Finite Element Modeling for Inspection of CANDU® Steam Generators

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Introduction

Steam generators (SGs) are a critical component of nuclear power generators. SGs act as a heat exchanger to convert water into steam using heat generated in the reactor core. SG tubes are supported by broach support structures, as shown in Figure 1, that have a trefoil shape, which prevents tube vibration while still allowing water to flow past SG tubes.

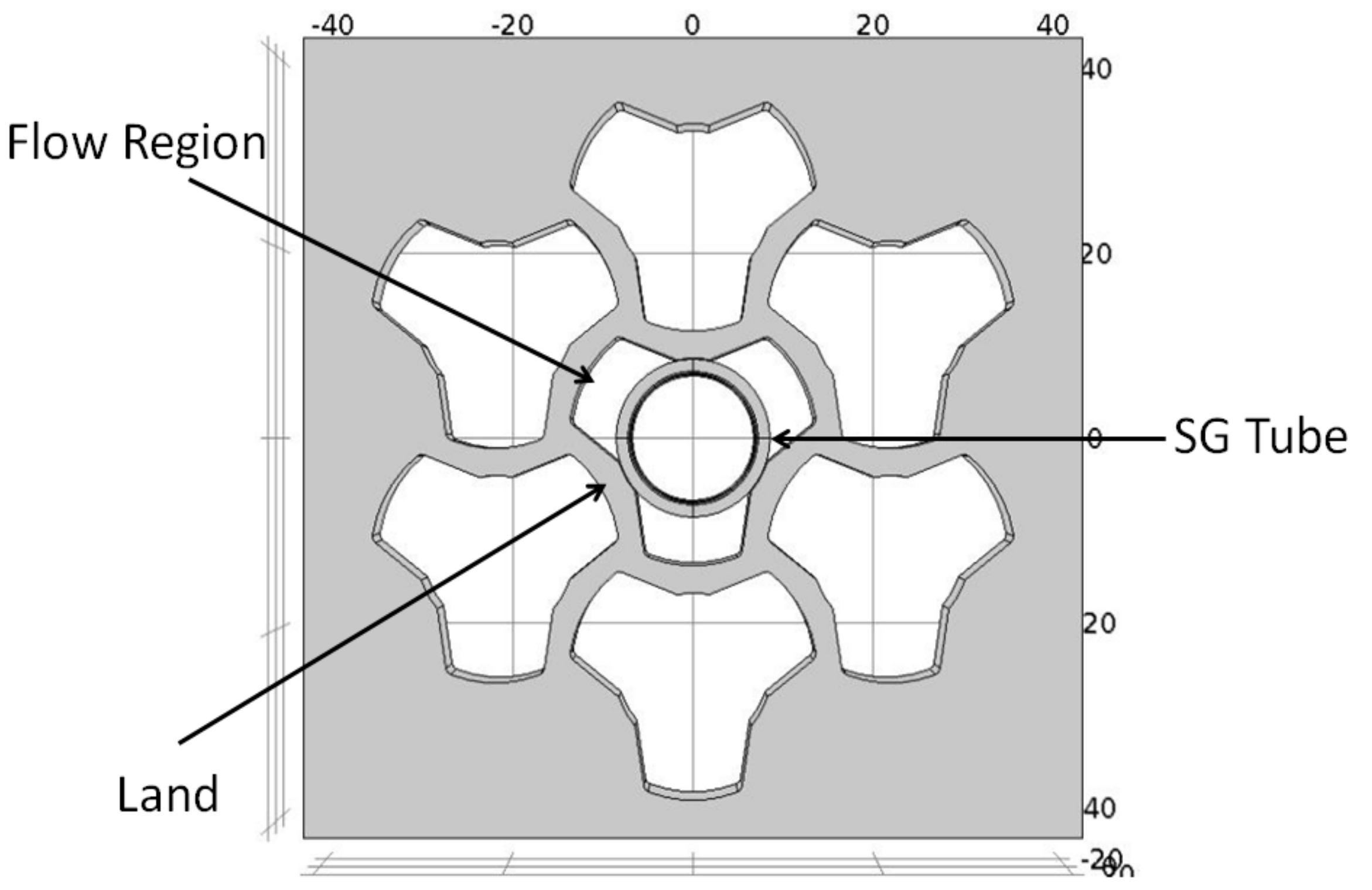


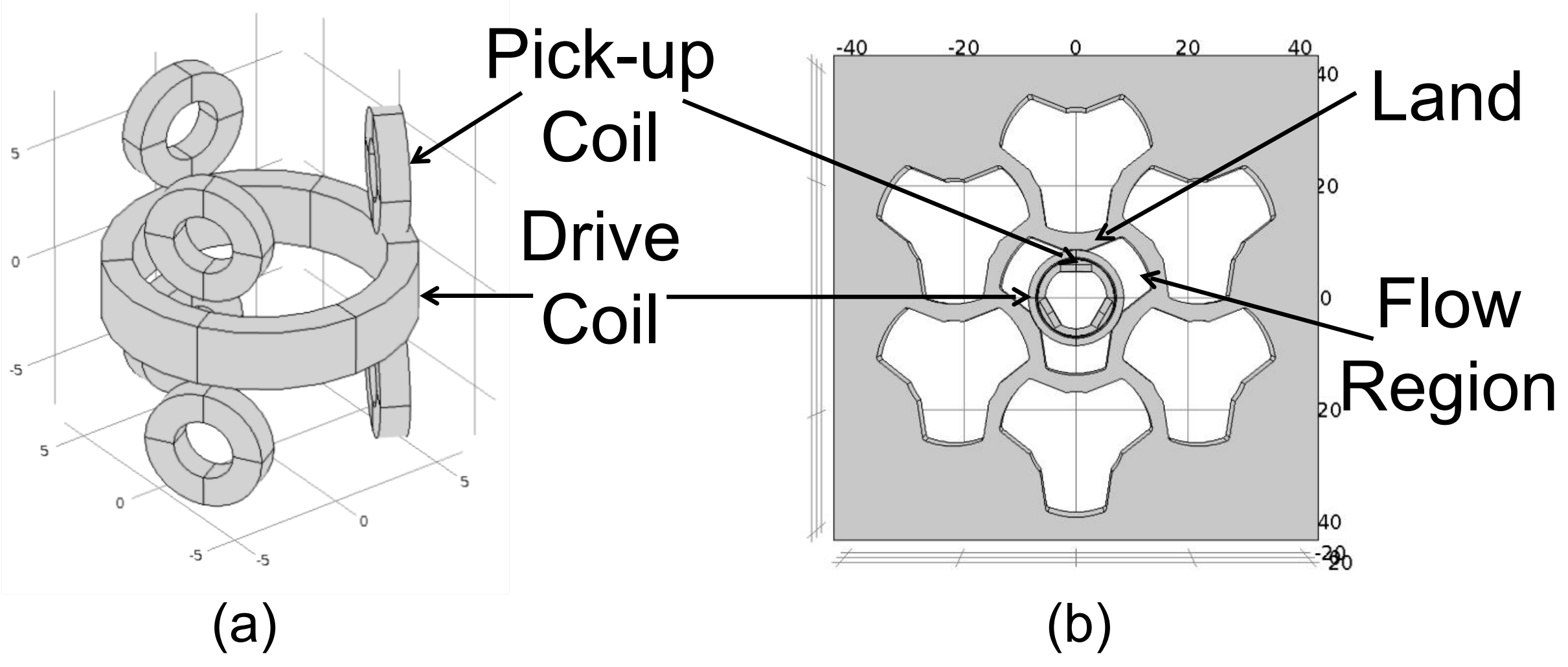
Figure 1: Broach support structure design used to support SG tubes.

Motivation

Inspection of SG tubes and support structures is required for maintaining reactor functionality and, with preventative maintenance programs, can extend reactor life time. Current inspection methods use eddy current technology (ECT) to inspect SGs, however this method is limited in its capability to inspect ferrous broach support structures. A method using pulsed eddy current (PEC) has been developed to more effectively inspect these structures from within Alloy-800 SG tubes.

Probe Design

A probe has been designed to examine broach support structures in SGs from within Alloy-800 SG tubes. The probe design, as shown in Figure 2a, has a drive coil wound coaxially with the tube, and six surface pick-up coils mounted perpendicular to the drive coil. Three pick-up coils are on either side of the drive coil and have a 120° separation between them. Figure 2b shows this separation in the ferrous broach support structure, and the coils can be seen to align with the lands at every 120°.



