Pulsed Eddy Current Technology for Steam Generator Tube Support Structure Inspection

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Abstract. Steam generator (SG) support structure degradation and fouling can result in damage to SG tubes and loss of SG efficiency. In the nuclear industry eddy current technology is widely used to detect tube defects at supports, but is challenged at evaluating the surrounding support structure condition if magnetite fouling is present, particularly if the structure is ferromagnetic. Pulsed eddy current (PEC) array probe technology has been developed for inspection of support structure degradation from within SG tubes. A probe design, adapted for inspection of ferromagnetic trefoil broach supports, demonstrates a linear dependence of peak response on permeability of magnetite. Response to far side ligament wall loss at later times is observed to be independent of magnetite fouling. Examination of PEC probe response in light of basic electromagnetic diffusion processes elucidates measured transient responses obtained during PEC inspection.

Introduction

Steam generators (SGs) consist of thousands of tubes that transfer heat generated in the core of thermal power reactors, including CANDU® nuclear reactors, for conversion into electrical energy [1]. The tubes are braced at intervals by carbon or stainless steel support structures [2]. These support structures can be lattice bar [1], trefoil or quatrefoil shaped holes [3] or drilled baffle supports [4,5]. The structures mitigate SG tube vibration and thereby, the potential for SG tube fretting, while allowing water to flow past the tubes [3]. An example of a simulated trefoil broach support plate (BSP) structure, with only a single SG tube passing through it, is shown in Figure 1. Also indicated in Figure 1 are the land, which is the SG tube support point, and the ligaments that separate the trefoil holes from the flow regions.

Steam generators are subject to a number of degradation modes at support structures including cracking, denting or fretting, which if serious enough can require plugging or removal of tubes [3]. Other common issues, such as flow assisted corrosion or tube vibrations, may cause wall loss in support structure ligaments [6]. Fouling, the accumulation of corrosion deposits on support structures, which includes magnetite, may also obstruct flow holes as simulated in Figure 1.

Eddy current testing (ECT) is used to perform the majority of SG tube inspection [7,8]. While ECT is successful at detecting and characterizing SG tube fretting [4] and cracking, it is challenged at identifying flaws that may arise at ferromagnetic steel support
structures [9], as well as in cases where overlapping degradation modes are present [4]. Inspection conditions may be further exacerbated by the higher relative permeability of magnetite fouling, which can mask indications [10].

A pulsed eddy current (PEC) probe, which uses square pulse excitation, in contrast to the sinusoidal excitation of conventional eddy current, has been developed for inspection of SG tubes at support structure locations [11]. The probe has been used to investigate the detection and characterization of multiple failure modes in Alloy 800 tube at baffle plates, including fretting [4,5,12]. Using a modified principal components analysis [13,14], combined with a trained artificial neural network, the PEC probe has also demonstrated the ability to simultaneously measure up to four parameters in Alloy-800 SG tube located within SS410 baffle plate supports [5]. The parameters include hole inner diameter (ID), which simulates support plate corrosion, tube off-centring in two dimensions and depth of rectangular frets [5]. The probe featured a single drive coil wound coaxially with the SG tube axis and eight surface pick-up coils with axes mounted perpendicular to that of the drive coil [4]. When pick-up coils are configured to align with 3-fold symmetry of trefoil supports the ability to detect as little as 20% far side wall loss has been demonstrated [15].

In PEC the transient voltage response of pickup coils has been regarded as consisting of a series of discrete frequencies, with the approach to direct current (DC) excitation providing deep magnetization of ferromagnetic materials, further enhancing pickup coil response [16]. This characteristic has been exploited for the case of ferromagnetic tubes, demonstrating that PEC provides an improvement over present ECT tools for NDT [17]. PEC has also been used to measure remaining wall thickness in conductive ferromagnetic containers [18,19]. More recently, a technique to measure remaining wall thickness from the outside of ferromagnetic pipes through a layer of insulation has been demonstrated [20].

An approximate expression for the diffusion time, $\tau$, of eddy currents into a target material, is given in terms of permeability, $\mu$, conductivity, $\sigma$, and characteristic length of the system, $\ell$, as [21]:

$$\tau \sim \mu \sigma \ell^2.$$  \hspace{1cm} (1)

This expression can be used to qualitatively describe observed effects of probe response to flaws in SG tube, dimensional changes in surrounding support structure as well as sensitivity to permeability and conductivity of surrounding materials [4,21].

This work uses laboratory measurements to investigate a PEC probe design adapted to inspect remaining wall thickness in the ligaments of ferromagnetic trefoil broach supports in the presence of magnetite. The effectiveness of a previously developed signal analysis method [15], is examined for measuring the amount of ligament wall loss on the far side of the broach support land when magnetite is present in adjacent flow holes.
**Experimental Technique**

A photograph of the probe, modified from that developed previously [22], is shown in Figure 2. The drive coil was excited with a 4 ms long 9V square pulse. Pick-up coil signals were amplified 10000 times and carried by shielded twisted pair cable to a National Instruments (NI) 6356 USB Data Acquisition (DAQ) board, digitizing them at 1 MHz. Data was recorded in a personal computer using LabView acquisition software, which was also used to generate the pulse.

Broach support samples were water-jet cut from ferromagnetic A516 Carbon Steel plate that was 25.4 mm (1”) thick. Sample 1, shown in Figure 1, had no flaws. Three remaining BSP samples had flaws machined into 2.7 mm thick ligaments on the far side of the lands to simulate wall losses of between 0 and 100%. Table 1 summarizes relative ligament wall loss and location in each sample. Details of which are given in Ref. [15].

