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MWM$^{®}$-ARRAY ELECTROMAGNETIC TECHNIQUES FOR CRACK SIZING, WELD ASSESSMENT, WALL LOSS / THICKNESS MEASUREMENT, AND MECHANICAL DAMAGE PROFILOMETRY

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ABSTRACT

Magnetic field-based eddy current sensor arrays are seeing increasing focus as an inspection technique that can deliver reliable and low-cost solutions for high resolution imaging of damage in pipelines. Eddy current methods don't require surface preparation (such as sand blasting) and external protection can be left in place, including corrosion protection coatings, thermal insulation, weight control coatings, and even metallic weather protection. This reduces the amount of time associated with non-inspection activities, which reduces overall costs.

This paper describes recent enhancements to the JENTEK's Meandering Winding Magnetometer (MWM$^{®}$-Array) very low frequency and higher frequency eddy current technologies for detection and characterization of damage in pipelines through coatings and insulation, including crack sizing, weld assessment, and wall thickness measurement [1,2,3,4,5, 6]. The MWM-Array technology uses eddy-current sensor arrays (with inductive and magnetoresistive sensing elements) and model-based inverse methods (using precomputed databases called hyperlattices) to determine properties of the pipeline materials, pipeline wall loss/thickness and mechanical damage profilometry, which are then related to damage conditions

INTRODUCTION

Eddy current sensors are used extensively in the aerospace and defense industry, but have had limited success in the oil and gas field compared to competitive techniques such as ultrasound, radiography, and magnetic flux leakage (MFL). Typical limitations have included limited liftoff tolerance (distance between the sensor and the part), limited coverage area, slow scan speeds, and the inability to detect defects on the far side of a material. However, these issues are not fundamental limitations of the eddy current method. JENTEK Sensors has been broadening the capabilities of its product line to address applications specific to the oil and gas field. By changing the design and construction of eddy current sensors and expanding the operating frequency range to very low frequencies, JENTEK has been able to overcome many of the limitations of traditional eddy current methods while maintaining the strengths of the technique, such as non-contact operation, insensitivity to non-conductive materials (such as insulation and coatings), and the ability to measure multiple material properties simultaneously. These advancements have lead to innovative solutions for corrosion under insulation (CUI) with and without weather protection, crack characterization (including SCC), wall thickness measurement, and mechanical damage characterization.

MWM SENSOR TECHNOLOGY

Many aspects of the original MWM technology have previously been published for both the aerospace industry and the pipeline industry [7,8,9]. The MWM sensors are eddy current-based sensors that are conformable and provide inspection and monitoring capabilities for conducting and magnetic materials.

As shown in Figure 1, the original single channel MWM sensor geometry had a meandering primary winding for creating a spatially periodic magnetic field when driven by an electrical current – hence the MWM name [7]. Secondary elements (sense elements) are located on opposite sides of the primary for sensing the response. These secondary elements can be inductive windings (simple turns of wire) or solid state (such as Hall effect or magneto-resistive).

While the sensor geometry in Figure 1 produces a very accurate and robust sensor, it is not useful for imaging applications where the goal is to provide high resolution maps of large areas. For these applications, the MWM geometry was adapted to accommodate multiple, high resolution sense elements placed next to a linear and compact drive winding, as shown in Figure 2 [1,2]. This simple, patented construct allows both deep penetration and relatively high-resolution imaging compared to attempts by other low frequency eddy current methods.

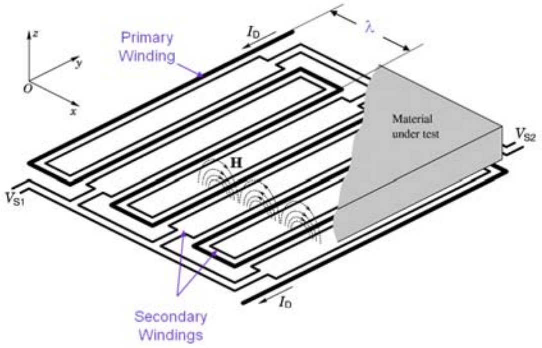


Figure 1. Original MWM sensor geometry.

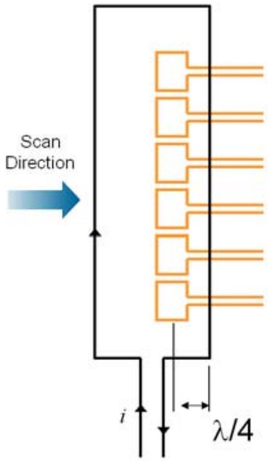


Figure 2. Schematic of an MWM-Array with a single linear drive winding (black) and multiple sense elements (orange), and defines the quarter spatial wavelength (λ/4) also called the drive-sense gap.

