Comparison of 2D and 3D FEM Models of Eddy Current Pressure Tube to Calandria Tube Gap Measurement

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Abstract: The separation between the pressure tube (PT) and calandria tube (CT) in CANDU® nuclear reactors is measured using eddy current based technology. However, there is currently no three dimensional model of the eddy current based gap measurement system. Current models use flat plates to approximate the pressure and calandria tubes. In this paper a flat plate model was shown to diverge from the solutions of a curved model, therefore demonstrating that a curved model is needed to accurately reproduce the measurement of gap between PT and CT. Curved finite element method model results, obtained using COMSOL®, were compared with experimental probe measurements. It was shown that the curved model accurately reproduces probe response under nominal variations in the pressure tube wall thickness. Curved model estimates of gap were to within ~0.1 mm for PT to CT gaps less than 10 mm, but increased to ~1 mm at maximum gap.

Keywords: Eddy Current, Fuel Channel, CANDU, Pressure Tube, Calandria Tube

1. Introduction

CANDU® (CANadian Deuterium Uranium) nuclear reactors employ up to 400 fuel channels each consisting of a 6 m long pressure tube (PT) held within a larger diameter calandria tube (CT) [1]. The hot PT (~300°C) and cooler CT (~50°C) are separated (the PT-CT gap) by a gas annulus maintained by four garter spring spacers. Nuclear fuel bundles are contained inside the PT and heavy water is used for heat transport as well as serving as a nuclear moderator. Pressure, heat and irradiation effects can cause sag and diametral creep deformation of the PT. Under extreme conditions the sag of the PT can cause PT-CT contact. Due to the temperature differences between the PT and the CT this contact can lead to hydrides precipitating in the PT. Hydride blisters can then form on the outer surface of the PT and these blisters can result in cracking and consequent failure of the PT. As such, reactor operators are required to have fuel channels inspected periodically to ensure that contact is not imminent and this may be done by measuring the PT-CT gap. The current technique to measure the PT-CT gap uses an eddy current based system. The eddy current method uses one drive coil and a pick-up coil with coil axes oriented perpendicular to the PT inner surface at some liftoff (LO) as shown in **Figure 1**. The LO is defined to be the distance between the nearest surface of a coil and the inner surface of the PT. The generation of a validated model is further motivated by a qualification process that is required in order to determine how sensitive the inspection system’s measurements are to variation of in-reactor parameters [2] and whether measurement objectives can be met as outlined in an Inspection Specification [3].

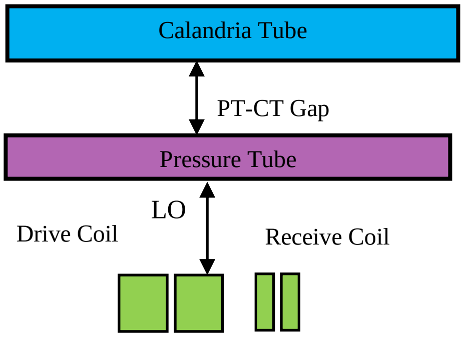

***Figure 1**: 2D representation of the PT-CT gap measurement.*

Analytic models, using a flat plate geometry have been constructed for the case of constant current amplitude excitation and coaxially oriented coils [4], using Dodd and Deeds’ solution [5]. The flat plate model only considers the driver and pick-up coil, which is a reasonable approximation due to the small coil spacing of approximately 11 mm relative to the nominal inner circumference of the PT of 330 mm [4]. This model, which also assumes a coaxial configuration for the driver and receive coil, has been validated against experimental data for resistivity and wall thickness [4].

2. Use of COMSOL Multiphysics® Software

2.1 Overview of the Flat Plate and Curved Model

The PC-CT gap probe model currently approximates the PT and CT as flat plates [4]. Curved and flat plate models of the PT-CT gap system were both designed in COMSOL® Multiphysics 5.2. **Figure 2** shows the curved model, while **Figure 3** shows the flat plate model. To reduce computational resources that are required, both the flat plate and curved model were split in half vertically and symmetry was employed along the cut plane. The sizes of both models were reduced further by removing most of the volume below the coils. The region of interest was above the coils and there is no contribution to the magnetic flux from the PT and CT below the coils. This helped save additional computational resources and time.