(a) (b)

Figure 2: (a) Probe design for broach support inspection. (b) Probe alignment with broach support lands .

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Eddy Current Technology

Eddy current technology (ECT) uses a sinusoidal voltage to drive an excitation coil and induce eddy currents in a conducting material, which are sensed 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 [1]. The penetration of electromagnetic fields in PEC can be described in terms of a diffusion time [2], [3], given by:

$$\tau \sim \mu\sigma\ell^2$$

where μ is the permeability, σ is the conductivity, and ***l*** is the characteristic length of the system. The square pulse excitation in PEC can be considered as a spectrum of discrete frequencies which approach to constant field, whereas ECT typically examines structures using up to four frequencies.

Recently, a method to inspect ferrous support structures in CANDU® reactors using PEC technology has been developed [4]. Previous research using PEC as a method to inspect aircraft structures was found to be capable of flaw detection even at remote distances of up to 20 mm [5], [6], .

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 simulated 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 lands.

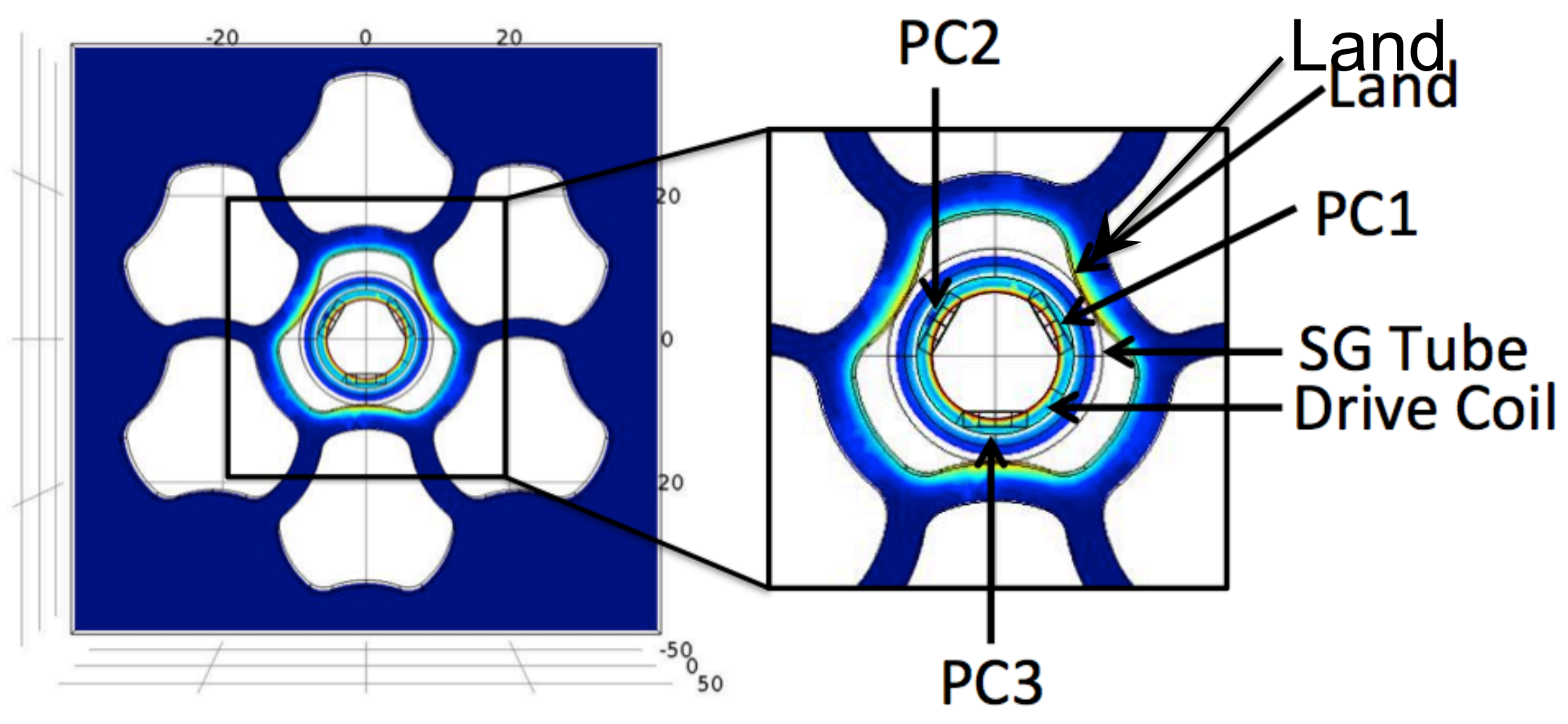

Figure 3: Normalized magnetic field induced in the trefoil broach support structure.

