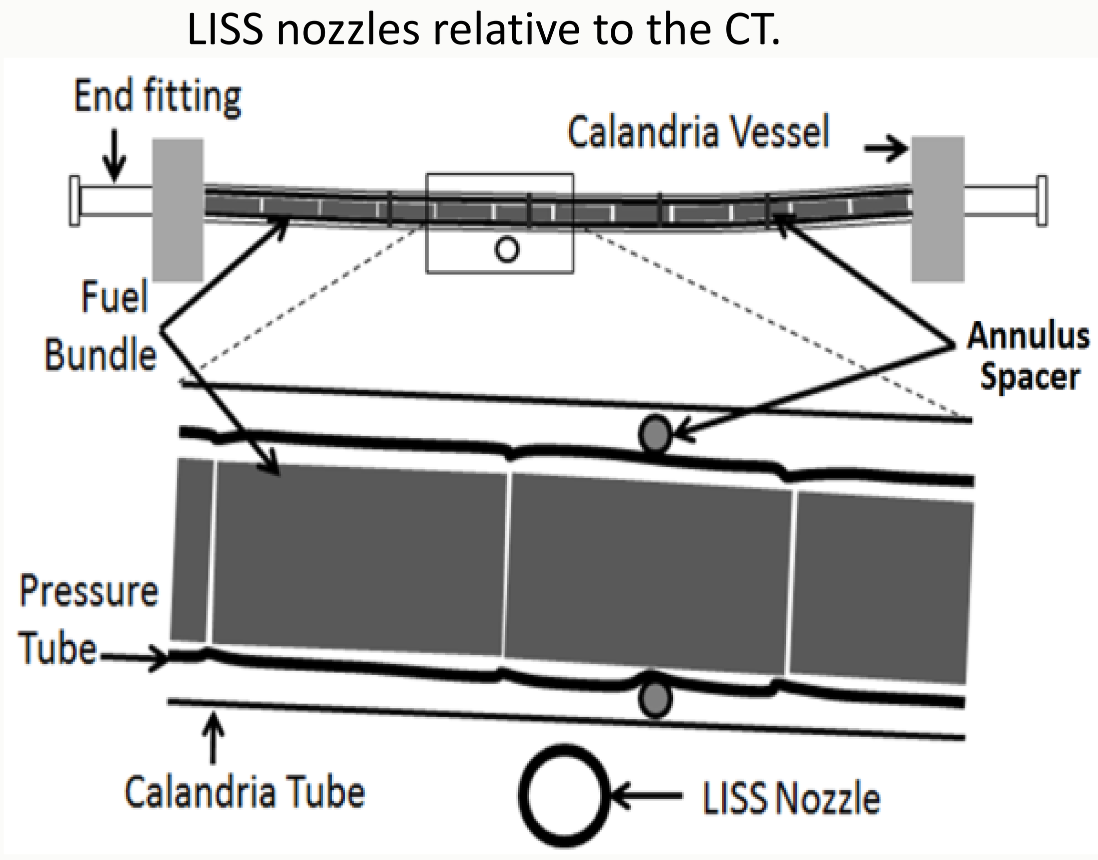

Figure 1: A schematic of a CANDU® fuel channel assembly (top) [1] and a schematic of an individual fuel channel (bottom) modified from [2].

PROPOSED EDDY CURRENT PROBE

- As shown in Figure 2 our group developed a pulsed Eddy Current (EC) probe, which uses the transient response to a step function voltage 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) ;
- Conversely, Conventional EC, only uses a limited number of frequencies obtained from separate time harmonic excitations;
- Rigorous qualification of this probe is required before it can be used in the nuclear industry, requiring an accurate numerical model.

