MWM-Array and MR-MWM-Array Eddy Current Testing for Piping and Vessels

Neil Goldfine, Todd Dunford, Andrew Washabaugh, Stuart Chaplan, Karen Diaz
JENTEK Sensors, Inc., 121 Bartlett Street, MA 01752
Example Problems: From Simple to Complex

(a) MWM-Array
- \( h \) (lift off)
- (permeability)
- (conductivity)

(b) MWM-Array
- \( h \)

(c) MWM-Array
- \( h \)

(d) MWM-Array
- \( h \)
- \( \varepsilon \)
- \( \mu \)
- \( g \)
- \( V \)
- \( V' \)

(e) Near Side Corrosion

(f) Far Side Corrosion

(g) Insulation and Weather Jacket

(h) Corrosion Under Fireproofing (with Wire Mesh)
## Example Problems: From Simple to Complex

<table>
<thead>
<tr>
<th>2-Unknowns</th>
<th>3-Unknowns</th>
<th>4-Unknowns</th>
<th>3 or 4-Unknowns</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conductivity and Liftoff</strong> <em>((\sigma) and (h)); or Permeability and Liftoff <em>((\mu) and (h))</em></em></td>
<td><strong>Conductivity, thickness and Liftoff</strong> *((\sigma, \Delta_c) and (h))</td>
<td><strong>Coating conductivity, coating thickness, substrate conductivity, and Liftoff</strong> *((\sigma_c, \Delta_c, \sigma_s) and (h))</td>
<td>Cladding thickness, gap thickness, and Liftoff, add substrate magnetic permeability (to detect substrate cracks also) <em>((\Delta_c, \Delta_g, h) and (\mu_s))</em>*</td>
</tr>
<tr>
<td>(a)</td>
<td>(b)</td>
<td>(c)</td>
<td>(d)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3-Unknowns</th>
<th>4 or 5-Unknowns</th>
<th>5-Unknowns</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Permeability, thickness and Liftoff</strong> <em>((\mu, \Delta_s) and (h))</em>* assume conductivity value</td>
<td>**Weather jacket thickness (assume w/conductivity), insulation thickness, pipe thickness, and Liftoff and pipe permeability (or estimate (\mu_p) at nominal (\Delta_p) <em>((\Delta_{wj}, \Delta_i, \Delta_p, h, + \mu_p)</em>)</td>
<td>**Concrete thickness <em>((ho+hj))</em> wire mesh permeability, vessel permeability, lift-off (ho) *(= distance to mesh) <em>((\Delta_c, \mu_m, \mu_s, \Delta_s h_0)</em>)</td>
</tr>
<tr>
<td>(e)</td>
<td>(f)</td>
<td>(g)</td>
</tr>
</tbody>
</table>
Three elements of the solution

   - Paradigm shift in sensor design (first priority is predictable response based on physics-based modeling)

2. Parallel Instrumentation
   - 3 frequencies simultaneously
   - All channels simultaneously
   - Wide bandwidth, accurate impedance

3. Multivariate Inverse Methods (MIMs)
   - Rapid, autonomous data analysis Performs multivariate inverse method (MIM) using precomputed databases
     - Defect Images
     - Performance Diagnostics
     - Noise Suppression
Definition of Real and Imaginary Parts of the complex Transimpedance $Z = v/j\omega i$

$|Z| = \text{Magnitude}$

$\theta = \text{Phase}$

$|Z| = \sqrt{\text{Re}^2 + \text{Im}^2}$

$\theta = \arctan(\text{Im}/\text{Re})$

$\text{Re} = |Z|\sin(\theta)$

$\text{Im} = |Z|\cos(\theta)$

$\omega = 2\pi f$

- GridStation Lattices for MR-MWM-Array wall loss imaging
- Used for external and internal wall loss imaging
HyperLattices (precomputed response databases)

a) 2- Unknowns: conductivity (σ) and lift-off (h), with magnetic permeability (μ) assumed constant.

\[
\frac{v_2}{l_2} \left( \frac{1}{\mu} \right)
\]

\[
\text{magnitude (m/deg/cm)}
\]

\[
\lambda = 12.7 \text{ mm} \quad \text{freq} = 100 \text{ kHz}
\]

Log(σ)

