Field Demonstrations of MR-MWM-Array Solutions for Detection, Imaging and Sizing of Corrosion under Fireproofing (CUF) with Wire Mesh

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Problem Description

Internal and External Corrosion Imaging through Fireproofing

- **Requirements:**
  - Inspect large areas through fireproofing with and without wire mesh
  - Correct for variations in fireproofing thickness
  - Correct for variations in steel properties
  - Provide an image of the wall loss
  - Differentiate between external and internal corrosion

- **Applications include vessel skirts, LPG legs, structures**

- **Related applications include:**
  - Inspection through insulation with weather jacket for vessels and piping
  - In-line inspection for corrosion and longitudinal stress
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

Images

Analysis

Solve Multiple Unknown Problems

MIM

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Consider Three Corrosion Imaging Problems

3-ununknowns (CUF)

\[ h, \Delta_v, \mu_v \]

- \( h \) = insulation thickness + external metal loss
- \( \Delta_v \) = remaining vessel wall thickness
- \( \mu_v \) = vessel magnetic permeability

4-ununknowns (CUF)

\[ h, \Delta_v, \mu_v, \mu_{\text{mesh}} \]

- \( h_o \) = distance between sensor & wire mesh = air gap + concrete thickness outside wire mesh
- \( h_i \) = distance between wire mesh and external surface of vessel = concrete thickness inside wire mesh + external metal loss
- \( \Delta_v \) = remaining vessel wall thickness
- \( \mu_v \) = vessel magnetic permeability
- \( \mu_{\text{mesh}} \) = effective magnetic permeability of the wire mesh for an assumed constant mesh thickness

NOTE: To simplify from 5 unknowns to 4 unknowns, \( h_i \) is assumed to be constant

5-ununknowns (CUI)

\[ h, \Delta_{wj}, \Delta_i, \Delta_v, \mu_v \]

- \( h_o \) = distance between sensor & external surface of weather jacket
- \( \Delta_{wj} \) = weather jacket thickness
- \( \Delta_i \) = insulation thickness + external metal loss
- \( \Delta_v \) = remaining vessel wall thickness
- \( \mu_v \) = vessel magnetic permeability
Demonstrations at Two Saudi Aramco Facilities

- Site teams included: Saudi Aramco, Al-Rushaid and JENTEK personnel

- Prototype scanner functioned well, but was too heavy. Modifications will be made to improve ease of use.

- Scanning of large areas was accomplished in multiple vertical passes, with automatic scanning in the vertical direction, and manual shifting of the scanner around the vessel.
How many Frequencies are Needed to Solve for 3-Unknowns?

2-unknowns (CUF)  
1 Frequency  
h and $\Delta v$  

Linear equations example  

$h + \Delta v = 3 \text{ in.}$  

$\Delta v = 1 \text{ in.}$  

Solve: $h = 2 \text{ in.}$  

Nonlinear equations example:  

Function 1 ($h$, $\Delta v$, $\mu_v$) = $S_1 = \text{Re}(V/I)$ at $f_1$  

Function 2 ($h$, $\Delta v$, $\mu_v$) = $S_2 = \text{Im}(V/I)$ at $f_1$  

Function 3 ($h$, $\Delta v$, $\mu_v$) = $S_3$ need 2nd freq.  

For Low Frequency Eddy Current Sensing  
Each frequency provides two equations.  
Thus, to solve a three unknown problem, two frequencies are needed. To solve a two unknown problem, only one frequency is needed. For 5 unknowns, three frequencies are needed.
1. A current is applied to a single large drive conductor
2. This time varying current is applied at a frequency, such as 5Hz (5 cycles/second)
3. This time varying current produces a magnetic field
4. The electronics measures a voltage at each sensing element at the same time for up to three frequencies at the same time
5. For each frequency a magnitude (V/I) is measured and a phase which is the time delay of the voltage relative to the current is measured
6. The Real part of the impedance is the Magnitude x cos(phase); the Imaginary part of the impedance is the Magnitude x sin(phase)
Flat Plate Demonstration of 3-Unknown Method

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.

MR-MWM-Array
(Curved or Flat surfaces)
3-Unknown Lattices

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

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

\[ \theta = \arctan(Im/Re) \]

\[ Re = |Z| \sin(\theta) \]

\[ Im = |Z| \cos(\theta) \]
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

$\Delta$ (Thickness)

$\mu$ (permeability)

$h$ (lift-off)

MWM sensor
Independent Wall Thickness and Permeability (Longitudinal Stress) Imaging

External Wall Loss

Internal Wall Loss

Thickness

Permeability

MWM sensor

h (lift-off)

μ (permeability)

Δ (Thickness)

- 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

\[
\text{Skin depth: } \delta = \frac{1}{\sqrt{\pi f \mu \sigma}}
\]

\[
\text{Low Frequency Limit } = \frac{\lambda}{2\pi}
\]

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

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

1 inch = 25.4 mm
Corrosion Under Fireproofing (CUF) with Wire Mesh

\[ h, \Delta_v, \mu_v, \mu_{\text{mesh}} \]
Wall Thickness and Concrete Thickness

Wall Thickness

Concrete Thickness

Welded Nuts
Wall Thickness and Concrete Thickness

Wall Thickness

304.8 cm (120 in)

Wall Thickness and Concrete Thickness

Concrete Thickness

228.6 cm (90 in)

Note that typical steel plate varies by ±10-15% without corrosion
Building Thickness Image from Multiple Scans
Building Thickness Image from Multiple Scans
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Scan Path

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Sensitivity to Mesh Permeability and Concrete Thickness

**Concrete Thickness Effect**

- \( \mu_s = 47.7 \) rel, \( \Delta_v = 12.8 \) mm, \( \mu_{\text{mesh}} = 2.4 \) rel, \( h = 71.2 \) mm

- \( \mu_s = 44.4 \) rel, \( \Delta_v = 12.6 \) mm, \( \mu_{\text{mesh}} = 2.7 \) rel, \( h = 66.3 \) mm

**Wire Mesh “Effective” Permeability Effect**

- \( \mu_s = 40.8 \) rel, \( \Delta_v = 11.4 \) mm, \( \mu_{\text{mesh}} = 4.0 \) rel, \( h = 69.8 \) mm

- \( \mu_s = 44.4 \) rel, \( \Delta_v = 12.6 \) mm, \( \mu_{\text{mesh}} = 2.7 \) rel, \( h = 66.3 \) mm

*Note: This mesh effect is in the vessel wall thickness direction*
Removing Mesh Contribution

Mesh Permeability

Wall Permeability

Mesh Overlap Region

Mesh Models Still Under Development
Problem Definition

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

Pre-Alpha System Performance (Wall Thickness Image)

Improved Resolution with Alpha System (Wall Thickness Image)
Summary

- **Demonstrated capability to:**
  - Correct for wire mesh
  - Image vessel skirt wall thickness
  - Scan large areas

- **Future work**
  - Improve scanner
  - Improve sensor effective footprint
  - Improve mesh model
  - Additional field trials in approvals