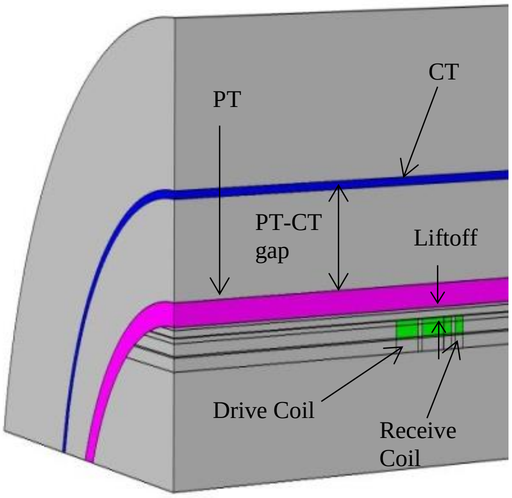

Figure 2*: Curved model for the PT-CT gap measurement system. The blue shows the CT, magenta shows the CT, green shows the coils, and grey shows the surrounding air. The PT-CT gap is 16.9 mm at nominal LO.*

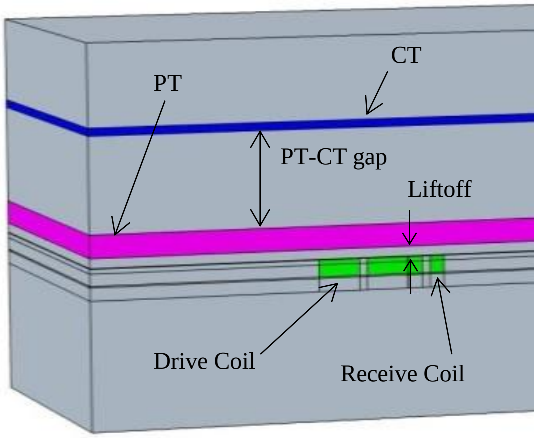

Figure 3*: Flat plate model for the PT-CT gap measurement system. The blue shows the CT, magenta shows the CT, green shows the coils, and grey shows the surrounding air. The PT-CT gap is 16.9 mm at nominal LO.*

The Magnetic Fields physics option was utilized through the AC/DC Module to solve for the voltage induced in the receive coils. This was done using the Coil Geometry Analysis solver and the frequency domain solver with a frequency of 4 kHz. The Electrical Circuits physics option was also used for both geometries to simulate how the voltages are measured with the physical probe, which is discussed below. Each model used a mesh determined by the *Physics Enabled Mesh* options, while setting the mesh on *Fine*. A parametric sweep was used to vary the PT-CT gap of each model.

2.2 Comparing the Flat Plate and Curved Models

Using both the flat plate and curved models the approximation that the flat plate can accurately represent the curvature of the PT-CT gap system for the receive coil was investigated. Both the flat plate and curved models had their PT-CT gaps range from 0.5 mm to 16.9 mm. As well, a comparison of the voltages induced in the far receive coils was examined. The drive coil was excited using a 1 V sinusoidal wave at 4 kHz. **Figure 4** shows the voltage induced in the receive coil based on its real and imaginary voltage components. The voltage responses in both the curved and flat plate models were offset to a PT-CT gap of 0.5 mm so both models could use a common reference point.

From **Figure 4** it can be observed that the flat plate approximates the curved PT-CT geometry model results for small PT-CT gaps. This small PT-CT gap region is the critical region for the CANDU® reactors as it represents the situation when the PT and CT are close to contact. However, as seen from **Figure 4** the flat plate and curved models diverge as the PT-CT gap increases.