MEASUREMENT AND DATA PROCESSING

When taking a measurement, a time-varying current is applied to the drive winding, which produces a time-varying magnetic field. When the drive winding is in proximity to a conductive material, the changing magnetic field induces currents in the material (eddy currents) that flow in the opposite direction of the drive current. These eddy currents produce associated magnetic fields that add to the magnetic field created by the drive winding. The total field is then measured by the sense elements. By measuring the current in the drive winding and the voltage produced by the sense elements, the properties of the material (pipeline) can be estimated and defects detected.

One advantage of the MWM geometry is that the sensor response can be accurately predicted using layered media models. Figure 3 shows a simple model of an MWM sensor over a material such as a pipeline. By assuming the parameters of the model (the permeability, conductivity, and thickness of the steel, as well as sensor geometry and sensor liftoff), the sensor response can be accurately predicted.

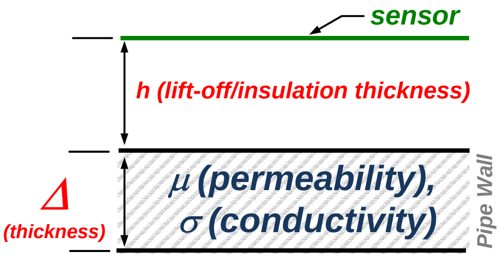


Figure 3. Simple layered media model for the inspection of a pipeline.

MWM and MWM-Array responses are converted into material or geometric properties using measurement grids (See Figure 4) [3]. These grids convert the sensor response into the unknown properties of interest, such as pipe wall thickness, electrical conductivity, magnetic permeability, and lift-off. The grids are generated by varying two of the parameters in the layered media model (Figure 3) to create two-dimensional database of precomputed responses. Figure 4 shows a conductivity/lift-off grid and data from one channel of an MWM-Array in scans performed with four different insulating coating thicknesses (which changes the sensor liftoff). This figure illustrates how the conductivity and lift-off can be independently measured by comparing the sensor response to the database of pre-computed sensor responses [9].

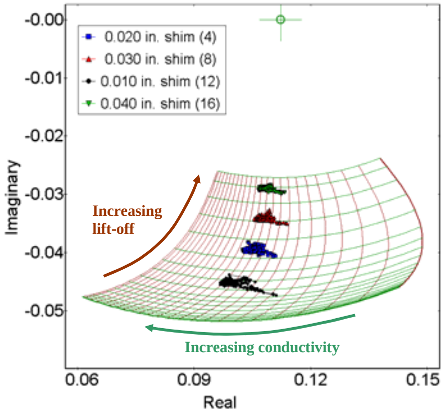


Figure 4: Representative measurement grid.

Higher-order databases are used for the determination of more than two unknown properties of interest, such as coating thickness (via sensor lift-off or proximity), pipe wall thickness, and pipe electrical conductivity and/or magnetic permeability. A higher-order database is called a hyperlattice. Figure 5 shows typical slices of a hyperlattice for measuring the thickness and permeability of a steel pipeline while accounting for a variable sensor liftoff (or insulation/coating thickness). The figure shows three measurement grids (green, red, and blue) that represent the sensor response for varied sensor liftoff and pipe permeability, but with an assumed and constant pipe thickness. The data shown on the grid was taken on three steel plates of the same thickness assumed by the individual grids.

Note this is just for illustration purposes. In application, these databases cover the range of possible thicknesses and algorithms are used to search through these hyperlattices and interpolate between the stored values. Figure 5 shows a hyperlattice at a single frequency. In order to separate the effects of multiple parameters such as pipe wall thickness, pipe permeability, and sensor liftoff, data taken at multiple drive frequencies must be combined. This calculation is difficult to visualize, but is rapidly performed by JENTEK's GridStation® software algorithms.

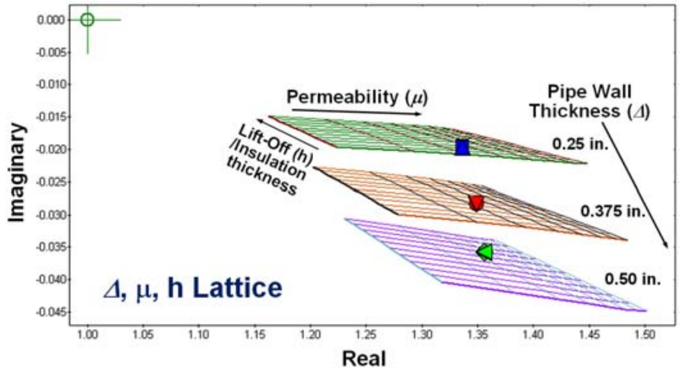


Figure 5. Representation of a 3-parameter Hyperlattice for the permeability and thickness of a steel plate, as well as the sensor liftoff.

MWM-ARRAY SENSORS

In order to ensure that MWM-Arrays match the physics based models, printed circuit microfabrication techniques are typically employed to produce the inductive sense elements, resulting in highly reproducible (i.e., essentially identical) elements. Drive windings can be either etched or fabricated by carefully locating multiple turns in a single plane of a flexible substrate. This patented [1,2,6] hybrid wound/etched fabrication is key to the MWM-Array success. The use of a flexible substrate makes the sensors ideal for scanning complex or variable geometries, or for adapting to different pipe diameters with a single sensor array.

