DRAFT PAPER

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MODELING AND VISUALIZATION FOR IMAGING OF SUBSURFACE DAMAGE

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ABSTRACT. This paper describes the HyperLattice® database method for visualizing and analyzing eddy current NDT data, specifically for imaging of subsurface damage in piping and vessels. HyperLattice databases are pre-computed databases of sensor responses. These databases are generated using a forward model of the interaction of the sensor magnetic fields with a multiple layered material under test. Over the past three decades, initially at the MIT Laboratory for Electromagnetics and Electronics Systems (LEES) and later at JENTEK Sensors, Inc., the authors and others developed forward models and inverse methods that enable rapid imaging of multiple properties simultaneously. The HyperLattice databases provide a unique tool for visualizing multiple unknown property spaces and building intuition that is valuable for sensor and measurement procedure adaptation as well as for calibration and data integrity verification. This paper describes the HyperLattice-based inverse methods, and provides a few case studies on subsurface damage imaging. These case studies include detection and sizing of hydrogen blisters under weld cladding overlay for refinery vessels and corrosion imaging through insulation or fireproofing. The focus of this paper is on the inverse methods and the key elements needed to perform practical measurements on piping and vessels.

INTRODUCTION

The innovation described in this paper is the use of precomputed databases of sensor responses (called Grids, Lattices and Hyper-lattices) to perform Multivariate Inverse Methods (MIMs). This sounds theoretical, but it has huge practical implications and enables improved performance for eddy current testing (ET) of layered material constructs such as pipelines, coating systems and aircraft structures.

First, in order to use this method it is necessary to meet two difficult challenges: (1) design an ET sensor winding construct that can be accurately modeled to enable accurate prediction of the sensor response over the range of Material Under Test (MUT) properties of interest; and (2) develop an instrument that provides extremely accurate and sufficiently precise measurements over the frequency and impedance range of interest for the ET sensor and the MUT properties. One sensor construct that meets this requirement is the MWM-Array (with inductive sensing elements) or the MR-MWM-Array (with magnetoresistive sensing elements). These sensors both use rectangular drive conductors with long linear drive segments and a row of sensing elements placed at a selected distance ($\lambda/4$) from one of the linear drive segments. Note that when the sensing elements are placed at the center of a simple dual rectangle MWM-Array drive construct, then λ is the spatial wavelength of the primary mode of the magnetic field created by this drive winding construct. This spatial wavelength is proportional to the magnetic field depth of penetration at lower frequencies, while the depth of penetration is inversely proportional to the drive current frequency at higher frequencies. For more on MWM sensor constructs refer to references [1-7].

Material Under Test (MUT) Layups

This paper considers a progression of more and more complex MUT layups, beginning with simple infinite half-spaces and foils. Figure 1 shows this progression, with simple schematics that represent the sensor (shown above the MUT as a dashed line with a liftoff gap between the sensor and the MUT). The caption of Figure 1 lists all the MUT layups considered in this paper. Note that each of these layups is assumed to be comprised of layers with uniform electrical conductivity and magnetic permeability as a function of depth within the individual layer. Note that it is also possible to assume a linear variation in these properties or other more complex property variations, but it is typically not necessary for most NDT applications.

One type of damage that is of interest is general corrosion, which reduces the thickness of a layer over a large surface area compared to the sensor's sensing element footprint (note that the footprint is larger than the actual size of the individual sensing elements and defines the region that each sensing element is sensitive to on the surface of the MUT). For damage such as general corrosion, a simple uniform thickness layer model provides a sufficient representation of the damage. However, for local damage, such as small corrosion pits and cracks, the damage is not well represented by a typical uniform thickness, layered media model for the underlying physics. Thus, for small local damage, as described below, the damage will be represented as a perturbation (deviation or change) from the simple uniform layer model. This perturbation approach is often sufficient for detection and even sizing of damage, if a correlation relationship is developed between the perturbed sensor response and the damage characteristic of interest, such as crack depth.

