Advancements in Imaging Corrosion Under Insulation (CUI) for Piping and Vessels

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Technology Summary / Overview

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

2. Next Generation 8200α GridStation® 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
Flat Plate Demonstration

For External and Internal Corrosion

Sensor
- 18-channel sensor
- Motorized scanning vehicle
- External and internal wall loss imaging

Flat Plate
Dimensions: 4 ft. x 4 ft.
Thickness: 0.25 in.

Flaw
Diameter: 2.25 in.
Depth: 0.150 in.
3-Unknown Lattices

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

|\(|Z|\) = Magnitude
\[\theta = \text{Phase}\]

\[\sqrt{|Z|} = \frac{\text{Re}^2 + \text{Im}^2}{\sqrt{|Z|}}\]

\[\theta = \arctan(\frac{\text{Im}}{\text{Re}})\]

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

\[\text{Im} = |Z| \cos(\theta)\]
Independent Plate thickness and lift-off imaging

- Channel over defect shows defect signature as thickness reduction and lift-off increase
Discrimination Between External and Internal Wall Loss

**External Wall Loss**

**Internal Wall Loss**

**Thickness**

**Lift-Off**

MWM sensor

\[ h \text{ (lift-off)} \]

\[ \Delta \text{ (Thickness)} \]

\[ \mu \text{ (permeability)} \]
Independent Wall Thickness and Permeability (Longitudinal Stress) Imaging

- **External Wall Loss**
  - Thickness
  - Permeability

- **Internal Wall Loss**
  - Thickness
  - Magnetic Permeability

- **MWM sensor**
  - Need to add correction for sensor construct effects
  - Longitudinal permeability is related to stress
MWM-Array 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

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

Low Frequency Limit = \(\frac{\lambda}{2\pi}\)

\[\Gamma_n = \sqrt{\left(\frac{2\pi n}{\lambda}\right)^2 + j\frac{2}{\delta^2}}\]

Skin depth: \(\delta = \frac{1}{\sqrt{\pi f \mu\sigma}}\)
MWM-Array Sensor Selection

Depth of Penetration MRA002

Operating Range

External Corrosion

Internal Corrosion

MWM-Array sensor (from outside)

Coating/Insulation

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MWM-Array Imaging of External and Internal Corrosion through Insulation with Weather Jacket

Problem Definition

\[\Delta_p = \text{Remaining pipe wall thickness}\]
\[\mu_p = \text{Pipe wall magnetic permeability}\]
\[\Delta_{ext} = \text{External wall loss}\]
\[\Delta_{int} = \text{Internal wall loss}\]
\[\Delta_n = \text{Nominal pipe wall thickness}\]
\[h = \text{Lift-off}\]
\[\mu_c = \text{Permeability of internal corrosion product layer}\]
\[\Delta_c = \text{Thickness of internal corrosion product layer}\]
\[\Delta_l = \text{Coating/insulation thickness}\]
MWM-Array Inspection for CUI

Pre-Alpha System Performance
(Wall Thickness Image)

Improved Resolution with Alpha System
(Wall Thickness Image)
Corrosion Under Fireproofing (CUF) with Wire Mesh

Concrete (Thickness)  \(\rightarrow\) Mesh (Thickness, Permeability)  \(\rightarrow\) Wall (Thickness, Permeability)

Vessel Scanner

MR-MWM-Array Sensor

GridStation 8200α
Wall Thickness and Concrete Thickness

Wall Thickness

Concrete Thickness

Welded Nuts
Removing Mesh Contribution

Mesh Permeability

Wall Permeability

Mesh Models Still Under Development
Other Example Applications

- SCC Mapping and Depth Measurement
- Post Weld Heat Treatment (PWHT) Assessment
- ILI (Internal Corrosion and Stress)
- Mechanical Damage Profile and Residual Stresses
- SHM for Crack Growth, Corrosion, and Stress
FA28 MWM-Array Imaging of SCC

Pipeline Sample Provided by Applus/RTD

Crack Response Image

Lift-Off Image

Paper to simulate coating

Sensing Elements

1 mm = 0.04 in.

0.25 mm

1 mm

Primary

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• Representative FA24 data at 100 kHz on EDM notch pipe sample
• Notches clearly indicated as increase in permeability
• Pairs of notches show resolution capability
Crack Imaging & Depth Measurement Capability

- Reasonable measurement correlation between depth and effective permeability change
- Sensitive to notch depth over this range

![Graph showing the relationship between EDM Notch Depth and Response Change at flaw center. The graph includes data points for Schedule 40 and 80, FA24, 100 kHz length (in.). A linear fit equation is also shown: \( p = 627.2 \cdot d - 15.1 \), with \( R^2 = 0.950 \).]
MWM-Array Residual Stress Imaging

Permeability/stress scanning across the weld

For Post-Weld Heat Treatment (PWHT)
Effect of Thermal Stress Relief on Weld in Witness Coupon, Pressure Vessel Steel

Before After

Developing solutions for through-thickness imaging of stresses in welds with crowns
Oil & Gas Summary - Application Examples

CUI
- Corrosion Under Insulation
  - NDT without coating/insulation removal
  - CUI detection through ~2in. insulation and weather jacket
  - Phased Array UT replacement

ILI
- Low cost ILI Cleaning Tool
- PIG-IT: Pipeline Inspection Gage, with integrated IT
- Internal and external corrosion imaging from inside the pipe

SCC
- Stress Corrosion Cracking
  - Mapping of SCC clusters
  - Developing depth screening capability
  - MPI replacement

MD
- Mechanical Damage
  - Magnetic profilometry
  - Crack Detection in Dents
  - Developing residual stress mapping
SHM for Crack Growth, Stress (and Corrosion Monitoring)

Under DOT and PRCI Funding with GDF Suez

Damage Monitoring

*During dynamic cycling*

Stress Monitoring

*Dynamic pipeline pressure testing*

4-pt static load testing of coupon
Summary

Internal and External Corrosion
- CUI (Insulation or Insulation with Weather Jacket)
- CUF (Concrete with Wire Mesh)

Other Applications
- SCC Mapping and Depth Measurement
- Post Weld Heat Treatment (PWHT) Assessment
- ILI (Internal Corrosion and Stress)
- Mechanical Damage Profiling and Residual Stress
- SHM for Crack Growth, Corrosion, and Stress