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.

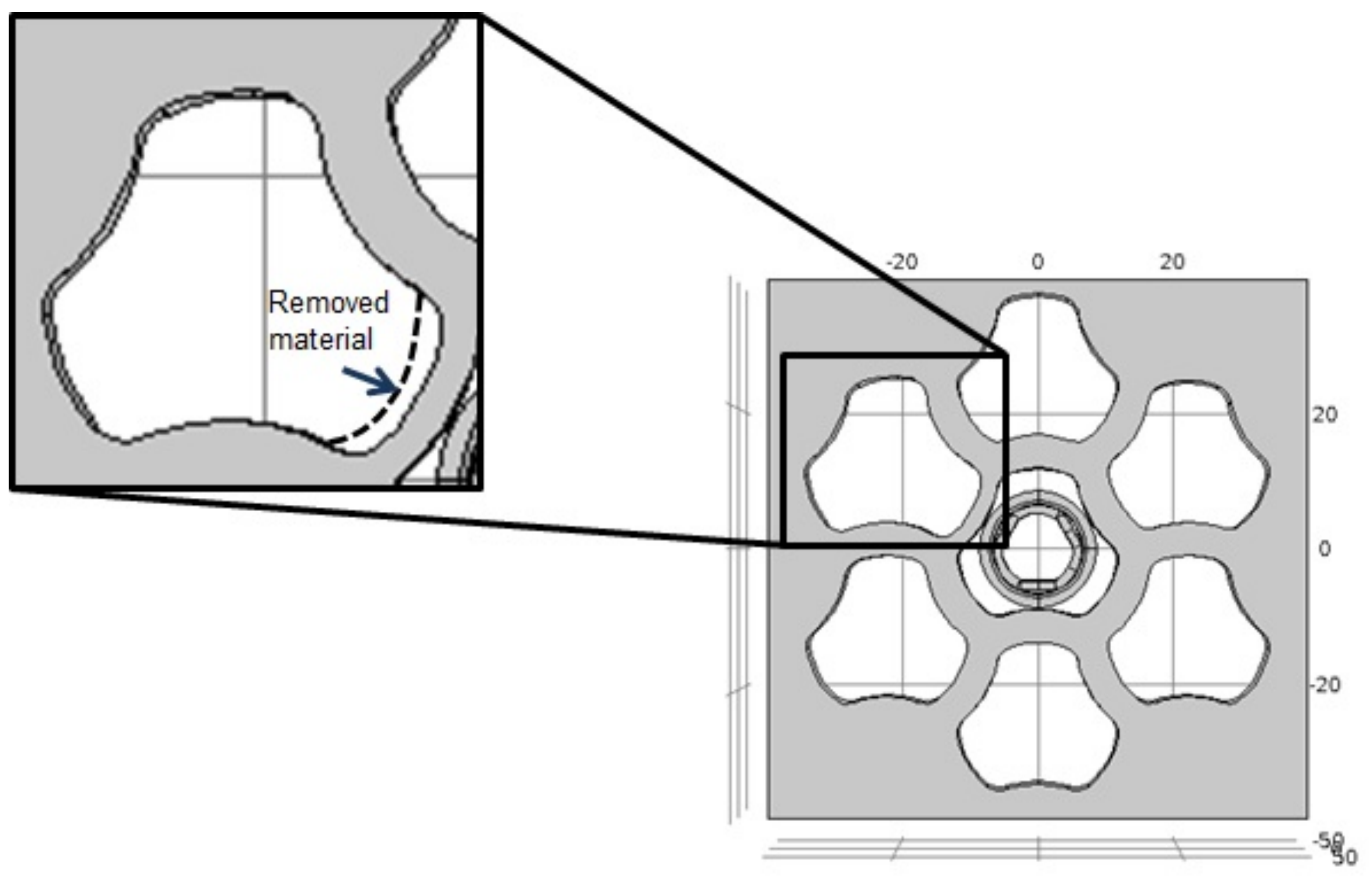

Figure 4: A typical flaw with 50% wall loss.

