Royal Military College of Canada – Thomas Krause CRD

CRD Title: Comprehensive Model of Eddy Current Based Pressure Tube to Calandria Tube Gap Measurement

Overview

CANDU® reactor fuel bundles are immersed in a heat transport coolant (~300 °C) within a 6 m long pressure tube (PT). A gas-filled calandria tube (CT) surrounds the PT and thermally isolates it from the heavy water moderator (~80°C) surrounding the fuel channels. Four annulus spacers separate the hot PT from the cool CT, to prevent contact and thereby, potential formation of hydride blisters on the PT, which can lead to cracking. In-reactor gap monitoring is performed from within the PT by an eddy current (EC) probe that is sensitive to CT proximity [1]. The EC based gap measurement is used in predictions of time-to-contact between PT and CT and is therefore, important for safety and licensing of CANDU® reactors. Gap measurement accuracy can be improved by correctly compensating for all the essential parameters that may affect the inspection outcome. These parameters include PT wall thickness, PT and CT resistivity, and probe lift-off from the PT surface [1-3]. The relative effects of various parameters can be evaluated by application of a comprehensive model of EC response to changes in gap. Analytical models that account for driver and pickup coil interaction with the PT and CT have been developed for an axially symmetric representation of PT to CT gap as a layered infinite planar structure [8]. A semi-analytical model has been developed by approximating the PT inside the CT as two concentric tubes [4-7]. While this concentric tube model accounts for PT curvature exactly, it allows the CT to have a variable radius of curvature in order to vary gap [4-7]. The concentric tube model allows rapid determination of response to gap and a means of accurately evaluating sensitivity to variation in essential parameters [5]. A full three dimensional (3D) finite element method (FEM) model of transmit-receive EC response to changes in PT to CT gap has also been developed for evaluating gap measurement accuracy [5]. The 3D model is required to incorporate effects of curved PT and CT geometry, local variations in PT diameter, ovality, PT wall thickness and resistivity, and probe lift-off and tilt. A validated 3D eddy current model could be used as part of an inspection qualification program by inexpensively supplementing laboratory and field measurements and assisting in quantification of the effect of essential parameters on gap measurement accuracy.

The objectives of this project are:

1. Generate a comprehensive model of eddy current measurement of pressure tube to calandria tube gap beginning with a 2D analytical model followed by 3D FEM (COMSOL) modelling in order to quantify the effects of essential parameters on gap measurement accuracy (completed).
2. Assemble an experimental set-up for laboratory PT to CT gap measurement using actual transmit-receive eddy current probe technology (completed).
3. Acquire EC signals under variable PT and CT gap, PT resistivity variation, local pressure tube diameter and wall thickness variations, PT and CT ovality, and proximity of external structures such as LISS nozzles (in progress).

4. Validate theoretical models with data obtained, first under laboratory conditions, simulating actual fuel channel geometries, and second, if available by examination of real in-channel inspection data (laboratory portion has been completed).
5. Use models to explore effects of variable in-reactor measurement conditions (completed).
6. Make recommendations for achieving improvements in accuracy within existing gap measurement systems and identify key parameters affecting PT to CT gap measurement accuracy with the goal of providing support for inspection qualification programs (in progress).

Program Results /Highlights

This project was funded as of August 1, 2014, but has received an extension to December 31, 2018. In the past 4 years progress was made towards objectives 1 to 6 above, with 4 of the 6 objectives having been completed and the remaining 2 nearing completion. Masters students starts have been September 2014, May 2016 and September 2017. Two masters students have graduated, one of whom, Mark Stephen Luloff, is currently empolyed at CNL, Chalk River Laboratories. Students have developed planar analytic, semi-analytic concentric tube and 3D FEM models of pressure tube to calandria tube gap probe response. Basic comparisons of all model results with acquired experimental data have been made.

