EPRI Steam Generator Management Program – Overview of Recent NDE Research Activities

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Recent Steam Generator NDE Research Activities

1. Development of Simulation Software for SG Eddy Current Inspections

2. Development of SG Eddy Current Automatic Data Analysis Algorithms
Development of Simulation Software for SG Eddy Current Inspections
Benefits of SG Tube Simulation (SGTSIM) Model

- Predict EC probe signals for different SG tube defect geometries
- Determine effect of probe wobble, test frequency, sludge characteristics on probe measurements
- Visualization of field/flaw interaction
- Optimization of sensor/system design
- Test bed for generating defect signatures
- Useful in Probability of Detection (POD) models at low cost
- Assist in determining root cause of complex signals

Key Advantages of Simulation Model:
- Provides an inexpensive and fast method to simulate realistic defect geometries in steam generator tubing
Practical Applications of Simulator Software

- Utility Engineers
  - Assist in complex signal interpretation & Tube Integrity Assessments
  - Assist in POD calculations
- Inspection vendors
  - Assist in signal interpretation
  - Assist in SSPD development
- Probe developers
  - Aid in probe design
- NDE instructors
  - Training tool
  - Generate signals for training data
- Researchers / Qualifying Institute
  - Generate signals for probe technique qualification (ETSS’s)
  - Generate signals for performance demonstration (QDA/AAPDD)
SG Tube Simulator (SGTSIM) Features - Summary

Probes
- Bobbin
- Pancake (.115)
- X-Probe
- + Point

Tube Geometry
- Support Plate
- Tube Sheet
- Free Span

Defect Geometry
- Location
  - Freespan
  - TSP
  - TTS
  - ID/OD
- Shape
  - Circular
  - Elliptical
  - Rectangular
  - Real Cracks
- Orientation
  - Circ
  - Axial

Other features:
- Calibration (Manual/ Auto)
- Data Export in MIZ Format
- Batch Processing

Results are validated with experimental eddy current test data

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Example of Simulated Signals Exported into EddyNet Environment

Plus Point® Signal from OD Axial Flaw 0.3”L x 40% TW

<table>
<thead>
<tr>
<th>50 kHz</th>
<th>200 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kHz</td>
<td>300 kHz</td>
</tr>
</tbody>
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Example of Simulated Signals Exported into Eddynet Environment

Plus Point® Signal from OD Axial Flaw 0.3”L x 40% TW

50 kHz  100 kHz  200 kHz  300 kHz
Examples of Simulated Signal Exported and Displayed in Eddynet

Simulated 100% Ax Notch +Point® 200kHz

Experimental 100% Ax Notch +Point 200kHz
Example of Exporting Data From a Simulated Flaw Signal

- Simulated data from a single channel can be exported in Eddynet format
- Simulated data from +Point® and pancake coil probes has been successfully injected into field data
Example Simulation of a Real Crack – Experimental Validation

+Point ® Probe Data @ 300KHz

Crack Profile from MET data

Experimental Signals (Field Data)

Simulated Signals

Vertical Channel

Horizontal Channel

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Example Simulation of Tube-to-Tube Wear
Bobbin Probe simulation compared to actual ECT data

Length = 10”
Max Depth 0.019” (50% TW)
Max Width= 0.194”

380 kHz

Simulated Symmetric Wear Depth Profile
Example Simulation of Tube-to-Tube Wear
Bobbin Probe simulation compared to actual ECT data

- Length = 10”
- Depth 0.019” (50% TW)
- Maximum Width=0.194”

Simulated Non-Symmetric Wear Depth Profile
Experimental Validation
Array Coil on X-Probe®: Axial Channel – Vertical – (190 kHz)

Tube OD: 0.628”; ID: 0.552”; Tube-to-tube wear length 10.1”; Depth 50%

Experimental signals

Simulated signals
Development of SG Eddy Current Automatic Data Analysis Algorithms
Benefits of Automated Data Analysis System

• Faster analysis of large volumes of data compared to manual data analysis.

• Increase in consistency of degradation detection.

• Increase in accuracy of degradation characterization.

• Addresses concerns about future workforce shortages by storing expert knowledge.

• Eliminate concerns about operator fatigue.
Typical Data Analysis Modules

1. Raw Data
2. Calibration
3. Preprocessing
   - Structure detection
   - Filtering
   - Frequency Mixing
   - Adaptive Thresholding
4. Feature Selection
5. ROI Detection
6. Classification
   (Feature Selection, Rule-Base)
Data Analysis Algorithm Development and Validation Process

Training Data* - w/ Analysis Results

Algorithm Development

Test Data* - Blind Results

Algorithm Optimization

* - Data is from EPRI Automatic Analysis Performance Demonstration Database (AAPDD)

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Recent Data Analysis Algorithm Development

• Loose part detection algorithms for carbon steel, stainless steel and copper materials
  – Rotating Probes
    • 115 Pancake Coil
    • +Point Coil®
  – Array Probes
Loose Part Detection Challenges

Case 1: As distance of the loose part from tube wall OD increases, detection becomes more difficult.