Results

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 5.

For these results, 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.

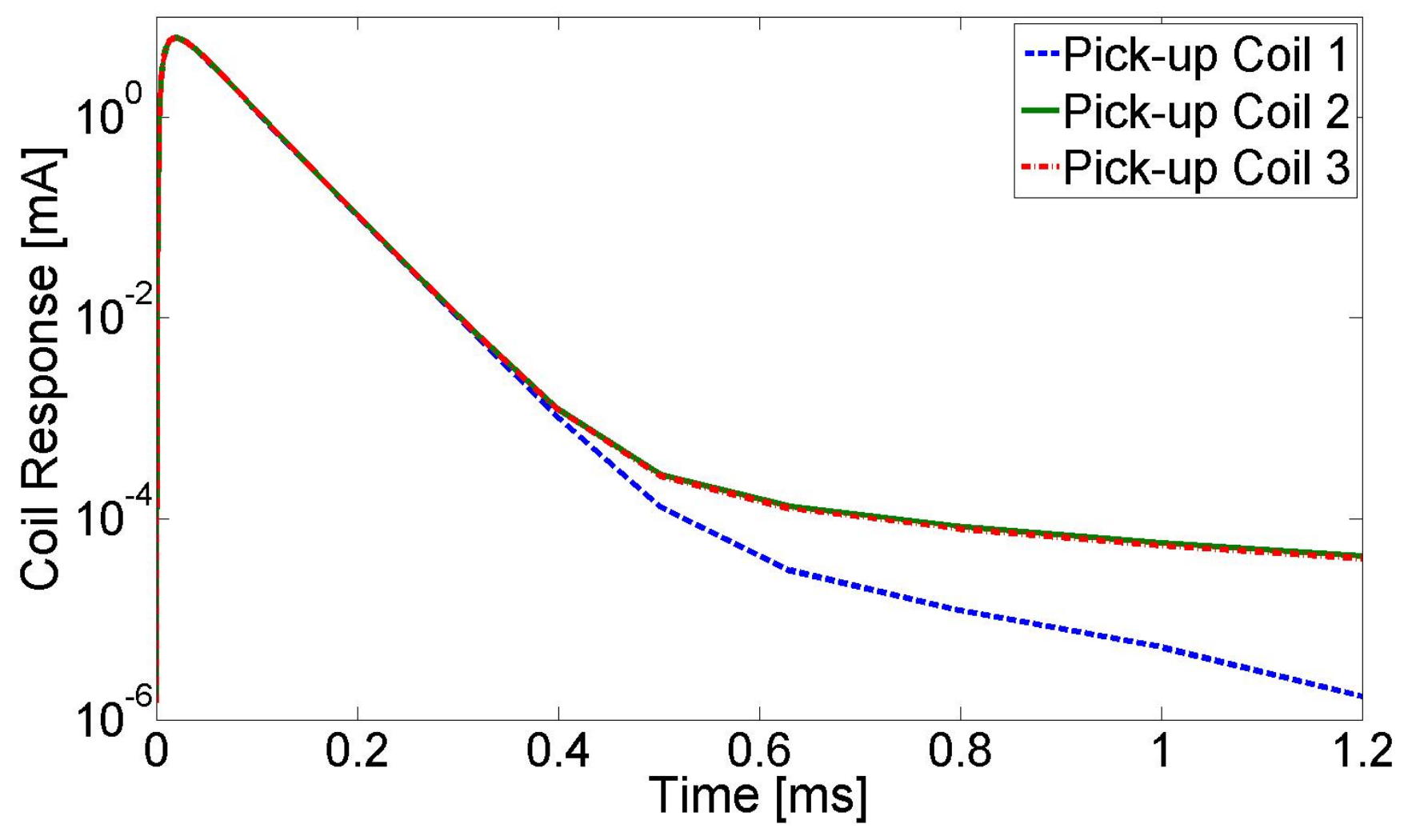

Figure 5: Pick-up coil responses when 100% of flow region material has been removed.

