Modeling and Visualization for Imaging of Subsurface Damage

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Outline

- Practical Applications
- Problem Definitions: *From Simple to Complex*
- Sensing Methodology
- HyperLattice Databases
- Example Results
- Summary
Practical Applications

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
Problem Definitions: from simple to complex

(a) $h$ (lift off)

$\mu$ (permeability)  
$\sigma$ (conductivity)

(b) $\Delta_{\text{Coating}}$

$\sigma$

(c) Coating layer

(d) $\Delta_g$

$\sigma_v, \mu_v$

(e) MWM-Array

Near Side Corrosion

(f) MWM-Array

$\Delta_i$

$\Delta_p$

$\Delta_{\text{wj}}, \sigma_{\text{wj}}$

Insulation and Weather Jacket

(g) MWM-Array

$\mu_{\text{mesh}}$

Insulation and Weather Jacket

$h_i$

$h_o$

$h$

$h_o$

$h_i$
Sensing Methodology

1. Sensors: MWM®-Arrays
   - Paradigm shift in sensor design (first priority is predictable response based on physics-based modeling)

2. Next Generation Electronics
   - 10x signal-to-noise improvement
   - Very low frequencies (deep penetration)
   - Crack detection through up to 0.5 inches of material
   - Reduced drift

3. GridStation Software using HyperLattices®
   - 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 $Z = v/j\omega$

- $|Z| = \sqrt{\text{Re}^2 + \text{Im}^2}$
- $\theta = \arctan(\text{Im}/\text{Re})$
- $\text{Re} = |Z| \sin(\theta)$
- $\text{Im} = |Z| \cos(\theta)$

- GridStation Lattices for MR-MWM-Array wall loss imaging
- Used for external and internal wall loss imaging

$\omega = 2\pi f$
HyperLattices (precomputed response databases)

a) 2- Unknowns: conductivity ($\sigma$) and lift-off ($h$), with magnetic permeability ($\mu$) assumed constant

![Graph of Log($\sigma$) vs. phase (degrees) with measurement and estimation for various materials like Brass and Aluminum with conductivity values of 1.6E7 mhos/m and 3.2 E7 mhos/m, and frequency of 100 kHz at 12.7 mm wavelength.]

![Complex plane graph showing 125.8 kHz, Chan 14 - Imaginary vs. Real (Analysis Grid, 125.8 kHz) with lines indicating Conductivity and Lift-off.]

**MWM-Array**

- $\mu$ (permeability)
- $\sigma$ (conductivity)

**Lift-Off ($h$)**
HyperLattices (precomputed response databases)

a) 2- Unknowns: magnetic permeability ($\mu$) and lift-off ($h$), with conductivity ($\sigma$) assumed constant
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

10,00 Hz - Imaginary vs. Real (multiple grids)

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

MR-MWM-Array

Depth of Penetration = $1/\text{Re}(\Gamma_n)$

Low Frequency Limit = $\frac{\lambda}{2\pi}$

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

Skin depth: $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$

1 inch = 25.4 mm
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.
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. permeability and position of wire mesh (simple layer)
4. vessel wall permeability
5. vessel wall permeability

Can’t visualize easily
Summary

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