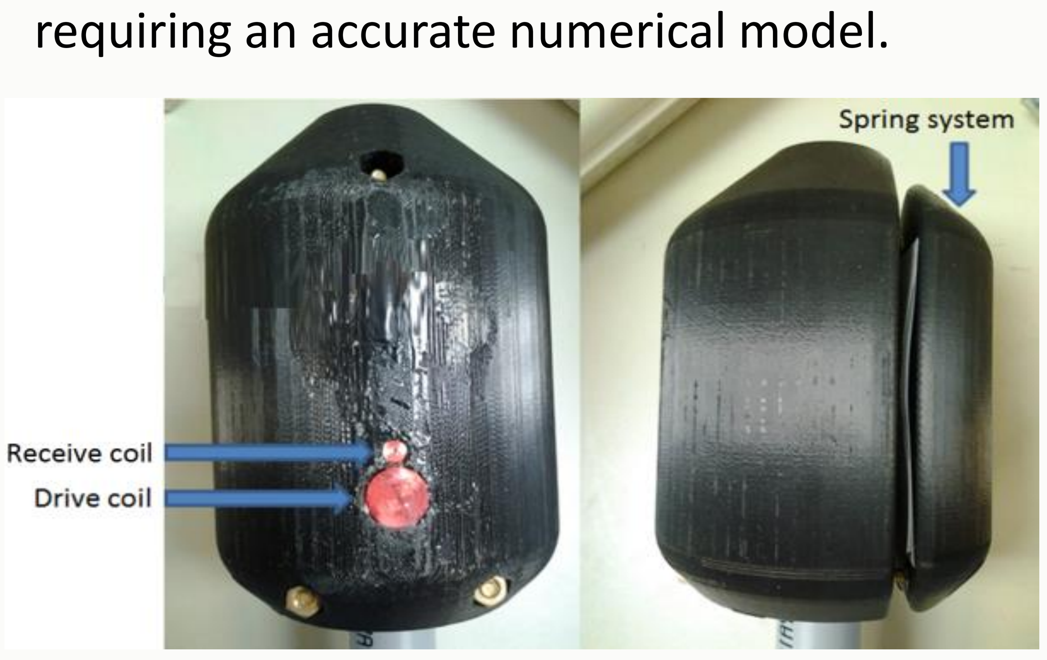

Figure 2: A photograph of the experimental PEC probe showing its basic components.

OBJECTIVES

The goals of this project are to:

- Develop COMSOL FEM models to simulate the probe response for conventional and transient eddy current probes, which match experimental measurements;
- Use the models to investigate the probe operation under normal test conditions, comparing the response against nuclear reactor inspection specifications;
- Compare the relative strengths of both eddy current technologies and create a proposal.

NUMERICAL MODELS

ANALYTIC SOLUTION FOR MODEL VALIDATION

- As shown in Figure 3, an analytic solution for low frequency conventional EC developed by Dodd et al. [3] was used to validate the COMSOL models;
- The analytic solution made the following assumptions [3]:
    - Coils were modelled as the integral sum of 3D, axially-symmetric Dirac-delta coils;
    - The PTs and CTs have infinite parallel-plate geometries;
    - The copper shielding is an infinitely long rectangular slab;
    - No skin effect in the coil windings.