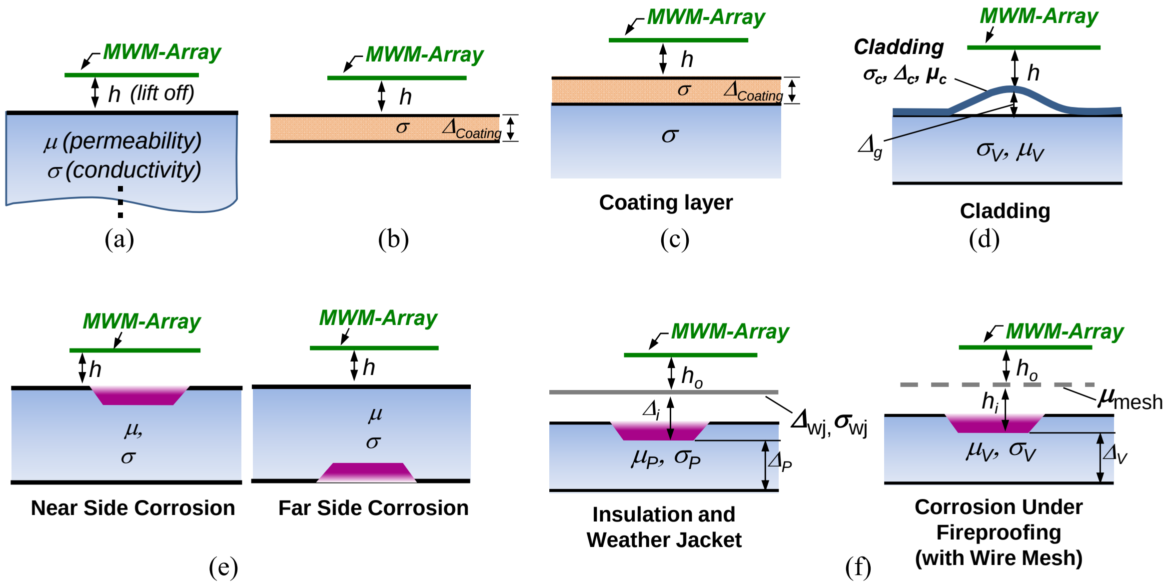

FIGURE 1. Schematics for (a) infinite half-space; (b) conducting, non-magnetic foil; (c) single layer conducting and non-magnetic coating on a thick conducting and non-magnetic base material; (d) single layer conducting and slightly magnetic coating with a disbond or blister between the coating and a magnetic and conducting base material – such as for cladding overlay on an internal vessel surface; (e) corrosion, wall loss, for with an insulating, non-conducting, coating on a conducting and magnetic single layer – such as a pipe or a vessel; (f - left) corrosion, or wall loss, for a magnetic and conducting layer, with insulation and a weather jacket – such as for refiner piping; (f - right) corrosion, or wall, loss for an concrete layer with internal wire mesh - such as for underwater pipeline weight coat or fireproofing for vessel skirts.

The most important thing to understand is that without such a model, behavior from varying unknown properties such as liftoff or insulation thickness or pipe wall magnetic permeability will dominate the responses and the correlation to damage will be unreliable. This is the key. Using a simple model, we can remove the effects on the response caused by things we don't care about, and focus on the response changes caused only by the damage of interest.

However, under some circumstances, it is necessary to use more complex numerical models to represent the 3-dimensional defect geometry. Such numerical models are not addressed in this paper. These more complex models are used after the simple models enable detection and rapid data analysis for gross sizing. Then a more complex model can be used to provide more reliable defect depth and extent sizing.

Grids, Lattices and Hyper-lattices for Multivariate Inverse Methods (MIMs)

Precomputed databases have been generated for each of the configurations in Figure 1, using the simple uniform layer modeling method. These databases are generated off line and used by the GridStation software to perform the MIMs. The GridStation software uses a rapid solver (essentially a database search method) to find the solution for multiple unknown MUT properties of interest for each position of the sensing elements along the inspected or monitored surface of the MUT. Figure 2 shows examples of Grids and Lattices for the two and three unknown layups shown in Figure 1. Note that Grids are for two unknowns and look like a curved sheet of graph paper; Lattices are for three unknowns and are simply a set of Grids. Each Grid in the Lattice represents the same range for two selected unknown variables. For each Grid, the third unknown variable is held constant. This third unknown is then varied from Grid to Grid. Hyper-lattices are difficult to represent visually, since they are used to solve problems with four or more unknowns.