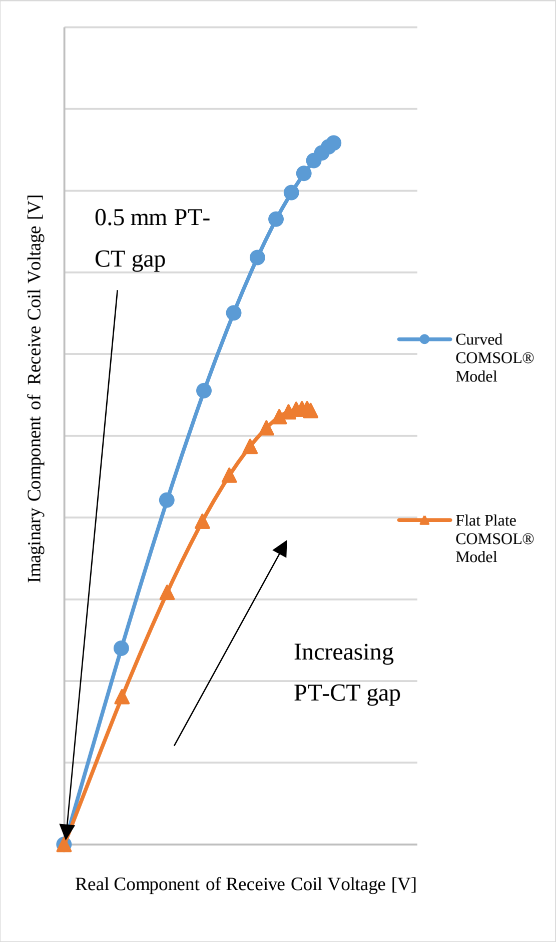

***Figure 4**: The real and imaginary voltage calculated in the receive coil as the PT-CT gap is varied for both the flat plate and curved COMSOL® models. The drive coil was induced by a 1 V, 4 kHz sinusoidal excitation. The PT-CT gap ranged from 0.5 mm to 16.9 mm. The PT wall thickness was modelled at 3.76 mm.*

Figure 5 shows the same results as **Figure 4**, but the flat plate responses have been scaled and rotated to match the curved response. The scaling factor was determined by finding the factor necessary to match the magnitude of the voltage response between the flat plate and curved models at maximum PT-CT gap.

In **Figure 5** it is can be seen that the results from the rotated and scaled flat plate model have the same shape as the results from the curved model. However, discrete voltage responses corresponding to the same PT-CT gaps do not agree. This shows that PT-CT gap measurements using the scaled and rotated flat plate model will overestimate of the PT-CT gap of the system.

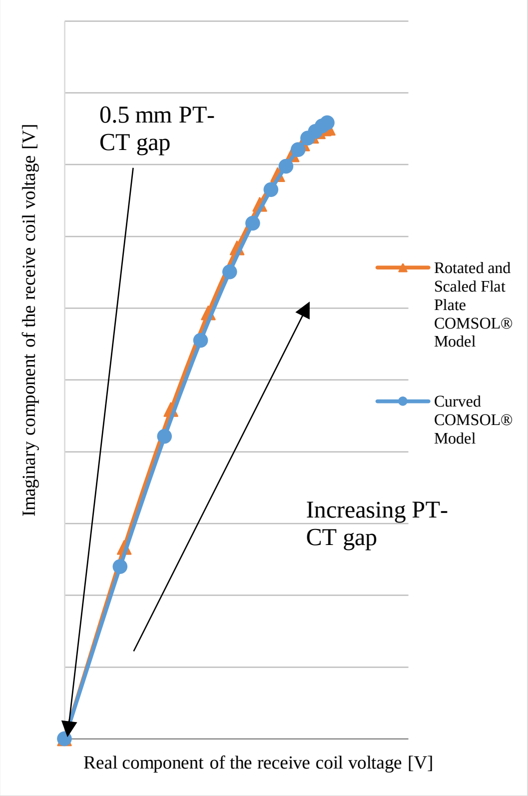

***Figure 5**: The PT-CT gap response from **Figure 4** where the flat plate response is scaled and rotated to match the curved model results.*

3. Experimental Validation

3.1 Experimental Setup

To be able to validate models, experimental measurements are required. This was achieved by using an in-house built probe as shown in **Figure 6**.

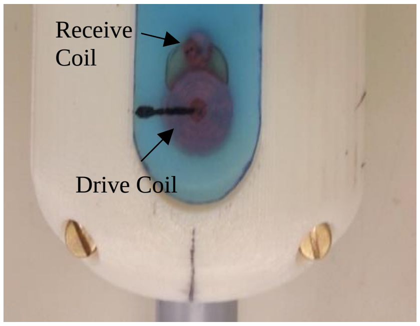

***Figure 6**: In-house built PT-CT gap probe.*

PT-CT gap measurements were performed using MS5800 data acquisition eddy current instrument with accompanying data acquisition system, and PT and CT samples. The PT samples were provided by Ontario Power Generation (OPG) Inc. The MS5800 excited the drive coil with a 1 V sinusoidal amplitude at 4 kHz.

Due to amplification and phase rotation from the MS5800 the FEM modelled responses must be calibrated to the experimental results. This was done by determining scaling and rotation fitting parameters to match the FEM model to experimental results. The fitting parameters obtained were then applied to the non-calibrated model results. These were then compared against experimental results to verify that the model follows the same trend as the experiment.