125.8 kHz, Chan 14 - Imaginary vs. Real (Analysis Grid, 125.8 kHz)

Conductivity - Lift-off - Analysis Grid, 125.8 kHz

Lift-Off (h)

Conductivity (σ)

Real

Imaginary
HyperLattices (precomputed response databases)

a) 2- Unknowns: magnetic permeability (µ) and lift-off (h), with conductivity (σ) assumed constant.
HyperLattices (precomputed response databases)

b) 3- Unknowns: coating conductivity, coating thickness, and lift-off, using hierarchical method. Grid is for conductivity and thickness of the coating. The lift-off is determined at a higher frequency, taken simultaneously.
HyperLattices (precomputed response databases)

c) 3-Unknowns: coating thickness, coating conductivity, and lift-off. Two frequencies are needed.

Each frequency provides two equations to solve for up to two unknowns. Two frequencies is enough for 3 or 4 unknowns.
HyperLattices (precomputed response databases)

d) 3- Unknowns: cladding thickness, blister gap, and lift-off
HyperLattices (precomputed response databases)

e) 3- Unknowns: pipe wall permeability, pipe wall thickness, and lift-off

- Real (Re)
- Imaginary (Im)
- Thickness
- Lift-Off (h)
- Permeability
- MWM-Array
- Near Side Corrosion
- Far Side Corrosion

HyperLattices (precomputed response databases)
Scanners and Implementation in the plant

\[ h, \Delta_{wj}, \Delta_i, \Delta_p, \mu_p \]

- \( h_o \): distance between sensor & external surface of weather jacket
- \( \Delta_{wj} \): weather jacket thickness
- \( \Delta_i \): insulation thickness + external metal loss
- \( \Delta_p \): remaining pipe wall thickness
- \( \mu_p \): pipe magnetic permeability
Sensor Selection

- Decay rate determined by skin depth at high frequency and sensor dimensions at low frequency
- Large dimensions needed for thick coatings/insulation
- Low frequencies needed to penetrate through steel pipe wall

\[ \text{Depth of Penetration} = \frac{1}{\text{Re}(\Gamma_n)} \]

Low Frequency Limit:

\[ \Gamma_n = \sqrt{(2\pi n / \lambda)^2 + j2 / \delta^2} \]

Skin depth:

\[ \delta = \frac{1}{\pi f \mu \sigma} \]

MR-MWM-Array
HyperLattices (precomputed response databases)

(f, left) 5- Unknowns:
1. pipe wall permeability,
2. pipe wall thickness,
3. weather jacket thickness (assume conductivity)
4. insulation thickness
5. lift-off (distance to weather jacket)

Can’t visualize easily
Example: Corrosion Imaging on Refinery Piping

Inspection was performed with the pipe in production at high temperature
CUI Performance Evaluation Results (July 2013)

**Internal Corrosion – Sample A**

16” Schedule 80 (0.500” wall)
2” insulation with aluminum weather jacket
0.175” max wall loss (35%) over 20-25 inches (full circumference)

**Internal Corrosion – Sample B**

16” Schedule 80 (0.500” wall)
2” insulation with aluminum weather jacket
0.100” max wall loss (20%) over 20-25 inches (full circumference)
HyperLattices (precomputed response databases)

(f, right) 5- Unknowns:
1. vessel wall permeability,
2. vessel wall thickness,
3., 4., permeability and position of wire mesh (simple layer)
5. vessel wall permeability

Can’t visualize easily

\[ MWM-Array \]

\[ h_o \quad \text{mesh} \]

\[ h_i \]

Insulation and Weather Jacket

Real

Imaginary

Wall Thickness

Concrete Thickness

Wall Permeability
Summary of Elements of Solution and Example Capabilities

Elements of Solution

1. Sensor designed to match the modeled response
2. Parallel architecture impedance instrument, providing at least 3 simultaneous frequencies
3. Rapid Model-Based Multivariate Inverse Method (MIMs)

Example Capabilities

1. Internal and external corrosion imaging through
   - Insulation
   - Concrete with wire mesh (fireproofing, weight coat)
   - Other coatings
2. Hydrogen blister imaging (through cladding overlay)
3. Buried crack detection
4. Coating characterization
5. In-line inspection for surface and subsurface defects
6. Stress mapping from outside and inside pipelines, structures