The MIM can be performed on all unknowns simultaneously solving for them by searching the Grid, Lattice, or Hyper-lattice for the best solution, using a single frequency method or a multiple frequency method. Note that each frequency provides a magnitude and phase measurement (or complex real and imaginary part measurement) for the impedance (sensing element voltage divided by the primary current). Thus, for two unknown problems a single frequency is sufficient, since the phase and magnitude measurements each provide the equivalent of one equation that can be solved. But for three of four unknowns, two frequencies are needed since we need either the same number or more equations (measurements) than unknowns – as in simple linear algebra problems. Note that because the physics equations are inherently nonlinear, we must use a search routine to find the solution – thus, by precomputing the solution spaces and searching them rapidly, we can solve complex problems very quickly. For problems with more than four unknowns, three frequencies or more are needed.

In the following sections, some brief descriptions are provided for a few important problems – including imaging of Stress Corrosion Crack colonies through coatings, imaging of corrosion under insulation (CUI) for piping or vessels, sizing of hydrogen blisters under overlay cladding inside vessels, and imaging of corrosion under fireproofing with wire mesh.

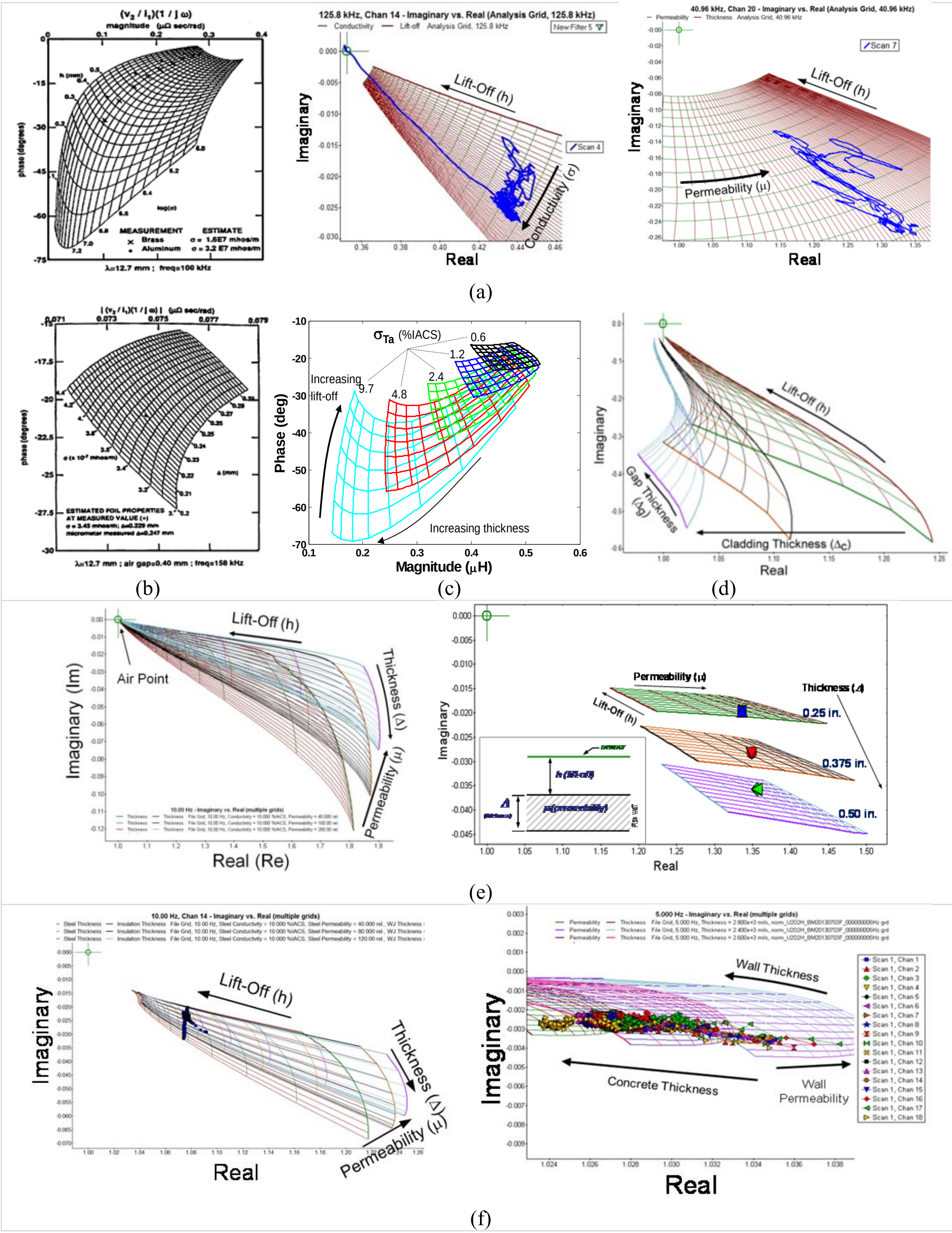

FIGURE 2. Grids and Lattices corresponding to schematics from Figure 1, (a) through (f). Grids a(left) and b(left) were generated in 1989 [4,7]. The b(left) grid is for conductivity and thickness. Before this grid is used a higher frequency measurement provides the lift-off in a “hierarchical” 3-unknown inverse method.

Stress Corrosion Cracking (SCC) Problem Description