Case 2: As distance of the loose part from TTS decreases, tubesheet signal becomes dominant and loose part detection becomes more difficult.
Development of Algorithms to Automatically Detect Loose Parts From X-Probe® Array Data

Carbon Steel Loose Parts
Loose Part Test Configurations

- **a: Distance from Tube Wall OD**
- **b: Distance above TTS**

For laboratory mock-up:
- a: 0-5mm
- b: 0-18mm

Loose parts used in laboratory experiments

Spacers used in laboratory experiments
Calibration & Phase Correction

File: LB00HCAL00702/DHR000C009I014 Circ. Channel 50 KHz, Vert. component, 18mm above TTS, in contact with tube

Before Calibration

After Calibration

Loose Part

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Step 1-TTS Detection & Segmentation

File: LB00HCAL00702/DHR000C009I007 50 KHz, Vert. component, 2mm above TTS, in contact with tube

Axial projection $P(i)$
Derivative of $P$, $D(i) = P(i) - P(i-1)$
Location of detected TTS by thresholding $D(i)$

2D data

Tube

Loose Part

Tubesheet

$P(i)$

$D(i) = \partial P(i)$
Step 2-Preprocessing - Median Removal

File: LB00HCAL00702/DHR000C009I014 50 KHz AF, Vert. component, 18mm above TTS, in contact with tube

Segmented data

Before median removal

After median removal

Loose Part

Input for step 3
Step 3- Adaptive Thresholding and ROI Detection

File: LB00HCAL00702/DHR000C009I025 50 KHz AF, Vert. component,

Segmented Image

Thresholding and ROI detection

18mm above TTS, in contact with tube
Step 4- Feature Extraction & Classification

• Features extracted from calibrated data inside ROI boxes:
  – Maximum and minimum signal amplitude
  – The corresponding phase at maximum and minimum signal amplitude

• Rule-based classification applied to the extracted features
Step 4- Feature Extraction & Classification

File: LB00HCAL00702/DHR000C009I025 50 KHz AF, Vert. component,

18mm above TTS, in contact with tube

File: LB00HCAL00702/DHR000C009I025 50 KHz AF, Vert. component,

Segmented Image

Thresholding and ROI detection

Classification

False ROI: Residue from TTS
Training Data Distribution & Result

- 100 files were randomly chosen and used for training
- The set contains both lab data (LP#1-10) and field data (LP#11 & 12)
- AA was trained based on this 100 flies

<table>
<thead>
<tr>
<th>Type/Total tubes</th>
<th># of tubes in training set</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP#1 / 10</td>
<td>6</td>
</tr>
<tr>
<td>LP#2 / 10</td>
<td>2</td>
</tr>
<tr>
<td>LP#3 / 10</td>
<td>3</td>
</tr>
<tr>
<td>LP#4 / 50</td>
<td>14</td>
</tr>
<tr>
<td>LP#5 / 50</td>
<td>9</td>
</tr>
<tr>
<td>LP#6 / 10</td>
<td>1</td>
</tr>
<tr>
<td>LP#7 / 10</td>
<td>1</td>
</tr>
<tr>
<td>LP#8 / 10</td>
<td>1</td>
</tr>
<tr>
<td>LP#9 / 51</td>
<td>16</td>
</tr>
<tr>
<td>LP#10 / 28</td>
<td>13</td>
</tr>
<tr>
<td>*LP#11 / 51</td>
<td>14</td>
</tr>
<tr>
<td>*LP#12 / 51</td>
<td>17</td>
</tr>
</tbody>
</table>

LP#1-LP#10:
*LP#11: Carbon steel weld backing ring
*LP#12: Carbon steel nail

<table>
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<tr>
<th># tubes analyzed</th>
<th>Detection rate by human analyst (PLP+WLP)</th>
<th>Detection rate by AA (PLP+WLP)</th>
<th>NDD by human analyst</th>
<th>NDD by AA</th>
<th>AA False Call Rate /Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>79%</td>
<td>85%</td>
<td>21%</td>
<td>15%</td>
<td>0.14 (14/100)</td>
</tr>
</tbody>
</table>

"PLP" - Possible Loose Part (High confidence)
"WLP" - Weak Loose Part signal (Not likely to be reported in a field exam)
"NDD" - No Loose Part signal - NDE technique limitation
Blind Test data

- After training was performed on the remaining 269 tubes

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<th>Detection rate by AA (PLP+WLP)</th>
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<th>AA False Call Rate /Tube</th>
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</thead>
<tbody>
<tr>
<td>269</td>
<td>71%</td>
<td>76%</td>
<td>29%</td>
<td>24%</td>
<td>0.21 (58/269)</td>
</tr>
</tbody>
</table>

- "PLP" - Possible Loose Part (High confidence)
- "WLP" - Weak Loose Part signal (Not likely to be reported in a field exam)
- "NDD" - No Loose Part signal - NDE technique limitation

- Analysis of other loose part materials (e.g. stainless steel and copper) is in progress
Summary

• EPRI SGMP conducts research to improve SG NDE capabilities, including:
  – detection, sizing and characterization of tube degradation
  – detection of foreign objects
• Results from SG NDE are used as input to decisions on:
  – tube repairs, inspection intervals, repair methods, deposit removal processes and the need for foreign object retrieval
• Important aspects of the SGMP NDE research include:
  – development of eddy current simulation modeling tools
  – development of efficiency improvements of data analysis through automation
  – qualification of data analysis processes and systems
Together…Shaping the Future of Electricity