When designing MWM-Arrays for a given application, the spatial wavelength is a significant design parameter. Figure 1 shows the definition of the spatial wavelength (λ) for the original MWM single channel sensor. Figure 2 shows the definition of the quarter spatial wavelength (λ/4) for a typical MWM-Array. Since it is the distance between the sense element and the nearest leg of the drive winding, it is often referred to as the drive-sense gap.

The spatial wavelength is an important consideration because it affects the depth of penetration (DOP) of the magnetic field into the test material. As shown in Figure 6, the DOP depends upon both the drive current frequency and sensor geometry. At high frequencies, the DOP is limited by the drive frequency and the properties of the material being inspected. However, at low frequencies, the DOP is limited by the sensor geometry. The magnetic fields from a larger spatial wavelength sensor will penetrate farther into the material under test than a shorter spatial wavelength sensor. While the drive frequency can be varied by the instrumentation, the spatial wavelength is part of the sensor design and must be determined in advance. To accommodate this limitation, JENTEK has developed a suite of sensors to suit specific groups of applications.

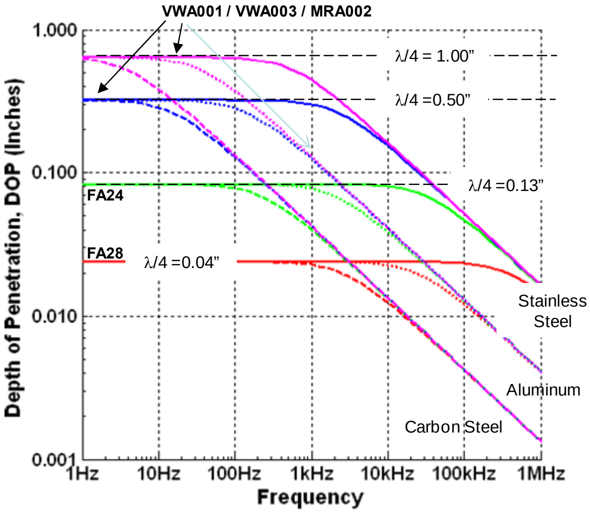
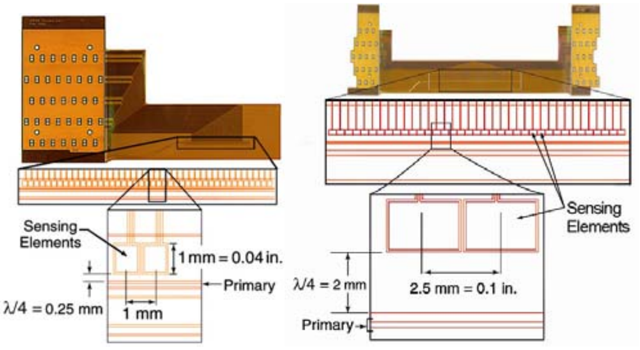


Figure 6. Depth of penetration variation with sensor dimension.

For high-resolution imaging of bare metal or very thin coatings up to 1mm (0.040 inches), as small spatial wavelength sensor such as the FA28 MWM-Array can be used (Figure 7 (a)). JENTEK has demonstrated this sensor as an MPI replacement for SCC imaging in pipelines. The advantages of the FA28 over MPI include digital record keeping, automated crack interaction assessment, insensitivity to environmental conditions (rain and lighting conditions), and the elimination of surface preparation (i.e. no sand blasting). This sensor can also be used for crack detection around mechanical damage sites. The flexible Kapton of the sensor can conform to complex dent geometries while still providing a reasonable scan width. It can also be used to characterize smaller corrosion defects, such as pitting.

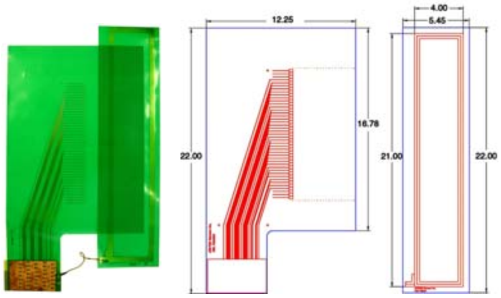
The FA24 MWM-Array shown in Figure 7 (b) has larger dimensions than that of the FA28 and permits inspection through thin coatings up to 6mm (0.25 in). The larger spatial wavelength can accommodate the larger coatings, but at the cost of producing a lower resolution image. JENTEK has demonstrated this sensor as a screening tool for SCC prior to the removal of protective coatings. This sensor is also useful for crack detection. It will produce lower resolutions images than the FA28, but cover area more quickly, which is useful for large area inspection and in situations where the critical crack size is larger.