Figure 2a (middle and right) provides two different representations of a pipeline SCC colony mapping method. In Figure 2 (middle) the MUT has been represented by a thick layer with a constant magnetic permeability and the effective electrical conductivity is allowed to vary. This is a two unknown problem with the unknowns being liftoff and electrical conductivity. Figure 2 (right) instead, assumes the electrical conductivity is constant and allows the magnetic permeability to vary as one of the two unknowns, along with liftoff as the second unknown. Goldfine [4] showed that the magnetic permeability and the electrical conductivity cannot be measured independently at relatively high frequencies (without use of a variable bias field); thus, either of these representations are sufficient for use of the perturbation method for crack detection and sizing, described earlier. In a perturbation method, the crack shows up as a change in one of the unknowns. This works best if the change is primarily in one unknown of the uniform layer representation. However, for cracks, the estimated liftoff value is also affected for relatively open cracks. Tight closed cracks have a smaller effect on liftoff.

As shown in Figure 3, the magnetic permeability response can also be correlated very well with crack depth and this can be displayed as a C-Scan image of depth for each crack or as a B-Scan for the individual channels. Figure 4 shows examples of crack maps that match very well with the actual crack morphology shown also in the Figure.

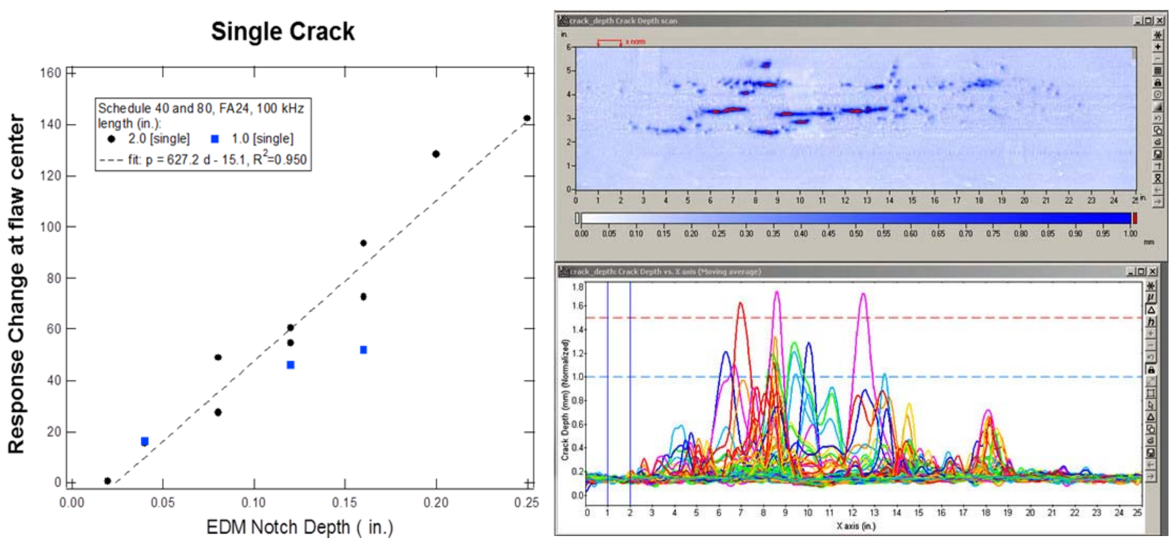

FIGURE 3. (left) Data showing magnetic permeability response can also be correlated very well with crack depth; (right) displayed as a C-Scan image of depth for each crack or as a B-Scan for the individual channels.