Perryn Bennett, a current masters student in the program, was one of four semi-finalists in the Ignite Durham 2017 Pitch Competition, making a presentation to the OPG Boardroom panel of judges, Nov.29, 2017 [12]. The pitch was to develop an algorithm to extract the proximity of Liquid Injection Shutdown System (LISS) nozzles, which pass perpendicularly underneath some fuel channels, from already existing or to-be-acquired EC gap data. Feasibility of the technique has already been demonstrated in the laboratory [10] and accuracy has been estimated as 2 mm to within two standard deviations [12]. The technique would reduce reliance on externally contracted LISS proximity measurements, performed using optical methods and would help reduce total radiation exposure to personnel.

Concentric Tube Analytical Model

The next step in development of analytical solutions, beyond the planar model [2,8], incorporated curvature by approximating PT and CT configuration as concentric tubes [4-7]. Figure 1 shows the parameters used in the semi-analytical model.

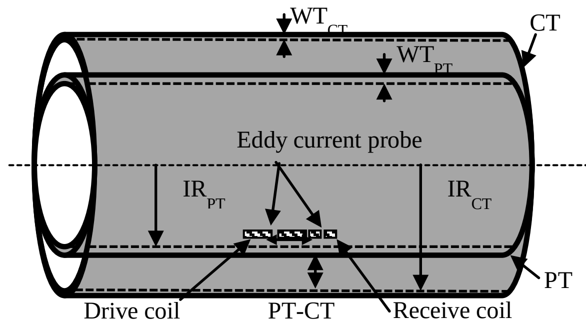

Figure 1: Side view of the drive-receive coil configuration inside the pressure tube (PT). The inner radii of the PT and calandria tube (CT) are denoted by IR_{PT} and IR_{CT}, respectively. The wall thickness of the PT and CT are denoted by WT_{PT} and WT_{CT}, respectively [5].

COMSOL Multi-Physics FEM Models

A 3D FEM model, using COMSOL version 5.2a (AC/DC module with frequency domain analysis), was developed to accurately account for PT and CT parameters, such as tube curvature, varying wall thickness and lift-off [5,7]. The model used the actual curved tube geometry along with a multi-turn drive coil excited by a 1 V, 4.2 kHz time-harmonic voltage source to match the experimental configuration. An example of the FEM model output for a single drive coil is shown in Figure 2.

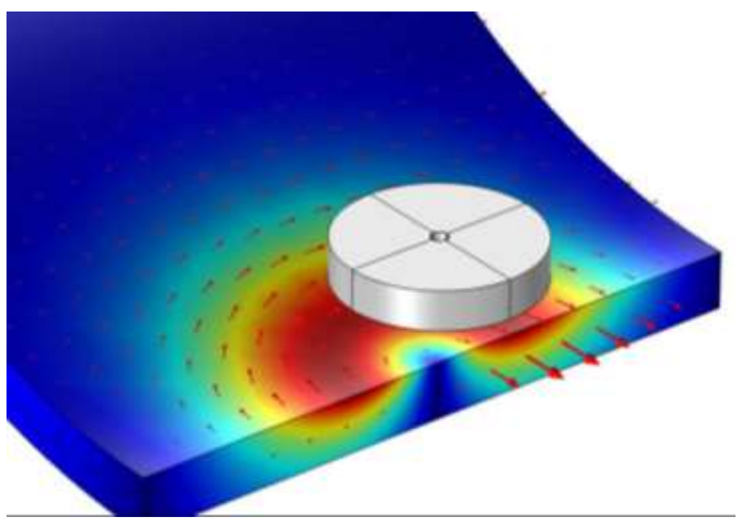

Figure 2: Eddy current distribution (arrows) due to excitation of a drive coil (grey) on a curved surface [5].

3D FEM, planar analytical and concentric-tube model results were compared with experimental results, obtained under conditions of variable PT wall thickness and resistivity for 6 PT samples with properties shown in Table 1 [5-7]. Impedance plane display of the three different model results, compared with experimental results of pickup coil response for gap changing from 0.5

to 16 mm, is shown in Figure 3. The origin corresponds to infinite gap (no CT), while data furthest from the origin corresponds to 0.5 mm PT-CT gap. The various analytical and FEM method models were compared, first with experimental results in the 0 to 5 mm gap range, which is the expected range of minimum gap at the bottom of the fuel channel and second, at the top of the fuel channel where maximum gap is located. The average root-mean-square error (RMSE) of the 6 PT samples, obtained for the flat plate analytical model was 0.3 mm, while the RMSE was 0.06 mm for each of the concentric tube and 3D FEM (true geometry) models. The relative error at maximum gap (at about 16 mm gap) was 6% for the flat plate model and 1% for each of the concentric tube and 3D FEM models.