(a) (b)

Figure 7. (a) The FA28 MWM-Array for high resolution defect mapping; (b) The FA24 MWM-Array for defect mapping through coatings.

For inspecting through thicker coatings, JENTEK has developed the Variable Wavelength Array (VWA) sensors. These sensors have a separate drive winding and sense element array, so the spatial wavelength can be adjusted to suit the specific application. The VWA001 is shown in Figure 8 and the VWA003 is shown in Figure 9. These sensors were developed specifically to address thicker coatings in the 6mm to 25mm (0.25 inch to 1.0 inch) range, although thicker coatings can be accommodated with minor modifications. These sensors have been demonstrated for the characterization of external corrosion in risers through protective coatings such as Splashtron®.



(c)

Figure 8. The VWA001 MWM-Array for defect mapping through thick coatings.

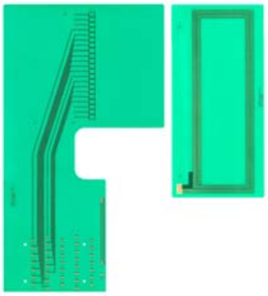


Figure 9. The VWA003 MWM-Array for defect mapping through thick coatings.

The FA28, FA24, and VWA MWM-Array sensors provide solutions for problems where the spatial wavelength is the limiting factor. However, there are a variety of problems in the oil and gas field where the required depth of penetration is limited by the drive frequency. However, the MWM-Arrays shown thus far cannot operate at low frequencies because the signal produced by inductive sense elements drops as a function of the drive frequency. To overcome this limitation, JENTEK has developed the MR-MWM-Array. This sensor uses magneto-resistive sense elements that produce more signal at low drive frequencies. One example of sensing elements for an MR-MWM-Array, the MRA002, is shown in Figure 10. This sensor has a separate drive winding (not shown) so that the spatial wavelength can be varied based on the application, similar to the VWA sensors. This MRA002 is used for deep penetration applications. JENTEK has demonstrated this technology for the characterization of internal and external corrosion through typical pipeline wall thicknesses, thick insulation, and metallic (aluminum or stainless steel) weather protection. The MRA002 includes both inductive and MR elements to enable characterization of a weather jacket, insulation thickness, and pipe wall simultaneously.

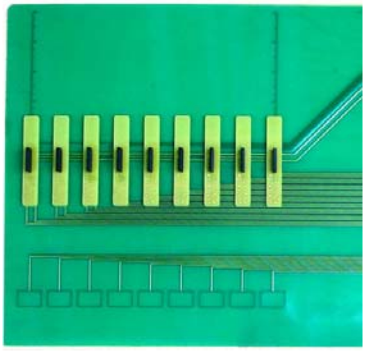


Figure 10. MR-MWM-Array sensor, MRA002.

AIR CALIBRATION

All of the applications described in this paper make use of JENTEK's air calibration techniques per ASTM E2338 [4, 11]. This type of calibration requires no calibration standards and greatly increases the repeatability of calibration, particularly with operators who have limited training. Since all of JENTEK's sensor arrays are designed and fabricated to match physics based models of the sensor response, an air calibration can provide accurate and repeatable measurements of absolute material properties and layer thicknesses.

FIELD DEPLOYABLE INSTRUMENTATION

JENTEK has developed two field deployable instruments. The GridStation Durable (GS-D) 8000-Series instrument is a 39-Channel fully parallel system that supports wide area scanning applications. The GridStation HandHeld (GS-HH) 8050-series is a 7-Channel fully parallel system for small scanning arrays and embedded sensor applications. Both systems feature a full Windows-based computer and JENTEK's GridStation analysis software. The GS-D has an optional battery pack, while the GS-HH has an integrated battery. Systems with larger number of channels (fully parallel, as well) will be introduced over the next few years.

Figure 11. JENTEK GS-D8000 (Left) and GS-HH8050 (right) systems.

APPLICATION - CORROSION UNDER INSULATION (CUI) IMAGING THROUGH COATINGS, INSULATION, AND WEATHER PROTECTION

JENTEK's VWA MWM-Arrays and MR-MWM-Arrays use wide bandwidth eddy current methods to characterize both internal and external corrosion in pipelines and vessels through coatings.

Figure 12 shows the VWA001 being applied for the detection of external corrosion from the outside through a 6mm (0.5 inch) coating. The samples, provided by PRCI as part of a blind test, contained manufactured defects covered by a Splashtron coating. Figure 12 shows the samples, the VWA001 scanner, and an MWM-Array image of a representative defect detected during the test.

