Pulsed Eddy Current Response to Magnetite at Broach Supports in Steam Generators

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Summary

Detection of corrosion and build up of corrosion products, such as magnetite, in CANDU® Steam Generators (SGs) at tube supports is critical for monitoring of SG condition. A Pulsed Eddy Current (PEC) probe has been developed to enhance SG inspection at support structures. The PEC probe demonstrated capability to detect magnetite at simulated broach support structures. Results were used to validate Finite Element Method(FEM) modeling of PEC signal response to magnetite. The validated FEM modelcan be used to further explore effects of magnetite on PEC probe responses.

1. Introduction

Steam Generators (SGs) are a central component of nuclear power generation, converting heat from the reactor core into steam that drives turbines for electric power generation. In CANDU® reactors thousands of Alloy-800 SG tubes, supported by ferrous support structures, are required for this process. SGs are part of the reactor coolant pressure boundary, helping to maintain the primary system's pressure and coolant supply as well as acting as a barrier to quarantine radioactive fission products [1].

Over time, tubes and support structures may begin to degrade due to numerous issues such as tube vibrations, flow-assisted corrosion, and build up of corrosion products [2]. Inspection of SG tubes and support structures is crucial for maintaining reactor functionality, safety and, when combined with preventative maintenance programs, can aid in extending reactor life [3]. Typically, the goal of SG inspections is to detect flaws in tubes, such as tube denting, cracking, or fretting and thinning. In order to further assess SG condition, it is desirable to monitor build up of corrosion products and degradation of ferromagnetic support structures.

Broach support structures have trefoil shaped holes, as represented by the simulated broach support shown in Figure 1. This unique shape allows water to flow past tubes, required for heat exchange, while still supporting SG tubes and minimizing tube vibrations. Major sources of degradation in broach support structures are a result of flow-assisted corrosion, which deteriorates the webbing in the broach support. Additionally, tube vibration can cause tubes to rub against lands, causing wear damage to support structures and fretting in SG tubes[4].

Magnetite is a hard sludge that forms from contaminants that appear in the secondary water system [2], and can pile up on tube sheets or broach support structures as indicated in Figure 1. These contaminants can appear from many sources, such as corrosion of support structures, or from impurities in water chemistry [5].Magnetite may also be deposited on the inside of SG tubes as a result of flow assisted corrosion of feeder tubes [3]. Large build ups of magnetite in SGs can lead to loss of reactor efficiency or unplanned reactor shut downs and therefore, early detection of magnetite is an important aspect of SG inspection [6].

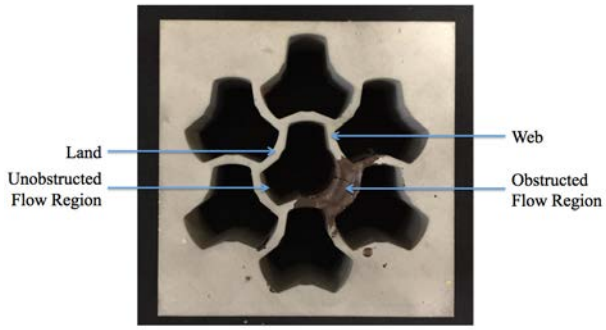

Figure 1 Sample broach support structure, exhibiting trefoil shape, with obstructed flow hole.

Currently, SGs are inspected using conventional Eddy Current Technology (ECT), however this method is insufficient for assessing ferrous support structure condition from within SG tubes, and is limited in its capability to characterize degradation and fouling [7]. Pulsed Eddy Current (PEC) is an emerging technology that has demonstrated potential to inspect support plate condition from within SG tubes [5][8]. PEC technology may be considered as complementary to conventional ECT. Whereas ECT uses a sinusoidal excitation, PEC utilizes a square pulse excitation to induce eddy currents within a sample. The frequency rich nature of the square pulse generates a breadth of information that may be correlated with characteristics of the sample or structure being examined. PEC technology has been shown in previous work to have a greater depth of penetration [7] and a reduction in effects due to lift off [9], when compared to conventional ECT.

This work uses Finite Element Method (FEM) to model a PEC probe design targeted for the inspection of broach support structures and evaluates its ability to detect the presence of magnetite that is external to SG tubes in broach supports. The FEM model is validated by experimental measurements of simulated magnetite introduced into the flow holes of a replicated broach support as shown in Figure 1.

2. FEM Model

Modeling of probe response was conducted using COMSOL Multiphysics 4.4, FEM software.Figure 2 shows the one-thirdmodel used to examine changes in probe response when in the presence or absence of magnetite.A one-third model employs symmetry and was used to decrease computation time. When validated, FEM modelscan be used to quantify pick-up coil response in the presence of varying magnetite conditions, examining such effects as volume, density or location of magnetite on PEC signal response.

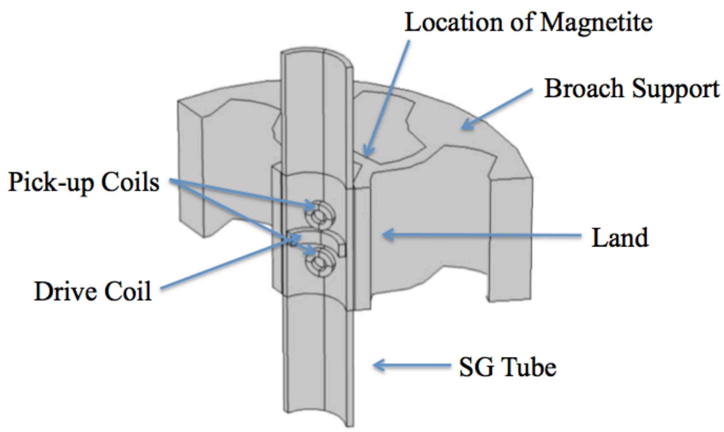

Figure 2 FEM one-third modelfor examining PEC response to magnetite in broach support structures.

