Finite Element Modeling for Inspection of CANDU® Steam Generators

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Abstract: Steam generators (SGs) are used in CANDU® nuclear reactors as heat exchangers to convert water into steam using heat generated in the reactor core. Ferrous trefoil broach support structures prevent excessive vibration of thousands of SG tubes. A probe that uses pulsed eddy current (PEC) technology has been designed for inspection of support structures, from within SG tubes, to detect and characterize degradation and fouling. The probe design has six surface pick-up coils, three on either side of a drive coil that is coaxial with the SG tube. Pick-up coils are arranged every 120° to coincide with the geometry of the broach supports. The PEC probe signal was simulated using COMSOL Multiphysics to observe the effects of various stages of support structure degradation. The modeled results demonstrated potential for PEC to detect broach support wall reductions of 100%, 50%, and 25%.

Keywords: Pulsed eddy current, steam generators, trefoil broach supports.

1. Introduction

Steam generators (SGs) are a critical component of nuclear power generation. Heat generated in the reactor core is transferred to high pressure primary water, which passes over the hot fuel. Primary water then passes through thousands of Alloy-800 tubes in the SG, exchanging heat with the secondary water, which is converted to steam that powers a turbine. SG tubes are supported by ferrous broach support structures, which have a trefoil hole, as shown in Figure 1. This allows SG tubes to be supported and prevents excessive vibration, while allowing the secondary water to easily pass through the flow regions past the tubes.

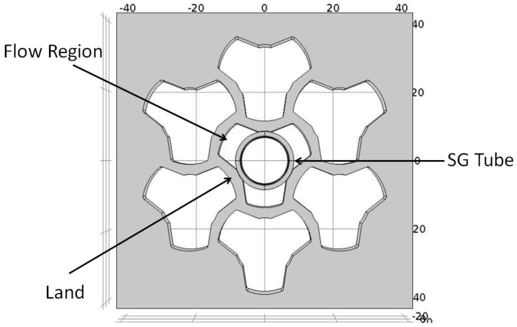

Figure 1: Broach support structure design used in CANDU® SGs.

Combined with preventative maintenance programs, inspection of SG tubes and support structures can be used to extend reactor life. Current inspection methods use conventional eddy current technology (ECT), however this technique is limited in its capability to effectively examine degradation and fouling of ferrous support structures from within Alloy-800 SG tubes [1]. ECT uses a sinusoidal voltage to drive an excitation coil and generate eddy currents in a material, which are received by pick-up coils. In contrast pulsed eddy current (PEC) utilizes square pulse excitation. PEC has been found to have a larger depth of penetration and greater magnetization of ferromagnetic materials [2]. The penetration of electromagnetic fields in PEC can be described in terms of a diffusion time [3], [4], given by:

$$\tau \sim \mu \sigma \boldsymbol{\ell}^2$$

where μ is the permeability, σ is the conductivity, and $\boldsymbol{\ell}$ is the characteristic length of the system. The square pulse excitation in PEC can be considered as a series of discrete frequencies with approach to constant field, whereas ECT typically examines structures using only up to four frequencies.

Recently, a method to inspect ferrous support structures in CANDU® reactors using PEC technology has been developed [1]. Previous research using PEC as a method to inspect aircraft structures was found to be capable of flaw detection [5], [6], even at remote distances of up to 20 mm.

A PEC probe has been designed using COMSOL to examine degradation and fouling in broach support structures in CANDU® reactors. The design consists of a drive coil, wound coaxially with the SG tube, and six surface pick-up coils mounted perpendicular to it, as shown in Figure 2. Three pick-up coils are on either side of the drive coil. Due to the geometry of the trefoil holes, pick-up coils are arranged at 120° increments to align with the lands of the broach support, as shown in Figure 2.

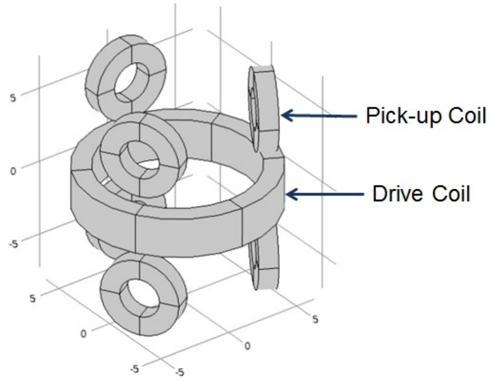

Figure 2: Probe design for broach support inspection.

2. Use of COMSOL Multiphysics

COMSOL Multiphysics version 4.4 was used to model the coil response from inside the Alloy-800 SG tube and broach support structure. The drive coil received a 2.5 V square pulse. Figure 3 shows the normalized magnetic field induced in the broach support by the drive coil. A nominal gap of approximately 0.315 mm separates the SG tube from the broach support structure.

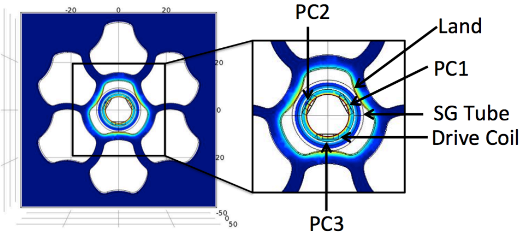

Figure 3: Normalized magnetic field induced in the trefoil broach support structure.

It can be seen in Figure 3 that the field can interact with the broach support from within the SG tube, even at the far side of the lands, which are 0.315 mm away from the 1 mm thick tube wall. This suggests the pick-up coils could detect flaws in this region.

Numerous types of flaws can be investigated with the use of COMSOL. Figure 4 shows an example of a typical flaw modeled in COMSOL, where 50% of the wall material has been removed from the far side of the land. This flaw is typical of wall loss due to turbulent secondary water moving through the trefoil holes.