3.2 Wall Thickness Validation

Using the curved model, shown in **Figure 3**, the wall thickness (WT) of the PT was varied. For each PT WT the receive coil voltage response was calculated at different PT-CT gaps. The modelled PT-CT gaps ranged from 0.5 mm to 16.9 mm. The experimental PT-CT gap ranged from contact to approximately 16 mm. The PT had characterized wall thickness, shown below and an electrical resistivity of 50.8 μΩ·cm.

Figure 7 shows the comparison of the curved FEM model's response, after calibration to an experimentally measured PT-CT gap profile at a PT WT of 4.38 mm. The arrow also shows the direction of increasing PT-CT gap. The fitting parameters used to determine the calibration were obtained by comparing the FEM results at a WT of 4.40 mm to experimental measurements at the same WT.

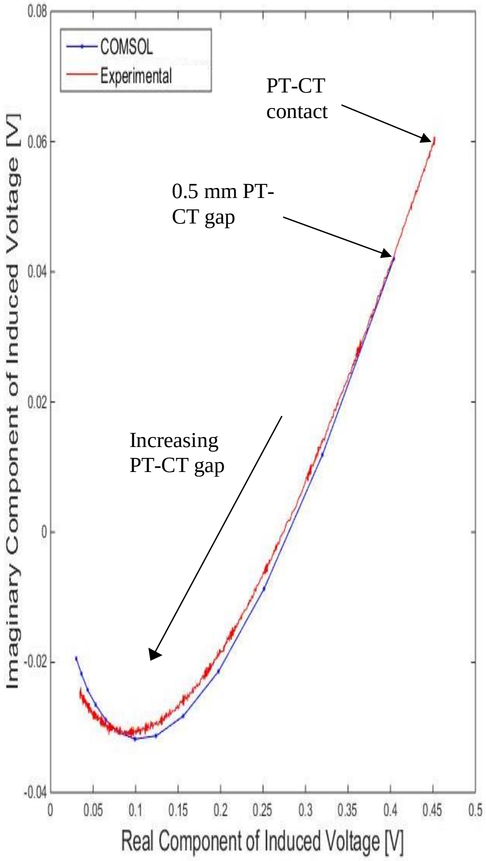

***Figure 7**: Comparison between model and experimental PT-CT gap measurements for PT sample with 4.38 mm wall thickness, after the FEM results were calibrated to experimental measurements.*

4. Results and Discussion

As seen from **Figure 4** the response in the receive coil from the flat plate model diverges from the curved model. If the flat plate model is scaled and rotated appropriately, then it can achieve the same shape as the curved model's results, as observed in **Figure 5**. However, even though there is a good shape agreement, the discrete points are not in as good agreement, showing that the voltage responses for the same PT-CT gaps do not agree. The scaled and rotated flat plate model results underestimate the PT-CT gap based on complex voltages for small gaps.

Figure 8 shows the error in PT-CT gaps of both the flat plate and curved FEM models when compared to the measured gap values using a 4.38 mm PT sample. The errors were obtained after the FEM model results were calibrated to experiment and were calculated based on Equations 1 and 2 below. In Equations 1 and 2 EMF_{model} and EMF_{exper} refer to the modelled and experimental PT-CT gap voltage results, respectively. Also, in Equation 2 ΔGap is a constant 1 mm.

$$error_{gap} = \frac{\left[Re\left\{\left(EMF_{model}-EMF_{exper}\right)^{2}\right\}+Im\left\{\left(EMF_{model}-EMF_{exper}\right)^{2}\right\}\right]^{\frac{1}{2}}}{\frac{\mathrm{dEMF_{exper}}}{\mathrm{dGap}}} \quad (1)$$

$$\frac{dEMF_{exper}}{dGap} \cong \frac{\Delta EMF_{exper}}{\Delta Gap} = \frac{\sqrt{Re\left\{EMF_{exper}\right\}^{2}+Im\left\{EMF_{exper}\right\}^{2}}}{\Delta Gap} \quad (2)$$

The results in **Figure 8** used a PT sample with a 4.40 mm WT for calibration. The error in the PT-CT gap of the flat plate model is larger than the curved model. The larger error in the flat plate model shows that it is necessary to consider the curvature of the PT-CT gap geometry and that a curved model is necessary to accurately reproduce PT-CT gap measurements.

Table 1 shows the PT-CT gap errors calculated using Matlab$^{©}$, comparing the FEM model and experimental results for the response in the receive coil for varying PT WT. The average PT-CT gap errors agree with the overall trend that PT-CT gaps under 10 mm have errors on the order of a tenth of a millimeter. For gaps greater than 10 mm the error increases and is on the order of a millimeter at 16 mm gap.