3. Experiment

A probe design,modified from that presented in Ref. [10]was used to examine 15.9 mm (5/8”) SG tubes and components. A drive coil was wound coaxial with SG tubes being inspected, and six surface pick-up coils were mounted perpendicular to the drive coil, as shown in Figure 3. Three pick-up coils were positioned above the drive coil, and three below. Pick-up coils were spaced at 120° intervals, to align with broach support structure landsas identified in Figures 1 and 2. Transient responses of the probe’s pick-up coils are sensitive to changes in material components, such as flaws or the presence of magnetite. Observing these changes can provide quantitative measures of SG condition.

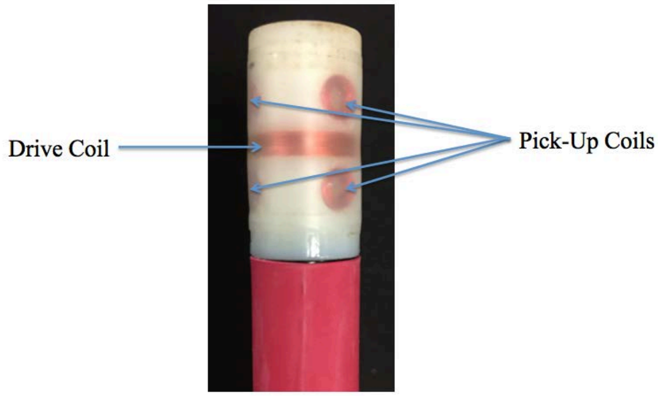

Figure 3 Experimental pulsed eddy current probe (only 4 of the 6 pick-up coils are visible).

The drive coil was excited by a 2.5 V amplitude and 1 ms long square pulse. Signals from pick-up coils were amplified by an external circuit and digitized using a 100 kHz USB NI DAQ. Digitized signals were analyzed using LabView.

To evaluate the sensitivity of the probe, and its ability to detect wall loss and the presence of magnetite, sample broach support structures were constructed to simulate in-reactor conditions. Trefoil shaped holes were water jetted out of one-inch thick stainless steel (SS410) and carbon steel (A516) plates, designed to support Alloy-800 SG tubes.

Sludge was simulated by combining magnetite (Fe_3O_4) powder and hard wax. The hot wax mixture was poured into the sample broach support structures and cooled, simulating obstructed flow regions, as shown inFigure 1.An initial relative permeability of 2.7 was experimentally measured, which is consistent with industry accepted values [11] for permeability of magnetite.

4. Experimental Results and Validation

A sample broach support structure with an obstructed flow region was examined using the six-coil probe. Experimental and simulated results obtained from this experiment are shown inFigure 4.A greater transient response is observed when examining the obstructed flow region, due to the increased relative permeabilityof the simulated magnetite, when compared to the unobstructed flow region.

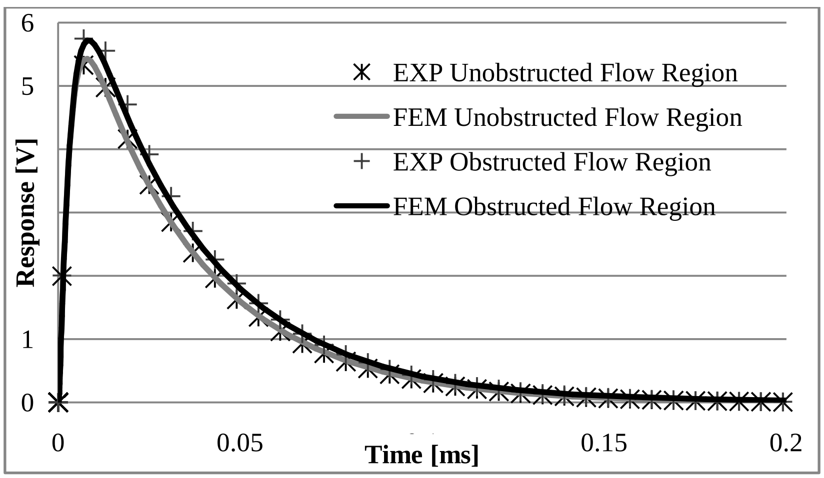

Figure 4 Experiment and FEM comparison of magnetite detection in broach support.

There is excellent agreement between experimental and FEM simulated responses. Using this validated FEM model can provide further insight into pick-up coil responses in the presence of magnetite, such as the case where more or less magnetite has built up around a flow region. Analysis of validated model signals such as peak height or full-width-at-half maximum could be developed to determine information about the volume, composition or location of magnetite. The introduction of 3 additional coils per row (for a total of 6 in each row) would increase the coverage. This is required as there is no control on pick-up coil orientation relative to supports. In addition,this would provide the additional symmetry required to inspect other structures, such as lattice bar supports or quatrefoil broach holes.

5. Conclusion

A PEC technology thatidentifiesthe presence of magnetite in the flow regions of broach support structures has been demonstrated. Signal response was found to be greater when analyzing simulated magnetite samples than when magnetite was absentin flow regions, due to the greater permeability of magnetite. Results were used to validate a COMSOL Multiphysics FEM model of the PEC response. The FEM model could be used to further explore the potential of the modified PEC probe toquantify magnetite build up on broach supports.

6. Acknowledgements

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