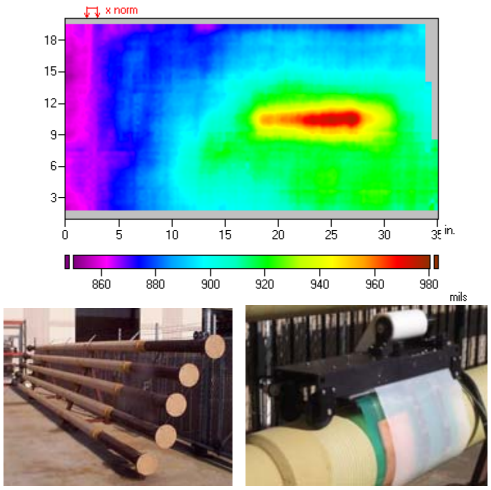


Figure 12. MWM-Array image (top) of a manufactured external corrosion defect through 1 in. coating on a riser (bottom left). Scanner is shown bottom right.

In addition to providing external corrosion imaging, JENTEK's low frequency MR-MWM-Array can be used to characterize wall loss due to internal corrosion. Figure 13 shows the MR-MWM-Array MRA002 mounted on a scanner designed for inspecting pipes for corrosion under insulation. This is a flexible scanner that can be adapted for a wide range of pipe diameters and insulation thicknesses. Figure 14 shows a scan of an internal corrosion defect in an 8-inch schedule 80 pipe (13mm, 0.50-inch wall). The scan was performed at 13mm (0.5-inches) per second through 25mm (1.0-inch) of a neoprene coating. Using hyperlattice methods, JENTEK is able to produce an absolute measurement of the pipe wall thickness and high resolution defect detection and sizing with just an air calibration. This reduces the complexity of the system and the overall system cost, and allows independent discrimination and sizing of both internal and external defects. Note that this array has nine sense elements for a 4.5 in. wide scan path. Future arrays will have more elements for faster wide-area inspections.

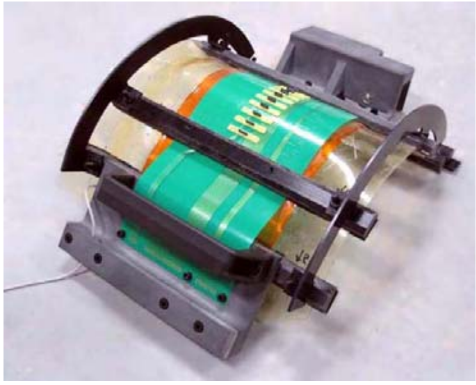


Figure 13. JENTEK MR-MWM-Array scanner, incorporating the MR-MWM-Array.

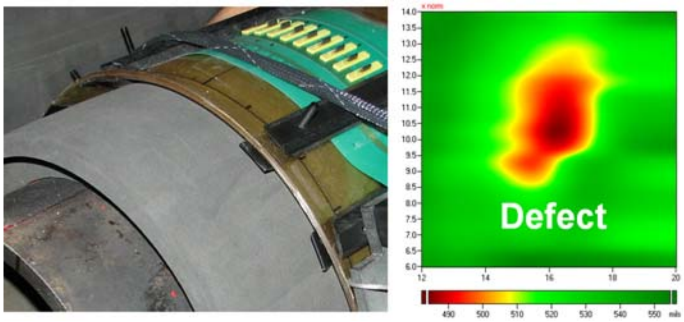


Figure 14. Detection of a 50mm (2-inch), 50% wall loss defect in an 8-inch schedule 80 (13mm, 0.50-inch wall) pipe through 25mm (1.0-inch) of insulation. The scan was produced at 13mm (0.5-inches) per second

JENTEK has also adapted its patented segmented-field magnetometry methods [8, 10] for the detection of internal and external corrosion through insulation and aluminum or stainless steel weather protection. Segmented field magnetometry uses parallel rows of inductive and MR sense elements at different distances from a linear drive to provide independent information used to estimate the properties of the weather jacket, insulation, and steel. The combination of the low frequency MR sense elements with the high frequency inductive sense elements allows the sensor to operate over a very wide range of frequencies. JENTEK's hyperlattices are used to rapidly correct for the presence of the weather jacket, the insulation thickness, the steel permeability, and the steel conductivity to measure the remaining pipeline wall thickness. Similar performance to competitive methods, such as phased array UT, can be achieved at similar scan speeds without removal of the weather jacket and insulation.

Figure 15 shows the MRA002 scanner on an 8-in. schedule 80 (13mm, 0.5-inch wall) pipe sample with a 0.64mm (0.025-in.) aluminum weatherjacket. Figure 16 shows a typical scan over two 50mm (2-inch) external defects with 20% and 35% wall loss. Using JENTEK's hyperlattice methods, the system produces a measurement of the absolute wall thickness while compensating for sensor liftoff, the weatherjacket properties, the insulation thickness, and the pipe properties.

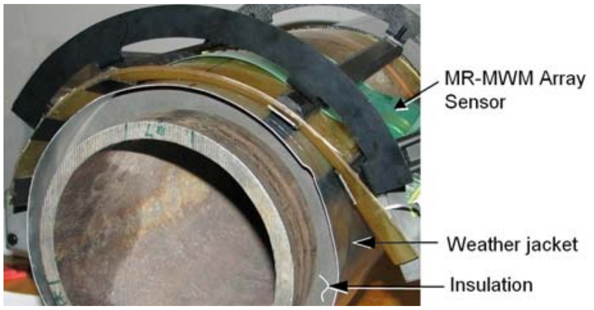


Figure 15. MR-MWM-Array demonstration set up of 1/2 in. thick pipe with 1-in. insulation and weather protection.