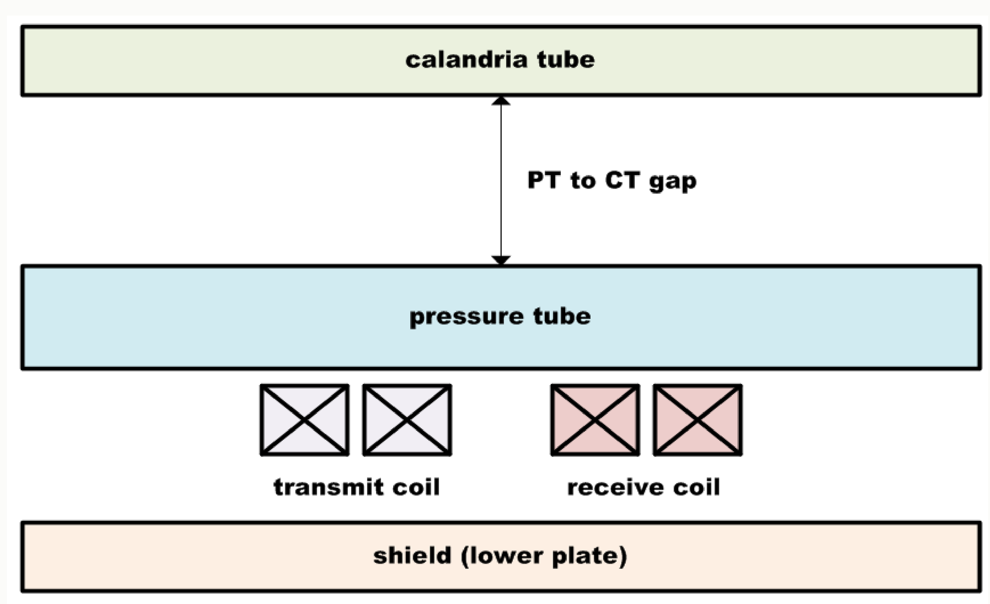

Figure 3: A representation of the geometry modelled by the analytic solution. Modified from [4].

COMSOL MULTIPHYSICS FINITE ELEMENT MODELS

- As shown in Figure 4, two 3D COMSOL models (COMSOL version 4.4) were made: one model assuming the geometry made by the analytic solutions and one model with the actual probe dimensions;