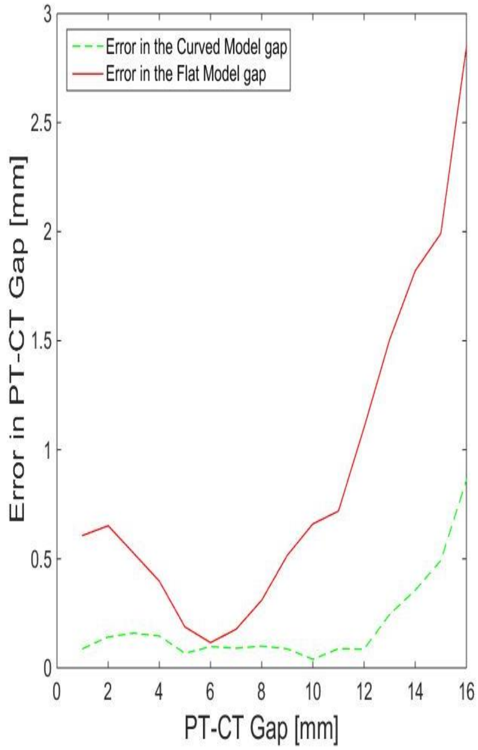

***Figure 8**: Errors in the modelled PT-CT gap for both the flat plate and curved FEM models. Models were compared to measurements using the 4.38 mm PT sample.*

***Table 1**: Error in the PT-CT gap when comparing the curved FEM model and experimental measurements for the voltage response in the receive coil for nominal pressure tube wall thickness (WT) variation.*

Wall Thickness [mm]	PT-CT Gap Error [mm]			
	1 mm Gap	5 mm Gap	10 mm Gap	16 mm Gap
4.40[1]	0.08	0.05	0.17	2.7
4.38	0.09	0.07	0.04	0.9
4.36	0.06	0.12	0.05	1.4
4.34	0.07	0.25	0.15	1.3
4.28	0.18	0.22	0.17	0.9
4.26	0.26	0.18	0.14	1.4
Average	**0.12**	**0.15**	**0.12**	**1.4**

[1] Results at 4.40 mm were used as calibration data for voltage rotation and scaling.

From **Figure 7** it is clear that there is some discrepancy between the model and experiment. One observation is that at smaller PT-CT gaps, the curve from the COMSOL® FEM model results do not go as far to the right as the experimental results. This is attributed to the experiment having PT-CT contact, a gap of zero, whereas the model had a minimum PT-CT gap of 0.5 mm. It may also be observed in **Figure 7** that at large PT-CT gap the agreement between the modelled and experimental results is not as good as for smaller PT-CT gaps. It is anticipated that the effects of curvature will scale with coil spacing. Therefore, larger coil spacing will demonstrate an even larger error if PT curvature is not taken into account.

5. Conclusion

The PT-CT gap of CANDU® reactors is measured using eddy current technology. An understanding of how PT-CT gap measurements vary due to changes in the system's parameters is required for establishing the accuracy of the measurement. In COMSOL® flat plate and curved models of the EC based measurement were designed. These models were able to show that the solutions from the flat plate model diverged from the curved model. Rotating and scaling the flat plate model resulted in a good shape agreement with the curved model, but the discrete PT-CT gap points did not agree as well.

Using an in-house manufactured probe, experimental measurements of PT-CT gap profiles were taken and compared against the curved model for variation in the PT WT. The curved model was in good agreement with experimental results under nominal PT WT variations.

Comparing the accuracy of the flat plate and curved models showed that the flat plate model had larger errors in its predicted PT-CT gaps. The error was especially noticeable in the regions of smaller PT-CT gap, when it is critical to be able to have accurate gap measurements as it is more likely for PT-CT contact to occur. When comparing the curved model to experimental data, the error in the modelled PT-CT gap was approximately 0.1 mm when the PT-CT gap was below 10 mm. The flat plate model had an error of approximately 0.5 mm compared to the experimental data when the PT-CT gap was below 10 mm. Above 10 mm, the error in gap increases in the curved model to approximately 1.0 mm and the flat plate model's error increases to approximately 3 mm. Therefore, since the error in the gap from the flat plate model is larger, especially in the critical small gap region, it is necessary to account for curvature of the PT-CT gap geometry in order to achieve the most accurate predictions the PT-CT gap.

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