**Table 1.** Carbon steel samples with far side wall loss (%).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ligament Wall Loss 12 O’clock (%)</th>
<th>Ligament Wall Loss 4 O’clock (%)</th>
<th>Ligament Wall Loss 8 O’clock (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>2</td>
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<td>75</td>
<td>57±5</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

![Fig 2. PEC probe developed for inspection of broach support structures.](image)

Magnetite plugs, for placement in neighbouring flow holes (only one is shown in Figure 1) with three different permeabilities, were prepared [23]. These were characterized with relative permeabilities, $\mu_r$, of 1.9, 2.3 and 2.7, respectively, based on a measurement of the inductance of a toroid [23]. Magnetite with $\mu_r=1.9$ is closest to a $\mu_r$ of ~2, which appears in reactors [24].

**Results and Discussion**

Figure 3 shows the pick-up coil responses for coils aligned with an unobstructed flow region (solid black curve) and flow regions completely obstructed by magnetite for three cases of increasing relative permeability. The inset shows a close up of the pick-up coil peak where the greatest effect due to changes in permeability was observed.
Fig. 3. Experimental results showing effect of relative permeability, $\mu_r$, on pick-up coil response. Inset shows 1.5x amplification of response at peak signal.

Figure 4 shows pick-up coil response peak height as a function of relative permeability of magnetite, with a linear best fit to the data. The results show a clear linear increase of peak height with relative permeability, $\mu_r$, of the magnetite. A slight increase in relative permeability is seen to have a large effect on the peak height. For the strong magnetite sample ($\mu_r=2.7$) the peak height increases by approximately 9%, relative to the no magnetite case. This effect can be explained by considering the probe, magnetite and broach support as forming a magnetic circuit. As $\mu_r$ of the magnetite increases, the reluctance of flux passing to the pick-up coil decreases and resulting pick-up coil response increases. Extracting peak height could provide a means of characterizing the relative permeability of magnetite obstructing flow regions.

Fig. 4. Signal peak height as a function of relative permeability of magnetite for hole obstruction. Uncertainty is to one standard deviation.
Fig. 5. Pick-up coil responses when flow regions are unobstructed and completely obstructed (0%, 40% and 75% wall loss only) by magnetite with $\mu_r=1.9$.

Wall loss on the far side of broach support lands was detected by observing the long transient decay times of pick-up coil responses. Figure 5 shows a semi-log plot of voltage response as a function of the experimental results for pick-up coils located at lands, for no wall loss 0%, and wall losses of 20%, 40%, 60% and 75%, as listed in Table I. Also shown are wall loss measurements in the presence of holes completely obstructed by magnetite with $\mu_r=1.9$ for wall loss cases of 0%, 40% and 75%. Little difference in response between open and magnetite obstructed flow hole cases is evident. The experimental results show progressively decreasing relaxation time with increasing wall loss, consistent with Eqn. (1) if wall thickness is related to characteristic length, $\ell$.

Solid curves in Figure 5 are a best fit of the signal voltage response to a power law expression given by [15]:

$$V = A t^{-b},$$

where $A$ is the power law coefficient and $b$ is the power law exponent. Figure 6 shows power law coefficient $A$ as a function of wall loss in the presence of magnetite and with no magnetite present. Error bars to one standard deviation are obtained from multiple measurements using Microsoft Excel’s LINEST function [25]. Results show that the presence of magnetite does not affect the long-time decay of the response to wall loss within the limits of uncertainty.

Figure 7 shows power law exponent variation with wall loss in the presence of magnetite and without. Error bars are obtained from multiple measurements using LINEST function [25]. Results again show that the presence of magnetite does not affect the long-time decay of the response to wall loss, within the limits of uncertainty, and that a linear response as reported previously [15], is retained.

While early time peak response is strongly affected by the presence of magnetite, as shown in Figures 3 and 4, late time response appears not to be affected, within the limits of uncertainty, as observed in Figures 5 through 7. As reported previously [15], as the amount of wall loss is increased, the transient decay time decreases. This result is consistent with that expected from Eqn. (1), if the characteristic term $\ell$ is associated with wall thickness.
Independence of response to wall loss in the presence of magnetite is attributed to the separate electromagnetic diffusion through the ligament that occurs at later times. At earlier times in the vicinity of the transient peak, separate diffusion processes associated with the presence of higher permeability magnetite are the dominant factors.

Fig. 6. Power law coefficient $A$ from pick-up coil responses as a function of wall loss when flow regions are unobstructed and fully obstructed by magnetite. Solid and dashed curves are polynomial best fits to the data.

Fig. 7. Power law exponent $b$ from pick-up coil response as a function of wall loss when flow regions are unobstructed and fully obstructed by magnetite. Solid and dashed lines are linear best fits to the data.

Conclusion

A PEC probe, configured to match the three-fold symmetry of trefoil broach supports, was used to investigate various conditions of wall loss in nominally 2.7 mm thick ligaments of broach supports in the presence of magnetite, which obstructed neighbouring flow holes. Transient response peak height, which occurs at earlier times, was observed to vary linearly with relative permeability of magnetite, indicating the potential for PEC to characterize fouling in SGs. A two-parameter power law fitting function that had been identified in previous work [15] was found to describe the pick-up coil responses in the presence of magnetite. Independence of wall loss response to the presence of magnetite was attributed to the clear separation of electromagnetic diffusion times associated with magnetite, which occurs at early times at the peak, from that of the surrounding ferromagnetic support structure that occurs at later times.
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References