Table 1: Wall thickness (WT) and resistivity (ρ) of different PT samples used in measurements and models. PT Sample 1 was used for the calibration between both models and measurements.

PT Sample	**PT WT (± 0.05) [mm]**	**PT Resistivity @ 20 °C (± 0.7) [μΩ·cm]**
1 **(Cal.)**	4.04	54.2
2	3.97	57.5
3	3.51	53.9
4	3.94	52.8
5	3.78	53.9
6	4.41	53.9

Conclusions

A semi-analytical model that accounts for PT curvature and approximates the PT-CT configuration in fuel channels as concentric tubes has been developed. In this concentric-tube model the gap is varied by changing the curvature of the CT. Model results show excellent agreement with both experimental and 3D FEM model results. RMSE in the 0 to 5 mm gap range, the expected range of minimum gap at the bottom of the fuel channel, is less than 0.1 mm, and at maximum gap relative error is 1% for a 4.2 kHz excitation frequency.

In the coming year development of inverse models based on analytical planar and semi-analytical concentric-tube models will be investigated for the simultaneous extraction of gap, resistivity and PT wall thickness from experimental gap data. In addition, the effect of LISS nozzles on gap measurement will continue to be investigated experimentally.

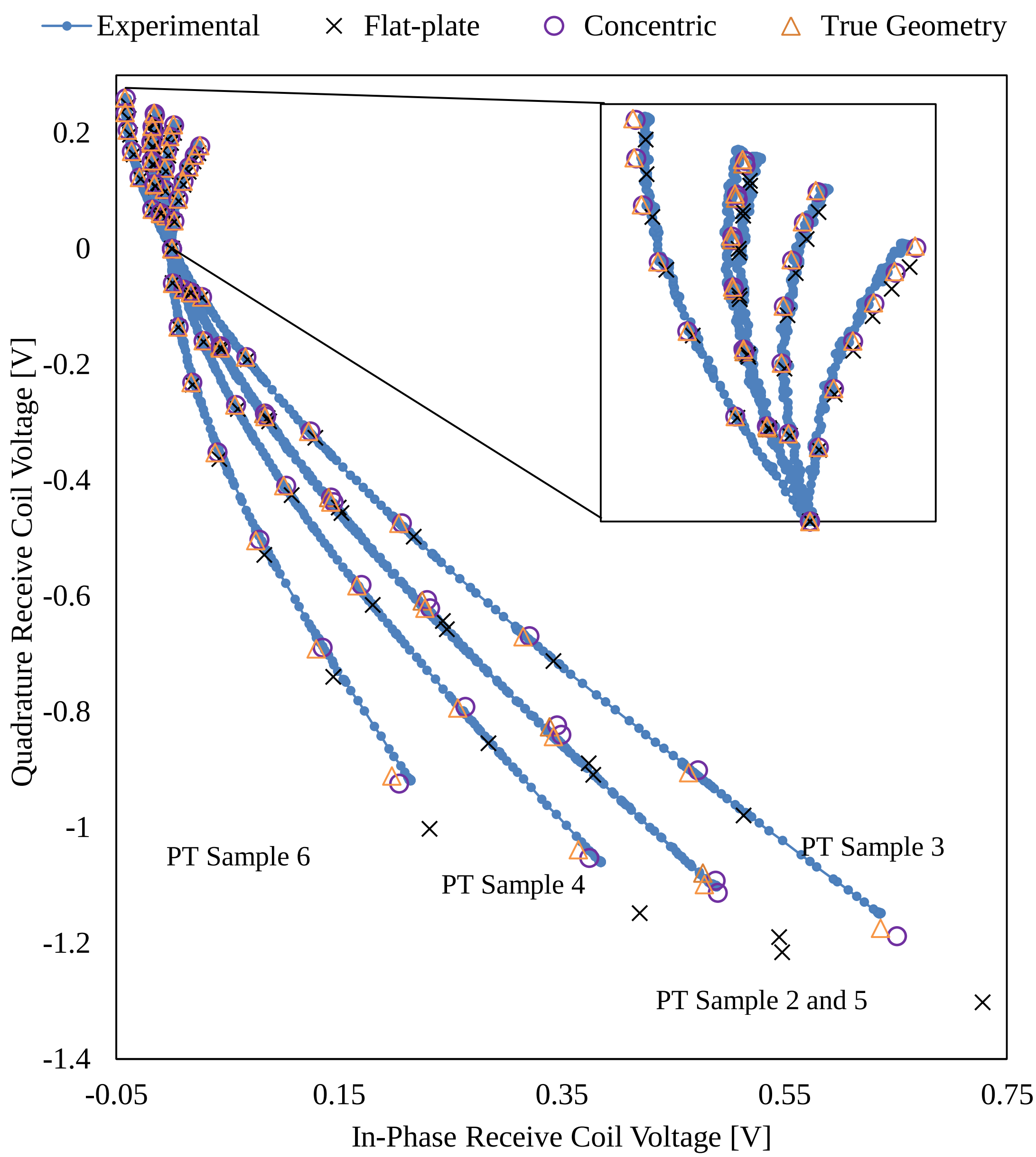

Figure 3: Impedance plane display of receive coil's voltage for concentric tube (o), flat-plate (×) and FEM true geometry (△) models compared with experimental results (•) for PT Samples 2 to 6 at 4.2 kHz. Inset in upper right corner shows a blow-up of signal and model response for 9 mm to maximum gap [5].

References