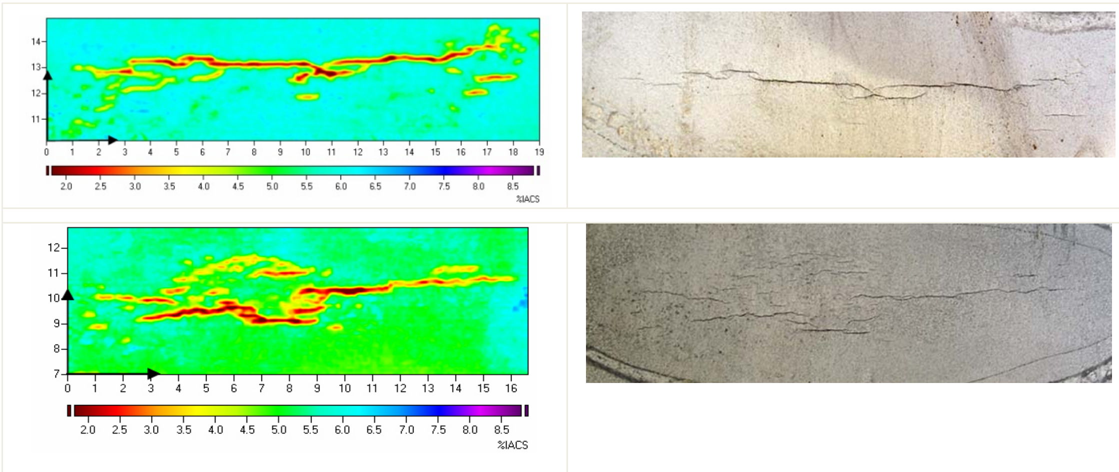

FIGURE 4: (left, top and bottom) MWM-Array crack response C-Scan images. (right, top and bottom) corresponding enhanced photographs of the crack morphology.

CUI (With and Without a Weather Jacket)

Figure 5 and Figure 6 provide results for corrosion under insulation imaging without and with a weather jacket, respectively. For applications without a weather jacket, this is a simple three unknown problem, if we assume the electrical conductivity of the pipe wall layer is constant. If we add the weather jacket, then this becomes a five unknown problem. When we solve five unknowns we typically use a hierarchical method, where we solve for a subset of the unknowns first.

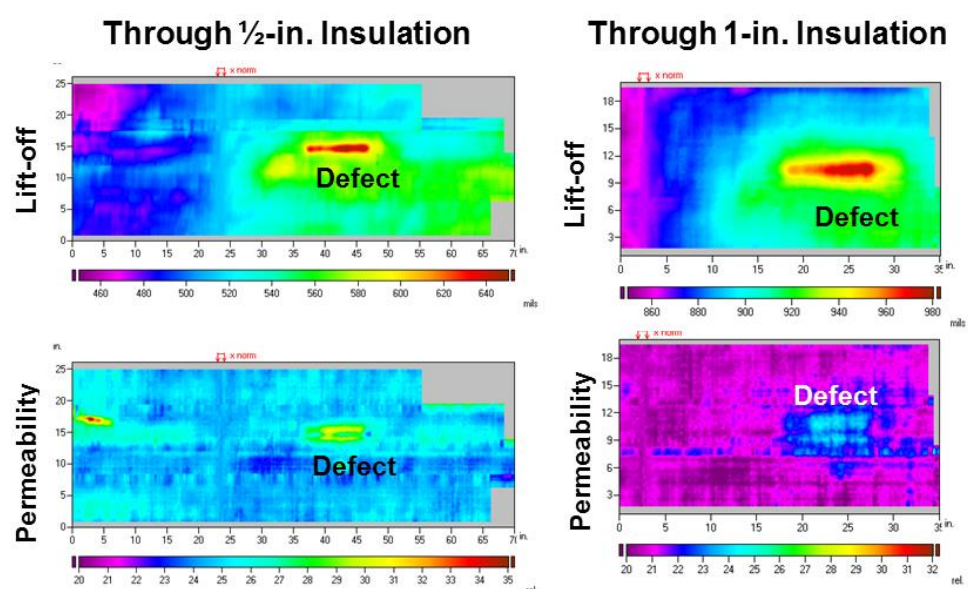

FIGURE 5. Images of lift-off (which is the same as the coating thickness in this case) and magnetic permeability for a riser with a relatively insulating coating. Both the lift-off and the magnetic permeability images show the defect, even when the insulating coating thickness is varied without informing the method.