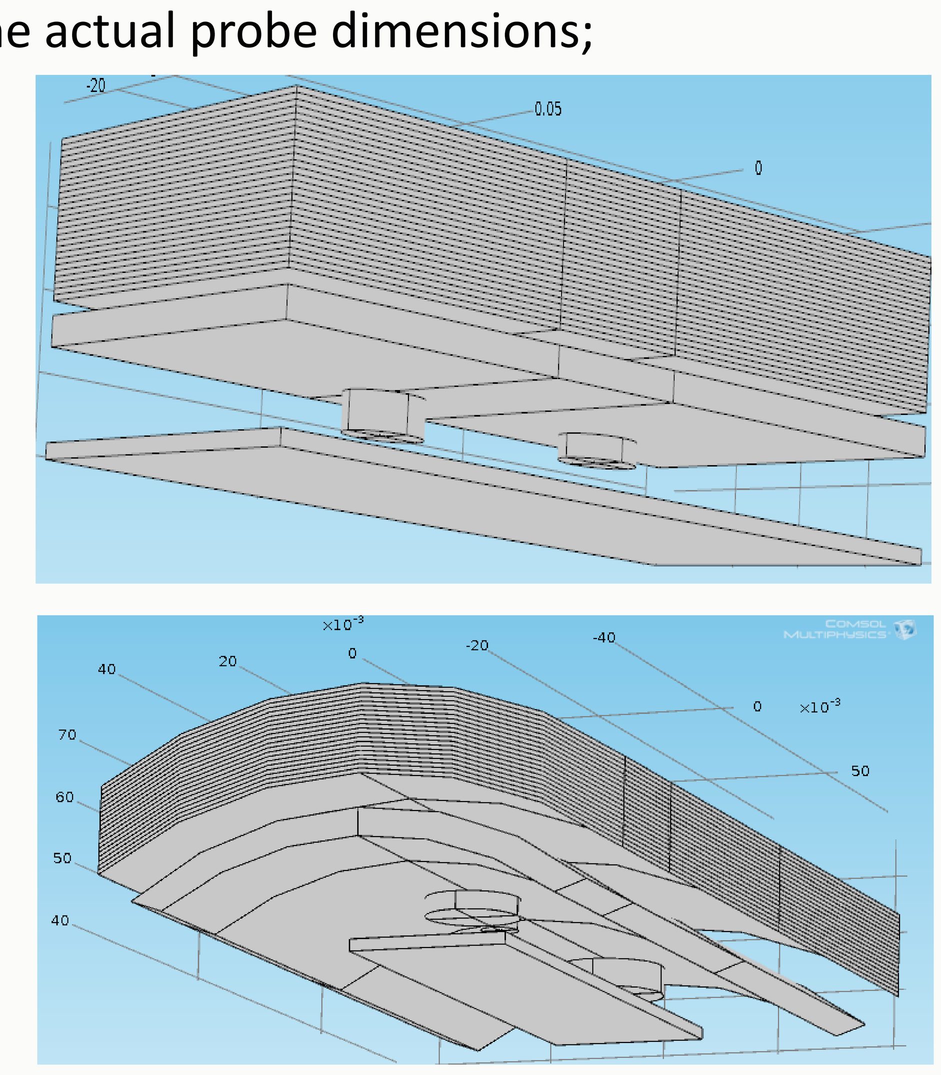

Figure 4: The two 3D COMSOL models: one with the same geometry as the analytic solutions (top) and the real geometry (bottom)

- Both FEM models use an mf module and a frequency domain analysis. In addition, both models make the following assumptions:
    - The coils were modelled as multi-turn coils, with the drive coil was connected to a 1 A current AC-source (same excitation as analytic model).
    - The pickup coil was excited by a 0 A AC source (open circuit configuration).
    - The outside faces of the model have perfect conductor boundary conditions

RESULTS

- Preliminary results show that the electromagnetic field spread is localized above the drive coil, thus reducing the effect of the PT and CT curvature in the model. This provides credence to the geometric assumptions made by the analytic model.

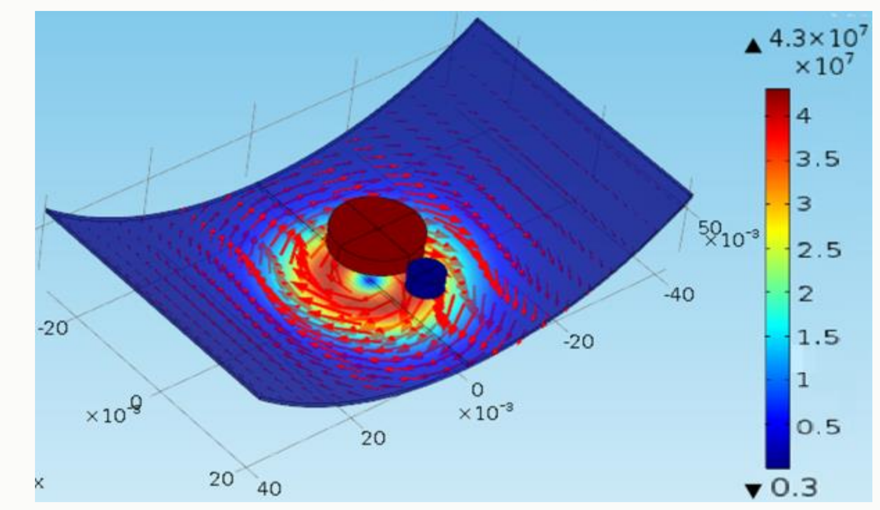

Figure 7: The PT eddy current distribution from a conventional EC probe operated at 16 kHz. Colour axis given in units of A/m².

- The PT-CT gap was allowed to vary from ~ 0 to 16 mm for various frequencies and the real and imaginary components of the pickup coil responses were plotted in Figure 8.
- Note that the origin corresponds to a ~0 mm gap while data furthest from the origin corresponds to a ~16 mm gap.