1. S. Shokralla and T.W. Krause, 'Methods for Evaluation of Accuracy with Multiple Essential Parameters for EC Measurement of PT-CT Gap in CANDU® Reactors', CINDE Journal, 35, No. 1, Jan/Feb 2014, pgs. 5-8.

2. S. Shokralla, S. Sullivan, J. Morelli, T. W. Krause, ‘Modelling and Validation of Eddy Current Response to Changes in Factors Affecting Pressure Tube to Calandria Tube Gap Measurement’, NDT&E International, 73, March 2015 Pgs. 15-21.
3. S. Shokralla, T.W. Krause, J. Morelli, ‘Surface Profiling with High Density Eddy Current Non-Destructive Examination Data’, Nondestructive Testing and Evaluation International, 62, March 2014, pgs. 153-159.
4. M.S. Luloff, ‘Numerical Modelling of Eddy Current Probes for CANDU® Fuel Channel Inspection’, M.A.Sc. Thesis, Queen’s University, Kingston, ON, Sept. 2016.
5. G. Klein, ‘Comprehensive Modelling for Eddy Current Based Pressure Tube to Calandria Tube Gap Measurements’, M.A.Sc. Thesis, Queen’s University, Kingston, ON, August 2017.
6. G. Klein, M.S. Luloff, J. Morelli, T.W. Krause, ‘Evaluation of Concentric Tube Model for Pressure Tube to Calandria Tube Gap Measurement’, IEEE Sensors Journal, to be published.

<u>Cases with Realized outcomes to Industry</u>

Mark Luloff has implemented analytical models of the gap response at CNL [4,7].

<u>Research Facilities and Equipment</u>

Royal Military College possess an MS5800 eddy current system as used for in-reactor inspections and 3 COMSOL licences operated on dual-quad workstations with average of 180 GBytes RAM, each, as well as coil winding equipment and 3D printing capability.

<u>Current HQP</u>

One Masters Level student (Perryn Bennett).