Note that the use of liftoff for the response in this method requires careful maintenance of relatively constant sensor proximity to the coating, since any variation will show up in the lift-off response.

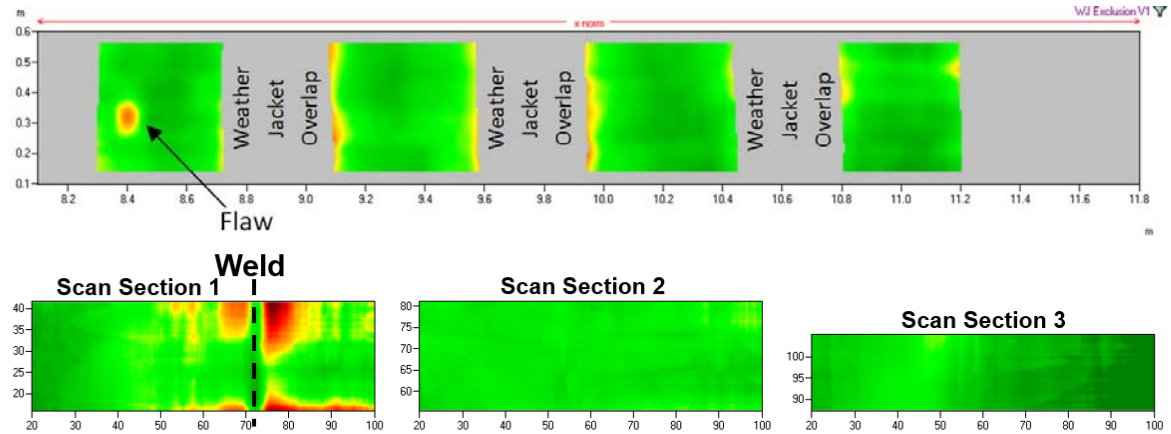

FIGURE 6. Pipe wall thickness images are shown above for imaging of corrosion through weather jacket and insulation. (top) Insulation thickness is 2 inches, the weather jacket is 0.5 mm thick aluminum, and the pipe walls are 0.25 inches and the corrosion is external. (Bottom) Insulation thickness is 2 inches, the weather jacket is 0.5 mm thick aluminum, and the pipe walls are 0.5 inches and the corrosion is internal.

Hydrogen Blister Imaging for Overlay Cladding and Base Material Crack Detection

One challenging application is the imaging of disbonds between overlay cladding and the base material for large vessels. To solve this problem the disbond is modeled as a simple gap and this gap is estimated as one of the unknowns. Details for this application are provided in a complementary paper at this conference [5]. This problem can be solved as a three unknown problem for liftoff, cladding thickness and gap; if we assume that the cladding conductivity and magnetic permeability are constant and known, and that the base material conductivity and permeability are also constant and known. For the more complex problem where the goal is to detect cracks in the base material, the base material magnetic permeability can be added as a forth unknown.

Corrosion under Fireproofing (CUF) or Weight Coat

CUF imaging or corrosion imaging through weight coat for underwater pipelines is also of interest. This problem adds the complexity of having a magnetic layer (the wire mesh) inside an insulating (non-conducting) layer of concrete. This problem can be solved by simply estimating the magnetic permeability of the wire mesh and then treating it as a constant, if we can assume we know the approximate position of the mesh within the concrete layer. One way to accomplish this is to assume that the nominal vessel or pipe wall thickness is known at a few locations and then use these locations to estimate the wire mesh properties and position, first. This has been demonstrated successfully both in the laboratory and in the field, and is also described in a complimentary paper at this conference [6].

SUMMARY

This paper provides a brief overview of the visualization value provided by Grids and Lattices for complex multiple unknown problems. Schematic representations have been described for problems that range from a simple foil, to a pipe with insulation and weather jacket or a vessel skirt covered by concrete with wire mesh. The key is to identify the unknowns of interest and to solve them rapidly with a MIM. The MIM relies on having a sensor that has a response that can be accurately predicted over the range of MUT properties of interest and an instrument that can provide accurate measurement of impedance at multiple frequencies over impedance range of interest.

This method has numerous practical applications, such as SCC crack depth measurement, internal and external corrosion imaging, and hydrogen blister volume estimation. This method is in use with the MWM-Array and MR-MWM-Array sensors, providing reliable services for a range of applications.

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