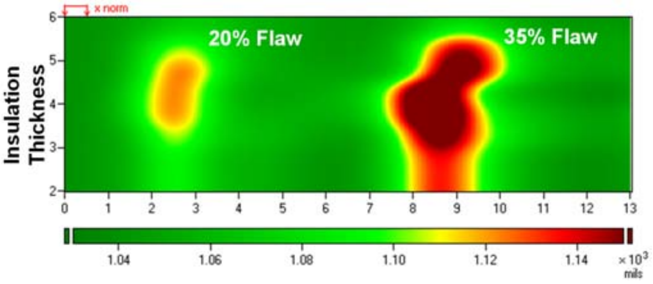


Figure 16. MR-MWM-Array scan through insulation and weather protection.

This CUI capability has been developed with funding from JENTEK Sensors, Inc. and DOT, and has been demonstrated under funding from Chevron and other oil majors. The system is currently transitioning for field deployment and is being demonstrated for select oil and gas companies (Figure 17). [9]

Figure 17. Redeveloped JENTEK MR-MWM-Array sensor, for scanning through-wall and insulation.

JENTEK's approach to detection of CUI overcomes several major challenges that have prevented solution of this problem for many years. Currently, only UT can provide sufficient performance, but it requires removal of the weather protection and insulation, which is impractical for the anticipated miles of pipeline that will need inspections. Alternative pulsed ET methods do allow inspection through insulation and weather protection, but are very slow and provide low resolution imaging. The patented MWM-Array design overcomes this image resolution limitation [2].

The MR-MWM-Array is the only practical tool that has demonstrated a realistic and fundamentally-sound solution to this pervasive need. The MR-MWM-Array is the first rapid scanning, high-resolution method that enables inspection without removal of coatings for risers, as well as weather jacket and insulation for pipelines.

APPLICATION – MECHANICAL DAMAGE

MWM-Arrays can be used for a variety of tasks for the characterization of mechanical damage. When investigating a mechanical damage site, the geometry of the dent and the detection of cracks are both needed to assess the pipeline condition. In addition, information about the residual stress around the dent can be used to identify re-rounding and to improve fitness for service evaluations.

MWM-Arrays can be used to produce a measurement of the dent geometry. Figure 18 (left) shows a VWA001 being used to image the geometry of a dent in a pipeline (Figure 18, bottom right). The 3D image (Figure 18, top right) rapidly produced by this system can then be used to make reference measurements for simple fitness for service calculations, or exported to finite element programs for more sophisticated analysis.

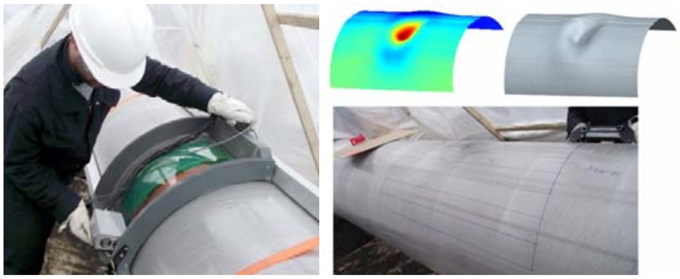
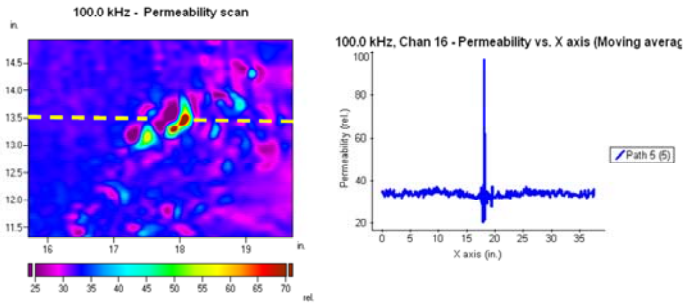


Figure 18. Left: MWM-Array VWA001 scanned over the dented area of an in-ditch pipe section (shown bottom right). Top Right: Dent 3D profiles produced using the VWA001 data.

For crack detection, high resolution arrays such as the FA28 and FA24 can be used. Figure 19 shows an FA24 scan over a crack at a mechanical damage site. Typically, a crack response will be localized and produce an apparent rise in magnetic permeability.



(C-Scan) (B-Scan)

Figure 19. The most pronounced indication within the dented area. The yellow line in the C-Scan shows the location of the B-Scan.