<u>HQP that Graduated</u>

Geoff Klein (November 2017)

<u>Publications /Journal Papers</u>

Peer Reviewed Journal Publications

7. G. Klein, J. Morelli, T.W. Krause, ‘Analytical Model of the Eddy Current Response of a Drive-Receive Coil System inside Two Concentric Tubes’, NDT&E Int. Vol. 96, June 2018, Pgs. 18-25. https://doi.org/10.1016/j.ndteint.2018.03.003.
8. M. S. Luloff, D. Desjardins, J. Morelli and T. W. Krause, “Solution for a Transmit-Receive Eddy Current Probe above a Layered Planar Conductive Structure,” NDT&E Int. Vol. 96, June 2018, Pgs. 1-8. https://doi.org/10.1016/j.ndteint.2018.02.003

Conference Proceedings

9. G. Klein, J. Morelli and T.W. Krause, ‘Model Based Optimization of Driver-Pickup Separation for Eddy Current Measurement of Gap’, 44th Annual Review of Progress in Quantitative Nondestructive Evaluation, Vol. 1949, (© 2018 AIP Publishing, Melville), AIP Conf. Proc., 110006, 6 Pgs.
10. P. Bennett, P.R. Underhill, J. Morelli and T.W. Krause, ‘Eddy Current Proximity Measurement of Perpendicular Tubes from within Pressure Tubes in CANDU© Nuclear Reactors’, 44th Annual Review of Progress in Quantitative Nondestructive Evaluation, Vol. 1949, (© 2018 AIP Publishing, Melville), AIP Conf. Proc., 230009, 4 Pgs.

Conference Presentations/Poster (not repeated from above)

11. P. Bennett, P.R. Underhill, J. Morelli, T.W. Krause, ‘Eddy Current Measurement Of Proximity Of LISS Nozzles To Fuel Channels In CANDU Nuclear Reactors’, NDT in Canada 2018 Conference, Halifax Convention Centre, June 19-21, Student Poster Competition, First Place Winner.
12. P. Bennett, P.R. Underhill, T.W. Krause, ‘LISS Nozzle – Fuel Channel Proximity Measurements’, Ignite Durham 2017, OPG Boardroom Competition, Whitby Town Hall,575 Rossland Road East, Whitby Nov.29, 2017. Semi-finalist Presentation to OPG Boardroom judges.
13. P. Bennett, P.R. Underhill, J. Morelli, T.W. Krause, ‘Proximity Measurements of LISS Nozzles to CANDU Fuel Channels using the Eddy Current Gap Probe’,11th International Conference on CANDU® Maintenance and Nuclear Components, Toronto Marriott Downtown Eaton Centre Hotel, Oct 1-4, 2017

Interactions /Consultations to Industry

14. P. Bennett, P.R. Underhill, J. Morelli, T.W. Krause, ‘Parameters Affecting LISS Nozzle – Pressure Tube Proximity Measurement using the Gap Probe’, 230 Westney Road, Station P55-4 Ajax, ON, Apr. 25, 2018.
15. G. Klein, J. Morelli and T.W Krause, ‘Comprehensive Modelling for Eddy Current Based Pressure Tube to Calandira Tube Gap Measurements’, 230 Westney Road, Station P55-4 Ajax, ON, Apr. 25, 2018.
16. P. Bennett, P.R. Underhill, T.W. Krause, ‘LISS Nozzle – Fuel Channel Proximity Measurements’, Ignite Durham 3 Minute Pitch Competition, Darlington Energy Complex, 1855 Energy Drive, Courtice, ON, Nov. 14, 2017.
17. G. Klein, J. Morelli and T.W Krause ‘ Comprehensive Modelling for Eddy Current Based Pressure Tube To Calandria Tube Gap Measurements’, Ontario Power Generation, 230 Westney Road, Ajax, Ontario, Aug. 31, 2017.
18. P. Bennett, K. Faurschou, J. Morelli and T.W Krause ‘Identification of frequencies for the minimization of lift-off effects in gap measurement’, Ontario Power Generation, 230 Westney Road, Ajax, Ontario, Aug. 31, 2017.
19. G. Klein, J. Morelli and T.W Krause, ‘ Comprehensive Modelling for Eddy Current Based Pressure Tube To Calandria Tube Gap Measurements’, Canadian Nuclear Laboratories, Chalk River Laboratories, Aug. 24, 2017.
20. P. Bennett, K. Faurschou, J. Morelli and T.W Krause, ‘Identification of frequencies for the minimization of lift-off effects in gap measurement’, Canadian Nuclear Laboratories, Chalk River Laboratories, Aug. 24, 2017.