Figure 6 shows the pick-up coil responses when 50% of the land material 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% removal case. These differences are attributed to the additional remaining ferrous material.

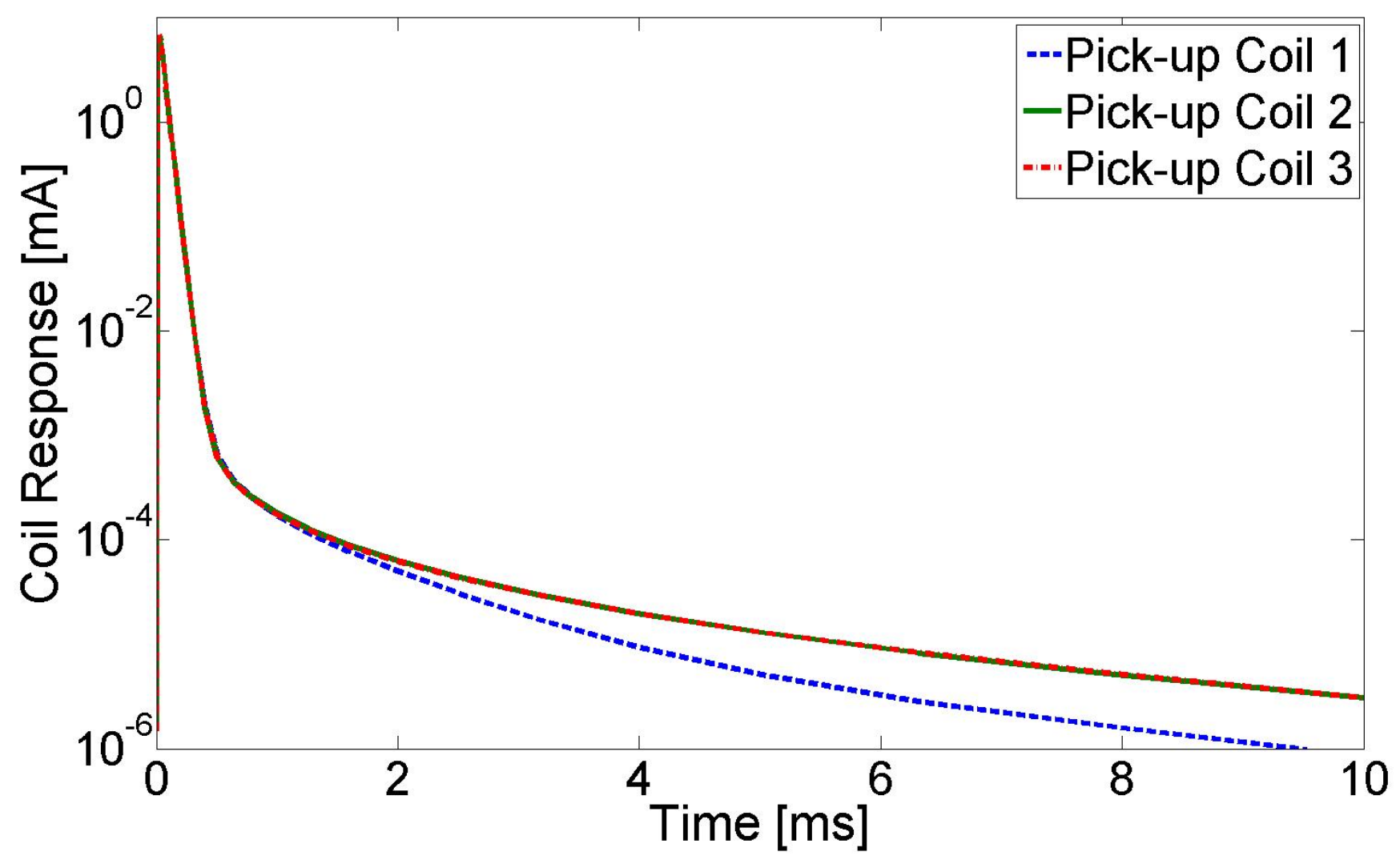

Figure 6: Pick-up coil responses when 50% of flow region has been removed.

Conclusions

Modeled results showed that detection of wall loss in broach supports is possible using a proposed PEC probe design. Characterization of the percentage degradation can be achieved by using a calibration curve based on location and slope of separation between pick-up coil responses.

References

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