Application of Bayesian Inversion Techniques on Multi Frequency Eddy Current Data for Sub Surface Crack Profiling In Steam Generator Tubing

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Abstract: Steam generator (SG) tubing in nuclear plant offers a barrier between the radioactive material and steam. Effective NDT of the SG tubing is mandatory to ensure the safe operation of nuclear power plants. Multi-frequency eddy current (EC) NDT is being exercised in the nuclear industry. Detection and subsequent crack profiling from the acquired EC signals is a challenging task once dealt with subsurface and OD cracks. Data fusion based EC signal inversion techniques are proposed to address the gap. Measurement data was acquired from the simulation of subsurface cracks in steam generator tubing at three different scan frequencies. The proposed spatial correlation data fusion technique has been applied on the acquired multi frequency EC data. Flaw profile prediction from single frequency and data fused results has also been performed by using recursive Bayesian estimation procedure based on Sequential Monte Carlo method. To investigate the efficacy of the proposed data fusion method; quantitative analysis has been conducted. The robustness of the proposed technique was also assessed injecting artificial noise in the EC measurements.

Keywords: Non Destructive Inspection, Multi-Frequency Eddy Current Measurements, Data Fusion, Spatial Frequency Correlation, Particle Filter Inversion

1. Introduction:

Pipelines in various fossil-fuel power plants and nuclear facilities undergo effects of corrosion. Non-destructive testing allows for a significant reduction in inspection of such systems and so increases plant availability. Repair actions if necessary can be made at an appropriate time which also contributes to better maintenance planning [1]. Using NDT for evaluation of the material condition and forecasting its degradation provides a greater opportunity to reduce the amounts and costs of testing the materials. It also contributes to the possible early warning of excessive component degradation. NDT will also enable plant operators and owners to optimize the long term operation of their power plants. This optimization should certainly result in increased cost competitiveness. The situation in the future will be essentially based on diagnostic systems and degradation modeling [2]. Predictive or condition based maintenance requires analysis of collected data for deciding whether or not maintenance action is mandatory. This method not only results in the decrease of needless preventive maintenance actions, but also insures that actions are performed only when the condition of equipment justifies it. [3]

Eddy-current testing (ECT) is a popular NDT technique used for locating cracks in steam generator tubes of nuclear power plants. Therefore it is pivotal to validate the reliability and flaw detection accuracy of this method [4]. The probability of flaw detection and its sizing accuracy
mainly depend on the way the crack is oriented and located on the material. The dependence is also based on tube support structures and corrosion deposits.

ECT information is used to determine tube integrity and for the selection of tubes which require repair or removal from service. Validation of the ECT method can be achieved by destructive examination of a defective tube pulled out from a steam generator during in-service inspection [5].

An eddy current probe is able to locate cracks based on the material resistivity and the frequency of the current flowing through the probe coil. Resistivity defines the conductivity of the material. Hence materials with higher resistivity values have a semi-conducting nature. The coil excitation frequency has an inverse relationship with the depth to which eddy currents can penetrate the material under test. This means that greater frequencies allow the current to have less penetration depth in sub-surface region of the test material [6].

With eddy current techniques there is no contact between the sample and the sensor, making it a desirable method for many practical situations. Conventionally, detection of flaws in conductive samples has been performed with room temperature coils, where the signal-to-noise ratio (SNR) is proportional to the frequency. However, normal coils have the required sensitivity only at high frequencies, limiting flaw detection to regions near the surfaces of the sample. Experimental results have shown that circumferential cracks can be better detected and sized using a plus point coil probe rather than a pancake or bobbin coil probe.

With the help of ECT, steam generator tubes having a non-magnetic nature can be inspected to ensure the safety of nuclear power plants. The inspection of tiny cracks formed due to stress corrosion cracking and fretting corrosion can become problematic. It is very hard to locate such flaws due to the lack of penetration and limited skin depth [7].

Subsurface damage to a structure cannot be visually observed, unless penetration of water and other agents results in surface rupture. Since early evaluation of tubes is desirable, passive methods of monitoring the inception of corrosion have been examined.