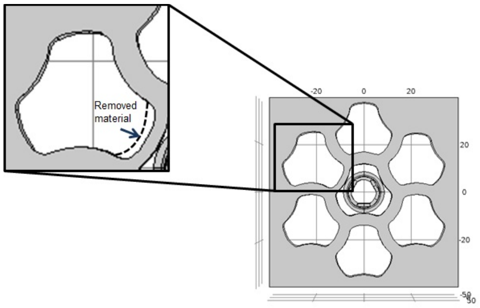

Figure 4: A typical flaw with 50% wall loss.

Modelling response from different types of flaws facilitates evaluation of inspection capabilities. Observing trends in coil response, in the presence of degradation, will assist in characterizing condition of broach supports from PEC signals.

3. Results

The response of one pick-up coil is shown in Figure 5. This response is taken from within the Alloy-800 SG tube inside an unflawed broach support. The approximate peak height of the response is 6.4 mA and the coil has an approximate resistance of 32 Ω. This same transient response is observed by all remaining pick-up coils when no flaws are present.

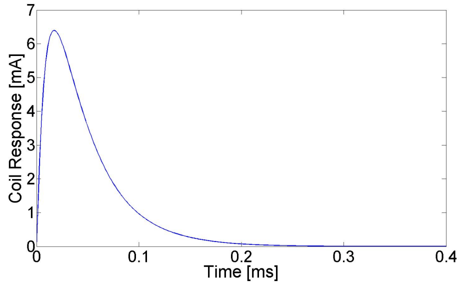

Figure 5: Pick-up coil response obtained from unflawed broach support structure.

Pick-up coil responses can be compared for a flaw in the broach support wall. First, to determine if detection is possible, 100% of the far side of the land material was removed. When the coil responses were compared on a semi-log plot a clear distinction is evident, as shown in Figure 6.

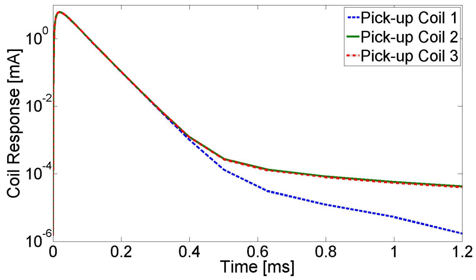

Figure 6: Pick-up coil responses when 100% of flow region has been removed.

For results shown in Figure 6, pick-up coil 1 (PC1) was aligned with the flaw, and pick-up coil 2 (PC2) and pick-up coil 3 (PC3) were aligned with the unflawed portion of the broach support. PC1 has a smaller response compared to PC2 and PC3 due to the reduced amount of ferrous broach material present. This suggests that detection of flaws is possible. To improve reactor maintenance and inspection programs, degradation must be characterized well before 100% wall loss occurs.

Figure 7 shows the pick-up coil responses when 50% of the wall was removed. Interestingly, the separation between PC1, and PC2 and PC3 occurs much later in the pulse, and the separation between the curves is reduced when compared to the 100% wall removal case. These differences are attributed to the additional remaining ferrous material

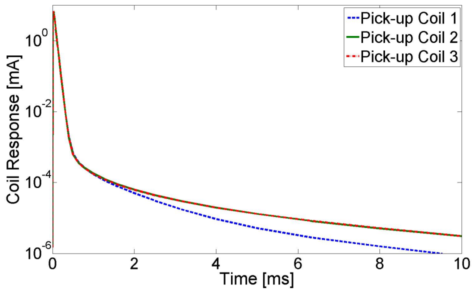

Figure 7: Pick-up coil responses when 50% of land has been removed.

Figure 8 shows the pick-up coil responses when the far flow region wall is reduced by 25%. Similar to the 50% wall loss, the separation between PC1, and PC2 and PC3 occurs later in the pulse and the separation between the curves is reduced.

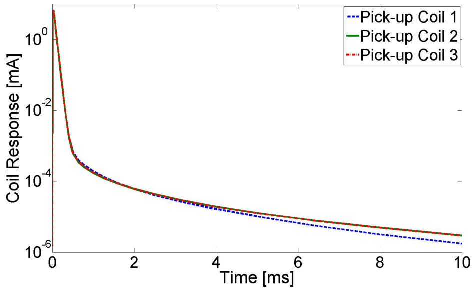

Figure 8: Pick-up coil responses when 25% of the land is removed.

4. Discussion

The results presented here show that detection of flaws in broach support structures may be possible using the proposed six-coil PEC probe. The modeled probe detected 100%, 50%, and 25% removal of the land wall material.

A method to characterize the percentage of degradation could be developed using the time where the pick-up coil responses separate or using the amount of separation between the pick-up coil responses. As the amount of degradation increases, the location of the separation occurs earlier in the pulse. This could be used to generate a calibration curve for in-service inspection.

The difference in the pick-up coil responses increases more at later times with increasing degradation. Again, this could be calibrated to determine the percent degradation based on amount of separation between responses.

5. Conclusions

Current inspection methods use conventional eddy current technology (ECT) to examine SGs, however ECT lacks capability to inspect ferrous support structures. A probe that utilizes PEC technology has been developed to more accurately characterize degradation in trefoil broach support structures.

The probe has been designed with six surface pick-up coils, three on either side of the drive coil, which aligns with the 120° symmetry of the trefoil shape. COMSOL Multiphysics was used to simulate this probe design.

Modeled results showed that detection of wall loss within the support structure is possible using the proposed novel probe design. Characterization of percentage degradation could be achieved by using a calibration curve based on location and slope of separation between pick-up coil responses for flawed and unflawed cases.

6. References

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7. Acknowledgements

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