The same sensors can be used to obtain information regarding the extent of the plastic deformation and residual stress field produced by the damage, including re-rounded regions. Figure 20 shows a specimen that was dented with a 50mm (2-inch) indenter. A scan performed with the FA24 shows the stress-induced permeability halo around the damage site. JENTEK is currently developing methods for converting this permeability measurement into a reliable measure of residual stress and plastic deformation.

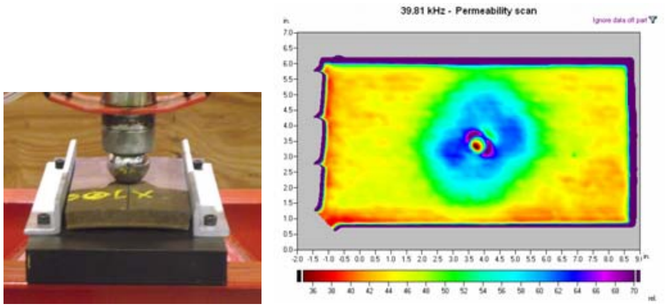


Figure 20. An example of the stress-induced permeability halo produced by mechanical damage. The stress-induced permeability halo (right) extended far beyond the region affected by the indenter (left).

APPLICATION – SCC MAPPING WITH AND WITHOUT COATINGS

SCC is a continuing problem for the pipeline industry. MWM-Arrays provide an advanced alternative to other crack detection methods such as magnetic particle inspection (MPI). JENTEK has a proven track record for detecting and mapping cracks in aircraft components and has extended this capability to pipeline inspection. MWM-Arrays can produce maps of SCC colonies that are highly repeatable and digitized for accurate record keeping. The digital maps can also be processed to access crack interaction criteria and to produce automated reports.

Since MWM-Arrays use magnetic fields to inspect the material, they can inspect for SCC through non-conductive coatings. Figure 21 shows five SCC maps of the same sample with five different coating thicknesses. As the coating thickness increases, the resolution of the image decreases, but the cracks are still detectable. This type of inspection can be used as a screening tool to detect SCC without removing the coating. Once the coating is removed, higher-resolution MWM-Arrays can be used to create accurate maps of the SCC cracks.

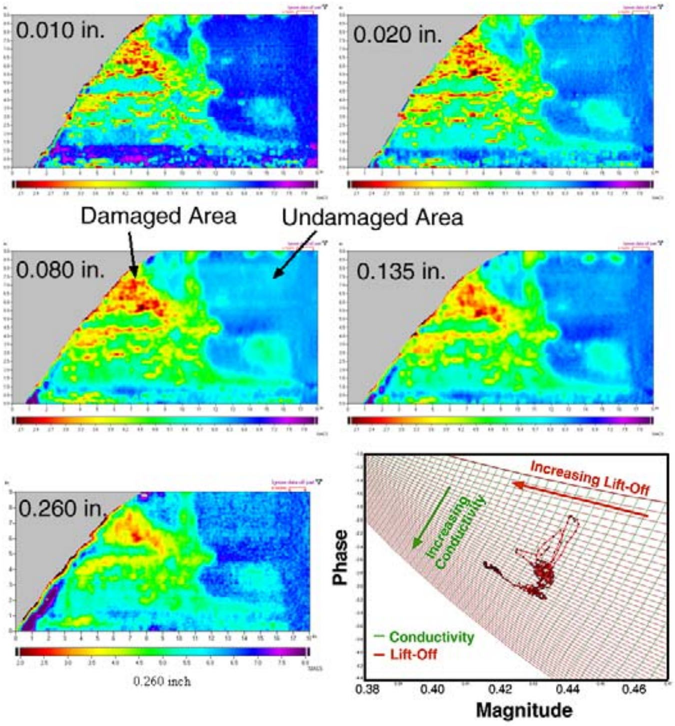


Figure 21. MWM-Array scans of SCC imaging through coatings, up to 0.25 in.

APPLICATION – WELD INSPECTION

MWM-Arrays can also be used to characterize defects in welds. This capability is similar to JENTEK's other crack and defect characterization methods, except that special care must be taken to account for the presence of the weld. Eddy current sensors are sensitive to changes in the material's electrical properties. These properties can vary across the weld, reflecting differences in the microstructure of the base metal, the heat affected zone, and the fusion zone. The properties can also vary along the weld. Finally, rough welds with a significant crown can require special fixtures to ensure that the sensor conforms to the surface of the weld.

Weld quality in ERW pipe is currently a significant concern for the pipeline industry. Fortunately, these types of welds tend not to have the large variations is electrical properties that can cause problems for eddy current sensors compared to other types of welds.

Figure 22, Figure 23, and Figure 24 show some typical scans of defects in an ERW weld. JENTEK received this sample containing API 5L reference notches from an industry partner. The sample contained two EDM notches, one on the OD and one on the ID, and one 1/8" thru hole. All features were placed directly on the weld. The exterior of the pipe is cover by a fusion bonded epoxy (FBE) coating approximately 0.10 inches thick. The coating was ground away in one location so that the OD notch could be added (see Figure 22).