In ECT, a conventional technique involves a single frequency excitation source to detect cracks by changes in voltage or impedance. However, such techniques are sensitive to various characteristics inherent to the crack. Multi-frequency EC measurements have also been used to offer a more robust inspection of structural integrity. These measurements allow for a decrease in signal anomalies that can potentially mask the cracks [8].

Although crack sensing using ECT is a relatively mature technique, only crack existence has been a major concern in actual inspections of steam generator tubes. Reconstruction of crack profiles has been considered an extremely difficult challenge and thus has not been attempted to date. However, determination of a crack profile is indispensable for more reliable evaluation of defects.
and optimization of maintenance. The study of eddy current inversion, aiming to reconstruct crack profiles from eddy current signals, has advanced greatly in recent years [6].

An inverse analysis is much more difficult than a forward analysis because of ill-posedness of the problem. Chen proposed a new fast forward solver based on $A-\varphi$ formulation to overcome this difficulty. The key idea of this new fast solver is that it is possible to compute eddy current signals taking only the flawed region into consideration using pre-computed unflawed potentials as a database [9].

Although the degree of acceleration using the solver strongly depends on the number of nodes inside the crack, it can compute eddy current signal within a few minutes in general once database is established. Chen applied the fast forward solver to ECT inversion problems. The scheme is based on a gradient method that needs forward analysis in every step in order to obtain the gradient of the total error function.

Popa’s approach to reconstructing crack profiles differed from Chen’s. He tried to simulate the mapping that exists between crack profiles and eddy current signals using neural networks and succeeded in reconstructing complicated cracks from both simulated and experimental data [6].

In spite of recent advancements in inspection technology, there still exists a clear need to quantify and enhance the reliability of in-service inspection techniques. Keeping this background in mind, an attempt to reconstruct the subsurface crack profiles was carried out using an inverse scheme developed by the authors. The scheme and its results are reported in this paper.

2. Research Methodology

2.1 Modeling of Sub-surface flaw

A two-dimensional sub-surface flaw was modelled inside the steam generator tubing. This model is used to determine the EC measurements. These EC measurements are then used for the inversion. Different filtering techniques are used for the inversion process. However, in this manuscript, a Particle filter (PF) based inversion technique is used. There are two variables that govern the modelling of sub-surface crack i.e. width of the flaw and its depth. The depth of the flaw is further based on two factors: initiation depth of the crack and the depth of the sub-surface crack itself. Multiple rectangular sub-surface flaws of various depths and widths were modeled inside the tubing. The cross-sectional view of the tubing shows one of the modelled flaws in Fig.1.
2.2 Data settings and description of FEM simulation

The modeled sub-surface cracks were simulated using a 2D finite element method (FEM) model [10]. Measurement data was acquired using eddy current (EC) signals at multiple frequencies from the sub-surface discontinuities on the steam generating tubing. Use of different excitation frequencies to acquire EC data provides complimentary information due to skin depth phenomena [11,12]. The coil used of EC measurements is of 100 turns and an inner and outer diameter of 16.4mm and 19.7 mm. The eddy current coil frequencies used for simulation of the cracks are 200 kHz, 400 kHz and 800 kHz. The thickness of the tube and its axial length was 2.5 mm and 3.75 mm, respectively.

2.3 Particle filter based inversion scheme

Particle filters are sequential Monte Carlo filtering methods. PF’s are the generalization of Kalman filters which are not bounded by the selection of linear state transition models as well the Gaussian noise. Detailed discussion of PF is discussed in [11-14]. In this manuscript, we assume the measurements as $y_k$ from a single measurement mode and the probability density function (PDF) of state $u_k$ $p(u_k/ y_k)$ may be obtained recursively in two stages i.e. prediction and update. In prediction stage, we predict the PDF from one measurement location to the next. Since the state is usually subject to random noise, the prediction step generally distorts the PDF [11-14] which is then corrected in the update stage using the available measurement.