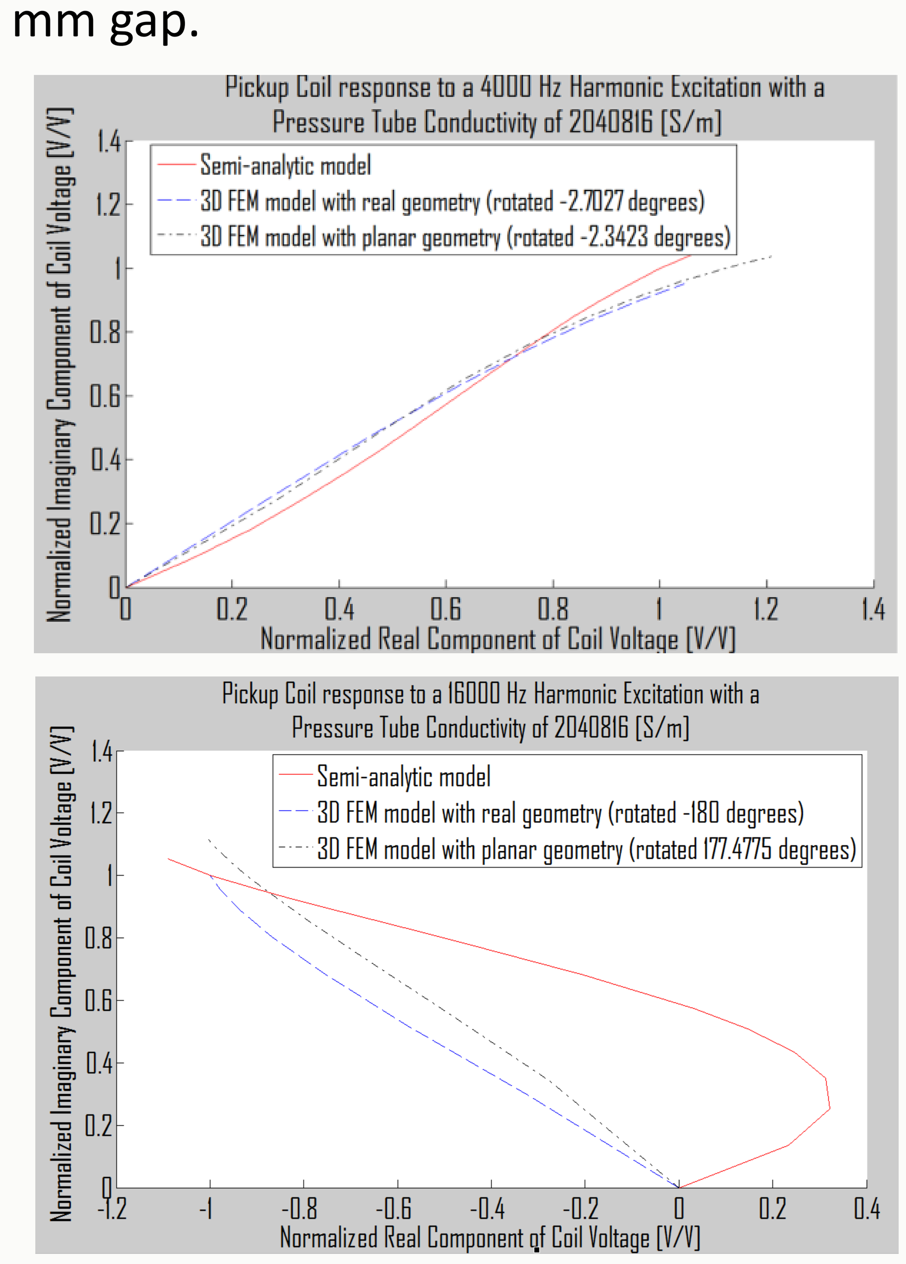

Figure 8: The pickup coil response from a 4 kHz (top) and 8 kHz (bottom) excitation predicted from the three models.

CONCLUSIONS

- The results shown in Figure 8 indicate that the FEM models only qualitatively agree with the analytic solutions.
- It is suspected that the FEM model takes into account non-ideal effects such as the skin effect in the coil windings;
- The 3D FEM models are fairly consistent with each other and deviate with increasing gap. Thus, the planar geometry approximation works best for small PT-CT gaps (<5 mm), when the eddy currents are highly localized in the CT;
- Experimental measurements are required to validate the FEM models;
- Pulsed EC models are under development.

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