A typical scan of the OD notch is shown in Figure 23. The EDM notch appears as a rise in effective magnetic permeability, which is consistent with real cracks (although the magnitude of the effect is likely to be different between an EDM notch and a real crack of similar dimensions). There is a large change in lift-off due to the coating that was removed around the EDM notch. However, this large lift-off change does not affect the effective permeability measurement. While there is some change in permeability around the ground area, it is likely that the magnetic permeability was changed by the grinding process.

Figure 24 shows a typical scan from the ID notch and the 1/8" thru hole. The EDM notch appears very clearly as a rise in effective permeability. The 1/8" thru hole appears in both permeability and lift-off. This cross-property effect is common for this type of feature. JENTEK has developed spatial filters that are designed to identify and categorize these types of defects automatically.

Figure 22. OD EDM notch. The FBE coating is removed around the notch.

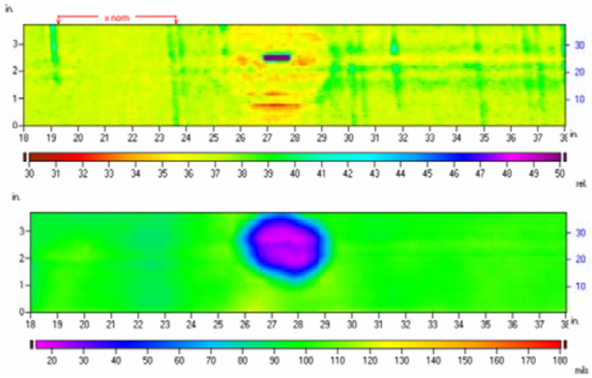


Figure 23. Typical scan images of the OD notch: (top) Image of the effective permeability; (bottom) Image of the effective lift-off.

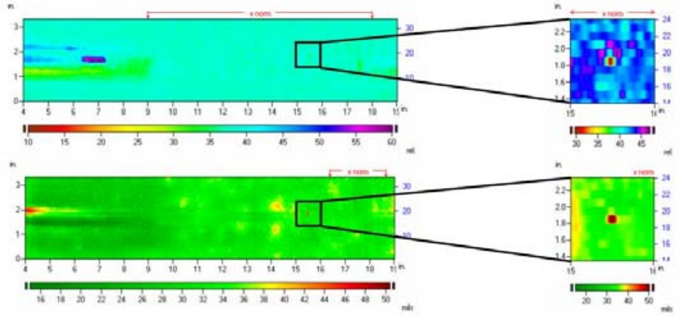


Figure 24. Typical scan images of the ID notch and 1/8 inch thru hole. (a) Image of the effective permeability. (b) Image of the effective lift-off.

DISCUSSION

Eddy current technology is seeing increasing focus as a practical alternative in petrochemical applications because it permits rapid and reliable imaging of pipeline material condition. Both with and without coatings, these methods can provide information about the material condition that can assist with characterization of damage conditions and support assessment decisions.

Performing a JENTEK MWM-Array or MR-MWM-Array inspection on a coated pipeline is simply a matter of selecting a sensor with an appropriate spatial wavelength. Selection of a sensor with a geometry that is too small would not enable inspection through the coating and selection of a sensor with a geometry that is too large would reduce sensitivity to the presence of small features.

Making sense out of the sensor data can be complex. However, by making sensors that accurately match physics based models, software algorithms can be used that convert these complex responses into real material properties (e.g. conductivity, permeability, and thickness). JENTEK has implemented algorithms using hyperlattices that make the complex data analysis invisible to the end user.

For several applications, including imaging of external corrosion, mechanical damage, and SCC, the technology is mature with demonstrated capabilities. For some applications, such as internal and external corrosion inspection through thick coatings and weather protection, feasibility has been demonstrated both in the laboratory and in limited field trials, but ongoing work is continuing to provide a mature field inspection tool. [10]

While the emphasis of this paper was on external inspection through coatings and insulation, the same basic technology can also be applied to in-line inspection (ILI) applications. While coatings are being applied to the inside of some pipelines, liftoff from the pipe wall is a more common issue. Eddy current sensors like the MWM-Array can measure and compensate for this liftoff. JENTEK is currently developing a high frequency ILI tool that will measure the internal profile (detection/imaging of internal corrosion) of the pipe and permeability variations related to stresses or microstructure changes.

JENTEK is currently developing a crack depth capability, specifically focusing on crack depth measurement for SCC colonies. This work is being funded by DOT, PRCI, and JENTEK. We have already demonstrated that data taken over a wide frequency range can be used to characterize the depth of individual cracks and we are currently extending this capability to include SCC colonies. As discussed earlier, high resolution MWM-Arrays can be used to create maps of SCC colonies. In order to add a crack depth measurement, these maps need to be combined with very low frequency data collected with the MR-MWM-Array. JENTEK is currently working on fusing these data sets to produce a crack depth assessment capability.

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