In order to apply particle filtering algorithm, the desired posterior PDF is represented in terms of samples and their associated weights at each location. Let $N_s$ be the total number of samples that are drawn from importance density, $u_i^k$ are the set of support points with associated weights $w_i^k$ where $i = 1:N_s$. ($N_s$ is equals to 1000 samples). According to the principle of Importance Sampling, the weights are normalized such that $\sum_{i=1}^{N_s} w_i^k = 1$ and the posterior density can be approximated as:
\[
p(u_k | y_k) \approx \sum_{i=1}^{N_k} w'_k \delta(u_k - u'_k)
\]

The samples can be drawn from the importance density \(q(u_{ik} | y_{ik})\) and the weights are given by:

\[
w'_k \propto \frac{p(u_{ik} | y_{ik})}{q(u_{ik} | y_{ik})}
\]

\(p(u_{ik} | y_{ik})\) is approximated with a new set of samples when the observation \(y_k\) is known at the loading cycle \(k\). Given the set of weights \(w_{k-1}^{i N_i}\) after loading cycle \(k-1\), the weights after loading cycle \(k\) can be calculated recursively using the weight update equation as:

\[
w_k \propto w_{k-1} \frac{p(y_k | u_k)p(u_k | u_{k-1})}{q(u_k | u_{k-1}, y_k)}
\]

In the Bootstrap version of PF, the prior density \(p(u_k | u_{k-1})\) is used as importance density. Therefore (3) becomes:

\[
w_k \propto w_{k-1} p(y_k | u_k)
\]

(4) can also be written as:

\[
w_k^i \propto p(y_k | u_k^i)
\]

When multiple measurement modes are available, just as in our case, likelihood PDF corresponding to each measurement mode need to be considered in weight assignment to the sample.

Assume that \(w_k^i\) is the weight of the sample \(i\) at the position index \(k\) assigned by the individual measurement mode \(q\). The likelihood function corresponding to the \(q\)th measurement mode is given by:

\[
w_k^i \cdot q \propto p(y_k^q | u_k^i)
\]

If the measurement process is assumed to be independent, then the joint likelihood due to measurement modes \(q=1,2,3,........,Q\) is the product of likelihood for the individual measurement mode, given by:

\[
p(y_k^q | u_k^i) = p(y_k^1 | u_k^i)p(y_k^2 | u_k^i)........p(y_k^q | u_k^i)
\]

And the final weight assigned to the sample \(i\) at the position index \(k\) is as follows:

\[
w_k^i \propto w_k^1, w_k^2, ........w_k^Q
\]
The acquired EC measurement data from the FEM simulations of the sub-surface cracks are related by a curve-fitting linear polynomial function. The measurement model is based on the linear function as given in (9)

\[ y = Ax_1 + Bx_2 + c \]  

(9)

2.4 Training database

The training of the measurement model was done by using multi-frequency EC measurement data acquired from different sub-surface crack profiles. Fig. 2 shows the simulated EC measurements of a sub-surface flaw profile with X1 and X2 as 0.2 mm and 0.46 mm, respectively:

![Figure 2](image)

Figure 2 Eddy current measurements of a simulated sub-surface crack

3. Results

The multi-frequency EC measurement data has been acquired from simulation of three different crack profiles. The EC measurements were taken at 200 KHz, 400 KHz and 800 KHz scan frequencies. To perform the PF inversion technique, measurement data at the three scan frequencies were fused together. Data fusion has been done by multiplying together the weights corresponding to each single frequency measurement mode. PF based inversion results obtained after data fusion is shown in Fig.3.
Table 1 shows the RMSE values of the inversion results at 200, 300, 400 kHz and of the fused data. It has been observed that the RMSE values of the fused data are less as compared to the RMSE values of the individual frequency results. The results of RMSE show the efficacy of proposed data fusion technique. The proposed technique has been applied to other eddy current data for inversion of sub surface crack.

Table 1 RMSE Values of Single Frequency and Fused data of three different crack profiles

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Crack 1</th>
<th>Crack 2</th>
<th>Crack 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>200KHz</td>
<td>0.0743</td>
<td>0.0401</td>
<td>0.1524</td>
</tr>
<tr>
<td>300KHz</td>
<td>0.1350</td>
<td>0.1082</td>
<td>0.1247</td>
</tr>
<tr>
<td>400KHz</td>
<td>0.0746</td>
<td>0.0462</td>
<td>0.1453</td>
</tr>
<tr>
<td>Fused</td>
<td>0.0723</td>
<td>0.0353</td>
<td>0.1431</td>
</tr>
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References


